

Stellingen

behorende bij het proefschrift

Robots in the Building Industry

Ronald Krom

18 november 1997

- 1 Bouwtaken die om improvisatie vragen kunnen vooralsnog niet aan robots worden overgelaten.
- 2 Robotisering op de bouwplaats vereist betere elektronische plaatsbepalingssystemen dan thans beschikbaar.
- 3 Alhoewel in dit proefschrift de verwachting wordt uitgesproken dat robots in de bouw in een geleidelijk proces hun intrede zullen doen (evolutie), is het denkbaar dat er in de toekomst onverwachte toepassingen worden gevonden die het invoeringsproces drastisch versnellen (revolutie).
- 4 Het doorberekenen van de werkelijke kosten van ziekteverzuim en arbeidsongeschiktheid in de arbeidskosten, zou de interesse voor bouwrobots sterk doen toenemen.
- 5 Wanneer de Japanse bouwbedrijven volgens dezelfde groeistrategie te werk gaan als de automobielfabrikanten, dient de Europese en Amerikaanse bouw er serieus rekening mee te houden dat de Japanse robot-bouwmethoden normbepalend zullen worden.
- 6 Voor toepassing van bouwrobotica moeten robots geschikt worden gemaakt voor de bouw en de bouw geschikt worden gemaakt voor robots.
- 7 Vanuit het oogpunt van de werkvoorbereiding moeten bouwrobots niet worden beschouwd als een nieuw stuk materieel, maar als een nieuwe bouwmethode.
- 8 De bouw is veel meer een informatieverwerkende industrie dan menigeen denkt.
- 9 Bouwrobots zijn géén ijzeren bouwvakkers.
- 10 Door de belasting op loon en BTW is uitbesteden van werk voor particulieren aanzienlijk duurder dan doe-het-zelven. Deze onbalans is macro-economisch gezien ongewenst omdat men zich bij het doe-het-zelven bezig houdt met taken waar men minder efficiënt in is.

- 11 Het huidige beleid in de gezondheidszorg waarbij het aantal medische verrichtingen per jaar gequoteerd is, is in tegenspraak met de wens van het paarse kabinet om meer marktwerking te introduceren.
- 12 De publieke discussie over de grenzen aan de door Schiphol veroorzaakte milieubelasting, wordt sterk vertroebeld door het gebruik van de onduidelijke maatstaf 'passagiersbewegingen'.
- 13 De aaibaarheid van katten is evenredig met de verstreken tijd sinds ze voor het laatst te eten hebben gehad.
- 14 Promovendi die verwachten dat ze langer dan gebruikelijk over hun promotieonderzoek doen, zijn gebaat bij de keuze van een onderzoeksonderwerp waarin de ontwikkelingen langzaam verlopen.

1. Introduction
2. Background
3. Methodology

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Robots in the Building Industry

Robots in the Building Industry

PROEFSCHRIFT

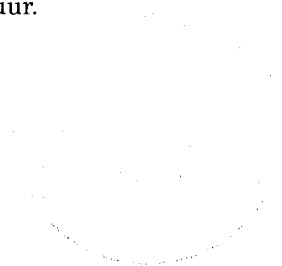
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Preface

The possible advent of construction robots on our building sites is a controversial subject, often treated with great scepticism. During the many years that I have been working on the subject, I have encountered few people in the building industry business, who truly believe that construction robots will be able to replace human workers in construction. An exception should be made for Japanese construction companies, where construction robotics is a serious research item. This situation seems to have much in common with the situation in the 1960s when George Devol and Joseph Engelberger started selling their first 'Unimate' robots. At that time, labour costs were low and robots were expensive devices with limited performance. It took until 1974 before robots were used in Japanese motorcycle production. In the 1980s Japanese car manufacturers perfected the car manufacturing process and showed the world their 'lean production', fully robotised factories. Since that period robots are associated with car manufacturing.

With this thesis I hope to be able to convince readers that robots will also come to the building industry. Although this thesis was primarily written to prove my proficiency to carry out scientific research, I hope that it is also of interest to the research community and building industry management.

Many people ceased to believe that I would ever finish this thesis. But after eight and a half years it is finally there. I feel proud that after all I have been able to finish it. It would have been a painful experience to have to abort this work. This nearly happened in 1994 when the ministry of defence became impatient and called me up for my military service. Fortunately their medical examiner noticed that I was unsuitable for the army. I am still very grateful to this medical examiner that allowed me to finish this thesis.

Furthermore I would like to acknowledge all those people who assisted me in all thinkable forms with the realisation of this thesis. First of all I thank Sylvia for her ever lasting pressure to work on this thesis. Of course I also have to thank Frits Tolman for his continuing believe in me during the years.

I am also grateful to Dr. Karl Schulz, Takatoshi Uneo, Hironori Adachi, Bob Hasara and Nario Yoshida for providing me with the interesting pictures in chapters 3 and 4. I also thank all those people who commented on the draft version and helped me to improve this thesis. This includes Chris and Stella Woulds, Henk Brockhoff, and Prof.ir. A.J. Kampstra. I am especially grateful to Wim Bakkeren who provided uncountable suggestions for improvement.

Finally I would like to express my thanks to the Technology Foundation (STW) and TNO for their funding during the many years that it took to complete the research and this thesis. Special acknowledgements are indebted to Peter Kuiper, Ger Kusters and Ruud Kloek for their continuing (financial) support.

Sassenheim, October 1997.

A handwritten signature in dark ink, appearing to read 'Ronald Krom'. The signature is written in a cursive, flowing style with a large initial 'R'.

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1

Introduction

In the previous decades, an increasing number of industrial companies has started using robot technology in their factories. The most widely known examples of robot applications are those from the automotive industry. All major car manufacturers use robots for paint spraying and spot welding of car bodies. While robot technology improves, the number of potential robot applications grows. Groover, Weiss et.al. (1986) identified a list of 'future applications' of industrial robots in 1986 including applications such as: coal mining, military operations, fire fighting, underwater operations, construction operations, space missions, cargo handling, garbage collection, medical treatments, farming and housekeeping.

Obviously many different branches of industry, including the building industry, are looking at the potential of robotics.

Research on construction robotics started more than a decade ago, resulting in many experimental construction robots. However, at the average building-site around the world, construction robots are still a rare phenomenon. A similar situation exists in the prefabrication of building elements although these production processes have more resemblance to the production in manufacturing industries where robots are used.

The building industry is undergoing many changes that have their influences on the products and production methods used. The Dutch Technology Policy Advisory Board for the Building Industry (ARTB) mentions the following developments: (ARTB 1993)

- the complexity and scale of newly designed buildings keeps increasing
- the building industry has to improve the working conditions for its personnel
- customers demand better quality products which require less maintenance
- growing social concern requires builders to use environmentally friendly processes and materials.

To cope with these changes, the building industry is looking for new, often overlapping methods and technologies, such as:

- just-in-time (JIT) production
- concurrent engineering
- computer integrated construction (CIC)
- information technology (IT)
- design for construction (DfC)
- lean production
- total quality management
- robot technology

Clearly robot technology is just one of the many promising technologies available to cope with the increasing demands.

This chapter introduces the position of *construction robotics* research and development by answering two questions:

- what specific advantages do robots provide to the building industry?
- why can the current state-of-the-art robot technology not be used in construction processes?

These two questions are discussed in section 1.2 and in section 1.3. Prior to a detailed discussion, some definitions of terminology are presented in section 1.1. Section 1.4 presents the goals and outline of the research in this thesis.

1.1 Definition of Terms

The Robotics Industry Association (RIA) uses the following definition for an *industrial robot* (Groover 1987):

An industrial robot is a re-programmable, multi-functional manipulator designed to move materials, parts, tools or special devices through variable programmed motions for the performance of a variety of tasks.

In this thesis a *construction robot* is regarded to be a type of robot which is specifically tailored to the building industry. Therefore a construction robot is defined as follows:

A construction robot is a re-programmable, multi-functional manipulator designed to move materials, parts, tools or special devices through variable programmed motions for the performance of a variety of tasks occurring in production processes of the building industry.

This definition is sufficiently broad to cover many applications of production automation equipment in construction processes.

According to this definition tele-operation manipulators that are completely controlled by a human operator, are not robots. In this thesis such tele-operation devices will be referred to as *construction manipulators*. The introduction of new technologies such as construction robots or construction manipulators in the building industry is referred to as *construction automation*. In order to avoid ambiguities, the term *manufacturing robots* is used to refer to industrial robots being used in manufacturing industries. Figure 1 shows the relations between the terms and definitions in a Venn diagram.

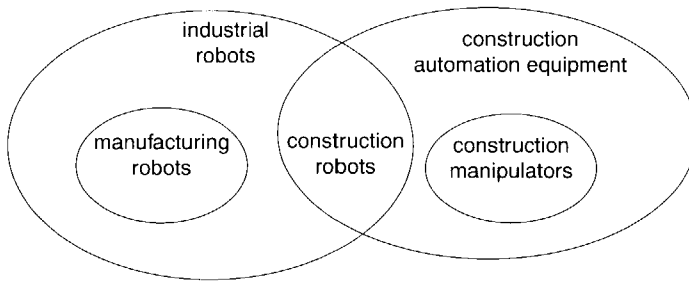


Figure 1 Venn diagram showing the relations between the concepts industrial robot, manufacturing robot, construction robot and construction manipulator. Construction robots and manufacturing robots are two different families of industrial robots being used in different branches of industry. Construction manipulators and construction robots are different types of equipment both used in the building industry.

Manufacturing robots and construction robots are different families in the set of industrial robots. Both families of robots can have an identical anatomy, but the robot geometry and capacity differs as a function of the type of application.

1.2 Benefits and Effects of Robots in the Building Industry

Attitudes towards construction robots vary with the point-of-views of the observer. In this section macro-economic and micro-economic effects of robotisation are reviewed.

1.2.1 Macro-Economic Benefits

From a macro-economic point-of-view, robot technology provides two major benefits. The first one is that robot technology supports the national economy growth by a productivity increase of the building industry. The second potential benefit is the reduction of the costs of the social security allowances needed to pay for the effects of the unhealthy and dangerous nature of the work in the building industry.

Statistical data in many countries shows that the productivity of the construction industry has slightly declined over the last decades. An explanation for this decline is the unpopularity of the building industry with young people. The lack of young people joining the building industry has increased average age of the building industry work force.

The building industry provides a contribution of approx. 10% to the gross national product (GNP) in most countries. In the Netherlands the building industry production was approx. 6% of the GNP in 1995 (CBS 1997). Warszawski (1990) argues that relative small improvements in construction productivity have a significant influence on the national economy. This is because lower building costs also reduce the amount of money invested in buildings, bridges, roads and houses. A reduction of these investments enables individuals, as well as companies to use their capital for other purposes such as investment in consumer goods and production equipment which stimulates the economy.

Statistics in the Netherlands (and probably in many other countries) show that the number of accidents in the building industry is relatively high. 24% of all work place accidents that occurred in 1991 are related to building activities (CBS 1994). This is approx. 1.8 times the average number of accidents occurring in industry. Also the number of people with permanent disabilities caused by their work, is relatively high in the building industry (EIB 1994). Depending on the social security system the costs of these accidents are paid by employer, employee or government. The total amount of money spent due to the high accident rates and unhealthy character, is significant. Therefore it is not only a social goal to relieve human workers from unsafe or unpleasant working conditions, there are also macro economic benefits to reduce the hazards of work in the building industry.

So far, government and industry have urged to reduce injuries and accidents in the building industry by establishing proper regulations and conducting publicity campaigns. The stimulation of the use of construction manipulators or construction robots is still an almost unrecognised solution to reduce unsafe or unhealthy work. Projects in other areas, such as dismantling of nuclear reactors, where human involvement is unacceptable, have demonstrated the technical capabilities of tele-operated manipulators, however, often at exorbitant costs.

1.2.2 Meso & Micro Economic Benefits

Although there are macro-economic benefits of robotisation, introduction of robotics in the building industry is not feasible without sufficient benefits at the micro-economic level. Benefits of using construction robotics will probably not be alike for every construction company. It should be kept in mind that the use of construction robotics is just one of the available alternative solutions for the problems presented by the changing demands on the building industry. Depending on the size of the company and nature of the building processes, robotics may or may not be an appropriate solution.

The most important benefits of robotisation as mentioned by Warszawski (1990) and Kangari & Halpin (1988) are that robotisation,

- deals with the increasing shortage of workers
- reduces the amount of dangerous or unhealthy work
- increases productivity
- reduces building time
- improves the quality of the end result

- improves the (high-tech) company image

Each of the above benefits of construction robots is discussed in more detail in the remainder of this subsection.

Reduction of the shortages of workers

Yoshida (1991) argues that shortage of workers has become the major reason for their interest in construction robotics in Japan. Partially due to the relative poor working conditions in the building industry, there is a negative attitude towards this industry branch in Japan.

The cartoon in figure 2 illustrates the negative image of the Japanese building industry. The Japanese characterise the work in the building industry with the following five K-words (Tucker 1992):

- kitanai ("dirty")
- kitsui ("hard")
- kiken ("dangerous")
- kiyujitsu ga sukanai ("too few holidays")
- kyukyo ga yasui ("not enough money")

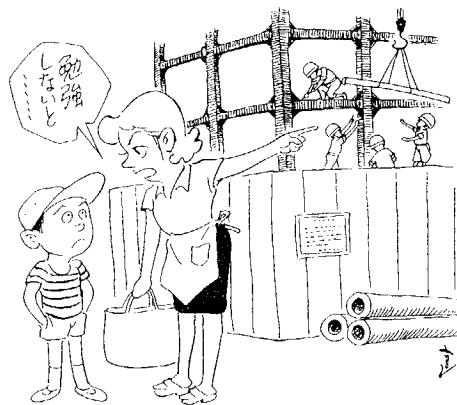


Figure 2 Cartoon illustrating the negative image of working in the building industry in Japan: "If you don't do your best you will end up like those people" (Naotoshi Tuchida).

Many of the developed construction robot prototypes are intended for compensating the permanent shortage of construction workers. Due to the poor reputation, it is getting more difficult to find skilled labourers. This effect is not yet very strong in the US and Europe, but it is expected to increase, at least in Europe (ARTB 1993). In Japan the building industry suffered from shortage of workers. Yoshida (1991) mentions that in 1988 the shortage of skilled workers in building was more than 25% of the number of skilled workers employed in building in that year.

Reduction of unhealthy and dangerous labour

Employers are increasingly being made more responsible for the costs of illnesses of (former) employees and for the costs of social security allowances to employees with occupational disabilities. The more responsible an employer is, the more financial benefit he/she has from improvement of working conditions. Groover, Weiss et al. (1986) argue that all manual (manufacturing industry) operations that are characterised as unsafe, hazardous, uncomfortable or unpleasant for human workers, are ideal candidates for robot applications. Not only because of compassion with those carrying out the work, but also to reduce (indirect) costs related to unhealthy or dangerous work. People carrying out unpleasant work are more often ill than those doing pleasant work.

Increase of labour productivity

The most obvious benefit of a construction robot is the potential increase in productivity. Most investments in construction equipment are justified by productivity increases, e.g. cranes, excavators, cement mixers and power drills. A survey conducted by Naoum (1994) indicates that experienced practitioners, contractors and construction researchers regard productivity improvement as the primary factor in economic feasibility of construction automation and robotics.

Productivity increases are undoubtedly to be expected from autonomous construction robots. Autonomous behaviour of construction robots enables one human operator to control two or more robots simultaneously. Construction *manipulators* primarily increase productivity due to their power amplification capabilities. Construction manipulators enable one human being to handle more material or larger components alone. Due to technical limitations, this power amplification often reduces handling precision. Robot technology can help to implement manipulators that increase productivity without diminishing safety, working conditions and quality.

Reduction of building time

Increasing awareness of the costs of investments (interest) during the construction process force customers to impose strict time schedules on the building process. New technologies such as concurrent construction are focused on reduction of the required building time. The use of robots can also reduce the building time. The availability of autonomous, fully self sufficient robots could make it possible to use such robots at night or in the week end.

Increase of product quality

The potential increase in quality of the work of robots, though significant, is hard to quantify. Robot experts in manufacturing industries stated in 1982 in a Delphi forecast that the benefits of improved quality are at least 50% of the value of achieved productivity gains (Smith and Wilson 1982).

The benefits of improved quality of the work using robots can be separated in direct and indirect benefits. The direct benefits are the savings in material usage due to the higher accuracy of robot behaviour. Especially for spraying operations reductions in material use could amount 5% to 10% (Warszawski 1990). The indi-

rect benefits of improved quality are probably higher than the direct benefits. Higher precision in positioning and dimensions for instance can reduce the work needed for minor size adaptations needed for exact fitting of many materials and elements such as panels, door frames, etc. Another indirect benefit could be gained from a reduction in repair work caused by mistakes.

Improvement of high-tech company image

One of the less tangible benefits of robotisation of construction is its influence on company image. Some of the Japanese contractors admit that they use robot technology experiments to support their high-tech image and distinguish themselves from their competitors. Not only do they try to improve their image towards the customers, they also use robotics to convince future employees of the challenges of working in the building industry. This last point is especially relevant for the previously discussed Japanese situation where severe shortages of skilled workers exist.

1.2.3 Other Micro Economic Effects

The decision whether or not to invest in a construction robot, assuming that such robots are commercially available, will nearly always be based on financial evaluations. All of the above mentioned potential advantages can be translated into financial benefits.

Warszawski (1990) uses a normal cost-benefit evaluation for feasibility analysis of construction robotisation. In this economical evaluation all associated costs, i.e. investment, setup, maintenance and operation, are compared to the value of all benefits, i.e. increased productivity, improved quality, elimination of hazardous and stressful tasks.

Rho & Fisher (1994) on the other hand argue that the economic justification methods developed for the mass-production oriented manufacturing industry are not appropriate for the project oriented building industry. Rho & Fisher use a simulation system to evaluate the sensitivity of project profits to a set of decision factors. Their research indicates that certain sensitive decision factors can cause large changes in the total expected profit. Decisions about construction automation should, according to Rho & Fisher, focus on the most sensitive factors.

In the current evolutionary stage of construction robotics it is difficult to acquire accurate predictions of robot costs and revenues. Some problems are:

- *Construction robot purchase prices are difficult to estimate*

Due to the lack of *economy-of-scale* in the production of construction robots the robot prices remain high. A significant proportion, if not all, of the development costs has to be covered by the price of a single robot because sales expectations for the robot manufacturer are uncertain.

- *Indirect benefits are difficult to translate into financial revenues*

Experience with construction robots is still limited. Especially the indirect benefits, i.e. reduced building time, increased product quality and improvement of working conditions, are difficult to translate into building cost reductions and nearly impossible to predict in a cost-benefits evaluation.

- *Benefits are circumstantial.*

Some of the above mentioned benefits are only of value in specific circumstances, e.g. when erecting high rise buildings, within a specific type of company, or during a shortage of skilled workers.

Several studies have made general calculations on the economic feasibility of construction robots. A number of these studies, including (Kangari et al. 1988; Arditi, Sundareswaran and Gutierrez 1990; Neil, Salomonsson and Skibniewski 1993), have calculated that building costs can be reduced while using a number of specific types of construction robots.

Even if construction robots can reduce building costs there are other consequences of investments in construction robots that have to be considered. The purchase of a construction robot or manipulator is a substitution of labour by a capital good. Warszawski (1990) describes the effects of the substitution of labour by capital goods in the building industry. The most important effect mentioned by Warszawski is that capital intensive companies are more sensitive to changes in product demands. The more capital is invested in production equipment, the higher the fixed production costs are, e.g. interest and investment write-offs, and the lower the variable production costs are. In situations with decreased product demand, production costs increase because of the relatively high proportion of fixed costs. Therefore it is only attractive to invest in production equipment when there is a sufficient and stable product demand.

Another negative aspect of robotics is the risk involved with investments in robots. When the introduction of a construction robot fails, either because the robot does not fulfil expectation, or because requirements or consequences have been overlooked, the investments made in the 'robotisation adventure' are lost.

Effects on the work force

From a craftsmen point-of-view, construction robots will probably be associated with negative aspects, such as loss of employment, inflexibility or increased production pressure. They tend to have negative associations because they see robots as a threat to their job. However, an important benefit mentioned earlier is that robots can improve working conditions because boring, heavy and dangerous work no longer has to be carried out by human labourers.

Another important effect is that the use of complex robot equipment requires skilled operators and maintenance personnel. Construction robots will be based largely on computer technology, requiring personnel with an entirely different professional skill. People with such skills are still relatively rare within the building industry.

1.3 The Gap Between Construction Automation and Robot Technology

The number of robots or construction manipulators being used in the building industry today is still negligible. The six largest Japanese contractors, the so called *Big Six* (Bennet, Flanagan and Norman 1987) are putting significant amounts of effort and money into developing and experimenting with construction manipulators and robots. A Delphi type survey amongst Japanese and German construction automation experts (NISTEP 1992; BMFT 1993) indicates that 71% of the Japanese experts and 60% of the German experts believe that the development of construction robotics is constrained by technical matters.

Evidently there is a large technological gap between the capabilities of today's commercially available robot technology and the building industry's needs for production automation.

The reason for this divergence can be found in the nature of the building industry. The differences between manufacturing industry production and building industry production hinder the use of today's commercially available robots. Comparison of the production in the building industry and the production in other industries shows four special characteristics of the building industry:

1 *Production takes place at building sites*

In the building industry products are assembled at (or sometimes close by) their final destination because products are large and heavy which makes them difficult to transport. All workers, equipment (including robots) and materials are transported to the production site. In other industries, the products are produced in factories or other special facilities (e.g. ship yards) where all equipment and materials are at hand.

2 *The production process moves along (or through) the product*

Because the product is assembled at its final location, the production resources (people and equipment) have to be transported to and from each building site. At the building site the production equipment has to move along the work pieces. This situation is different from factory production, where the production equipment is installed at fixed locations and the products are presented to the machines using conveyor belts or other means.

3 *Products are usually one-of-a-kind*

The products of the building industry are one-of-a-kind products which are unique or sometimes produced in small series. Compared to manufacturing industries, production series are negligible. New designs and production plans are prepared for every project.

4 *Responsibility for the production is shared by many partners*

A different joint-venture of architects, engineers, contractors and subcontractors is formed for each new civil-engineering or building project. Innovations in production that require changes in more than one 'area' are nearly impossible in the ever changing combinations of enterprises in construction projects.

The commercially available robots are all designed with applications in manufacturing industry production in mind. Properties of commercially available robots are:

- The robots are meant to be installed at a fixed place in a factory.
- Robot controllers are normally programmed once and will execute their program many thousands of times without major changes.
- The robots are designed without any restriction on their weight and are thus often very heavy (up to several tons).
- Robot manipulators have sufficient reach to work on medium scale products.

Unfortunately these robot properties do not meet the requirements of the building industry, which are:

- Robots have to be transported to building sites and through buildings under construction.
- Robot tasks are one-of-a-kind and thus custom programs are needed for each task.
- Robot tasks do not consist of fixed motion-patterns. Each robot operation cycle is different because the robot has to work along its workpiece.
- Robots have to operate on large scale objects such as walls, doors, ceilings, floors, roofs etc.

Obviously there are discrepancies between the characteristics of the current industrial robots and the production circumstances in the building industry, but do these differences present insurmountable technical problems? The answer to this question is discussed in this thesis.

1.4 Introduction to the Research

The conclusion that can be drawn from an initial survey of construction robotics is that there are convincing arguments for future applications in this branch of industry. However, there seem to exist problems that prevent construction companies and equipment manufacturers from developing or selling construction robots.

One of the problems is technology. The present state-of-the-art of robot technology has not yet reached the stage at which manufacturers and contractors can be persuaded to adopt wide scale use of robots. Therefore an answer to the following question is sought:

Which problems prohibit robot technology from being applied in building industry production?

In the first part of this thesis, this problem is analysed in more detail. For the analysis, the subject of construction robotics is looked at from two points-of-view:

1 *A building industry point-of-view*

to identify the priorities to set the correct direction to technical developments,

2 *A robotics point-of-view*

to see what has already been developed and tried and with what positive and negative results.

These two points-of-view are discussed in the next three chapters. Chapter 2 analyses economic aspects of robotisation. In particular, it is investigated which types of construction processes provide the best opportunities for robotisation. Chapters 3 and 4 discuss and analyse the technical state-of-the-art in construction robotics and robot technology. Chapter 5 brings the results of its preceding chapters together in order to identify the technological problems which hinder development of (commercially) viable construction robots. From this list of technological problems, one particular problem is selected for further investigation in the second part of this thesis. This particular problem is the problem of construction robot programming and instruction. The motivation of this selection and the significance of the problem is discussed in chapter 5.

Chapters 6 and 7 discuss a solution strategy for the selected problem of robot instruction. In chapters 8 and 9 the theory presented in this thesis is verified in two case studies. Finally chapter 10 summarises the main conclusions of this thesis.

2

An Analysis of Robotisation Opportunities

This chapter investigates a number of different classes of construction tasks and assesses the opportunities for robotisation for each of them.

To be able to direct research and development work on the subject of construction robotics, it is desirable to know which types of tasks are the best candidates for the first steps of robotisation in the building industry. Studies of the economic feasibility of robots do not help much to identify the types of construction tasks in which robots are potentially most successful. As mentioned in the previous chapter, several researchers have investigated the economically feasibility of construction robotisation, e.g. (Kangari et al. 1988; Arditi et al. 1990; Neil et al. 1993). These studies have the objective to show that robotisation is economically attractive when some type of robot can replace X workers for a robot investment less than Y \$, given certain costs of labour, transportation costs, operational costs etc. However, these studies do not help to find the applications that are best suited for robotisation.

This chapter investigates the *robotisationability* of six clusters of construction processes according to a set of aspects that are believed to determine it. The *robotisationability* of a construction process is defined as the *economic* feasibility to robotise that process. Section 2.1 describes the six clusters of construction processes that are distinguished. Section 2.2 describes the assessment of the robotisationability of the process clusters. Section 2.3 discusses the characteristics of each of the process clusters for the investigated aspects and presents the analysis results of the evaluation of robotisation opportunities. Finally section 2.4 presents the main conclusions and discusses possible strategies for successful robotisation.

2.1 Construction Process Classification

In this thesis the *building industry* is regarded as the branch of industry taking care of the realisation of constructions such as: residential buildings, office buildings, hospitals, bridges, roads, viaducts, etc. In the construction process of these products, a number of categories of processes are executed. In this research the classification of the CI/SfB *construction indexing manual* is used (Ray-Jones and Clegg 1976). This construction indexing manual distinguishes the following clusters of construction processes:

- 1 *ground and substructure works*
 - site preparation (excavation, retaining wall construction, layout work)
 - foundation construction (piling, concrete beams, construction of basement)
 - ground floor construction (concrete floor construction, pre-cast concrete elements)
- 2 *erection of building carcass (structure, primary elements)*
 - wall erection (load bearing walls, curtain walls, interior walls)
 - construction of vertical divisions (monolithic slab floors, assembled floors)
 - erection of building frames (column and beam or slab frames)
 - construction/installation of vertical circulation elements (stairs, lifts)
 - construction of roof
- 3 *completion of building structure (secondary elements)*
Installation of secondary elements to the building carcass (windows, doors, hatches, suspended ceilings, balustrades, etc.)
- 4 *finishing of building structure*
Finishing of the building carcass elements (pointing, plastering, coating, impregnating, wall papering, tiling, etc. of external walls, internal walls, floors, roofs, ceilings and stairs)
- 5 *installation of piped services*
Installation of piping for: cold & hot water supply, waste water drainage, gases supply (natural gas, compressed air, vacuum), heating, air conditioning, ventilation and cooling (HVAC) systems
- 6 *installation of electrical services*
Installation of electrical systems (power, lighting), communication systems (telephone, computer networks), transportation systems (lifts, escalators, conveyors) and security systems (fire detection, alarms, cameras etc.).
- 7 *installation of fittings*
Installation of culinary and sanitary fittings
- 8 *installation of loose furniture and equipment*
- 9 *external works*

In this chapter the above classification is used in a simplified version. Items 5 and 6 are grouped because of their similarity in the types of tasks involved in these processes. Items 8 and 9 are not discussed because they are regarded to be out of the scope of the building process. In the rest of this chapter the relative robotisationability of above listed clusters of construction processes is investigated.

2.2 Analysis Method

Robotisationability is an abstract and difficult to quantify aspect. The method used in this chapter is referred to as the *grading method*. It has been developed to assess the performance in a difficult to quantify performance aspects (Warszawski 1990). In this case the competing alternatives are the construction processes clusters, and the performance aspect is *robotisationability*.

The grading method assigns grades (e.g. between 0 and 1) to a list of aspects that influence the performance aspect. The total performance of each of the competing alternatives is calculated from the grades assigned for each aspect. In order to balance the relative importance of each of the aspects, each aspect grade is multiplied by a weight factor. Formula (1) shows how the performance is calculated from the assessed grades and aspect weights.¹

$$P_i = \sum_j G_{ij} \cdot w_j \quad (1)$$

Where:

- P_i = the performance of alternative i
- G_{ij} = the assigned grade on aspect j of alternative i
- w_j = weight factor of aspect j

For this grading method assessment the following steps are executed:

- 1 Identification of *aspects* that determine a process' robotisationability (identification of *j*'s).
- 2 Assessment of weights w_j to the process characteristics identified in step 1.
- 3 Assessment of process characteristic grades G_{ij} for each of the clusters.
- 4 Calculation of robotisationability performance P_i using the assigned grades and weights.

Steps 1 and 2 are discussed in the rest of this section. Steps 3 and 4 are discussed in section 2.3.

2.2.1 Identification of Process Aspects

In today's market-oriented society, economic decisions are based on financial calculations. Robotisation of construction processes is no exception. Robotisation is successful if money is saved, unsuccessful if money is lost.² But where do you find construction tasks which can be economically robotised? The following construction process aspects are identified as being of influence on process robotisationability:

1. In the remainder of this chapter more formulas such as the one above are used. The notation of these formulas is similar to the notations used in many books including (Thuesen and Fabrycky 1988).
2. Besides the economical aspects there are also non-economical aspects that do influence robotisationability. Examples of such aspects are: loyalty to employees, fear of technology or affection for technology. These aspects cannot be converted to financial values and are not discussed in this research.

- task complexity
- labour costs of replaced workers
- health hazard of the manual process
- repetitiveness of the process
- the product quality demand
- the level of mechanisation

The relation of these aspects to the robotisationability of a construction processes is discussed below.

Robotisation Economics

The financial aspects of robotisation have been identified in previous research on the economic feasibility of robotisation. In his feasibility study, Warszawski (1990) distinguishes primary and secondary economical aspects. Primary economic aspects are aspects related to direct costs and revenues. Examples of primary aspects are the investment in the robot hardware and the labour costs savings. Secondary aspects are aspects that do not directly involve money, but can be converted into economic values; e.g. product quality. A problem here is that these are more difficult to quantify as financial values.

Warszawski (1990) distinguishes the following primary economical aspects of robotisation:

- initial investment costs of the robot
- saved labour costs per worker that is replaced by the robot
- number of workers that is replaced by the robot
- robot's maintenance costs
- robot's operational costs (electricity, etc.)
- robot's transfer and set-up costs
- tax reduction rate
- interest rate
- economic robot life time

In addition to the above aspects, Warszawski also mentions the following secondary aspects:

- improvement for working conditions of non replaced workers
- improvement of product quality
- indirect robotisation costs (change of working methods, education training, etc.)

Process Aspects

The above primary and secondary aspects determine the economic feasibility of the use of a particular robot in a particular situation. However, in this analysis, the objective is to compare different clusters of construction processes on the aspect of robotisationability. Therefore it is necessary to identify the dependency

of each aspect to construction process characteristics. Some aspects are completely determined by the engineering of the robot hardware, while others are determined by the characteristics of the process being robotised. Four categories of aspects are distinguished according to their dependency on process characteristics.

- 1 *The category of aspects that are determined externally*
- 2 *The category of aspects that are primarily determined by the features of the robot*
- 3 *The category of aspects that depend partially on robot design and partially on the nature of the process*
- 4 *The category of aspects that are fully determined by the nature of the construction process*

Each of the above categories is discussed in more detail below.

- 1 *Aspects that are determined externally*
 - interest rate
 - tax reduction rate
 - economic robot life
- 2 *Aspects that are primarily determined by the features of the robot*
 - number of replaced workers
 - robot maintenance costs
 - robot operation costs
- 3 *Aspects that depend partially on robot design and partially on the nature of the process*
 - *robot investment*
The size of the investment needed for the purchase of a robot depends on the design and engineering of the robot. However, the complexity of the robot is related to the complexity of its task. The more complicated the robot is, the more expensive it is. Therefore there is a relation between the robot investment and the *complexity* of the robot task.
 - *indirect robotisation costs*
The indirect costs of robotisation are the expenses made for all changes in the organisation, working methods and personnel skills to be able to robotise. These indirect costs can be significant. Indirect costs depend on the design of the construction robot and on the process organisation in the pre-robotisation situation. A parameter that indicates the magnitude of indirect robotisation costs, is the current *level of mechanisation* of the process. When a process is already mechanised, the organisation is already familiar with the consequences of the usage of some piece of equipment in the production process.
 - *benefits of improved product quality*
The benefits of improved product quality depend on: (1) the ability of a robot to actually improve the quality, and (2) the economic value of the quality improvements. The value of quality improvements are composed of direct and indirect benefits. Direct benefits such as reduction in material waste, are easy to quantify. Indirect benefits are more difficult to quantify, but they can

be assessed from the costs spent on repairs and modifications for poor quality work in the prerobotisation situation. Especially when inaccuracies or mistakes have far-stretching effects, their costs can be significant.

– *robot set-up costs*

The robot set-up costs are dependent upon: (1) the ease of set-up of the robot (user friendliness of the robot), (2) the number of times the robot has to be set-up. The less time a task takes (because only a small number of operations have to be performed) the more often the robot has to be set-up. Therefore the repetitiveness of operations in a task determines the amount of time the robot can work without the need to do another task set-up. set-up costs are reduced by the *repetitiveness* in tasks.

– *robot transfer costs*

The robot transfer costs are determined by: (1) the size and mass of the robot, and (2) the frequency of robot transfers. The less time a task takes, the more often the robot needs to be transferred. Therefore the transfer costs depend on the *task repetitiveness*.

4 *Aspects that are totally determined by the characteristics of the construction process*

– *labour costs per replaced worker*

The construction *process aspects* that influence the robotisationability of some construction process (categories 3 and 4) are:

- task complexity (X)
- labour costs of replaced workers (L)
- health hazard of the manual process (W)
- repetitiveness of the process (R)
- the product quality demand (Q)
- the level of mechanisation (M)

When the above process aspects are substituted in formula (I), the following formula for assessment of robotisationability emerges:

$$Z = w_L \cdot G_L + w_Q \cdot G_Q + w_W \cdot G_W + w_X \cdot G_X + w_R \cdot G_R + w_M \cdot G_M \quad (II)$$

The next step is to assign the relative weight factors in the above formula. This requires the different aspects to be quantitatively related to each other, i.e. how does cost of labour relate to robot complexity? The assessment of weight factors is discussed in the next subsection.

2.2.2 Assessment of Weight Factors

For the assessment of the relative weight factors each of the aspects has to be converted into an aspect independent magnitude. Economic value is selected as the independent magnitude. The economic value of each process aspect is calculated using economic relationships as presented by Warszawski (1990). Formula (III)

shows how the total 'profit' of robotisation is calculated from the aspects discussed in the previous subsection. The quantities that depend on the process aspects identified earlier, are substituted by functions of these process aspects.

$$V_{robot} = \left(kL + Q + W - M - O - f_T(R) - f_S(R) + \frac{\alpha}{n} f_P(X) \right) rp(i, n) - f_P(X) - f_I(R) \quad (III)$$

Where:

- V_{robot} = total profit that is made by a robot during its entire economic life
- L = saved labour costs per year per replaced worker
- k = number of replaced workers
- W = economic benefits of improved working conditions (annual)
- Q = economic benefits of improved product quality (annual)
- M = costs of robot maintenance (annual)
- O = costs of robot operation (annual)
- $f_T(R)$ = costs of robot transfers as a function of the repetition (R) (annual)
- $f_S(R)$ = costs involved with robot task set-up as a function of the repetition (R) (annual)
- $f_P(X)$ = initial investment in the robot as a function of the task complexity
- $f_I(M)$ = indirect cost of introduction of robot (change of working methods, education, training, administration, etc.) as a function of the level of mechanisation (M).
- α = tax reduction rate
- i = interest rate
- n = economic life of a robot
- $rp(i, n) = \frac{(1+i)^n - 1}{i(1+i)^n}$, the present worth equivalent of a series of n annual payments with an annual interest rate i .

The design dependent parameters M and O are included into the above formula for completeness, but for the assessment of the relative robotisationability these aspects are ignored. In formula (III) all annual benefits and expenses are converted to a so called *present worth* value in order to be compared with initial investment (one time) costs. This conversion depends on the economic life of a robot and the interest rate. In the analysis in this chapter it is assumed that the interest rate is 8% and that the economic life cycle of a robot is 5 years. In that case the present worth coefficient has a value of 3.99. The tax rate for companies is assumed to be 25%. The analysis in this chapter evaluates the situation that robotisation investments replace one worker (i.e. $k = 1$).

Formula (III) is now used to assess the weights of the aspect grades of formula (II). The grades G_{α} in formula (II) are defined as numbers ranging between 0 and 1. A grade of 0 represents a *low* rating. A grade of 1 represents a *high* rating. The aspect weights w_{α} are determined by means of an estimate of the amounts of money involved with the ratings of *low* and *high*. For example: It is estimated that a construction robot costs between: $200 \cdot 10^3$ Dfl. (The *low* value) and $800 \cdot 10^3$ Dfl.

(The *high* value), depending on the complexity of the robot task. In that case the costs vary $600 \cdot 10^3$ Dfl. between *low* and *high*. Therefore, the value of w_x is estimated at $600 \cdot 10^3$ (with $0 < G_X < 1$).

All the weights w_α can now be assessed in a similar manner as explained above.

- *the influence of task complexity (w_x)*

The investment costs (hardware) of a robot which replaces one worker is estimated to be between $200 \cdot 10^3$ Dfl and $800 \cdot 10^3$ Dfl depending on the complexity of the robot task. When the robot has an economic life cycle of 5 years, one fifth of this investment can be deducted from taxes every year. With a tax rate of approx. 25%, 5% of the robot investment is effectively paid by the government. Taken the investment and tax deduction into account, the variation in robot investment costs between low and high is $(600 \cdot 10^3 - 3.99 \cdot 5\% \cdot 600 \cdot 10^3) \cdot G_X$. Thus w_x is estimated to have a value of approx. $480 \cdot 10^3$.

- *the influence of labour costs (w_L)*

The average annual labour costs for one worker in the building industry were $71 \cdot 10^3$ Dfl in 1995 (CBS 1997). It is estimated that the costs of labour vary between approximately $35 \cdot 10^3$ Dfl and $75 \cdot 10^3$ Dfl depending on their level of education, skills and experience. This range represents more than 60% of the building industry work force. The costs of labour are on an annual base, therefore, these values have to be converted to the lifetime labour costs. The value of w_L is estimated at $40 \cdot 10^3 \cdot 3.99 \approx 160 \cdot 10^3$.

- *the influence of improved quality (w_Q)*

The benefits of quality are difficult to assess. The potential benefits of improved quality is high because significant amounts of money are spent on repairs and modification caused by poor quality work. Therefore, both labour costs and material costs can be saved by improved quality. In this analysis the value of quality improvements is estimated to vary between 0% and 40% of the labour costs plus 0 to $5 \cdot 10^3$ Dfl in material savings. The value of w_Q is assessed at the present worth value of 40% of the average labour costs ($64 \cdot 10^3$ Dfl.), i.e. w_Q is $3.99 \cdot (40\% \cdot 64 \cdot 10^3 + 5 \cdot 10^3) \approx 122 \cdot 10^3$.

- *the influence of mechanisation (w_M)*

Indirect costs are estimated to be between 10% to 20% of the robot investment. The average robot investment was estimated at $(200 \cdot 10^3 + 800 \cdot 10^3) / 2 \approx 500 \cdot 10^3$. This means that w_m is: $10\% \cdot 500 \cdot 10^3 \approx 50 \cdot 10^3$.

- *the influence of improved labour conditions (w_w)*

In manufacturing robots are very often used to relieve human workers from heavy, boring or unhealthy tasks. In the building industry the improvement of labour conditions is a very interesting benefit. In the building industry in the Netherlands, 20% of the labour costs are due to payment of social security premiums. An improvement of labour conditions, can help to reduce absence due to illness and injuries. Not only for the robotised process, but also for other tasks related to the robotised task. The the benefit of improved labour conditions is estimated to be in order of magnitude of 10% of the average costs of one worker. This results in a value of w_w of $3.99 \cdot 10\% \cdot 64 \cdot 10^3 \approx 26 \cdot 10^3$.

- *the influence of task repetitiveness (w_R)*

- a *costs of robot transfers*

The costs of robot transfers between job sites and task locations are dependent on the amount of repetition of a robot task. The longer a robot can work on a task autonomously, the lower the costs of robot transfers will be. The amount of time a robot can work autonomously on a task, is a function of the repetitiveness of a process. This repetitiveness varies considerably for different types of construction processes. The frequency of transfers is estimated to vary between once each day and once a week. The repetitiveness is strongly influenced during the product design and can be increased in order to facilitate robotic construction. The transfer costs are estimated to vary between $10 \cdot 10^3$ and $20 \cdot 10^3$ Dfl. Therefore value of w_R^t is estimated as $10 \cdot 10^3 \cdot 3.99 \approx 40 \cdot 10^3$.

- b *costs of robot set-up*

The annual costs of robot job set-ups depends on the number of times the robot has to be set-up. It is estimated that a robot has to be set-up approximately 100 times a year (i.e. 2 or 3 times a week). Every time a skilled instructor has to spend one or two hours on a set-up. The set-up costs are estimated to vary between 1 and 5 man hours per project, 100 times a year. This means that set-up costs can vary 100 times 4 hours at 50 Dfl, is: $20 \cdot 10^3$ Dfl annually. Thus $w_R^s \approx 3.99 \cdot 20 \cdot 10^3 \approx 80 \cdot 10^3$ and thus $w_R = w_R^t + w_R^s \approx 120 \cdot 10^3$.

When the above assessed weight factors are substituted in formula (II) the following expression is obtained:

$$Z = 160 \cdot G_L + 122 \cdot G_Q + 26 \cdot G_W - 480 \cdot G_X + 160 \cdot G_R + 50 \cdot G_M$$

When the weight factors are all scaled down to a total of 100, the following formula is the result:

$$Z = 16G_L + 3G_W + 12G_Q + 16G_R - 48G_X + 5G_m \quad (IV)$$

The dominant aspect in robotisationability is the complexity of a task. The task complexity determines the complexity of the robot and thus its costs. A second important aspect is the labour costs of the worker that is replaced by the robot. Other aspects with less influence on robotisationability are repetitiveness and the demand for quality. In the next section each of the construction process clusters is evaluated and grades for each of the aspects are assigned.

2.3 Robotisation-Aspect Grades

Although the subjects of investigation are six clusters of construction processes, the assignment of grades is discussed per aspect. After the assignment of grades, the assigned values are filled in formula (IV) to calculate the robotisationability of each of the processes at the end of this section.

2.3.1 Costs of Labour (G_L).

The costs of labour are primarily dependent on the level of skill required for a particular task. Together with the advancement of the production process, the level of skills required increases. The more a product nears its completion, the more specialized the construction work becomes. The more specialized the work is, the more skilled the labourers are and the higher their costs are. Figure 3 shows the assignment of grades for the aspect of labour costs for the different process clusters. In special situations, such as when there is a shortage of workers, as was the case in Japan in the 1980s, the costs of specific operations can be much higher and be different from the general trend as shown in figure 3.

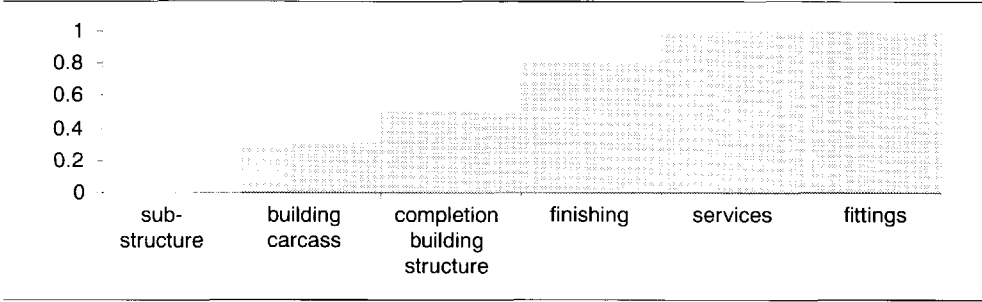


Figure 3 Assignment of G_L ; the relative costs of labour. Labour costs are the lowest in substructure work and the highest in the installation of services and fittings.

2.3.2 Task Complexity (G_X)

The complexity of construction tasks increases as the product completion progresses (see figure 4). Excavation and site preparation is much less complex than the installation of electric light switches or the installation of wash basins. Tasks of low complexity can be recognised by the fact that they are already mechanised! For example, no one will use a spade to excavate a building site. Earthwork has been mechanised by almost everyone.

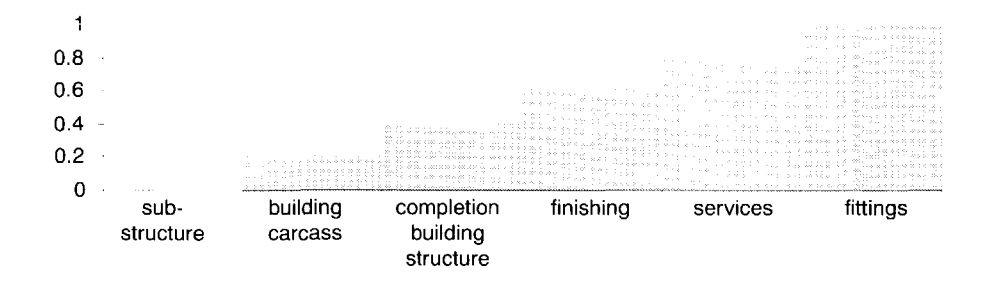


Figure 4 Assignment of G_X ; the relative complexity of tasks.

2.3.3 Repetitiveness (G_R)

Repetition in process tasks is highest in the early stages of production and decreases with the progress of the production process. This relation is shown in the assignment of grades G_R as shown in figure 5. Building foundations and car-

casses tend to be very modular and uniform. As the product nears its completion, the tasks become more detailed and the repetition rate decreases. The construction of a foundation or building carcass involves more repetitive tasks than the installation of fittings and services. The latter is limited to the number of identical components that are installed (e.g. sockets, taps, wash basins etc.). The situation in which these components are to be installed varies significantly.

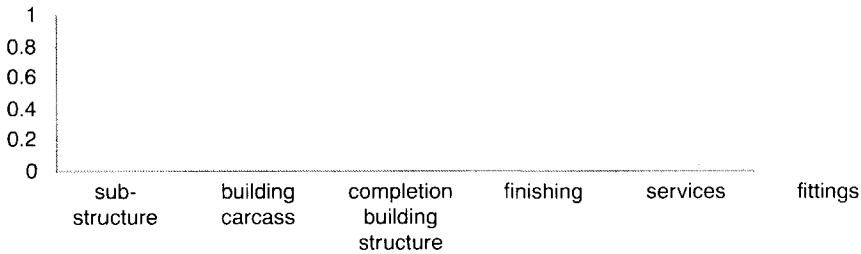


Figure 5 Assignment of G_R ; Relative repetitiveness of tasks per site and per task.

2.3.4 Unhealthiness (G_W)

The reduction of the health hazard of a construction process depends on the amount of unhealthy and dangerous tasks involved. An important factor in unhealthiness is the mass of objects to be manipulated. As a project progresses, the objects to be handled decrease in size and weight. Another factor which improves the working conditions is the level of mechanisation of the work. As the level of mechanisation decreases throughout the production, the unhealthiness is believed to be the highest in the installation of secondary elements in the building carcass (see figure 6).

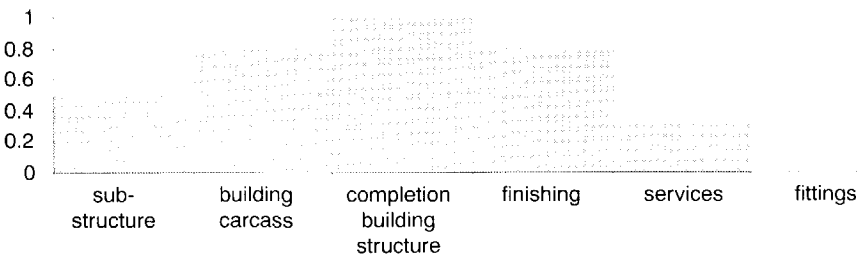


Figure 6 Assignment of G_W ; Relative levels of unhealthiness of labour.

2.3.5 Quality Improvements (G_Q)

The pay-back value of improved quality primarily consists of a reduction in costs needed for repair and modification. In the early stages of production, the consequences of mistakes and inaccuracy can be large and therefore costly. It is assessed that the value of quality is at its maximum in the construction of the primary structure (See figure 7).

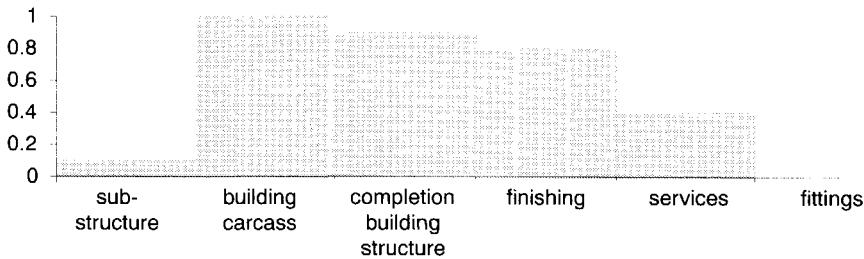


Figure 7 Assignment of G_Q ; Relative values of quality.

2.3.6 Mechanisation (G_M)

It can be observed at nearly every building site that the level of mechanisation is the highest with substructure work and the construction of the building carcass. Nobody will excavate a pit without an excavator. Also building cranes are essential for the construction of the building carcass. As the production progresses, the objects to be handled decrease and the proportion of manual labour increases. For the installation of services and fittings only small hand tools are used. This relationship is shown in the grade assignment shown in figure 8.

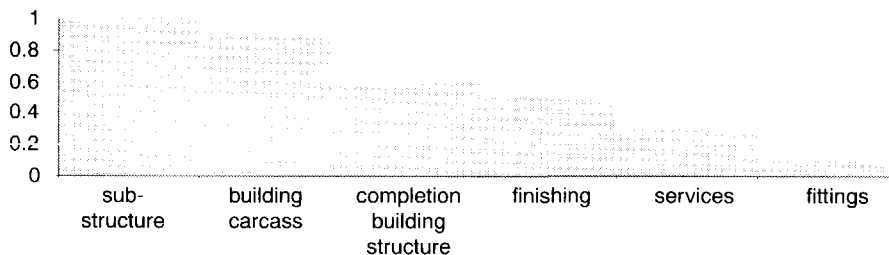


Figure 8 Assignment of G_R ; The relative levels of mechanisation.

Now that all grades have been assessed, it is time to calculate the robotisability of each of the construction process clusters using formula (IV).

2.4 Conclusions and Discussion

In general, robotisability of construction processes is the best for processes involved in the early stages of production. This is primarily caused by the relative simplicity of the tasks in processes in the early stages of construction.

Figure 9 shows the relative robotisability of each of the six construction process clusters.

The analysis shows that the erection of the *building carcass* (primary elements of the building structure) and the *ground and substructure works* are the best candidates for robotisation. The completion of the building structure is the second best

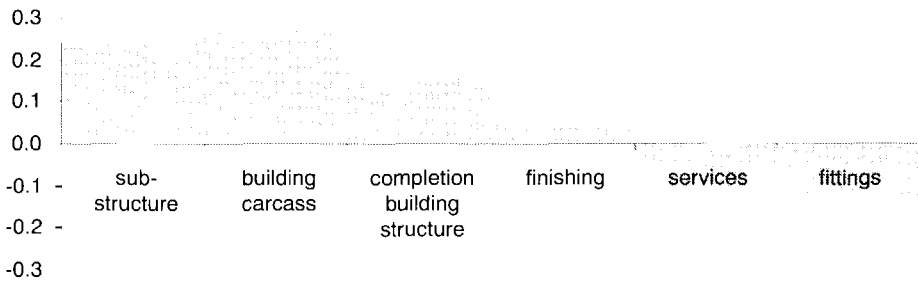


Figure 9 Relative robotisability of each of the construction process clusters.

candidate for robotisation. The process clusters installation of *services* and *fittings* are the least suitable for robotisation. The general trend seems to be that the robotisationability diminishes with the completion of the product.

The initial costs (investment + introduction) of robotisation are a dominant component in an application's robotisationability. Therefore the best opportunities for robotisation are when the initial costs can be kept as small as possible. There are several possible strategies to do this.

- *selection of simple tasks (development of smart tools)*

Smart tools are devices that are relatively simple and are able to perform operations of limited complexity without constant supervision of a human workers. The idea is that one operator keeps one or more smart tools working while he sets up another one. The commercial advantage of this strategy might be that the use of smart tools involves a limited investment in equipment and indirect costs, while it increases productivity.

- *modification of equipment that is already owned*

Many of the currently used construction machines are suitable to be upgraded to mechatronic manipulators. Mechatronic manipulators can assist an operator to deliver a higher productivity or higher quality work and can have autonomous behaviour. The use of existing mechanisation equipment as a starting point, reduces the robotisation investment to an investment in the machine control system which reduces the financial risks in case the development fails.

The high initial costs present a problem. Rapid robotisation forms a risky investment. In order to minimise the risks involved in radical changes in production methods, the desire will always be, either to minimise the costs of robots that require a radical change in work methods, or to minimise the changes in work methods needed for the use of the robot. An option to break this barrier is to offer construction robots in rental or lease to avoid the problem that contractors are unwilling to invest in robots. This strategy was successfully used by Xerox Co. for the introduction of their photocopy machines which were regarded as a substitute of carbon paper.

An approach in robotisation that is sometimes mentioned, is to use *multi-purpose robots* that are able to perform more than one type of task. The obvious advantage

of a multi-purpose robot is that the amount of work per site/project can be much larger, which reduces the transportation and set-up costs. A drawback is that multi-purpose robots may need to be more complex and therefore more expensive than single-purpose robots. This is strongly dependent on the nature of the operations to be combined. Similar types of operations, such as drilling, grinding or milling can be combined more easily than non similar operations such as spraying, drilling and masonry. Because robot complexity is strongly related to the robot investment-costs, great care should be taken in the decision how much functionality is to be incorporated into one robot.

3

State-of-the-art in Construction Robotics

This chapter analyses the current state-of-the-art in construction automation and robotisation of the building industry. Four generations of construction robots are distinguished. Of each generation a number of construction robot developments is discussed.

The goal of this chapter is to analyse the current state-of-the-art in construction robotics. The point-of-view from which the state-of-the-art is described, is that of a construction-robot developer. The analysis focuses on two aspects. The first is the aspect of evolutionary development. The second is the type of construction function the robot performs.

Evolutionary Robot Development

The introduction of construction automation is an evolutionary process in which construction processes undergo a number of changes. According to the types of changes that occur, different phases in this introduction can be identified. The following four phases can be identified:

- *phase I*
transformation of *mechanic* equipment to *mechatronic* equipment
- *phase II*
introduction of mechatronic equipment for (traditionally) manual tasks
- *phase III*
introduction of autonomous robots
- *phase IV*
introduction of Design for Robotic Construction (DfRC)

The far stretching effects of the changes together with the natural human resistance to change, requires a stepwise introduction of robotics. How large these steps should be, depends on the strategy and culture of each company.

Using the previously defined phases as a scenario for the introduction of robotics in construction, four corresponding generations of construction automation equipment can be pictured. These generations are characterised as follows:

- *first generation*
A first generation of construction automation equipment evolves from existing construction equipment by the addition of electronic sensor and digital circuits (mechatronics). The goal of this 'upgrading process' is primarily to increase productivity and quality. First generation construction automation is based on currently existing construction manipulators such as excavators.
- *second generation*
Second-generation construction automation equipment largely consists of construction manipulators. These manipulators are no longer based on the existing equipment but they are still primarily controlled by human operators. An example could be a wall cladding element manipulator.
- *third generation*
The third generation of construction automation equipment are autonomous devices which execute tasks without control by an operator. These devices can be classified as construction *robots*. The robots require operator assistance for their setup and occasionally during operation.
- *fourth generation*
Fourth-generation construction robots are technologically not different from third generation construction robots but these robots are designed to be an integral part of new construction methods which are adapted to the use of construction robots (Design for Robotic Construction DfRC).

The above listed four generations are distinguished by changes on the following four aspects (See also figure 10).

- increased use of electronic sensors and control systems in equipment
- increased development of new types of mechatronic equipment
- decrease in human involvement in control of equipment
- increased adaptation of design and engineering for use of robots

A 1992 Delphi forecast in Japan (NISTEP 1992) shows that Japanese construction experts expect drastic progress in construction work efficiency and safety by the year 2010 as a result of the introduction of intelligent robots and large scale construction machinery. The results of this Delphi forecast can be used to estimate the time scale of the evolutionary introduction of construction robot technology in the building industry production. Figure 11 shows the estimated time scale of the growth curve of construction robotisation.

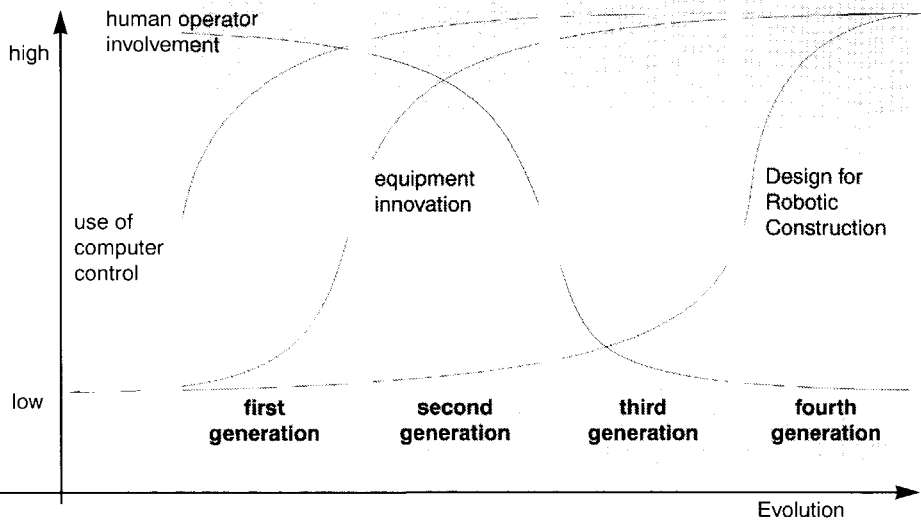


Figure 10 Four generations of construction equipment, characterised by changes in control technology, equipment usage, human control and robotisation facilities provided in design.

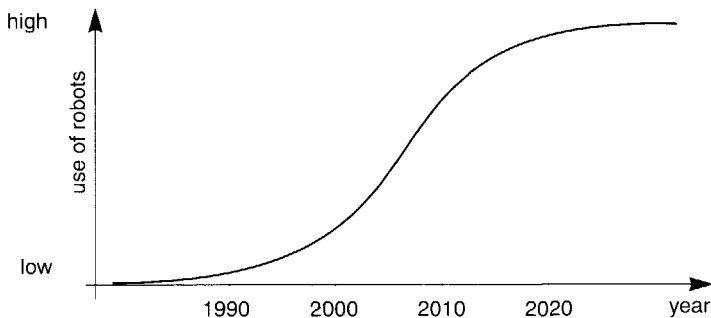


Figure 11 Expected development of use of construction automation equipment.

The Functionality Point-of-View

The second aspect in the analysis of the state-of-the-art in construction robotics is the type of construction function performed by the robot. For a classification of the aspect of robot functionality a classification from the CI/SfB Construction Indexing Manual (Ray-Jones et al. 1976) is used. The Construction Indexing Manual distinguishes the following nine types of construction operations:

1 protecting

E.g. realisation of temporary accommodation, protection of labour, protection of materials and works in progress.

2 *clearing, preparing*

E.g. demolition, rock blasting, site roads, scaffolding, formwork, excavation, digging, levelling, setting out, surveying.

3 *transporting, lifting*

E.g. horizontal transportation (trucks, conveyors, fork-lifts, wheel barrows), vertical transportation (lifting, hoisting)

4 *forming: cutting, shaping, fitting*

Changing the basic shape and/or size of material, which are divided into two groups depending whether the function produces waste or not. Examples of forming operations not producing waste are bending, smoothing, mixing and texturing. Examples of waste producing operations are cutting, grinding and sandblasting.

5 *treatment: drilling, boring*

Working on materials without changing the basic size.

6 *placing: laying, applying*

Locate and fix operations such as assembling, coating, pouring, compacting, fixing, installing, laying, placing, securing, driving etc.

7 *making good, repairing*

Correction of errors and damages.

8 *cleaning up*

9 *other functions*

The primary aspect in the analysis of the state-of-the-art in construction-automation equipment is the evolutionary point-of-view. Sections 3.1 to 3.4 discuss the equipment for each of the four distinguished generations.

3.1 First Generation: Computer Controlled Equipment

Existing equipment in use by contractors is the base of the first generation of construction robots. New devices for sensing and data processing, provide the users of expensive construction equipment with advanced control and operator feedback systems that improve the productivity and quality. The more expensive the equipment is, the more interesting it is to invest in the machine to achieve higher productivity. This strategy can apply to excavators, cranes, foundation pile-driving machines, etc. In the category of first generation construction robots a number of prototype systems and even some commercially available systems exist. The first generation systems discussed in this section fulfil three different types of construction functions (The numbers between parenthesis refer to the CI/SfB classification discussed above):

- excavation (2)
- horizontal transportation of earth and rock (3)
- concrete transportation and pouring (3 & 6)

Prototype robots belonging to each of the listed types of construction functions are discussed in the next three subsections.

3.1.1 Earthwork

Earthwork activities are heavily mechanised. Common earthwork machines are dozers and excavators. In different sizes and configurations the earthwork equipment is being used in levelling, digging of trenches for pipe laying, road construction and many other applications. The majority of all earthwork machines are *construction manipulators*. Since a number of years accessories for earthwork equipment are being sold to assist the equipment operators. An example of a commercially available accessory is a level control system for dozers. This system controls the elevation of the blade to realise smooth and level sites. Such a system improves the quality of the end product, as well as productivity. Because the operator is relieved of one of his tasks he can give all his attention to the steering of the bulldozer. (See also figure 12)

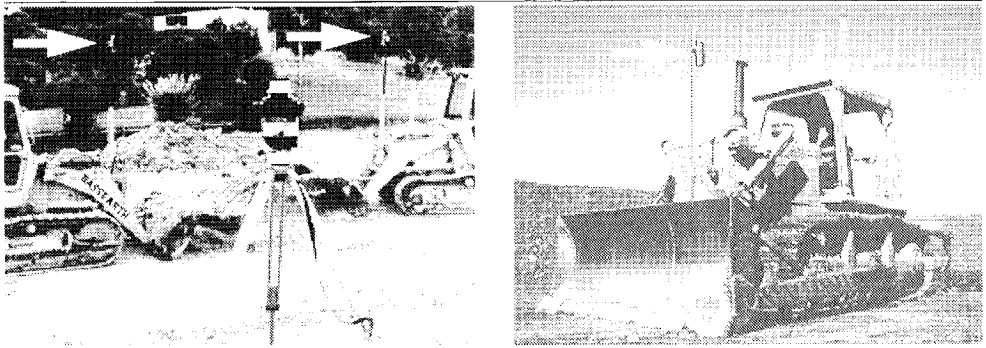


Figure 12 Example of level control system for dozers. A rotating laser on a tripod (left) provides a horizontal elevation reference plane. On the dozer, a control system adjusts the dozer blade height such that the laser receiver (arrow) follows the laser plane (Courtesy Spectra Physics Laserplane Inc.).

The major share of the costs of earthworks is capital investment in the machine. Benefits of improved productivity and performance can be obtained at the relative low costs of a control system accessory. The cost - benefit ratio is much better because only the costs of the control system accessory are compared with the increased performance.

Several research projects, such as presented by Vähä (1991), Bracewell (1990) and Green (1990) investigate excavator automation. Important issues involved with excavator automation are:

- *safety*
An automatic excavator might seriously injure people who are near the excavator.
- *reliability*
The conditions at the excavator arm are often too extreme for sensors to survive.
- *varying soil conditions*
- *unexpected underground "obstacles"*

3.1.2 Concrete Distribution

Distribution of concrete is hard labour. At large job sites the concrete is pumped to its desired location. A large manipulator arm is used distribute the concrete at large building projects (see figure 13). The control of the arm is a complicated task requiring a skilled operator. A German firm has developed a computer controlled version of their concrete distribution manipulators (Benckert 1991). This controller primarily assists the human operator. Using the robot controller, the arm can be used more efficiently. Benckert (1991) mentions the following benefits of the computer controlled concrete pump: increased pouring volume per hour, the possibility of using remote control and increased concrete quality.

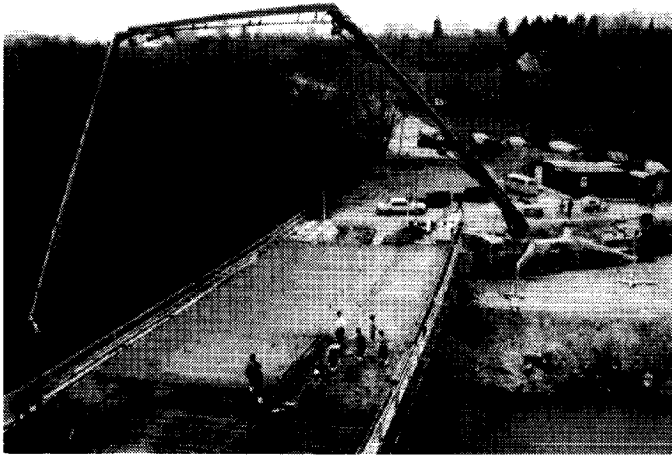


Figure 13 Large scale manipulator for concrete distribution.

In Japan both Obayashi Corporation and Takenaka Comuten Co. have developed a concrete placing robot arm similar to the German development (JIRA 1992).

3.2 Second Generation: New Equipment Applications

The next logical evolutionary step after the first generation construction robots is to develop new “tools”, using the technology and experience from the first generation equipment.

It is difficult to predict what the applications of second generation robots will be. It is up to the expertise and ideas of contractors and tool manufacturers to develop equipment to automate and support conventional construction processes. Several research groups have already studied development of completely new robots. In this paragraph some prototype developments are described. The functions performed by the second generation equipment are:

- *forming* (4):
 - concrete floor surface finishing
- *placing* (6):

- re-inforcement bar placement
- *transportation: carrying, handling* (3)
 - brick laying
 - interior wallboard manipulation
 - suspended ceiling installation

An important issue related to the development of second generation construction robots, is the improvement of working conditions. Nearly all second generation prototypes are manipulators which eliminate handling of heavy tools or materials by human workers to reduce the unhealthy character of manual labour tasks.

3.2.1 Concrete Floor Finishing Robots

A number of Japanese contractors has developed concrete floor finishing “robots” for concrete trowelling. These machines are developed with the primary goal to eliminate the unhealthy and strenuous character of the concrete trowelling work. Several different prototypes exist from Shimizu (see figure 14), Obayashi, Kajima and Takenaka (JIRA 1992). Most of the floor finishers can better be classified as construction manipulators than construction robots because they are controlled remotely by an operator. However, the floor finishers from Kajima, Obayashi and Shimizu can also operate autonomously. In Sweden a similar floor finishing robot has been developed (Berlin and Weiczer 1992).

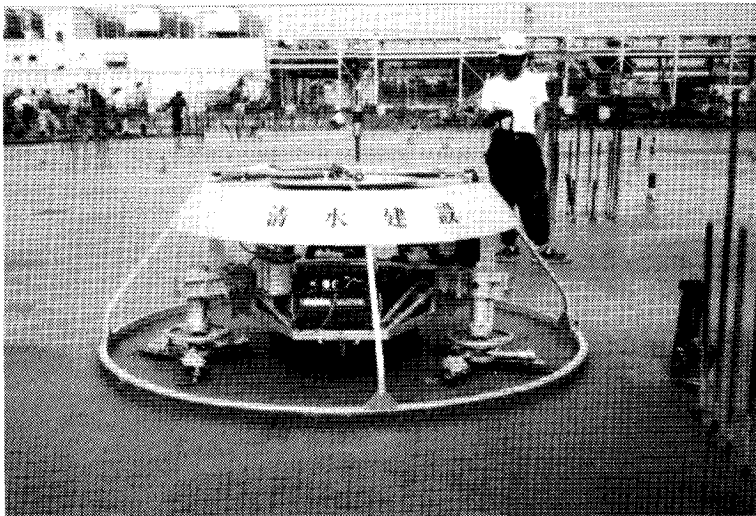


Figure 14 Concrete floor finishing robot ‘FLAT-KN’ in action (Courtesy Shimizu Co.).

3.2.2 Concrete Re-inforcement Placement

The Japanese contractors Kajima and Takenaka have developed prototypes of manipulators for the placement of large and heavy re-inforcement bars (JIRA 1992).

Taisei Co. (Sakamoto, Takeno and Shirato 1992) has developed a machine that bends and assembles re-inforcement cages. This machine performs on-site prefabrication of re-inforcement cages for concrete beams. The machine was developed because of the increasing shortage of skilled workers.

3.2.3 Bricklaying

In the Netherlands and in Germany sand-lime blocks are used frequently for the construction of the load bearing walls in residential and small office buildings. Depending on the size of the blocks used, different types of manipulation tools are used. In the Netherlands a small manipulation crane, such as shown in figure 15, is used to pick and place the sand-lime elements (0.6 x 0.9 x 0.1 m). In Germany, where smaller blocks are used, special masonry platforms are sold which allow the mason to work at the correct height and manipulate the blocks using a hoist or other means. Some masonry platforms have a gravity compensating, pneumatic arm which allows blocks to be manipulated weightlessly (See e.g. Böhm 1991).



Figure 15 Example of a small crane, developed for the manipulation of sand-lime elements.

Several other projects aim at full automation of the bricklaying process. These developments are classified as third generation automation and are discussed in section 3.3.1

3.2.4 Interior Wall Building

Taisei Co. has developed a wall board placement manipulator (Warszawski 1990; JIRA 1992). This manipulator is used to place heavy boards on walls.

3.2.5 Suspended Ceiling Installation

At least three Japanese companies (Shimizu Co., Kumagai Gumi Co. and Tokyu Construction Co.) have developed construction manipulators for the installation of gypsum boards for suspended ceilings (JIRA 1992; Tokioka et al. 1992).

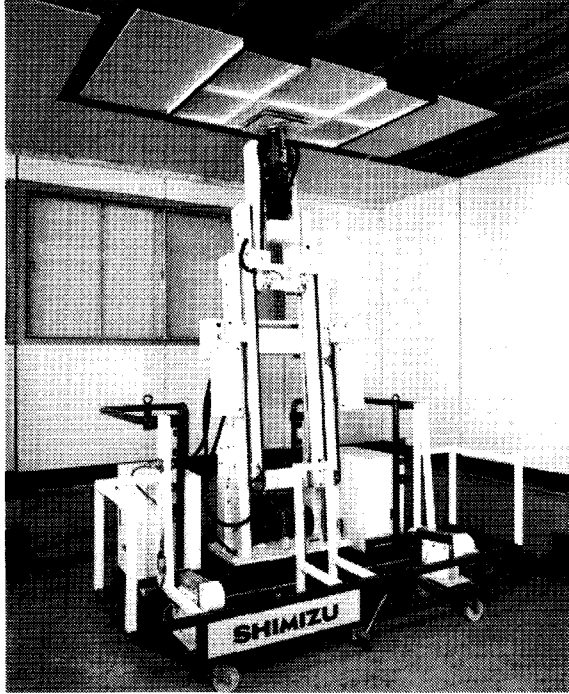


Figure 16 Ceiling board installation robot 'CFRI' (Courtesy Shimizu Co.).

The machines all have a similar concept. A manipulator handles the large boards and positions them at the installation location. Both the machines from Kumagai and Tokyo also automatically screw the board to the ceiling frame (JIRA 1992). On all three robots, an operator controls and supervises the installation process.

All three companies claim to have improved the working conditions of the ceiling board installers. With conventional methods the installation would require two persons. Using these ceiling board installation "robots" the same amount of work can be done by one person.

3.3 Third Generation: *Autonomous Robots*

Third generation construction robots automatically execute construction processes that up to then are performed manually. They distinguish themselves from second generation robots by the fact that these robots have the ability to do their work autonomously requiring operator assistance only periodically. A typical example of third generation construction robots is an autonomous trench digging excavator.

Such a construction robot (when it is ever developed) is the result of the evolution of a piece of equipment existing today into an autonomous robot. It has a minor impact on the building methods or business or the user of such equipment in contrast to fourth generation construction robots.

The remainder of this section describes a number of existing construction robots that can be classified as third generation robots. The construction functions performed by these third generation pieces of equipment are:

- *placement* (6):
 - robotic masonry
 - tile setting
 - application of coatings
- *transportation* (4):
 - concrete floor surface finishing
- *other operations* (9):
 - inspection

3.3.1 Robotic Masonry

Automation of masonry work has drawn much attention in European R&D projects. Two projects are working on the development of autonomous bricklaying robots. The largest project is the European ESPRIT III project 'Rocco' (Bock and Leyh 1995a; Bock and Leyh 1995b; Bock and Leyh 1995c). A prototype version of the bricklaying robot developed in this project is shown in figure 17. Another development is taking place in the 'Bronco' project which is carried out at the German Institute for Equipment Control (ISW) (Pritschow et al. 1996; Pritschow et al. 1994; Pritschow, Dalacker and Kurz 1993).

The German firm Anliker prefabricates masonry wall elements for residential buildings using a robotic device in a factory installation (Anliker, Anliker and Rothenbacher 1991). A research group at the City University in London is developing a collection of robot peripherals, sensor systems and end effectors that are essential for robotic masonry. The developments include a clamp type brick gripper, a suction type block/panel gripper, a brick feeding conveyor belt system and a vision sensor for inspection of the bricks (Chamberlain et al. 1992).

Several prototypes of construction automation devices for interior wall building exist. Slocum (1988) describes a robot from a family of robots consisting of the 'Blockbot', the 'Studbot' and the 'Wallbot' performing different tasks for interior wall building.

At the Technion in Israel a prototype multipurpose robot called TAMIR was developed. One of the applications for which this robot can be used is building of interior walls of gypsum blocks (Rosenfeld, Warszawski and Zajicek 1993; Rosenfeld, Warszawski and Zajicek 1991). Special solutions are developed to deal with tolerances occurring during the picking up of gypsum blocks.

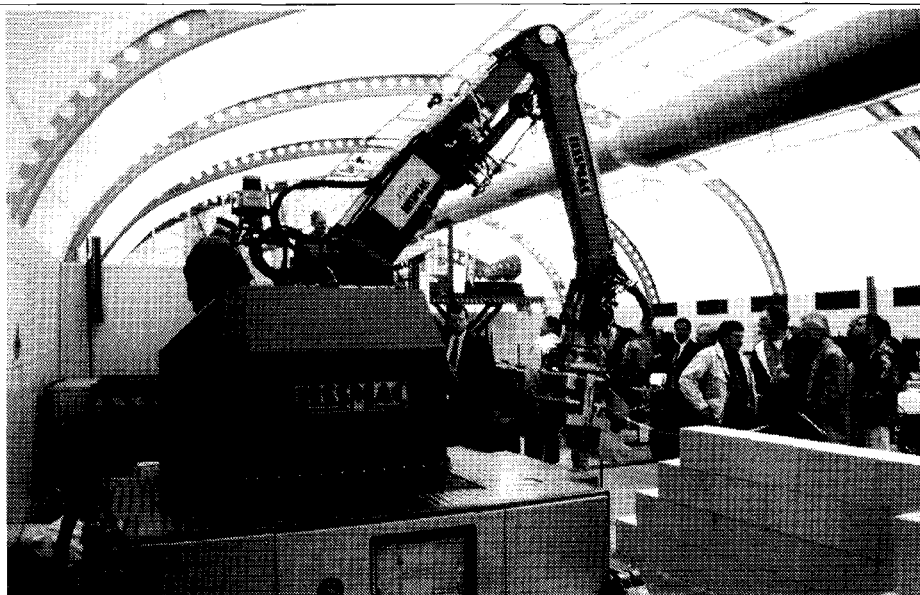


Figure 17 Prototype masonry robot developed in the 'Rocco' project.

3.3.2 Tiling

Several research projects have realised working prototype configurations of tiling robots. The projects carried out at the Technion in Israel (Rosenfeld et al. 1993) and at the VTT in Finland (Lehtinen et al. 1991) have both used a standard type industrial robot. Both research groups have developed special purpose vacuum gripper end-effectors, tile feeding and mortar dispensing mechanisms. Navon (1995) presents a conceptual 'from scratch' design of a high performance floor tiling robot which is analysed using a computer simulation tool.

Another revolutionary approach has been followed in a joint development of Komatsu Ltd. and Hazama Corporation (Tomaru, Haino and Ishikawa 1991; Kikawada et al. 1993; JIRA 1994). The developed tiling robot uses a kind of rubber conveyor belt equipped with vacuum suction cups to apply a number of tiles simultaneously. This robot is designed to tile large surfaces such as building exteriors. The robot is guided along the building facade by rails mounted on scaffolding.

3.3.3 Spraying of Paints and Coatings

The handling of discrete parts by robots has always proved to be very complex. Therefore the application of liquid materials such as paint, cement, concrete and fire proofing material have belonged to the first applications of robot technology.

Shimizu Co. and Taisei Co. have both developed similar painting robots for treatment of exterior of high buildings (JIRA 1992). Figure 18 shows the Shimizu painting robot. The robots are suspended by steel wires from the top of the building.

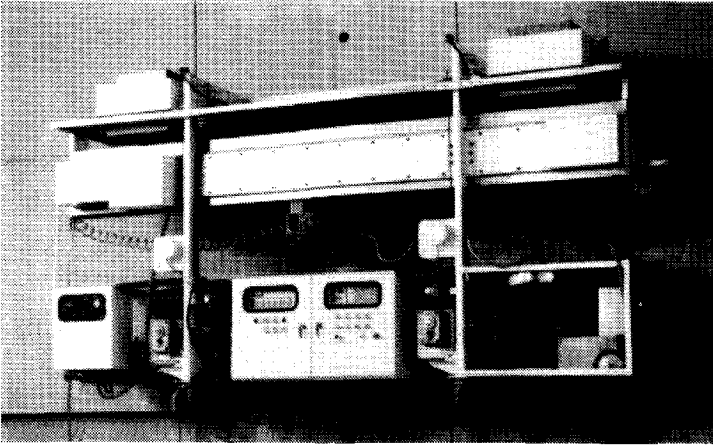


Figure 18 Painting robot for exterior walls on high rise buildings 'SB-Multi Coater' (Courtesy Shimizu Co.).

Shimizu Corporation has developed three generations of spraying robots for the application of fire proofing to steel structures in high rise buildings. During the development of the three versions Shimizu Spraying Robots (SSR), several aspects of the original design have been improved. The features of the third version of the robot (SSR-3, see figure 19) are: an off-line programming system and ultrasonic sensors for position corrections due to tolerances. Kobe Steel Ltd. (JIRA 1992), Takenaka (Uchizaki and Uchida 1993) and Fujita (Miyamoto et al. 1992) have also developed fire proofing spraying robots.

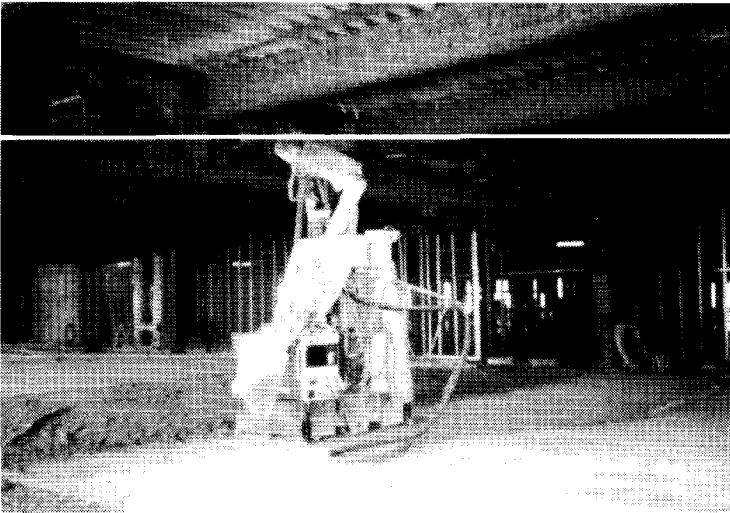


Figure 19 Fireproofing spray robot 'Shimizu Site Robot No. 3 (SSR-3)' (Courtesy Shimizu Co.).

3.3.4 Transportation of Building Materials

A significant proportion of effort in the construction of buildings is put in the transportation of building materials. Especially during the interior finishing stage large amounts of materials have to be transported to the location of the construction activity.

In Japan a material handling system has been developed which transports interior finishing materials to the desired location in a building under construction. The system uses an elevator to transport the materials to the desired floor, where radio controlled AGVs transport materials to a designated place (Honda et al. 1992).

Transportation of materials on building sites is one of the physically straining and unhealthy types of work, taking place at building sites. The technology to automate this type of work is available, but the fragmented business structure of the building industry is a major obstacle for economic use of this technology.

An automation development in earthwork deals with the automation of the driving of loader vehicles that transport earth, rock, coal, etc. at large excavation sites and open mines. The drivers of these vehicles are replaced by autonomous vehicle navigation systems. Developments of such systems are described by Gocho (1992) and Hatakeyama (1992).

3.3.5 Inspection Robots

Because of the significant number of high rise buildings in Japanese cities and the dangers involved with work on high rise buildings, a number of robots for inspection and treatment of exterior walls of high rise buildings have been developed.

Two examples of some typical inspection robots are:

- *ultrasonic weld inspection robots*

The inspection robots are spider like devices that use magnets to clamp onto gas holders to inspect welds using ultrasonic sensors (see figure 20) Two gas holder weld-inspection robots are developed by Hitachi Ltd. and Ishikawajima-harima Heavy Industries Co. both for Tokyo Gas Co.

- *tiled surface inspection robots*

Kajima Co. has developed a robot for the inspection of tiled surfaces on high rise buildings (JIRA 1992), (Terauchi et al. 1993). This robot is suspended by a pair of cables from the top of a building. Taisei Co. and Kumagai Gumi Co. have developed similar devices (JIRA 1994). Obayashi Co. and Takenaka Komuten Co. have developed similar inspection devices that use vacuum suction force to climb walls (JIRA 1994).

3.4 Fourth Generation: Design for Robotic Construction

Fourth-generation construction robot systems are characterised by Design for Robotic Construction (DfRC). After (probably inevitable) introduction phases where robots will be used more and more, a new era will start. As soon as the

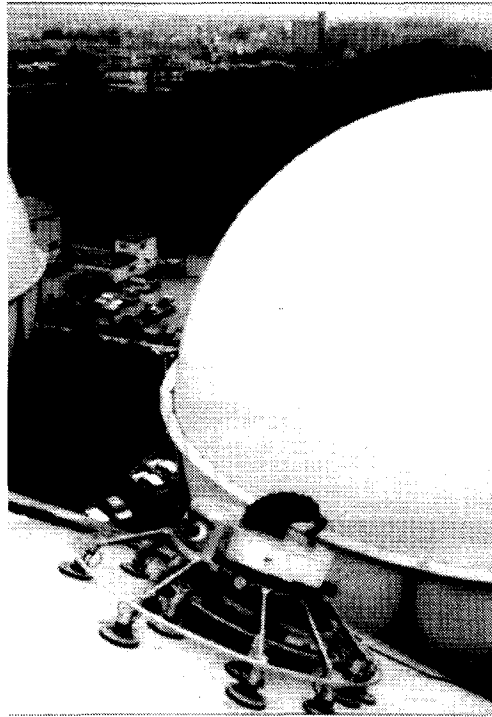


Figure 20 Gas tank inspection robot.

building industry is convinced that construction robots are more than a temporary phenomenon, building processes, methods and materials will be adapted to robot use.

The fourth generation of construction robots is characterised by an integral design of end product, building materials, and construction robot functionality. Although existence of fourth-generation construction robot systems seems unlikely in the current state-of-the-art in construction automation, four different Japanese companies have already developed prototype systems and constructed new buildings with these systems.

The Japanese developments, which are called *integrated automated construction systems*, are best characterised as *re-engineered construction systems*. The systems are all aimed at the automation of the erection of high rise buildings. In the re-engineering process new, but available technologies and concepts are introduced into the building construction process. The most important characteristics of the integrated construction systems are:

- *automated transportation and lifting of materials*

Steel structure subassemblies for columns and beams, floor slabs, facade elements, are all transported automatically from an unloading area to their destination locations

- *use of prefabricated subassemblies*
Forming and treatment operations are avoided at the building site.
- *just-in-time delivery of building components and subassemblies*
- *automated placing and fixing*
Prefabricated steel columns, beams, floor elements, facade elements, pipe assemblies etc. are automatically brought to the correct position. Welding robots join steel structure members. Snap-fit connections are used to fix facade elements.
- *lift up system*
An jack-up system raises the hoisting equipment to the next floor.
- *design for construction*
All building parts and joining methods are designed or adapted to make them suitable for automatic handling and assembly.

The benefits of the automated building systems mentioned in various publications are (e.g. Tanijiri et al. 1996; Maeda 1994):

- improvement of working environment
- elimination of dangerous tasks
- reduction of man hours on site
- reduction of construction waste
- reduction of workload of site management
- shorter construction period
- improvement of productivity
- improvement of construction quality

Some typical examples of integrated construction systems are:

- *SMART*
The Shimizu Manufacturing system by Advanced Robotics Technology (SMART) (Miyatake 1993; Maeda 1994; Maeda 1995) is the most advanced integrated construction system (See figure 21).
- *ABCS*
Obayashi Co.'s Automated Building Construction System (ABCS) is very similar to SMART. Features and concepts of the ABCS are described in (Shiokawa and Noguchi 1994). The ABCS is controlled by two systems: a workflow control system and an equipment control system. The ABCS has been tested in practice in the construction of a 10 storey building for Obayashi Real Estate Ltd.
- *T-UP*
The T-UP system from Taisei Co. (Sakamoto and Mitsuoka 1994) is not as advanced as SMART or ABCS. The T-UP system puts the emphasis and priority on the optimization of the steel structure assembly process in the erection of high rise buildings.

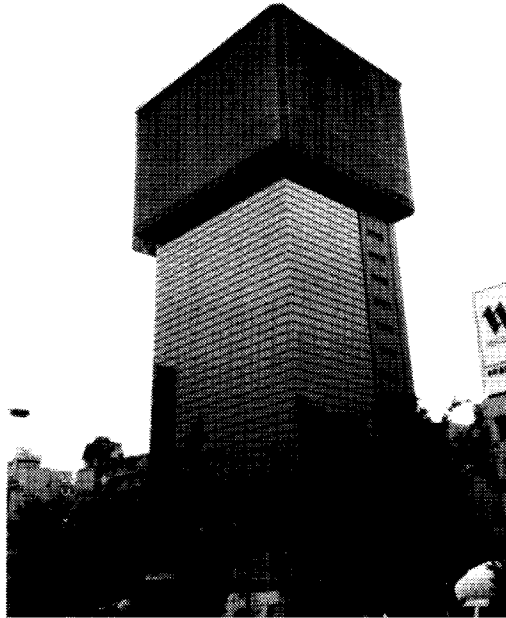


Figure 21 Building being constructed using SMART system (Courtesy Shimizu Co.).

- *Automated Weather Unaffected Building Construction System'*

The 'Automated weather unaffected building construction system' has been developed by Fujita Co. (Tanijiri et al. 1996). The system uses the same principles as the other automated building systems.

- *FACES*

The Future Automated Construction Efficient System (FACES) is developed by the Penta-Ocean Construction Company (Yoshida et al. 1997). Figure 22 shows the interior of the upper floor assembly area of FACES.

Integrated building systems seem to provide the most cost-effective (long term) approach to the implementation of automation. Re-engineering of the construction process enables optimal efficiency in the use of proven automation techniques such as welding robots and automated transportation.

3.5 Conclusions and Discussion

In table I, the robot applications discussed in this chapter, are classified showing both their generation, as well as their construction function. As expected, the difficult to automate construction functions *protecting* (1), *making good* (7) and *cleaning up* (8) are unpopular. Such construction functions, especially *making good*, require experienced craftsmen which know how to deal with specific situations. Robots are not suited for such tasks. It is remarkable to find that no robot seem to exist that fulfil the functionality of *treatment* (5).

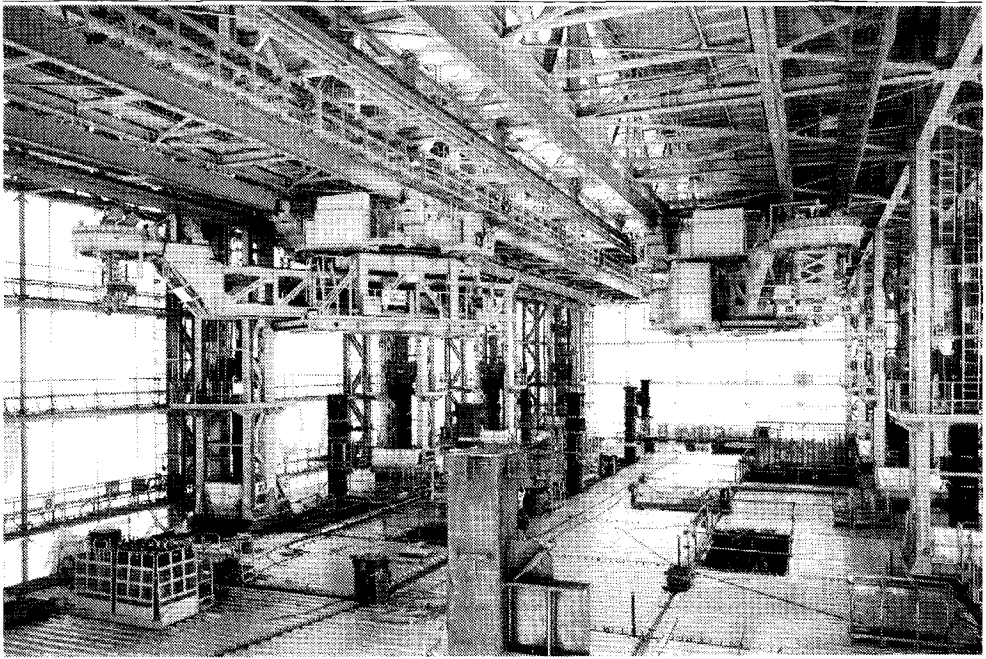


Figure 22 Interior of FACES assembly cranes that operate at the upper most floor to assemble the building structural system (Courtesy Penta-Ocean Construction Co.).

Table I Matrix of robot generations and robot functions.

	I	II	III	IV
protecting(1)				
preparation (2)	robot excavation			
transportation (3)	robot dumpsters concrete placement		AGVs	SMART, T-UP ABCS, FACES
forming (4)		concrete screeders	grinders concrete screeders	
treatment (5)				
placing (6)	concrete pouring	re-bar placement brick handling board handling	robot masonry tile setting coating (SSR)	SMART, T-UP ABCS, FACES
making good (7)				
cleaning up (8)				
other functions (9)			inspection	

It is expected that in the next 5 years, computer technology and electronics will be used more and more on construction equipment. At first this computer equipment will enable equipment operators to deliver better quality end results, or realise a higher productivity in first generation systems. On the longer term, computer equipment is expected to take over more and more equipment control tasks. This slow and gradual automation will eventually lead to equipment that can perform tasks autonomously.

Possible Future Trends

The real breakthrough in construction robotics usage is believed to take place in fourth generation systems. The *top-down re-engineering* of the construction process includes the adaptation of product design, engineering, planning and production to the possibilities and impossibilities of the robot technology. The possibilities of the top-down approach are demonstrated by the Japanese prototypes of *integrated, automated construction systems*, such as T-up, ABCS, FACES and SMART. These prototype implementations show that it is possible to use available robot technology in construction as long as product design and construction methods are adapted. However, the adaptations necessary to accommodate today's robot technology are far stretching because integrated construction system 'sites' show more resemblance to factories than to traditional building sites.

Although the fourth generation approach of automated building systems is the way to go, it will be unrealistic to robotise construction without going through each of the four distinguished phases. Each phase involves changes in some aspect of the work methods. In order to avoid problems an evolutionary introduction of robot technology seems preferable. However, fourth generation robotisation should be the long term goal in order to exploit the full potential of economic benefits of robotisation.

The further advancement in robot technology enables the implementation of robotic construction systems which require less adaptations to the product and production process. More intelligent control systems and better sensing will enable robot systems to cope better with existing uncertainty in construction products and processes. On the other hand computer design tools will support the adaptation of building industry product design for use of robotic construction.

Human factors are believed to play an important role. The construction labour force in Europe and the United States is not expected to accept the drastic robotisation as demonstrated by the Japanese integrated construction systems. The Japanese circumstances, where labour shortages justifies the current approach, has not yet been met. The non Japanese construction labourers will oppose robotisation because of the fear of losing their jobs. The gradual introduction of robot technology in the building industry through each of the phases outlined in this chapter seems to be one of the most likely scenarios: not revolution, but evolution!

4

State-of-the-art in Robot Technology

This chapter presents an overview of the state-of-the-art in construction robotics from a robot technology point-of-view. The available state-of-the-art robot technology is discussed for each of six different aspects of robot functionality.

Warszawski (1990) argues that robot performance requirements can be defined in a uniform manner concerning six robot aspects, which are:

- manipulator performance
- end effector characteristics
- material feeding
- control
- sensing capabilities
- mobility

This chapter uses these six aspects as a guideline to discuss the state-of-the-art of technology available for construction robot development.

4.1 Manipulators

The term robot *manipulator* is used to refer to the mechanical device of the robot which positions and orientates the robot's *end effector*. The robot manipulator is often constructed similar to the human example and consists of a *base*, *arm* and *wrist*. The function of the manipulator *arm* is to bring the robot end effector to the desired position. The function of the manipulator *wrist* is to bring the end effector in to the desired orientation. The manipulator *base* can be attached to a mobile vehicle or at a fixed position.

Positioning and orientation of an object in a three dimensional space requires six degrees of freedom. Therefore the majority of all robot manipulators have six joints to provide the six degrees of freedom. Different types of joints are available to provide the degrees of freedom. In total four types of joints are distinguished (Groover et al. 1986). Figure 23 shows these different types of joints.

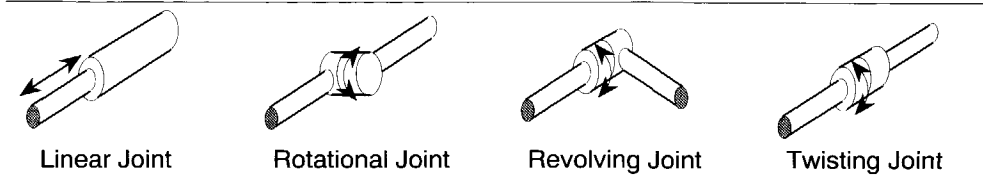


Figure 23 Types of manipulator joints.

Theoretically this allows the existence of $4^6 = 4096$ different manipulator configurations (six joints, each of one out of four joint types). However, in practice only four different joint type configurations are being used: polar, cylindrical, cartesian and jointed arm. These four types are shown in figure 24. These different types of robot manipulator configurations and their applications in manufacturing are discussed in several books on industrial robots, including (Groover et al. 1986) and (Reijers and Haas 1986).

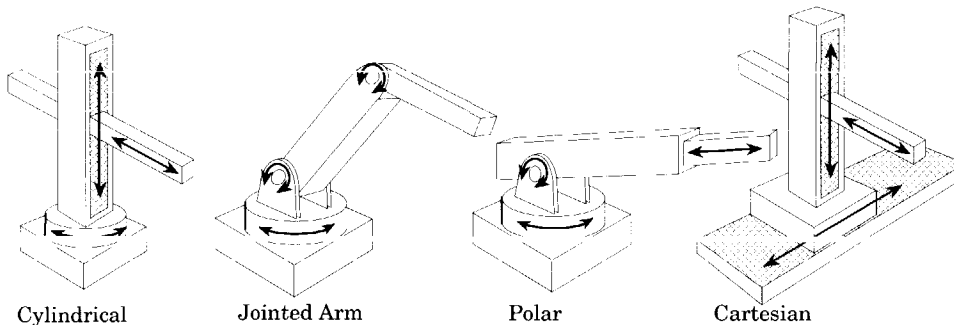


Figure 24 The four basic configurations of current industrial robots.

4.1.1 Manipulator Performance

Robot manipulator performance is characterised by a number of aspects:

- *work volume*

The *work volume* is the term that refers to the space in which the robot can manipulate its wrist end. (Groover et al. 1986) The robot work volume is of great relevance for building industry applications. The work volume of most of the commercially available manipulators is inadequate for construction applications because they are intended to be used in manufacturing processes of small or medium size products.

- *load-carrying capacity*

The *load-carrying capacity* of a robot manipulator is the maximum mass of the load that can be handled safely and positioned accurately. The load-carrying capacity depends on the manipulator configuration, structure, size and drive system. The load-carrying capacity also varies with the pose of the manipulator. The maximum load-carrying capacity of the larger industrial robot manipulators is about 1000 Kg's. Only hydraulic-driven manipulators have such large load-carrying capacities.

- *motion speed*

The maximum speed of the manipulator end determines how quickly a robot is able to accomplish its task. However, manipulation of heavy objects is not possible at high speeds because of inertia forces on the manipulated objects. Therefore the speed of motion is often practically limited by manipulator stability and accuracy.

- *accuracy*

The manipulator *accuracy* refers to the robot's ability to bring the manipulator end to a desired location in the work volume. This accuracy is influenced by several factors:

- the control resolution (i.e. the smallest motion steps the joint can make)
- tolerances in the joints and actuators
- deflection of the manipulator when carrying a load.

- *compliance*

The term *compliance* of a robot manipulator refers to the effect of manipulator end displacement in response to a force or torque against it. Industrial robot manipulators are constructed to have a low compliance (very little displacement when forces are applied). A higher compliance reduces the manipulator's precision when handling a heavy load.

4.1.2 Construction (Robot) Manipulators

Reijers & De Haas (1986) argue that the mechanical design of an industrial robot manipulator represents an engineering compromise between work volume and dynamic behaviour, i.e. compliance, speed and accuracy. An increase of the manipulator work volume and load-carrying capacity by adopting the same mechanical engineering approach as used in the industrial robot manipulators inevitably leads to very large and heavy manipulators. An example of an existing (medium to large scale) construction manipulator is the excavator. Excavators have a large work volume, a medium compliance, a relatively high speed of motion, a reasonable accuracy, but they have a mass ranging from 25 tons for a mid size excavator to 50 tons for a larger model. The size and weight of large machines is often limited by the legal limits that apply for transportation of such machines on public roads.

The ratio between load-carrying capacity and manipulator mass is a constant factor in the traditional manipulator engineering approach. Increase of the manipulator work volume or load-carrying capacity without increase of the manipulator mass is not possible using the conventional mechanical engineering approach as used in the industrial robot or excavator engineering.

The design of large scale construction manipulators or limited mass interior operating manipulators requires a different approach. The most obvious and promising approach is to use advanced manipulator control systems. These systems can counteract the dynamic effects that occur in manipulators that have a higher load-carrying capacity to mass ratio. Several research groups have investigated the implementation of large scale manipulators for different construction material manipulation activities. Hsieh and others (1993) at the Construction Industry Institute have investigated several large manipulator applications including a large scale sandblasting manipulator. The ESPRIT II project LAMA was directed on the development of a large scale manipulator (Wanner, Engeln and Rupp 1991). In the project an advanced sensing and robot control system has been developed which deals with the manipulator arm deflections in a large scale manipulator. The LAMA project has delivered a large scale manipulator with a special end effector for cleaning aeroplanes using a large rotating brush (Schraft, Wanner and Herkommer 1994) A second generation design of the aeroplane cleaning machine is shown in figure 25.



Figure 25 Large scale manipulator for aeroplane cleaning (Courtesy Dornier GmbH).

Within the LAMA project the control of existing large scale construction manipulators such as concrete distribution booms was also investigated. A prototype system of a Putzmeister concrete distribution boom with a robot controller was built and tested. The robot controller enables more precise and easy control of the boom end. Also safety is increased because the stability of the machine is checked by the controller and also collisions of the arm with obstacles near the building site (buildings, electricity cables) can be avoided. (Benckert 1991)

Another large-scale general purpose construction manipulator development project is presented by (O'Brien 1992). A full scale prototype of a large-scale manipulator has been developed. It has a load-carrying capacity of 100 Kg, a reach of 10 m and an accuracy of 2-5 mm. O'Brien argues that such manipulators are technically feasible and can be exploited economically.

It can be concluded that manipulator design is complicated because it involves a balanced trade-off between contradictory aspects of mass, load-carrying capacity, speed, accuracy and compliance. Conventional manipulator designs require manipulators to be rigid enough to eliminate dynamic effects. This rigidity is obtained at the expense of the manipulator mass. This approach can unfortunately not be used for construction robot manipulators. Large-scale robot manipulators have to remain transportable between sites, which imposes limits on their mass and size. Small-scale interior-use robot manipulators should also be limited in mass to remain within the allowed floor-load limits. The building industry needs lightweight, high load-carrying capacity manipulators where advanced control systems deal with the dynamic effects of non-rigid manipulators.

4.2 End Effectors

Groover, Weiss et al. (1986) define the *end effector* as: the special tooling that permits the general purpose robot to perform a particular application. Two types of end effectors can be distinguished:

- *object-handling mechanisms*
Object-handling mechanisms are end effectors that can pick-up and handle some kind of object (e.g. gripper, electromagnet, suction cup etc.)
- *tool mechanisms*
Tool mechanisms are end effectors that are tools that can perform a specific operation on an object (e.g. drill, weld torch, paint spray gun, sand blasting gun, etc.).

Both types of end effectors are discussed in more detail in the remainder of this section.

4.2.1 Object Handling Mechanisms

A very common type of object handling mechanism is the *gripper*. An alternative object handling mechanism to the grippers is a vacuum suction cup. Although a large percentage of robot applications in mechanical industries involves object handling, construction robot applications do tend to avoid object handling. This situation is probably caused by the properties of the building materials and components. Building materials have large dimensional tolerances and also the packaging is often unsuitable for machine handling. For reliable and simple supply, components are to be supplied in structured packaging systems such as cartridges, on pallets, cassettes, on rolls, in strips etc.

4.2.2 Tool Mechanisms

Many different kinds of tools are being used as robot end effectors. Some examples of robot end effector tool are:

- spot-welding clamp
- (paint) spraying gun
- sand-blasting nozzle
- arc-welding gun
- screw driver
- nailing / riveting gun
- grinding / polishing machine
- drill
- measuring pen
- water-jet cutting nozzle

The need for a supply of discrete parts such as nails, rivets, screws, generally complicates an end effector and reduces its reliability of operation.

To improve the versatility of robots one may employ interchangeable tools. *Tool-change adapters* provide a mechanical interface between the manipulator and the end effector and allow electrical and pneumatic lines to be connected. There are some practical limitations to such types of end effectors. For instance sand blasting, paint spraying, arc welding or spot welding end effectors are less suited to be made interchangeable because of the special type of connections and material supply required.

In summary, numerous types of end effectors are available for many different applications. End effector technology seems to be very applications specific. Conceptual end effector technology problems apparently do not hinder the development of construction robots.

4.3 Material Feeding

Material feeding is the term for the system that presents parts and/or materials to the robot's end effector. All robot applications that install parts or apply materials require feeding mechanisms. Robots used in applications that involve handling of discrete objects tend to have more complicated object feeding systems than robots handling materials that can be transported through pipes and hoses.

Several alternative solutions are available. Four types of material feeding methods can be distinguished:

- *structured packaging*

By using pallets, trays or magazines, parts can be presented to the robot at pre-determined positions with a known orientation.

- *mechanical feeding*
Special machines can be used to bring randomly orientated parts in a predetermined location and orientation. A common type is the vibrating bowl feeder.
- *sensor detection*
A sensor system can be used to observe the current position and orientation of an object to let the robot know where and how to pick up the object.
- *manual feeding*
A human worker presents the parts to the robot.

Material feeding is a difficult problem in the robotisation of construction processes. The most simple approach (from robot implementation point-of-view) is to use a structured packaging approach. However, this requires cooperation from the component supplier. If the materials are already packaged in some semi structured way, such as on pallets or in stacks, a sensor detection approach can be used.

4.4 Control

The computer-control system is the “nerve centre” of the robot and controls the motion and behaviour of all the mechanical components of the robot. Therefore the control system is just as influential on the robot functionality as the manipulator. Especially the programming facilities (or better *instruction facilities*) of a robot, determine what type applications the robot can be used for.

In the area of research on robot control, four levels of abstraction are defined (see e.g. Reijers et al. 1986). These levels of instruction are (in sequence of increasing abstraction):

- *joint-level control*
Joint-level control instructions control the robot manipulator joint actuators and end-effector actuators directly. Joint-level control is generally impractical.
- *robot-level or motion-level control*
Robot-level instructions enable control of the motion of the end effector in perpendicular coordinate systems. The control system has robot-configuration knowledge which is needed to translate robot-level instructions into joint-level instructions.
- *object-level control*
Object-level instructions enable handling of objects. An object-level control system needs object handling knowledge to determine what motions are needed to move an object from location A to B and how to pick-up and handle objects.
- *task-level control*
Task-level control instructions enable execution of complete tasks, such as the assembly of a product. Task-level instruction requires task-planning knowledge to determine how to carry out an assigned task.

Instructions of higher abstraction are translated into lower abstraction-level instructions until the instructions can be given to robot-control hardware (joint-level).

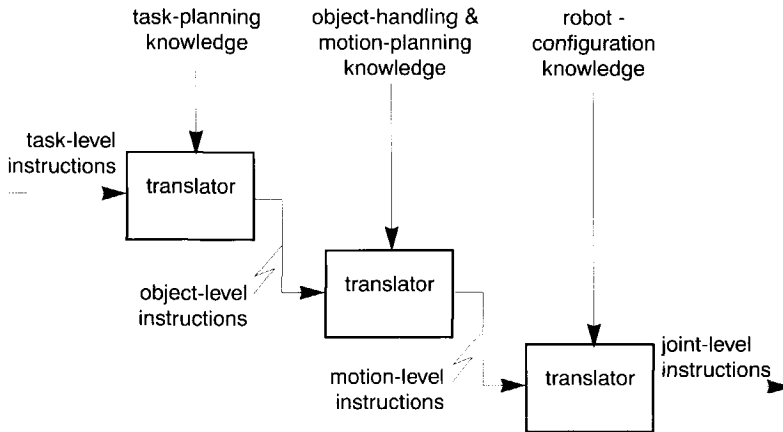


Figure 26 IDEF₀ diagram of the translation process of task-level instructions into joint-level robot instructions. Task-level instruction are translated into object-level instructions using task planning knowledge as a resource. In two consecutive steps object-level instructions are translated into joint-level instructions using additional object handling and robot configuration knowledge.

The level of abstraction pertains to the abstraction of the instructions. The higher the level of the instructions, the more knowledge is needed in the control system. Figure 26 shows an IDEF₀ diagram of the conceptual process in which abstract task-level instructions are translated into joint-level robot motion instructions using additional knowledge resources.

The current generation of commercially available robot controllers are capable of dealing with motion-level instruction and translate these into joint-level instructions.

4.4.1 Robot-Level Control

At robot-level the robot controller provides the ability to control the motion of the end effector *Tool Centre Point* (TCP) in robot related or workpiece related coordinate systems. The robot controller provides facilities for TCP motion along lines or curves defined in any coordinate system. Motion characteristics such as velocity, acceleration and sometimes also force, can be controlled. Besides the motion control facilities, robot controllers also provide *motion-programming* facilities. These programming facilities enable the specification of complex motion patterns of the robot manipulator and end effector. These end effector motion patterns let the robot perform a task. Groover, Weiss et al. (1986) distinguishes two types of programming methods:

- *lead-through methods*

The lead-through methods are used to program a robot in a “teach-by-showing” manner. Lead-through programming is often used for paint-spraying robots.

- *textual robot programming methods*

The textual programming is also called *off-line* programming. In contrast to the *on-line* location teaching, off-line programming does not require the robot to be available. Several different programming languages exist (one for each different robot manufacturer). Most of the textual robot languages use a combination of textual programming and teach-in programming. The structure of the robot program is typed in, while specific workspace locations are programmed by guiding the end effector to the desired position and orientation and storing that location.

The (im)possibilities of a robot are primarily determined by the control systems capabilities. A common feature of all robot-programming methods and languages is the motion-oriented character. Disadvantages of the motion-oriented character are the time consuming nature of programming and the strong relation between robot program and workcell layout.

4.4.2 Object-Level Control

Object-level control systems can deal with pick-and-place type operations. An object-level system needs knowledge of how to pick up (grab) an object, and how to move without colliding into something. The developments of object-level control systems is generally an intermediate goal in the development of task-level instruction systems.

4.4.3 Task-Level Control

The ultimate goal in robot programming is to realise task-level systems which can deal with high level tasks without help of human programmers. A task-level robot system is a system that allows instruction of a robot in terms of the problem to be solved or the goal to be achieved. In other words; an action is characterised by its desired effects rather than by the actions required to achieve the task. The obvious advantage is that a robot programmer (or better robot instructor) does not have to describe in detail how the robot has to perform its task. Obviously this automation of the robot programming significantly reduces the amount of work involved in robot instruction.

Prototype implementations have been developed as part of several research projects. A famous task-level system is the HANDEY system (Lozano-Pérez et al. 1992). The HANDEY system is a piece of software which is able to generate robot (motion-level) programs automatically for assembly and pick-and-place type of tasks. The HANDEY system input consists of solid-model descriptions of parts to be assembled and the topological relations between the parts to be established.

Another recent implementation of a task-level system has taken place in the ESPRIT project 'Operational Control of Robot System Integration into CIM' (ESPRIT project No. 623) (Bernhardt et al. 1992). Bernhardt (1992) argues that the changes in demands in manufacturing industry towards shorter product life-cycles and increased product variety, cause that current robot-level programming methods prove to be no longer suitable.

Task-level instruction systems are an important tool to reduce the time and effort required for robot instruction. Therefore task-level instruction is believed to be an essential development for construction robotics. Task-instruction systems enable the use of robots for the production of smaller quantities and with a larger product variety than the production processes that robots are now successfully used for.

4.5 Sensing

Motion-feedback sensors on the robot-manipulator joints are part of nearly all robots. Besides for motion feedback, sensors are also used to enable the robot to adapt its behaviour to the circumstances of this environment. These behaviour adaptations can vary from simple wait states to intelligent adaptations of the robot's work strategy. A wide range of sensors is available for use in robot work cells. The simplest forms are the on/off type sensors such as limit switches. More complex types of sensors register one, two or three dimensional phenomena such as location. An example of a very complex sensor is a 3D stereo vision image sensor.

The typical industrial robot workcell design avoids uncertainties in environment of the robot, preventing the need for sensor systems. A robot environment with the least uncertainty is called *structured*. In a fully structured robot workcell a robot can perform its task without a need for sensors. Objects are presented to the robot gripper using special feeding devices to enforce repetitive part placing at the same location and orientation. Fences around the workcell prevent that human beings or other obstacles enter the workspace of the robot.

For construction robots, sensing is an unavoidable need and an important design aspect. The characteristics of construction processes require construction robots to be equipped with a fair amount of sensing capabilities. Because construction robots have to work in and around the product they work on, they also have to deal with on site "working conditions". These working conditions include, amongst others unexpected obstacles when changing position, tolerances in: object dimensions, object locations and robot location. Unfortunately (from a robotisation point-of-view) the building industry has a poor history concerning tolerances. Dimensional tolerances are often unknown or supposed to be non-existent. To be able to use robots reliably, sensors are required to measure the dimensional tolerances in the robot environment and in the objects to be handled by a robot.

Introduction of robotics in construction processes will in many cases require changes to the building site in order to improve the robot's "working conditions". In many cases it will be more expensive to equip a robot with the sensing and reactivity capabilities to deal with site conditions than it is to change the site conditions.

4.6 Mobility

The majority of the industrial robots used in industry is fixed at one specific location. Providing robots with the ability to move under their own power and control, greatly increases the potential use and work volume of a robot. This ability to move under their own power and control is referred to as *mobility*.

Unfortunately the term *mobile robot* is often being used ambiguously. The most straight forward interpretation of the term *mobile robot* is a robot manipulator mounted on a mobile platform. The other interpretation often used in literature is that a mobile robot is a programmable *vehicle* for purposes such as transportation. In this thesis the first interpretation of the term *mobile robot* is used (i.e. a vehicle and manipulator system). The term *robot vehicle* is used to refer to a programmable vehicle.

The most important benefit of mobility is the significant increase in work volume compared to the stationary robot. A special advantage of mobile robots compared to large-scale robot manipulators is that the robot work volume is increased without the penalty of a huge increase of the robot's dimensions and mass. This is particularly interesting for the development of construction robots which operate inside buildings. The fact that building industry production takes place at building sites instead of factories, requires construction robots to be transportable. The larger and heavier a robot becomes, the more difficult and expensive it becomes to transport the robot from site to site. Therefore mobility seems the most effective approach to realise construction robots with large work volumes, but without increasing their size and weight beyond practical limits.

Robot manipulators can be made mobile by mounting them on a mobile platform. In order for a robot vehicle to provide the type of mobility that is needed, two aspects of robot vehicle design should be considered. These two aspects are:

- *locomotion*

The type locomotion system used, greatly determines the robot's capabilities to relocate itself under various circumstances. Wheeled locomotion for example, allows relocation at relative high speeds, but is unsuitable for climbing stairs. The type of locomotion systems available are discussed in subsection 4.6.1.

- *guidance and navigation*

Turennout (1994) distinguishes two types of robot guidance: guided vehicles and free-ranging vehicles. Guided vehicles are restricted in their motion to a set of predefined paths in their working environment. These guide paths can be indicated by tracks, magnetic or optical lines, inductive guide paths or a table of paths in memory. Industrial robot vehicles, also known as Automated Guided Vehicles or AGVs belong to this first class. Non-guided vehicles are referred to as free-ranging robot vehicles.

Navigation has two aspects:

- *localisation*

establishing where the robot is

- *motion planning*

figuring out how to get from A to B without colliding into obstacles

Subsection 4.6.2 discusses state-of-the-art navigation systems that are available for the implementation of free-ranging robot vehicles for construction robots.

4.6.1 Locomotion

Locomotion of robot vehicles can be realised using a wide range of alternative locomotion approaches. Each of the techniques has its specific advantages and areas of applications. A selection of relevant locomotion techniques is discussed below.

- *wheeled systems*

Obviously wheels are the worlds most used solution for mobility. Many different wheeled vehicle configurations can be used. Important parameters are: the total number of wheels, the number of driven wheels, the number of steering wheels, etc.

- *tracked systems*

Another locomotion method are caterpillar tracks. This locomotion method provides a good grip, and low pressure on the surface which is a benefit in many outdoor construction applications. A disadvantage of caterpillar tracks is the unavoidable slip between the tracks and the surface when moving along curved trajectories which can cause damage to the floor surface.

- *legged systems*

Legged systems can have any number of legs ranging from one to indefinite. The advantage of legged locomotion systems are the ability to cross rough and uneven surfaces, including stairs. Disadvantages are the complexity concerning the mechanical structure as well as the control of the motion of each of the legs. Special versions of legged locomotion systems using suction cups have been developed for wall climbing applications. Examples of such systems are described in (Cusack and Thomas 1992) and (JIRA 1994). An example of a legged locomotion robot is shown in figure 27.

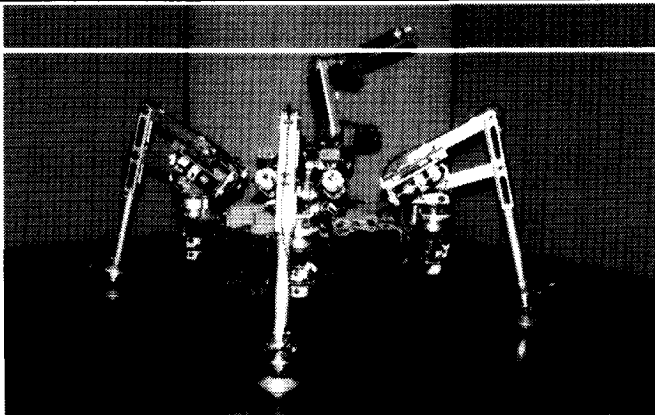


Figure 27 Example of a legged locomotion system on the experimental robot 'Melmalec'. A special feature of the legged robot is that the legs can also be used as manipulator arms (Courtesy Mechanical Engineering Lab, Ministry of Trade and Industry, Japan).

- *non-contact systems*

Non-contact locomotion systems include hovercraft type systems. These type of locomotion systems require relative smooth surfaces which makes them less suitable for construction robotics. A special vertical motion version of a hovered vehicle has been presented by Nishi (1991; 1993). This vehicle uses a propeller to provide the upward force to move along vertical surfaces of buildings for inspection purposes. The propeller is inclined slightly to press the vehicle onto the vertical surface. Wheels are used to steer the vehicle along the vertical surface, which makes this example not truly "non contact".

4.6.2 Navigation

Although many potential applications of mobile robots exist, no off-the-shelf low-cost mobile robot platforms are currently available. The basic problem encountered in the development of robot vehicles is that of *navigation*. Turenout (1994) defines *navigation* as the process of: *planning* the motion, *sensing* the environment and *controlling* the position and vehicle course. The problem of robot-vehicle navigation has received much attention in the research areas of computer science and artificial intelligence. Navigation in unstructured environments seems to be an important theme in robot-vehicle research such as presented in papers collected by Cox & Wilfong (1990), Iyengar & Elfes (1991) and Zheng (1993.) Most of the research is aimed at applications in defence and space exploration. The reason for this situation is that in these applications reliable vehicle navigation is indispensable, while on the other hand funding for research is available through US and European defence and space research agencies.

Currently several types of position measurement systems have been developed for various application areas. Four types of position measurement methods can be distinguished that are useful for mobile platform navigation. These methods are:

- *laser triangulation*

Laser-triangulation systems use a rotating laser beam to measure angles to a set of reflecting targets installed in the surroundings of the position-measurement system. (See figure 28). From the measured angles and the target locations, the current sensor location (2 dimensions) is calculated using the method of triangulation. Two examples of such position measurement sensors are: the Computer Aided Positioning System (CAPSY™) (Vos and Schouten 1989; Vos and Hasara 1993) and the NDC LazerWay™ (NDC 1996). The CAPSY™ system is the most accurate and provides a position measurement accuracy of approx. ± 3 mm in areas up to 50 by 50 m which is ample for position measurement of robots on building sites.

- *environment perception*

Two classes of environment perception systems exist. These are:

- *scanning systems*

Scanning environment perception methods are characterised by the use of some kind of rotating scanning device which measures the distance to objects in the environment. This scanner can use pulses of laser light, radio waves or ultrasound. The environment image that is measured is matched against an environment model to determine the current location.

The accuracy of environment perception methods is generally limited to several centimetres or more because of several reasons. First the reflective properties of the environment vary, reducing the accuracy of distance measurements. Second the scanning beam is not very precise. Finally atmospheric changes can influence the propagation speed of pulses.

– *camera systems*

Instead of a rotating scanner a set of two cameras or one camera plus a structured light source can be used to measure distances. Optical perception is more accurate and precise than other methods of distance measurement. A problem with camera systems is that the interpretation of camera images is computationally expensive. Therefore this method is less suitable for position measurement while moving. Also the resolution of affordable cameras is limited which limits the accuracy.

• *rangefinding*

A popular position measurement instrument that uses rangefinding is the so called *total station*. A total station is the combination of a traditional theodolite (optical angle measurement device) and a laser distance measurement sensor (See figure 28). Total stations measure the (3 dimensional) relative location of a reflecting prism (or a piece of special reflective tape) in polar coordinates. Recently total stations have become automatic and able to track a moving object and determine its position several times a second with an accuracy of approximately $\pm 2 \text{ mm} \pm 0.2\%$ at distances up to a few kilometres. Auto-tracking total station are commercially available from all the major vendors of surveying equipment such as Wild, Leica, Sokkia, Geotronics and Topcon.

There also exist rangefinding devices which continuously scan distances to objects in their environment using radar waves or laser light (lidar). These distance images can be processed to obtain the current position relative to the objects in the environment. Such scanning systems which can provide an accuracy of several cms are commercially available at prices below US \$ 10 000.

• *satellite position-measurement*

A satellite position-measurement system measures its 3-D location relative to three or more satellites orbiting the earth (See figure 28). Two sets of satellites for position measurement purposes are currently in orbit. The best known system is Navstar GPS (Global Positioning System) which is an initiative of the US Department of Defence. The second system is GLONASS, the Russian counterpart to GPS. The accuracy of satellite position-measurement depends on the type of receiving equipment being used. The maximum obtainable accuracy is currently approx. 7 mm. However, for that accuracy, it is necessary to take satellite measurements for many hours to eliminate atmospheric disturbances in the propagation times. Differential GPS systems use two receivers to perform relative position measurements to cancel out atmospheric disturbances and the random errors introduced by the DoD for strategic reasons. DGPS systems currently have an accuracy of approximately 1 cm even in non-stationary conditions.

A very promising development based on GPS technology is to use local transmitters instead of satellite signals. This enables an increase in accuracy and enables

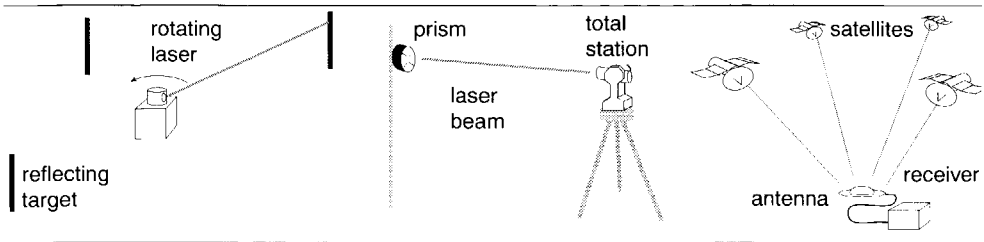


Figure 28 Three systems of position measurement. From left to right: laser triangulation, total stations and satellite position measurement.

indoor use. It is expected that it will take a number of years before this technology is commercially available.

Navigation of mobile construction robots requires a reasonably high accuracy in relation to the state-of-the-art position measurement technology. Tolerances in the building process are generally between one millimetre and one centimetre. Only laser triangulation systems, total stations and high-end GPS systems can provide such accuracies. However, each of the above position measurement techniques have their specific weak and strong points. GPS is especially useful for position measurement of large outdoor construction equipment such as cranes, dozers, excavators, drilling equipment, pile driving equipment etc. Laser-triangulation sensors are especially suitable for position measurement of indoor vehicles where 2D position measurement is sufficient. Total stations are suitable for high accuracy 3D position measurement.

Due to the very broad scope of the problem of position measurement, it is expected that position measurement technology will go through an enormous development in the next decade. Position measurement sensing equipment will become available at decreasing costs and increasing accuracy. New technologies for indoor GPS like systems and more versatile laser equipment are expected to become available.

4.7 Summary and Conclusions

A multitude of technical solutions for the various aspects of robot engineering is available to build state-of-the-art robots. However, the requirements for construction robots differ substantially from those imposed on manufacturing robots. This makes it difficult and often impossible to use the available technical solutions to implement a construction robot.

Some of the techniques applied in the field of defence and space exploration are useful in construction robot engineering. However, these technologies are developed without the concern for costs constraints in building industry applications.

Construction robots are used for different types of tasks and circumstances than in manufacturing applications. Looking at the six aspects of robot functionality, it can be recognised that the available (robot) technology is not always suitable for use in construction robots. In the next chapter this technological gap between

available robot technology and the construction robotics technology demand is discussed in more detail.

5

Selection and Motivation of the Research Problem

Chapter five confronts state-of-the-art robot technology with construction automation requirements in order to deduct a list of technologies needed to bridge the gap between robot technology and technologies needed for construction process automation. From this list one fundamental problem is selected for further research in this thesis.

Time, money and effort put in construction robotics R&D by the Japanese *Big Six* has made them world leaders in this area of R&D. The large-scale character of the experiments with fourth generation construction systems indicate that the Japanese contractors seriously believe in construction robotics. This is acknowledged by a technology forecast survey that was held in Japan (NISTEP 1992). The same survey was also held in Germany a year later (BMFT 1993). Both surveys shows that experts believe that intelligent robots will become common on construction sites between 2005 and 2010. Both surveys also acknowledge Japan's leading position in construction robotics.

The Japanese and German experts indicate that the major constraints on realisation are costs and technical problems. The cost of solving the technical constraints of the state-of-the-art robot technology is regarded too high for achieving success in construction automation. More research is needed to enhance the state-of-the-art technology to make cost effective construction robots feasible. This chapter discusses the nature of the technological gap between building construction and robot technology, to identify a list of fundamental technological issues. From this list a research topic is selected.

5.1 The Gap between Construction Automation and Robot Technology

In the current situation, where technical issues are regarded the major constraints in the development of prototype construction robots, the selection of construction processes to automate is a compromise between technical feasibility and the benefits from automation. The collection of prototype construction robots existing today, probably represents the capabilities of today's state-of-the-art robot technology better than it represents the greatest benefits of construction automation. Therefore it is not realistic to forecast technological needs by extrapolating current state-of-the-art in construction robotics. Instead the point-of-view of 'robot features' (as in chapter 4) is adopted to discuss which concepts and technologies are still lacking for the realisation of cost-effective construction robots. The rest of this section discusses requirements regarding: manipulator performance, end effector characteristics, feeding mechanisms, control, sensing and mobility.

5.1.1 Manipulator Performance

Use of robots on construction sites presents problems which do not exist in the manufacturing industry where robots are installed at a fixed location in a factory environment. The circumstances of the building industry production are very different, requiring different characteristics of the robot manipulators. The most important requirements for construction (robot) manipulators concern the aspects:

- *work volume*

Obviously a robot manipulator must have a sufficient reach to be able to perform its task. The scale of building industry products requires construction robot manipulators to have a large work volume. This can be realised using either small or medium scale *mobile* manipulators or large-scale non-mobile manipulators. Large-scale manipulators seem to be more suitable for the early construction stages involving the handling of large and heavy materials for the foundation, structural system or exterior. Small or medium scale *mobile* robots seem to be more suitable for interior processes. Large-scale manipulators cannot enter buildings, while small mobile robots can. Both approaches require technology that is not yet available, mature or integrated. Conventional manipulators are rigid, to eliminate undesirable dynamic effects. However, this rigidity comes at the costs of manipulator mass which is limited in construction applications. The know-how and technology for robot-level motion control of lightweight, non-rigid robot manipulators, either large-scale or small and lightweight, is complex and not yet available for applications.

- *transportability*

It is essential for construction robots to be transportable between different work locations either on the same building site or between different sites. Interior application robots must fit through corridors, doorways and in elevators. Maximum robot dimensions of interior operating robots are limited. Large-scale manipulators are limited by the maximum dimensions and mass allowed on the roads.

- *mass*

Contrary to industrial robots where robot mass is unimportant, the maximum mass of construction robots is limited. Interior type mobile construction robots are not to exceed the maximum floor load of the building in which they operate, which is typically limited to approx. 500 Kg/m². Transportability requirements also require the robot to be handable by available transportation equipment such as cranes or on trucks.

- *load-carrying capacity*

The majority of the currently available robot manipulators have a load-carrying capacity of less than 50 kilograms. The load-carrying capacity is inverse proportional to the motion accuracy. In order to achieve a low compliance, all manipulator segments and joints are made extremely rigid and thus very heavy which reduces the load-carrying capacity of the manipulator. Advanced sensing and feedback control is an alternative solution to achieve accuracy without sacrificing the manipulator load-carrying capacity.

The main conclusion which can be drawn from a comparison between the current robot manipulator technology and construction automation needs, is that the industrial type robot manipulator is unsuitable except for a few applications. The ideal construction robot manipulator is a light weight, easy to transport manipulator which can handle heavy loads with a positional accuracy of a few millimetres.

5.1.2 End Effector Characteristics

Robot end effectors for handling building materials are currently not available. The available manufacturing-industry type end effectors are intended to handle small and medium scale, limited mass components. These grippers are unsuitable for large and heavy building components. For some types of building components special grippers exist. E.g. floor slabs and stacks of bricks are handled using a special clamp when they are to be relocated. In general, object handling requires a dedicated gripper and special handling facilities in the objects to be handled, e.g. brackets, notches, holes, etc. to ensure a firm and rigid connection between the end effector and the handled object.

Many tool-type end effectors used in manufacturing applications (e.g. arc welding, grinding, spraying) can also be used in construction processes. Also many available construction (hand) tools can be converted to robot end effectors. Obviously the development of end effectors is very application specific.

Although no special end effectors for building industry applications exist, no general or conceptual problem seems to exist concerning the state-of-the-art end effector technology.

5.1.3 Material Feeding

Experience with material feeding in manufacturing applications has learned that feeding is a complex matter which should, in first instance, be simplified as much as possible. Instead of supplying components in boxes where all components are randomly placed and orientated, new packaging methods have been developed to

simplify feeding. This approach should also be adapted in the field of construction robotics. Currently building parts and materials are not packed in such a manner that they can be picked up by a robot. Autonomous handling of traditional building materials such as bricks, blocks, boards tiles, etc. requires either complex sensing (e.g. vision systems) or standardised packaging methods that present objects in a structured manner. Feeding of non-discrete materials such as paint or glue has always proved to be less complex. However, handling of such materials requires the material to have constant properties, e.g. viscosity of liquids.

Material feeding is a very application specific matter. In the current evolutionary stage of construction robotics development, conceptual or structural problems with material feeding cannot be identified.

5.1.4 Control System Capabilities

Groover, Weiss et.al. (1986) mention 'repetitive operations' as one of the characteristics for potential robot applications. Current state-of-the-art industrial robots are primarily suited to perform repeating fixed-motion patterns without deviation from one cycle to another. This type of repetition is virtually nonexistent in construction processes. The fact that robots move along or through the product they are working on, implies that the motion sequences in repetitive construction tasks, require motion patterns that differ every operation cycle because the location of the operation changes. Also the one-of-a-kind character of building industry products causes repetitiveness of construction tasks to be generally low, especially when compared to manufacturing industry production.

A lack of repetition does not make application of robots in construction processes technically impossible. However, lack of repetition does hinder economical usage of construction robots. The motion-oriented character of current robot programming methods makes robot programming more time-consuming than carrying out the task manually. This is a problem for tasks that are to be carried out only a few times. The relatively inefficient robot-level programming methods of current industrial robots have received only limited attention because robot programs are executed so many times, that their costs per product are negligible. However, in the building industry this is not the situation.

The concept of task-level instruction, as discussed in section 4.4 on page 51, seems to suit the requirements of building industry circumstances. Construction robots require simple, efficient and effective robot instruction methods. Construction robot instruction needs to be *simple*, because the people working at building sites are not used to working with high-tech computer equipment. Construction robot programming must be *efficient*. Without efficiency the number of projects where robots can be used economically, is reduced. The less effort is needed, the smaller the projects can be where the use of robots is still attractive. Robot programming must also be *effective*. Communication errors, such as in situation where the result of the robot work is not what its instructor expects, are unacceptable.

Prototype implementations such as the HANDEY system or the system developed in the ESPRIT project 623 have demonstrated the benefits of task-level instruction.

However the developed concepts and systems are specially developed for manufacturing industry applications, and do not suit construction robot task instruction problems because of the following two reasons:

1 *The concepts are focused on manufacturing industry type problems instead of building industry type problems.*

Requirements for task instruction are different for construction robots than for manufacturing robots. First, building industry robots have to work along their work pieces, which makes their program different from the repeated cycles in manufacturing. Second, task-instruction systems for manufacturing industry are required to generate efficient process plans, while construction robot task-instruction systems should generate effective, and safe process plans with minimal human assistance.

2 *The concepts are not suited for semi-unique tasks.*

The state-of-the-art task-level systems such as the HANDEY system (Lozano-Pérez et al. 1992) and the ESPRIT 623 system (Bernhardt et al. 1992), have in common that they focus on the problem how to use robots in small quantity production in one robot workcell. The objective of a construction robot task-level systems on the other hand is different. Construction robots are used to do similar tasks (semi-unique) in different circumstances. These different circumstances are a change of building site and changes in product geometry. Only parameters such as locations or dimensions differ. Although some of the state-of-the-art task-level systems can perhaps be used for construction robots, probably a much more simple and effective approach can be used.

Because of the two issues mentioned above, it is believed that the available solutions for task-level instruction are not suitable to solve the building industry type of robot instruction problems. This conclusion does imply that the concepts and solutions of current task-level system implementations cannot be used for the implementation of construction robot task-level systems.

Because of the influence of the programming costs on the economic efficiency of construction robots, it is believed that construction robot instruction deserves more attention than it has been given so far. There is a need for a concept for construction robot task-level programming that deals with the one-of-a-kind, semi-unique type of tasks of construction robots.

5.1.5 Sensing Capabilities

The less structured the robot environment is, the more sensing devices a robot needs to react to the external situation. Building sites have always been untidy and sometimes even chaotic. One approach to this problem is to equip construction robots with sensors and intelligence to deal with these circumstances. However, this approach is not the most cost effective. If possible the building site should be adapted to the "comfort" of the robot. The use of sensors to deal with robot environmental phenomena should be limited as much as possible.

Although specific sensing needs are difficult to identify, there are some general issues. One problem is the nature of the building-site environment (outdoor, dust,

rain, rough handling) which is problematic for many types of sensors and sensing methods. Especially first-generation construction robots, require robust, add-on sensors for existing machines to measure their state. Available industrial sensors can fulfil the sensing requirement but often lack robustness to cope with the (out-door) building site environment.

One specific sensing problem is related to the fact that robots have to come to the building site and work along or through the product being produced. This situation requires accurate position measurement. Position measurement is a sensing need, common for many different construction automation and robotics applications, ranging from first-generation control systems on existing construction equipment to fourth-generation building systems. During the last half decade several position measurement devices have become available, however the capabilities of the available position measurement devices are still limited. The issue of position measurement is also discussed in the next subsection.

Sensing devices are an essential aspect in the development of construction robots. There is one specific sensing need, position measurement, which is of great importance for the development of construction robots.

5.1.6 Mobility

Mobility is desirable for many construction robot applications. The dimensions of the building industry products, require construction robots to have a large work volume. However, the larger the robot manipulator becomes, the larger its mass is, the less stable it is, the more difficult it is to get it in and out of buildings and the more difficult it is to transport. One solution to this problem is to mount a robot manipulator on a mobile base. In factory environments this is realised by mounting the robot manipulator to a gantry or rail. This approach is not feasible in building environments.

In building-industry environments mobile robots cannot use physical guidance mechanisms such as rails because it is impractical and the costs of such temporary systems are too high. Mobile construction robots need robust locomotion systems such as wheels or tracks and easy to set-up guidance systems.

Much of the current research on mobile platforms, e.g. as presented in (Cox et al. 1990; Iyengar et al. 1991; Turenout 1994; Zheng 1993), is still devoted to the development of basic concepts of vehicle navigation, such as: path planning, obstacle avoidance, locomotion principles and control. Much emphasis is put on the realisation of systems which are able to navigate through remote, unstructured or hazardous environments such as space, nuclear power plants, combat areas. This is probably caused by the interest in robot vehicles from US federal agencies such as: NASA, Department of Defence (DoD) and Department of Energy (DoE). Application of mobile platforms in building industry applications have not received much attention.

State-of-the-art developments of robot vehicle technology can also be used to provide mobility to construction robots. Many aspects of mobile platforms are unre-

lated or have little relation to the application the platform will be used for. The aspects of path planning, motion planning, motion coordination apply to mobile platforms in general and are also essential for construction robot mobile platforms. There may be some aspects which need additional R&D. The current DoD and DoE sponsored research puts much emphasis on functionality, reliability and autonomy, while the building industry would emphasize on other aspects such as cost, size or stability.

Many of the prototype construction robots presented in chapter two are mobile robots. However, these robots have in common that they perform low and medium accuracy operations. Accurate, easy to set-up mobile systems are required for the implementation of robots for many construction applications.

5.2 Research Constraints

The nature of the building industry excludes certain technical solutions for the research problems. The building industry boundary conditions taken into account in this research are:

- *affordable*
The building industry is largely fragmented into small to medium size companies which cannot afford exploitation of expensive equipment. The lower the cost of the equipment, the sooner money will be invested in the equipment.
- *robust*
The transportation from site to site requires construction equipment to be robust enough to be loaded on and off trucks, handled by cranes and withstand minor collisions with obstacles during handling. Much of the construction work takes place in a wide range of climate circumstances; Construction robots must operate during for instance rain, frost, heat or humidity.
- *“open” (vendor independent)*
The building industry benefits most from “open” (mutually “compatible”) construction robots. Open systems are systems with neutral, vendor independent “interfaces” which allow integration and cooperation with other systems.
- *multi purpose*
The more functionality can be included in a single robot, the more economic value it can have. However, this increased economic value is dependent on the circumstances. E.g. increased robot functionality can be used to reduce the need to transport a robot between work location (reduction of idle time). Or for small contractors, multi-purpose robots can more easily be exploited commercially because it is less difficult to put the robot to work all day performing different tasks.

5.3 Selection and Motivation of the Research Problem

Any construction robot development will involve study of engineering problems regarding performance aspects relating to the manipulator, end effector, feeding, control system, sensors and mobility. However, with the current state-of-the-art technology, more problematic technical limitations exist concerning the following three robot performance aspects:

- *manipulator design*
The building industry needs manipulators which are lightweight in relation to their load-carrying capacity to allow them to have a large work volume and remain transportable.
- *control*
There is a need for a concept for robot task instruction that allows robots to be instructed about their task with a minimal effort.
- *sensing*
On-site robots are not installed at fixed positions. This requires that the robot can measure its position every time it is relocated. Autonomous mobile robots also need position measurement to guide their motions.

Development of construction robots is currently only affordable when the above listed fundamental problems are avoided. This approach is employed in nearly all prototype robot developments discussed in chapter 3. The mentioned technological limitations have in common that they are related to the fundamental differences between the building industry and the manufacturing industry.

The problem of robot task instruction is selected as subject for further research in the second part of this thesis. Robot instruction deserves more attention than it has been given so far. Robot operations in construction applications do not consist of repeated fixed motion patterns as in manufacturing industry applications. The combination of the facts that construction robots move along the product, and that the construction industry produces one-of-a-kind products, makes current motion oriented robot programming unsuitable. The elaborate, detailed, and error-prone character of motion-oriented robot-level programming makes robot programming many times more time consuming than the task performed by the robot. This is unacceptable in building industry applications where the task repetition rate is a few magnitudes smaller than in manufacturing industry. This problem is relevant for all robots involved in the production of one-of-a-kind products not only for on-site production but also for production of prefabricated building components in factory environments.

The goal of the research presented in the second half of this thesis is formulated as follows:

Develop a concept for efficient construction robot task instruction.

The term *task instruction* is used instead of programming to indicate that the aim is to realise some method which enables the instruction of a robot in terms of the

required end results. A concise description of the term *task* is provided by Dean & Wellman (1991), which reads as follows:

A task is an abstract operation that the robot is committed to perform. Tasks are abstract in the sense that they dictate the general nature of what the operations is to accomplish without necessarily specifying its precise implementation.

The term *efficient* is used in its meaning of economical efficiency. The word *efficient* is to emphasize that task specification should involve as little *human* effort as possible. Whether the concept is *efficient* in the sense that it requires much computational power is regarded as irrelevant. It is also not of major relevance whether a construction robot task-instruction system is able to let the robot perform its instructed task in optimal efficiency.

An important aspect of the selection of the research problem is the *economic relevance*. In the analysis in chapter 2 it has been shown that robot set-up costs represent a significant proportion of robotisation. Especially when the task-repetition rate at each project is relatively low, the set-up costs per unit of production increase. A task-instruction system can reduce the robot set-up costs because the large amount of human effort needed to program the robot are replaced by less complicated and less time consuming instruction work.

The semi-unique nature of the robot tasks provides a interesting opportunity for other approaches in the realisation of task-instruction systems. Intuitively one is lead to capturing the knowledge required to perform semi-unique tasks in some kind of *template process plan* which can be applied to specific situations.

6

Introduction to Task Instruction

This chapter discusses the requirements for a construction robot task-instruction system. Also some research results from previous and related research are discussed. This chapter is concluded with a formulation of the hypothesis that is worked out and verified in the rest of this thesis.

In the previous chapter it has been discussed why the current *robot-level* programming methods are unsuitable for construction robots. It was argued that the building industry needs a robot *instruction* method that allows construction robots to be instructed about their tasks in a simple, fast and effective manner. The idea of task-level instruction, such as discussed in section 4.4.3, seems to fulfil these demands. Unfortunately the approach used for the realisation of task-level instruction in manufacturing (as described by Lozano-Pérez et al. 1992; Nnaji 1993; Bernhardt 1992; Dean et al. 1991) leads to complex reasoning systems. This approach is believed to be unsuitable for construction robots.

The hypothesis is that the semi-unique nature of construction robot tasks provides opportunities to reduce the complexity of task-instruction significantly, making implementation in practical situations possible. Given the semi-unique nature of construction robot tasks, it seems possible to use a template robot program that can be instantiated into a task-specific plan.

In section 6.1 the requirements for a construction robot task-instruction system are discussed. In section 6.2 related and previous research relevant to the subject of task instruction is discussed. Finally in section 6.3 conclusions are drawn and the hypothesis how to realise task-instruction systems is presented.

6.1 Task-Instruction System Requirements

Requirements for a task-instruction system can be divided into functional requirements and boundary conditions that have to be obeyed. The coming two subsections discuss both.

6.1.1 Functional Requirements

A task-instruction system has to provide the following functionality:

- The task-instruction system should be able to instantiate plans for specific tasks, using a knowledge base which contains the knowledge how tasks of a category of semi-unique tasks are to be carried out. This task-instruction system functionality is referred to as *planning capability*.
- The task-instruction system should be able to communicate with its users via a simple and effective user interface. This user interface should enable construction planners, supervisors, and machine operators to specify what the robot is supposed to do. Therefore, the user interface should use the concepts and jargon of the people that work with the system, or in other words, the interface should be product and process oriented. This capability is called *capability to interact with human beings*.
- The task-instruction system should also be able to access and interpret the databases that contain the design information of the product to be constructed. This ability enables the task-instruction system to have access to relevant design information (such as dimensions, locations and material properties) without the need for a human robot instructor to provide this information to the robot manually. This ability is referred to as the *capability to have access to design and engineering information*.
- Finally the task-instruction system should be able to deal with *contingencies* that can occur during the execution of the plans. A contingency is defined as an unexpected event that causes the prepared plans to become invalid. Some types of contingencies can be recurring with an unpredictable frequency and timing. A task-instruction system should be able to deal with recurring contingencies to avoid the need for frequent operator assistance. This capability to deal with contingencies is known as *reactivity*.

Each of these capabilities is further discussed in the rest of this section. An imaginary example robot is used to illustrate the discussions. The selected example concerns a masonry robot, which can pick-and-place wall blocks to build walls. The pick-and-place type operations occurring in wall building represent a large class of robot applications where a high-level task decomposes into a number of object-manipulation operations. Examples of such assembly tasks also occur in the fourth-generation automated building systems discussed in section 3.4. Other examples of pick-and-place type of tasks are the installation of floor slabs and cladding elements.

Planning Capability

Nearly all construction operations are *irrecoverable*, meaning that they cannot be undone. Examples of irrecoverable operations are brick laying, painting, nailing etc. Because of the irrecoverable nature of the operations, it is essential to reason about the sequence of operations before the operations are actually carried out. This reasoning process is called *planning*. A useful definition of the word *planning* is given by Dean & Wellman (1991):

The problem of constructing courses of action based on properties of causal event models is called planning.

Planning is a process which can be very complicated because the number of combinations of operation sequences in the execution of a task, is exponentially related to the number of operations to be performed.

The planning of the construction of a wall by a masonry robot is of limited complexity because the process has a procedural nature. This procedural nature is typical for a large proportion of construction tasks. A task-instruction system has to be able to generate a planning for the construction of a wall, using the design characteristics of that wall and a (procedural) process-type model which contains the knowledge how to deal with certain tasks.

If necessary, the construction process planner (person) or the robot operator should be able to make small modifications to adapt the robot task-execution. This adaptation can be to optimise the plan, or to resolve possible interferences with other construction processes. For instance, it can be necessary to change the building sequence of a number of wall sections to resolve an interference with another construction process.

Capability to Interact with Human Beings

Effective and efficient interaction between task-instruction systems and human beings is essential. Conventional robot controllers very often have a robot-oriented user interface with many buttons. These user interfaces resemble the user interfaces of computers from the 1970s. Current generation desktop computers demonstrate how *user-friendly* interfaces can be implemented. Metaphors (symbols that relate to objects or concepts that the user is familiar with) are used to present functionality in a manner that is easy to understand. Task-instruction systems are required to use metaphors to allow the (non robot-expert) users, such as the construction manager or robot operator, to communicate with the robot system in the concepts they are familiar with.

Three types of users of task-instruction systems are identified. These are:

- *construction managers*

Construction managers are users that plan the robot use and make task assignments.

- *robot operators*

Robot operators start, stop and supervise the execution of the plans produced by the task-instruction system.

- *construction robot software developers*

The robot software developers are task-instruction system users that create the software that enables the robot hardware to perform some construction task. The developers write the software that is used by the construction managers and robot operators when some construction task is assigned to a robot.

In the example of the masonry robot, the task-instruction system could for example present its task capabilities in the form of drawings of the building. In these drawings it can be shown which walls can be erected by the robot. The construction work planner can determine the sequence of building just by 'clicking' on the walls that have to be erected by the robot. When the task assignment is to be executed by the robot, the robot operator loads the task plan into the robot controller and gives a 'start' instruction to the robot controller.

Capability to have Access to Design and Engineering Systems

In order to avoid unnecessary data entry, task-instruction systems have to be able to extract information they need from the various Computer Aided Engineering systems that are used. Unnecessary (manual) data entry work should be avoided. In order to realise this, it is necessary that some kind of neutral information-access interface exists. This neutral interface should allow exchange of information and knowledge which is: meaningful, complete and unambiguous. E.g. in the case of a masonry robot, the robot task-instruction system should be able to obtain the wall dimensions (thickness, length, height) and locations.

Reactivity

Unfortunately the environment around the robot is not always predictable. Unexpected effects and phenomena can occur. Especially on building sites where other construction processes take place it is possible that events occur which were not expected. The fact that the robot's universe is unpredictable is in contrast to the desire to plan robot actions in advance. In extremely unpredictable environments, planning is even a waste of effort. The most difficult robot-control problems are to control irreversible robot tasks in an unpredictable environment. Such problems occur in applications such as: fire fighting, disarmament of explosives and nuclear power plant troubleshooting.

The fundamental problem with planning is that a plan is always based on assumptions that can prove to be untrue. The task-instruction system has to check the planning assumptions during the execution of the task plan. In case an assumption proves to be untrue (i.e. a *contingency*), the plan loses (a part of) its validity and re-planning is needed.

An approach to deal with contingencies that is generally applied in industrial automation is to eliminate the chances of contingencies as much as possible. Robot work cells are designed as isolated, fully-structured worlds with fences around the work-cell and delivery of parts in pallets to avoid contingencies as much as possible. In the building industry, this is probably not the most cost-effective approach. There are two reason for this. These are:

- 1 The costs of structuring of the robot environment are costs that recur at every job-site instead of once when the work-cell is built.

- 2 The robot task has interaction with the results of other (robotised or non robotised) construction process results (e.g. the floor where the wall is built on, the facade where the wall is to be built against, etc.). These interactions introduce uncertainties in the dimensions of the robot task environment that cannot easily be eliminated.

The above mentioned differences are the primary cause of the fact that the contingency chances are many times higher in construction applications than in manufacturing applications. A suitable approach to deal with this problem is to find the right balance between the implementation of contingency-proof robots and the implementation of contingency-less robot environments. Obviously it is not possible to exclude contingencies completely. Therefore, contingencies should be detectable by non-complex sensor systems and the consequences of contingencies should be limited as much as possible. Difficult to detect circumstances of contingencies that require a complete change of plans, should be avoided; preferably by structuring the robot environment to reduce the chances of contingencies.

In case of the masonry robot example, there is little sense in using an expensive vision system to detect obstacles in the robot's environment. It is probably less expensive when obstacles in the surrounding of the robot are removed.

6.1.2 Boundary Conditions

A fundamental boundary condition for the implementation of a task-instruction system is that the system should be usable and integratable in the practices of the building industry. This integration has several sides. In this subsection the following two integration points-of-view are discussed:

- *organisational integration*
The responsibilities of instruction, supervision and control of the construction robot should be divided in such a manner that these responsibilities correspond to the responsibilities in the traditional organisation of the building processes.
- *technical integration*
The computer applications and systems that deal with the task instruction and robot control have to be technically integrated with the other computer systems which are used to plan, control and monitor the construction processes.

Organisational Integration

For an efficient organisational integration of construction robots, it is important that the task-planning process is as much as possible compatible with the construction management of conventional non-robotised construction methods, at least at the introduction stage of robot technology. The more sophisticated and advanced a construction robot is, the more important a profound preparation of the use of the robot is required. For an efficient and unproblematic use of the robot, it is essential that the robot is provided with the information it needs during the construction management. A task-instruction system should support the organisational separation in responsibilities of the many different professionals involved with a construction project.

Integration in Construction Management

A task-instruction system does not only affect the construction process itself, but also the management, planning and control processes that precede the actual construction.

The construction management process is a complex and large task that is subdivided in several sub-processes. A comprehensive model of the construction control processes is made by Melles & Wamelink (1990). According to this model there are two distinct stages in the construction planning that affect the instruction of a construction robot. During the first stage a rough planning of the construction process is made. In this rough planning, required processes are identified and construction methods are selected for these required processes. In the later stages of the construction planning all details of the construction processes are worked out.

In general two types of construction management 'experts' have interaction with a task-instruction system. These are the construction managers that set out the general approach in the construction process. These people specify *what* the robots task is. Beside these construction managers there are the construction *planners* that work out the planning of the construction process in detail. It is the responsibility of these construction planners to guide *how* the construction robot will execute its task. The robot operator has the responsibility that the prepared *what* and *how* plans are being executed by the robot without problems. The operator is allowed (and should be able!) to make small scheduling changes in the task plans prepared by the construction management, as long as the modifications do not affect the end result.

The best strategy to integrate a task-instruction system in the conventional construction planning process is when a distinction is made between *what* has been done and *how* it should be done. The specification of the *what* is done during the rough planning. The specification *how* it is to be done is made during the detailed planning. To create a detailed plan *how* to realise the specified task, it is necessary to know what the state of the building site is. First, to know which obstacles there are at the moment the robot executes its task, and second to avoid interactions of the robot process with other processes going on at the same time. Therefore a detailed plan is preferably made in conjunction with other detailed plannings.

The decision whether to use a robot has to take place during the early stages of the planning process. The consequences of the use of construction robots are generally relatively large because construction robots are not 'iron labourers' but 'stupid machines' that require many adaptations in their environment for their optimal functionality. The use of a construction robot should be regarded as an alternative construction method and not as an alternative piece of equipment. This is best demonstrated by the fourth-generation automated building systems discussed in section 3.4.

Integration at the Building Site

At the building site it is the responsibility of the robot operator to take care of the execution of the robot plans prepared at the construction management office. The fundamental problem with this responsibility is that these plans are based on assumptions about the building site. These assumptions can prove to be untrue during the actual execution of the plans. As mentioned before, two approaches can be followed. Either the operator can change the robot environment such that the contingency is resolved. Or the plans are changed in order to deal with the situation. The operator should be able to select between both approaches for an optimal integration of the robot in the construction process.

The robot operator should be able to make minor changes in the plans that specify how the robot will execute its task. This facility allows the robot process to be integrated more easily with the other construction processes that take place at the building site. For example when some interference occurs between the robot process and some other construction process, because both processes take place in the same room, than the robot operator should be able to change the robot task execution sequence to resolve the conflict (assuming that the sequence of operations of the robot can be changed).

To summarise, there are three types of experts involved with construction robots at different stages of the construction process. These are:

- a construction manager that selects the building methods, creates the rough planning and specifies *what* the robot tasks are,
- a construction planner that takes care of the robot task planning (specification how the robot has to execute its task)
- a robot operator that takes care of the execution of the robot plans at the building site.

Technical Integration

A problem of a technical nature is the integration of a task-instruction system with other computer systems used in the building industry to allow the cooperation of the task-instruction system with other computer systems. Nowadays computer applications are used for many types of tasks. However, software packages of different vendors or for different type of applications, do not allow easy exchange of information. This phenomenon is referred to as *island automation*. A task-instruction system should not become another 'island' in the automation 'archipel'.

A task-instruction system should be an *open system* in the sense that it can communicate with other computer applications. The information entered into computers is too expensive to be re-entered for other applications. A task-instruction system should be able to read project information from other design, engineering and planning systems. In order to be able to communicate with other systems and have an open, neutral interface, some kind of standard for exchange of engineering and planning information is needed.

6.1.3 Summary

Essential capabilities of the task-instruction system are: the ability to determine *what* a robot can do and what the task of the robot is, the ability to determine *how* the robot will perform its task, and the ability to let the robot carry out the task. In order to realise these abilities, it is necessary that the task-instruction system can: (1) plan the realisation of a task, (2) interact with the human users, (3) exchange information with other computer systems, and (4) modify the robot plans to deal with unexpected circumstances.

The instruction process of a construction robot can be decomposed into three distinct sub-processes. These are: *task preparation*, *task planning* and *task execution*. Figure 29 shows the interactions of the task-instruction with its environment. A task-instruction system is an *information system (IS)* that processes the information that describes a *real system (RS)*. The real system comprises construction planners, robot operators and the robot hardware. Information is exchanged between the real system and the information system and between subsystems in the information system.

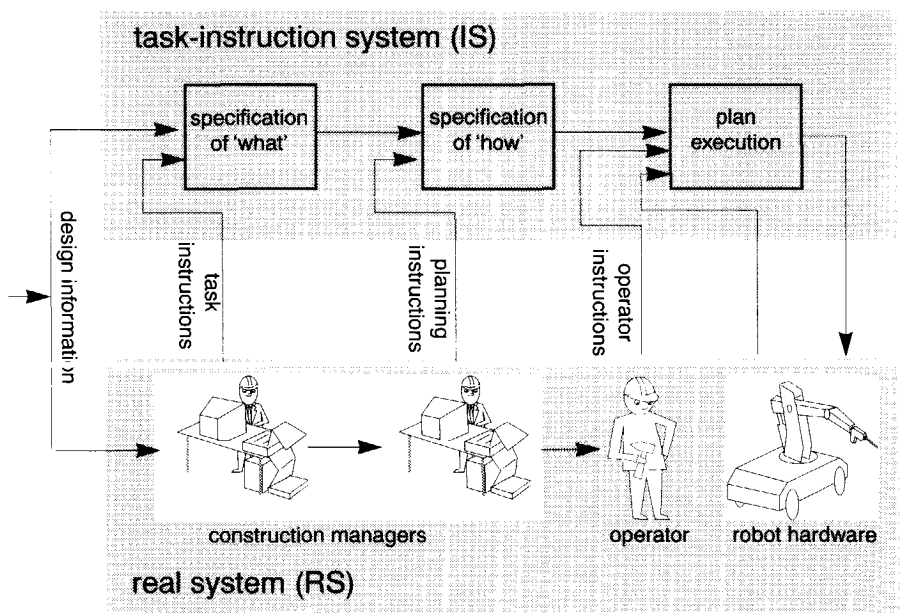


Figure 29 Three main functions in the construction robot task instruction information system (all arrows indicate flows of information).

The next section discusses research efforts and results of the subjects related to the requirements formulated for task-instruction systems.

6.2 Related Research

Several requirements for task-instruction systems have been discussed in the previous section. As much as possible of available research and development results should be used for the realisation of task-instruction systems for construction robots. This section discusses relevant research results concerning: task-planning, system integration and reactivity.

6.2.1 Related Research on Robot Task Specification and Planning

The realisation and implementation of true task-level robot programming systems for robot applications in manufacturing has been a research subject since the 1960s. Research on task-level systems has primarily concentrated on pick-and-place and assembly type tasks. Several researchers, including Sheu & Xeu (1993), Lozano-Pérez et al. (1992), Dean & Wellman (1991), Bernhardt (1992) and Nnaji (1993) have investigated the subject and developed methods, algorithms and approaches to plan robot operations for specific types of problems. Bernhardt and Lozano-Pérez et al. both describe prototype implementations of task-level instruction systems for assembly and pick-and-place type of robot tasks.

The above mentioned research has revealed that the realisation of task-level instruction systems is quite considerable. Lozano-Pérez (1992) argues that only a few of the task-level systems developed in the last decades can deal with true task assignments. The purpose of task-instruction systems such as the HANDEY system (Lozano-Pérez et al. 1992) or the system developed in ESPRIT project No 623 (Bernhardt et al. 1992), is to generate robot programs to assemble products such as produced in manufacturing industry. An example that clarifies the scope of this research is the test product called the Cranfield benchmark that is shown in figure 30.

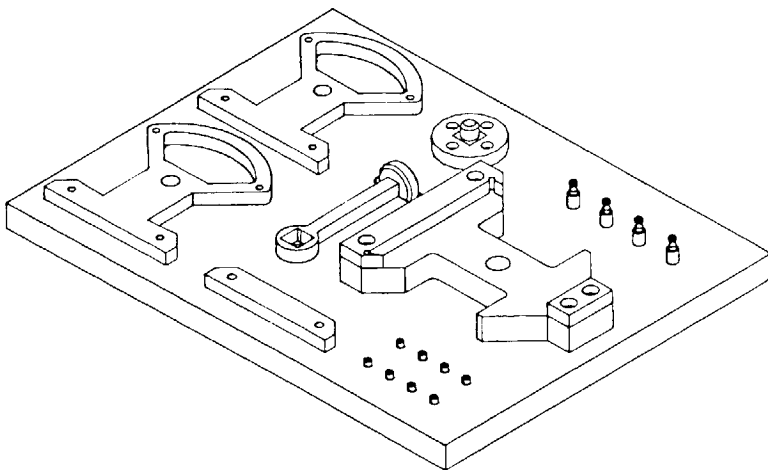


Figure 30 The parts of the 'Cranfield benchmark', a test case for task-instruction systems.

The task instruction methods used in the HANDEY and the ESPRIT project No. 623 systems, reason about possible assembly sequences, using the geometry and topological relations of the product to be assembled. This approach can be compared with the use of exploded view drawings in which all parts are shown separated, and the relations between parts are shown with lines. An example of such a drawing is shown in figure 31. The exploded view drawing gives an impression how difficult the reasoning process about the assembly sequence can be. Because the exploded view representation only includes the geometric descriptions of all parts and some of topological relations (adjacency information) between the parts; there is relatively little information to reason what the sequence of object manipulations is, in order to assemble the product. Many humans will also have trouble to assemble the hammer drill using only the exploded view, because information about the formation of stable sub assemblies is lacking.

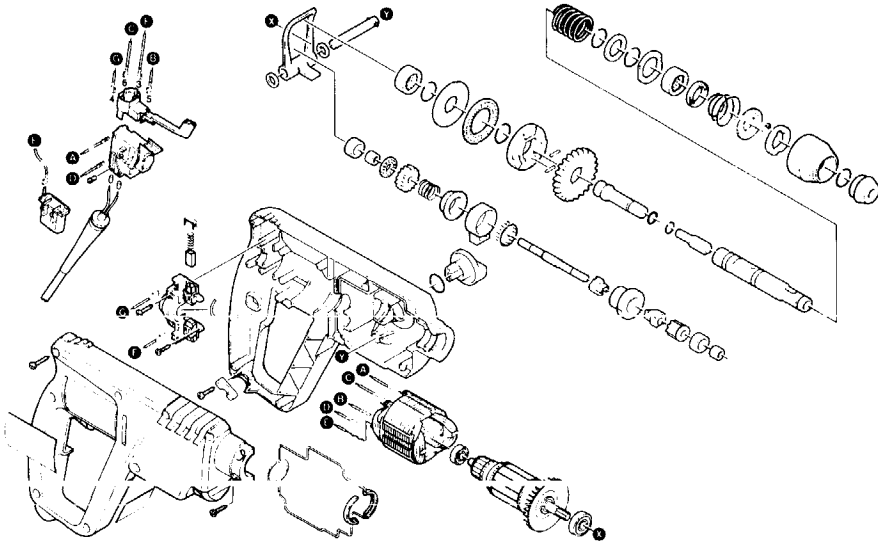


Figure 31 Exploded view of a hammer drill.

An approach that uses only geometric and topological information ignores the fact that a product design includes *Design for Assembly (DfA)* features and that the product design assumes a certain assembly sequence. However, due to the fact that product design information is communicated using technical drawings, the DfA-related information is not communicated. Therefore it is difficult to extract the correct assembly sequence in the approach followed by the pioneering researchers in this field.

Because of the lack of information in technical drawings, the problem of assembly plan generation is a complex problem. The computational complexity of the problem is comparable to the complexity of the famous travelling salesman problem. To find the best assembly strategy it is required to evaluate all possible combinations of subassemblies that can be made from the parts.

A more promising, but also much more pragmatic, approach is to use a top-down problem solving strategy where assembly knowledge about a certain class of products is used to plan the assembly of the products. The more and better information can be transferred from the design stage to the production planning stage, the easier and the better the production planning can produce efficient and effective plannings for robotic construction.

Task Reduction

Dean & Wellman (1991) describe an interesting top-down approach that is called *task reduction*. This task-reduction approach reduces the level of abstraction of a specified task in a recursive decomposition process until all subtasks can be carried out by the robot hardware. Non-decomposable subtasks that are executable by the robot, are called *primitive operations*. Of course, primitiveness is a relative property. The more powerful robots become, the higher the level of abstraction of primitive operations will become.

The task-reduction approach assumes that the task planning problem is *decomposable*. Decomposable implies that there are no mutual dependencies between the sub-tasks distinguished in each decomposition step. In practical situations, this is often not the case. Nevertheless the task reduction approach assumes that the planning problems are decomposable into independent pieces. Any potential conflicts that occur in the generated plan, are resolved afterwards when the sequence of the operations in the plan is determined. The idea behind this is, that planning details should not obstruct the general structure of the produced plans.

The planning know-how used in the task-reduction method uses a knowledge base which contains a library of pre-cooked, domain specific plans that describe how abstract tasks are reduced to robot operation plans (Dean et al. 1991 p. 185). These domain-specific plans contain the information that describes how a task can be executed by a specific robot. The approach using pre-cooked plans, is based on the assumption that the advantages of the use of pre-cooked plans are bigger than the costs to make these plans. The costs of this approach are the effort needed to create the plans, and the possible lack in efficiency of the generated plans.

The approach of task reduction is believed to suit the requirements of construction robot task instruction because of three reasons:

- *It suits the semi-unique nature of construction task.*
A large proportion of all construction processes is of a semi-unique or even procedural nature. Many tasks that are currently performed in construction processes are already standardised in some form. These task-execution procedures can exist in a variety of forms, e.g. code of practice, product installation procedure, quality assurance procedure, safety procedure etc.
- *Task planning in construction processes is often based upon implicit assumptions.*

The reality of task planning is very complex. Often the planning of tasks is based upon implicit assumptions and previous experiences. This implicit knowledge makes it impossible to generate correct plans in a reasoning process.

When bottom-up reasoning mechanisms are used in such situations, it is possible that the generated plans overlook certain phenomena in the real world. The problem is that the effects of ignorance for unmodelled phenomena are unpredictable. Some effects can be harmless, while others can cause dangerous situations. Using pre-cooked plans, this problem can be avoided because a pre-cooked plan can prescribe a certain approach without having to explain the *why* information. Using a bottom-up reasoning mechanism, such *why* information is essential in order to be able to generate correct plans.

- *The efficiency of the robot plans is of secondary importance*

Construction robot tasks are generally one-of-a-kind tasks. Optimization of the robot task plans which are executed only a limited number of times, is often not worth while because plan optimization is too costly in relation to the potential benefit of a more efficient robot-motion sequence.

Sequence Planning

The approach of task reduction provides a method to *decompose* the abstract task specification into a set of primitive operations that have to be executed in order to accomplish the assigned task. However, this does not produce a deterministic sequence of execution of all primitive operations.

In order to determine the sequence of execution of operations, it is necessary to use a search algorithm that evaluates the set of all primitive operations and 'puzzles' in what sequence these operations are best executed. It is considered desirable that the non time sorted plan produced by the task reduction algorithm, contains all sequence constraints that are imposed by the product design. The remaining sequence possibilities should be evaluated by a search algorithm.

Sheu & Xue (1993 ch. 4) discuss a number of the 'classical' planning algorithms for operation sequence planning and present some non-linear planning strategies for typical robot task planning problems (1993 ch. 5 p. 85). They distinguish between *consumer ordering problems* and *producer ordering problems*. Consumer ordering problems are problems where every operation consumes some resource (e.g. space); but the applicability of each operator is dependent on the availability of another resource. An example of a consumer ordering problem is to build a block wall. The placement of a block consumes wall space. The placement operation requires that the blocks below are placed. A producer ordering problem is the opposite of the consumer ordering problem. Instead of consuming some resources, each operation produces some resources. An example of an producer ordering problem is the unstacking of a stack of bricks. Many real world robot-planning problems are consumer-producer ordering problems. An example is to build a block wall using blocks that are stacked near the robot.

6.2.2 Related Research on Product Data Technology (PDT)

With the introduction of computers in engineering, these computers have been used as tools to automate and simplify traditional tasks. Although computers are able to communicate better and better, the means of communication of technical information in the building industry have remained the same, i.e. technical draw-

ings and text documents. This phenomenon is being referred to as *island automation*. Product designers use CAD systems to make drawings which are provided to the planning to prepare the actual production of the designs.

The problem of island automation has been recognised many years ago and since the beginning of the eighties research groups and committees are working on methodologies to realise effective exchange of information. The long term objective of these research project is the realisation of *Computer Integrated Construction*, or CIC. The objective of CIC is to provide the building industry with a platform of standards and standard software interfaces that enable the exchange of product information between systems of different vendors, used by different actors (e.g. architect structural engineer), for different purposes (e.g. design, evaluation analysis) or in different life-cycle stages (e.g. in engineering, construction, maintenance).

Research on CIC has led to the development of Product (or Project) Data Technology (PDT). PDT is the subject of the ISO¹ committees that are involved with the development and specification of standard 10303, which is also known as STEP (STandard for Exchange of Product model data) (ISO 1994a). In short, the objective of these ISO committees is to provide an open standard for exchange of product and project information for a range of industries. The realisation of this objective has proven to be very complicated. The development of STEP is already going on for more than ten years.

In the beginning of the development of STEP, the subject of attention was focused on the exchange of digital versions of technical drawings and geometrical representations. During the development of STEP, it was realised that exchange of more *semantical* information is more effective and valuable. *Semantical*, or *definition data* describes an object in the terms normally used in the building industry practice. For instance a building design is described in terms such as: *wall, floor, ceiling, column* or *beam*, each accompanied with its characteristic parameters such as for instance *length, width, colour, load bearing capacity* etc. The idea is that definition data can automatically be translated into *representation data*. Representations can be a finite element model for structural analysis, or a geometric model for spatial analysis. Representation data can be transformed automatically into presentation data such as 2D views in technical drawings, bill of materials, or 3D virtual reality models.

The division between definition, representation and presentation is mainly applied to product data, but can equally well be applied to process data (ISO/TC184 1989). A semantical process data model describes activities and tasks of a project in terms of their characteristics that are used in practice. Process definition data can automatically be transformed into process representations such as directed graphs, which can again be transformed into presentations such as Gantt charts or Petri nets.

It was argued before that the realisation of the proposed strategy for the realisation of task-instruction systems requires the availability of a communication channel that allows the transfer of meaningful design information. PDT provides some powerful mechanisms that seem to be very beneficial to the realisation of task instruction.

6.2.3 Related Research on User Interfaces

The introduction of new technology such as computers or robots is often inhibited by resistance of humans to these new devices. This initial resistance is often related to the employment threats that people see in robots. Besides that, there is often a discrepancy between the concepts that need to be understood to use a robot and the concepts that a construction worker or planner is familiar with. A similar 'friction' has occurred with the introduction of office automation in the previous decades. Although computers are very powerful tools, many people have problems using computers because they are not familiar with the abstract concepts such as bytes, files and directories.

The solution that has been widely accepted to simplify the use and control of computers is the use of graphical user interfaces. Graphical user interfaces project computer concepts on user concepts using small pictures (icons) that visualise the user concepts. Nice examples of such user interfaces are those of the computer operating systems Mac OS™ and Windows 95™. The interfaces of both operating systems use metaphors for computer functionality to simplify the use of computers. Some examples of metaphors that are used are: *file cabinet*, *folder*, *waste basket* and *desk top*.

A task-instruction system for construction robots should preferably use state-of-the-art user-interface technology to communicate with its users. Therefore it must be known which metaphors can best be used for construction workers and construction planners. The metaphors such as desk top, folder or file cabinet will probably not be the most appropriate metaphors for construction workers. Eventually it is desirable to standardise the operator interface metaphors to make instruction of different robots more easy.

An additional advantage of the use semantical information, such as discussed in the previous subsection, is that it enables more effective communication with humans. Abstract building-industry concepts and jargon can be used in the interaction between the task-instruction system and its human user, because this type of project information is available to the task-instruction system.

6.2.4 Related Research on Reactivity

Reactivity is an ability that is required when actions are planned in advance. As mentioned before, plans are always based on assumptions about the situations to be encountered. As soon as a contingency occurs, a plan loses its validity. Construction robots needs reactivity capabilities to deal with contingencies up to a certain level of complexity.

Dean & Wellman (1991 p. 198) describe a strategy for the implementation of reactivity called *conditional plans*. Conditional plans are plans that contain a number of alternative approaches to execute the assigned task. The actual plans used to execute that task depends on information gathered during the execution of the plan. This approach has the advantage process re-planning is not needed, every time a contingency occurs. The potential disadvantage is that conditional plans may become very large when the plans have to include many alternative approaches for a wide variety of contingencies.

The use of conditional plans seems suitable for application in construction applications because of the following two reasons.

- It is desirable to have a distinction between planning and plan execution. In the building industry different people are responsible for planning work and for the actual building process. With the use of conditional plans, this separation in planning and plan execution is maintained.
- From the robot operator point-of-view, the robot actions should be as predictable as possible. Conditional plans are deterministic, in the sense that given a certain situation, the robot will always have predictable behaviour. Re-activation of the planner, may result in a different approach for every new product being worked on. This last situation may be undesirable for safety reasons.

6.3 Summary, Conclusions and Hypothesis

The basic hypothesis formulated at the beginning of this chapter is that the semi-unique nature of construction robot tasks, provides opportunities to reduce the complexity of task-level instruction significantly, making implementation in practical situations possible. Now that the requirements and state-of-the-art technology have been discussed in more detail, the hypothesis can be formulated more sharply.

The hypothesis is that a construction robot task-instruction system can be realised using the PDT mechanisms to effectively generate robot operation plans from abstract task instructions. By using PDT for exchange and storage of project information (at a high semantic/definition level) it is possible to:

- implement task planning with less complex algorithms because more powerful reasoning rules can be used
- realise communication with human beings in their jargon,
- exchange information with CAx systems effective without (manual) re-entry of information, and
- react better to unexpected events, because more project knowledge is available to plan an alternative approach.

The next chapter presents a system architecture for the realisation of a task-instruction system using PDT. Task-instruction systems are required to have (at least) the following functionality:

- A task-instruction system should be able to generate a plan of robot operations that performs the assigned task. The method of task reduction seems to be a suitable solution to implement the functionality
- The task instruction specification and other interactions between the system and human beings should be product oriented, meaning that the concepts used refer to the concepts that the humans are used to deal with. A task-instruction system should preferably use graphical presentations of concepts that construction managers and robot operators are used to.
- A task-instruction system should be able to communicate (electronically) with other computer systems that are already used in today's building industry. PDT provides useful mechanisms to realise exchange of semantical information between systems.
- When some kind of contingency occurs during the execution of a robot task plan, the robot controller should be able to deal with simple contingencies. This functionality is called reactivity. A suitable strategy for the implementation of reactivity seems to be the use of conditional plans. Conditional plans are plans that include alternative approaches to execute the assigned task.

7

An Architecture for Task-Instruction Systems

Chapter seven presents a reference architecture for task-instruction systems. This architecture distinguishes five subsystems. The function of each subsystems is discussed together with methods for implementation.

This chapter presents a so called *reference architecture* which describes a functional decomposition of task-instruction systems in general. This reference architecture distinguishes five main functions in task-instruction systems. Each function is fulfilled by a separate subsystem. Section 7.1 presents the general overview of the proposed architecture. The succeeding five section (sections 7.2 to 7.6.) discuss each of the distinguished subsystems. Finally section 7.7 summarizes the main aspects of the presented architecture.

7.1 General Overview

This first section explains the general overview of the proposed architecture. Subsection 7.1.1 explains which subsystems are distinguished. Subsection 7.1.2 explains the proposed approach for integration and coordination of the subsystems. Finally, subsection 7.1.3 presents an example of a imaginary masonry robot, that is used throughout this chapter to clarify various topics.

7.1.1 System Functionality

The proposed architecture for task-instruction systems distinguishes the following subsystems:

1 *task-specification subsystem*

In the task-specification subsystem it is specified *what* the robot has to do. This is done by selecting the building parts, that have to be realised or treated, from the project model. The task-specification subsystem verifies whether the robot is able to fulfil its assignment.

2 *task-planning subsystem*

The task-planning subsystem transforms the template process-type model into a project-specific process plan, containing all operations that are to be performed to fulfil the assigned task.

3 *operation-sequence planning subsystem*

The operation-sequence planning subsystem evaluates the generated process plan and determines in what sequence the operation are to be executed.

4 *motion planning subsystem*

In the motion-planning subsystem it is determined what robot motions are required for each operation. Information about the shape and locations of objects is used to generate motions.

5 *plan-execution subsystem*

The plan-execution system monitors the correct execution of the prepared plans. Plans are, by definition, based on assumptions about situations. The plan-execution subsystem verifies the correctness of planning assumptions, using sensor readings. If assumptions prove to be incorrect, the plan-execution subsystem can re-activate the sequence-planning subsystem to try to resolve the problem. If this fails, operator assistance is needed.

Each of the above listed subsystems is described in more detail below.

Task-Specification Subsystem

The function of the task-specification subsystem is to determine the *what* has to be done. The task specification is *result oriented*, meaning that the task is specified in terms of the required end result instead of in terms of robot operations. The system uses knowledge about the products or product states to determine whether it is possible for the robot to carry out requested tasks. E.g. the task-specification system knows that a wall-building robot can build walls that are not higher than 3 m.

It is assumed that construction project information is available in the form of a *project-model database*. A project model is the PDT term for an application and system independent database, containing all technical information about a project. The information in a project model is accessible in an application independent semantic representation. The task-specification subsystem has to be able to understand the project-model information to identify (filter out) the information that is relevant to the robot and the task it has been assigned.

The output of the task-specification subprocess is an unambiguous specification of the task to be performed by the robot. Figure 32 shows an IDEF₀ diagram of the task-specification process with its information input, output and resources. The task-specification subsystem is described in more detail in section 7.2.

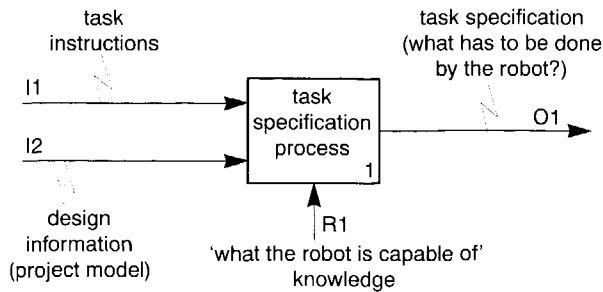


Figure 32 IDEF₀ diagram showing the task-specification process with its *inputs*, *outputs* and the *resources* used. Each diagram shows one or more processes, represented by rectangles. Arrows represent material and information flows. Process input flows, enter on the left side (arrows I1 & I2). Process output flows exit on the right side (arrow O1). Control information comes from above, resources come from below (arrow R1). According to the IDEF₀ method, input and output flows are material flows. In this thesis, all input and output flows are informations flows. A comprehensive explanation of IDEF₀ is given in (SofTech 1981).

Task-Planning Subsystem

After the specification of *what* is required to be done by the robot, it has to be determined *how* the robot will take care of its assigned task. This process is called *task planning*. In the previous chapter it was argued that the task-planning functionality is to be implemented by a reduction method where pre-cooked process-type models are used to generate process plans out of a task specification.

Figure 33 shows an IDEF₀ diagram of all input, output and resource information flows of the task-reduction process. The task-planning subsystem uses the output of the task-specification subsystem and produces a task plan. This transformation requires additional knowledge and information.

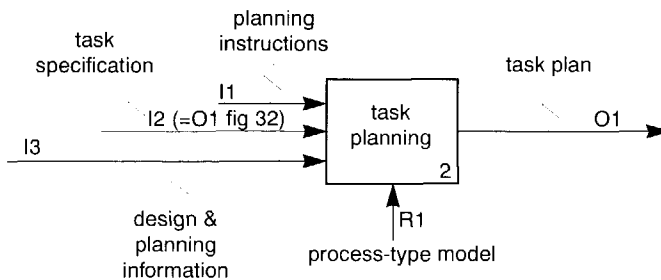


Figure 33 IDEF₀ diagram of information input and output of task-planning process. The main input of the task-planning subsystem (input I2) is the output of the task-specification subsystem. Together with additional product and process knowledge (I3), and optional planning instructions (I1), a task plan is produced.

The core of the task-planning subsystem is a knowledge representation for pre-cooked task-execution plans. This knowledge representation is referred to as a *process-type model*. A process-type model is an knowledge representation that describes the mutual properties of a class of processes, e.g. building walls.

The output of the task planning process is a *conditional plan*. A conditional plan is a plan that contains not only a linear sequence of operations, but also possible alternative sequences which all produce the same end result. Conditional plans enable last-minute modification of the exact sequence of execution of robot sub tasks or operations. This is a feature that enables the robot to deal with *contingencies*.

In section 7.3 the method used for task planning and the process-type model knowledge-representation is discussed in more detail.

Operation-Sequence Planning Subsystem

The *operation-sequence planning* process determines in what sequence the sub-tasks and operations are to be executed by the robot hardware. The conditional plan, produced by the task reduction process, is evaluated to determine the preferred sequence of operations (See figure 34).

This process uses a *sequence-planning algorithm* to determine the sequence of execution of robot operations. The operation sequence is determined by the robot's capabilities on the one hand, and on the topology and geometry of the structure to be assembled or treated on the other hand. An example of a dependency of sequence planning on the robot hardware, is when a wall robot is able to pick and place two elements simultaneously.

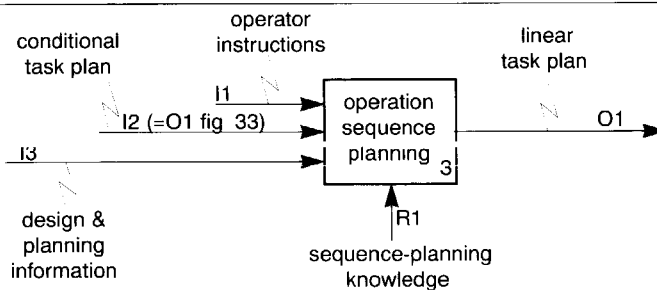


Figure 34 IDEF₀ diagram of operation sequence planning process including the information input, output and resource streams.

Operation-sequence planning can be a complicated problem when it is required that the generated robot plans are also optimised for efficiency of robot motions. In industrial applications where robot-operation sequences are repeated many thousands of times, optimization is generally worth while the effort. However, in building-industry applications where robot plans are executed only once, the effort needed for plan optimization is generally not earned back. The effectiveness of sequence planning (meaning being able to generate plans with as little possible

human assistance) is regarded preferential to the efficiency of the generated plans.

The output of the operations-sequence planning subsystem is a conditional plan that contains a preferential operations-sequence together with possible alternative sequence relations. These alternative sequence relations can be used when the preferential sequence loses its validity when a contingency occurs. In that case an alternative operation sequence can be deducted to carry out remaining operations.

Motion-Planning Subsystem

The *motion-planning* process, is the process where the robot manipulator's motions are planned in detail. Motion planning is essential in order to avoid collisions between the robot and objects in its environment.

The information that is needed for the motion planning is the geometry of the objects that surround the robot (the building being constructed). Reasoning about the best trajectories to move from A to B is complex. Nevertheless, several effective, but computationally expensive algorithms for motion planning exist. The project model can provide the required information about the location and shape of objects that are to be manipulated or avoided.

As mentioned earlier, the efficiency is regarded to be of lower importance than effectiveness. Therefore it is required of the robot-motion planning to generate motions that avoid (collision) risks, even if these motions are less efficient. The implementation of motion planning is discussed in more detail in section 7.5.

Plan-Execution Subsystem

Finally the generated plans are to be executed by the robot in the real world. The goal of the plan-execution process is to control the execution of the prepared task plans.

The primary task of the plan-execution subsystem is to handle contingencies. A *contingency* implies that (part of) the task plan has lost its validity because some assumption about the real world proved to be untrue. The nature of the contingency determines the impact of the contingency on the plans. Contingencies where assumptions about the product geometry prove to be untrue, require the *motion planning* to be partly redone. Such type of contingencies can be caused by an obstacle which blocks the robots motion or that an object is not where it is supposed to be. If possible these types of contingencies should be handled by the task-instruction system.

7.1.2 Subsystem Integration and Coordination

Figure 35 shows an IDEF₀ diagram of the complete task-instruction system architecture with all distinguished subsystem processes and information flows between them. The project model is a source of information for several subsystems. Additional knowledge is used to translate the product design, contained in the project model, into robot operations to be handled by the plan execution subsystem.

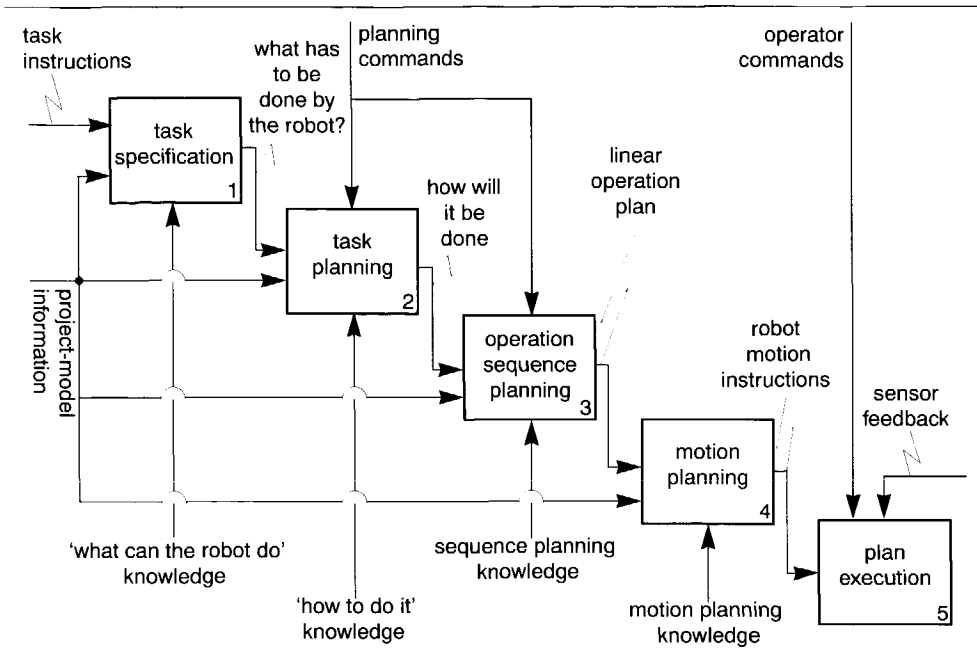


Figure 35 IDEF₀ diagram of task-instruction system architecture.

Although all subsystems together, form the task-instruction system, this does not necessarily imply that the task-instruction system has to be implemented as one software system. For organisational and technical integration purposes it may be desirable to implement the system modular. This way different subsystem modules can be activated at different moments, by different people, and at different locations. E.g. the task specification and task planning subsystems are desired to be used in the office during production planning. On the other hand operation sequence planning, motion planning and task execution subsystems are best located at the building site near the robot hardware and activated shortly prior, or during task execution. Also the perceptions of sensor systems are essential to verify the correct execution of robot plans. For reasons of efficiency and safety it seems unwise to control the robot hardware from an off-site location through (wireless) data communication links. However, this situation can change as result of the rapid technical advances in (wireless) data communication technology and infrastructure.

Because each subsystem uses information provided by other subsystems, there is a distinct sequence in which subsystems are to be activated. In the chain of subsystems the robot operation plan is detailed step-wise. Each subsystem incorporates other types of information and knowledge into the robot operation plan. Depending on the nature of the robot application or the nature of the information used, the moment when information becomes available can vary. Some information will be available before it is needed, other information will be provided by other (parallel executed) planning processes.

A special source of information is the sensor feedback. The information obtained from sensors becomes available during the execution of the robot plan. Such information should normally not influence the structure and sequences of operations in the robot plan. If sensors detect something that is not expected, a contingency occurs, and the task-execution subsystem can decide to change the sequence of operations. The task-execution subsystem cannot re-activate the task-planning subsystem. This is because it introduces the dangers of on-site improvisation. On-site improvisation is to be avoided, because in extreme situations, task duration and task results can become unpredictable. When improvisation is needed, it is better left over to human beings instead of robots.

Coordination

For the coordination of the system an information-control process is needed. This information-control process fulfils three functions. These are:

- 1 *work-flow management support*
Control the sequence of completion of each of the task-instruction subsystem processes.
- 2 *access control*
Manage the access rights of different people to add or modify information in the task-model database.
- 3 *subsystem iteration cycle control*
Iteration cycles may be needed when changes are made or contingencies occur. For instance when an obstacle is detected by the robot, the motion-planning subsystem may need to be re-activated to find out whether the robot can avoid the obstacle.

The proposed system architecture uses a strategy known as *least-commitment strategy* (Rich and Knight 1991) to avoid re-planning when possible. The idea of the least-commitment strategy is to postpone decisions as long as they can be postponed. The purpose of the least-commitment approach is to reduce the risk that planning assumptions made in early stages prove to be untrue.

The least-commitment strategy is used in the presented task-instruction system architecture in two aspects. The first feature is that motion planning is performed as the last step before the plans are executed. The second feature is that the plans produced by the task-reduction subsystem and by the operation sequence planning subsystem are *conditional plans*. A *conditional plan* is a plan that incorporates alternative sequences of operations that can be used to realise the same end result. A potential disadvantage of *conditional plans* is that they can become very voluminous when more alternatives have to be taken into account.

Integration

The presented task-instruction system architecture uses a logically centralised database for storage of all information relevant to task instruction. This centralised database is called a *task model*. The task model is a special kind of project model which is organised and extended such that all task instruction related

information can be stored in the model. The task-model database stores all information that is processed by the subsystems of the task-instruction system. (See figure 36)

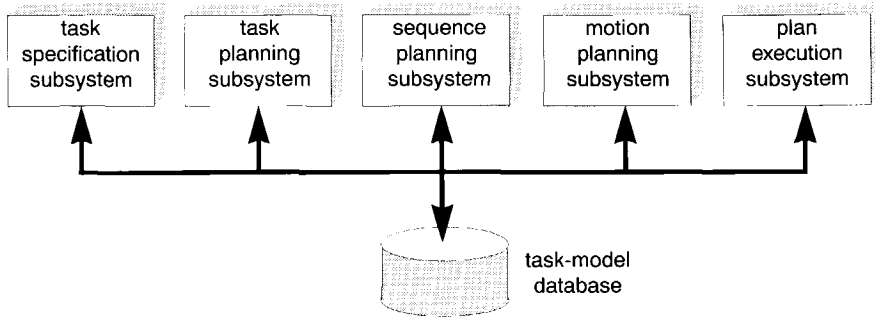


Figure 36 Exchange of information between subsystems via a shared task model database.

A task model is a so called *view model*. The information stored in the task model is structured to accommodate the function of the model, which is to store all task instruction related information. Each robot task goes through a life cycle. In the task-instruction architecture each subsystem adds information to the robot operation plan making the plan more concrete. Consequently, the task-model database grows after each subsystem is activated, as more information is stored in the task-model database.

The task model is preferably compatible with the project model that is provided as input of the task-instruction system. The better the compatibility between task model and project model is, the better the task-instruction system can be integrated with other computer applications in construction planning and management. Unfortunately current PDT developments do not yet include much process modelling facilities to be used for task-instruction.

7.1.3 Example: Instruction of a Wall Erection Robot

In this chapter an example of a task-instruction system is discussed to illustrate the presented architecture. The example concerns an imaginary robot that erects load-bearing walls by manipulation of sand-lime elements.

The example is used because of two reasons. The first reason is that the construction method using sand-lime elements is a very popular method for building residential buildings in the Netherlands. The second reason is that the development of robots that can erect these types of walls seems to be a realistic perspective, for which a German and European research project are carried out.

The chosen example deals with the construction of load-bearing walls using sand-lime elements, such as commonly used in the Dutch building industry. The elements have a standardised size of 60 by 90 cm and a thickness that can vary between 10 and 30 cm. On the building site, the elements are manipulated using a

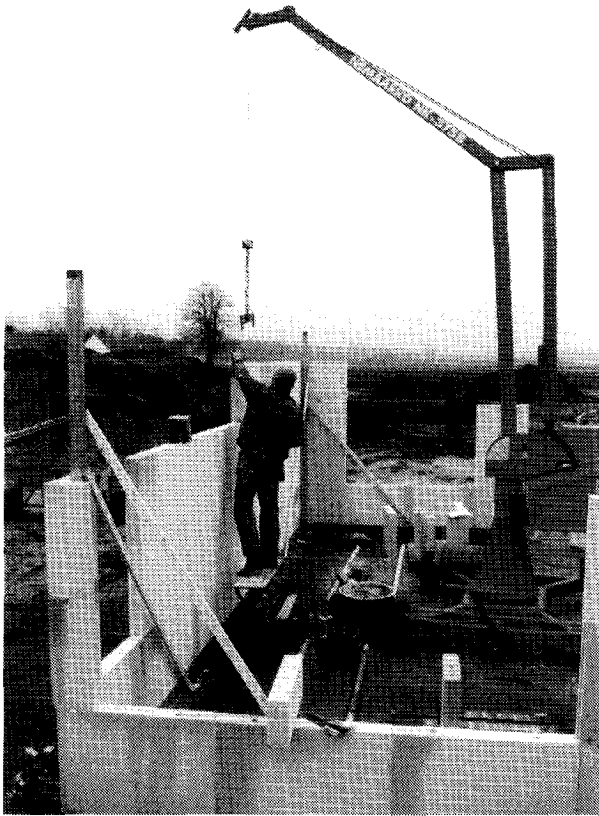


Figure 37 Conventional method for erection of load bearing walls of residential buildings using a small crane to pick-up and place sand-lime elements.

small crane (See figure 37). Non-standard size elements, needed for wall edges and openings, are cut to the correct shape in the sand-lime element factory and delivered to the building site on pallets.

The design and planning of element walls is carried out by the sand-lime element sales organisation in cooperation with the contractor. The sales office creates an element layout for each wall using information provided by the contractor. The element layouts specify where custom size or custom shape elements are used (see example layout in figure 38).

The wall layouts are communicated back to the contractor for approval. The wall layouts also provide the numbering of custom elements to identify them at the building site. The information in the detailed design is also used by the supplier to control the sawing machines that cut the custom elements to the desired shape and size.

The current practice is that project information is communicated in the form of technical drawings on paper. At the sand-lime elements sales office, these draw-

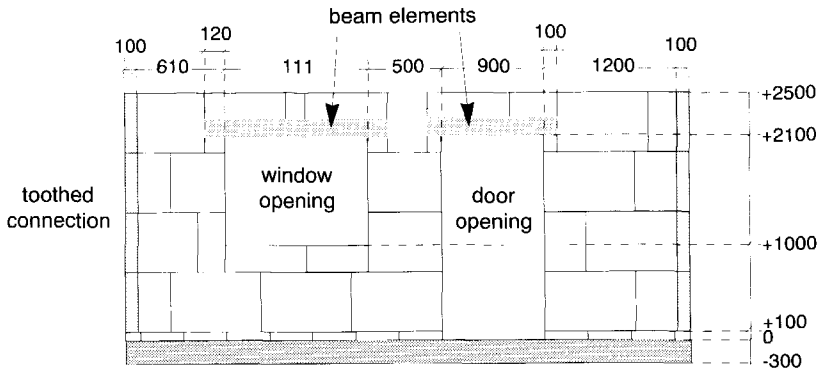


Figure 38 Example of element-layout drawing.

ings are interpreted and relevant information about the load-bearing walls is re-entered into a computer. This manual re-entry would not have been needed when a suitable standard for the exchange of building-design information existed. It is assumed that in the future, *computer integrated construction* (CIC) will become a fact, and that the exchange of information will take place using project models, eliminating manual re-interpretation and re-entering.

In this chapter it is assumed that the wall-layout design information, that is the input for the robot task-instruction system, is accessible in a project-model database (beside all other project information of course). How the wall-layout design can be stored in the project model is now discussed in more detail. The storage of sand-lime element wall designs in a project model is used as an example in the rest of this chapter to explain how project-model information can be translated into a robot operation plan.

A wall-layout design specifies a number of different aspects of a wall that are relevant to the design and construction of that wall. The most relevant design specifications are:

- the shape of the walls to be erected (dimensions: length, height, thickness)
- the relative locations of the walls
- the locations of openings (for door, windows etc.)
- connections between walls (type of connection)
- location of expansion joints
- layout of sand-lime elements in a wall

Figure 39 shows an EXPRESS-G diagram of the wall layout design specifications for a sand-lime element wall. From now on the graphical representation technique EXPRESS-G is used to visualise information structures. A comprehensive description of EXPRESS-G is given in (ISO 1994b). In figure 39 it is shown that every *sand-lime element wall* entity has an *is-built-of* relation with *sand-lime element* entities. This says that every sand-lime-element wall is built from a set of sand-

lime elements. Every sand-lime-element wall also has a certain location and shape. Optionally a wall can have openings and expansion joints. Furthermore a wall has connections to the floor above or underneath it, or to other walls.

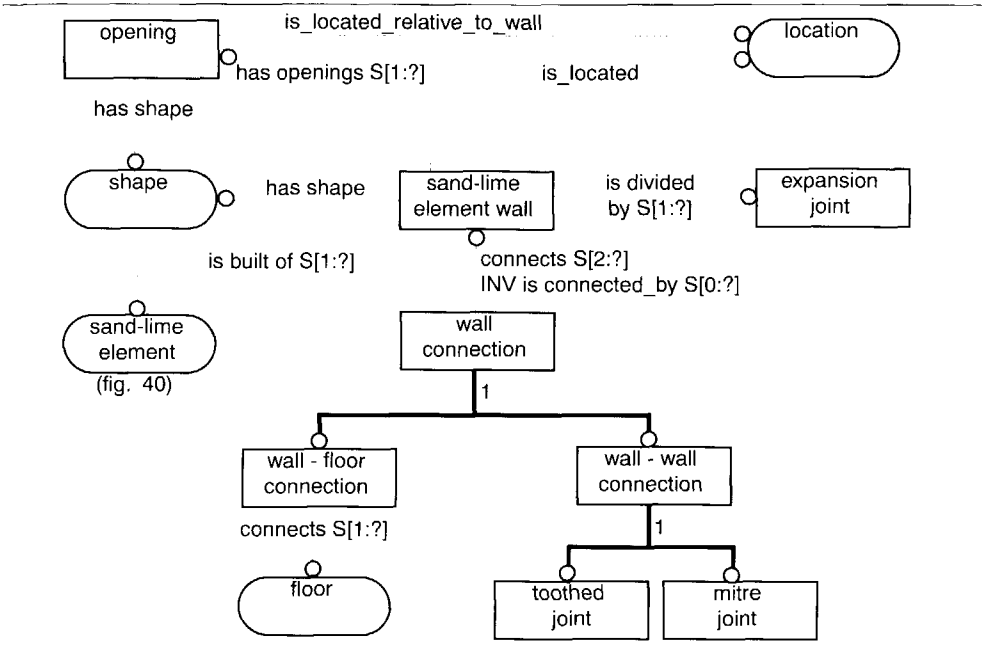


Figure 39 EXPRESS-G diagram of conceptual model of task-instruction input. Rectangles represent entities. Rectangles with rounded corners represent *off-page* entities that are defined in another diagram or model. Lines are used to represent relations. The circle at the end of a relation line indicates the direction of the relation. Subtype relations are represented by thick lines. Dashed lines indicate optional relationships. The EXPRESS-G technique is described in (ISO 1994b).

The EXPRESS-G diagram in figure 40 shows the definition of the *sand-lime element* entity. Each element can be one of three types: *standard element*, *custom-shape element* and *beam element*. Beam elements are used above door or window openings. Elements are connected to each other by three types of connections: either they are glued onto each other or glued next to each other, or placed next to each other without glue (expansion joint). Walls can be connected through a toothed joint or a mitre joint.

In the following sections the above presented example is used to clarify various subsystems in the task-instruction system architecture.

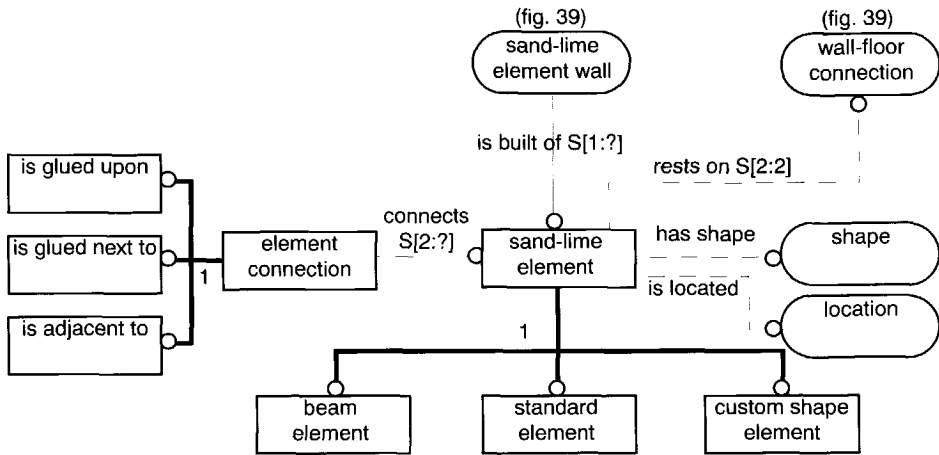


Figure 40 EXPRESS-G diagram of conceptual model of wall layout design. Every sand-lime element wall is built of sand-lime elements. Three types of elements are distinguished which have different shapes. Elements can have connection relations between them to specify where they are glued together.

7.2 Task Specification

The task-specification subsystem implements result-oriented specification of the robot task. The robot instructor (i.e. construction planner) selects the building parts to be realised or treated by the robot. The task-specification subsystem supports this selection, by a presentation of possible robot tasks to the robot instructor. For this, the task-specification subsystem performs the following two steps:

1 *project evaluation*

Project (model) evaluation is the step in which it is determined what possibly can be done by the robot. The project model is analysed using the robot capability knowledge to find all possible robot tasks. In the case of the example wall-erection robot, all load-bearing element-walls in the project are identified. The task-specification subsystem verifies whether the wall properties do not conflict with robot capabilities concerning, e.g. reach (wall height) or load-carrying capacity (element mass).

2 *task assignment*

The second step is the *task assignment*. In this step, the robot instructor assigns tasks to the robot by a selection from the set of possible robot tasks produced in the previous step. The resulting set of task assignments is the *task specification*. In case of the example, the instructor selects the walls that are to be erected by the robot. The list of all walls to be erected by the robot is the task specification.

Both steps are discussed in the next subsections.

7.2.1 Project Evaluation

Project evaluation requires the information contained in a project model, to be compared with the robot-capability knowledge. Because the task specification is required to be result oriented, the evaluation is performed on building components instead of building tasks. For each building component, described in the project model it is established whether the building component can be 'manipulated' by the robot. The robot-capability knowledge is used to determine this.

How this works can be explained using set theory. Suppose that R is the set of all building components to be realised in a building project (project model) and T is the set of all possible manipulation tasks that can be performed by some particular robot (See figure 41). The project analysis requires that it is identified which elements belong to the subset of these two sets, e.g. the load bearing walls in the project that can be erected by the robot. Set R is defined by its *extention*, which is the complete summary of its contents, which are the building components in the building ($R = \{e_1, e_2, \dots, e_n\}$). Set T on the other hand is uncountable and is defined by its *intention*, which is the characteristics of its elements ($T = \{t|\dots\}$), e.g. 'the erection of sand-lime element walls not higher than 3m'.

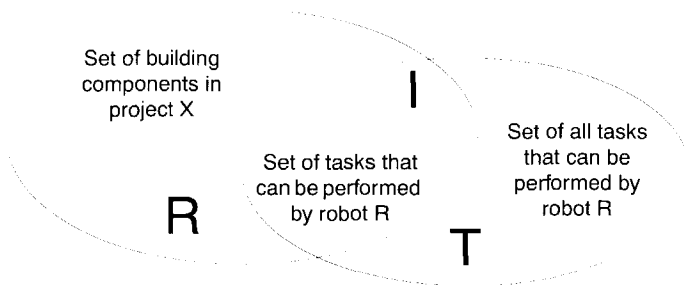


Figure 41 Venn diagram showing the goal of the project evaluation process. The purpose of this process is to identify the intersection of the set of all tasks needed to realise a building and the set of all tasks that can be performed by a robot.

Only when the properties of elements of R can be matched against the required properties defined in T , the subset $I = R \cap T$ can be identified. This requires that:

- 1 the information describing the building components in the project model contains sufficient semantic information to identify whether they are eligible candidates for construction by the robot, and
- 2 the information of both the project model and the robot capability knowledge is modelled in a similar (or at least compatible) manner.

The first of the above requirements implies that project models should contain sufficient information to establish whether a robot can realise the required end result or not. The semantic information-content of project models is a major issue in the development of project-modelling concepts. In the research discussed in this thesis, it is assumed that project models do contain all the semantic information needed.

To fulfil the second of the above requirements, some kind of standardised modelling concept is needed, both for project models, and for robot-capability representations. E.g. the same meaning of the concepts of wall, floor, length, width, height, etc. are needed to be able to apply the robot-capability knowledge to the project-model information. Without standardisation, the evaluation of building designs against robot capabilities requires complicated interpretation-software or manual assistance.

The scope of a standard for project models can vary between branch level and international level. Currently there are a number of groups working on the development of standards for representation of building project-models. It is expected that it will still take some years before these standards are completed and accepted throughout the world.

Representation of Robot Capabilities

The concept of knowledge representation is generally associated with the field of artificial intelligence (AI). Product and project modelling also deals with knowledge representation but this area of research has its origin in database technology. Nevertheless project modelling and AI knowledge representation have many things in common. The representation methods used in project modelling are very similar to the AI concept of *conceptual dependency* (Rich et al. 1991). The difference is that both worlds have a different point-of-view on the purpose for which knowledge is represented. In database technology much value is set upon *representational adequacy* (how to store all relevant information?) and *acquisitional efficiency* (how to insert and maintain the information?). In AI applications more value is set upon *inferential adequacy* (how to manipulate knowledge structures to derive new structures containing new knowledge) and *inferal efficiency* (how to include meta knowledge to direct problem solving in the most promising direction?).

The reasoning mechanism needed in the project evaluation, can be kept uncomplicated when project-model information is accessible via a standardised access method. Apart from this, it is required of the robot-capability knowledge representation to provide representational adequacy and acquisitional efficiency. The data-modelling language EXPRESS is a suitable language for the representation of robot-capability knowledge.

EXPRESS is a data-definition language that has its origin in PDT. EXPRESS is part of the ISO 10303 standard for computer-interpretable representation and exchange of product data (STEP) (ISO 1994b). EXPRESS is the lexical representation language on which the graphical notation EXPRESS-G, which is used in figure 39, is based. Due to the strong relation between EXPRESS and EXPRESS-G it is possible to translate EXPRESS-G diagrams into EXPRESS schemata automatically. EXPRESS schemata can again automatically be converted into computer program skeletons in a programming language of preference, e.g. SQL, C++, Java etc.

EXPRESS is a suitable knowledge-representation language because it has the following properties:

1 *good representational adequacy*

The kind of knowledge that is to be modelled is constraint knowledge. EXPRESS has facilities such as rules to model constraint knowledge.

2 *support for acquisitional efficiency*

Because the EXPRESS language is specially designed to support both computer interpretation and human interpretation, the acquisitional efficiency of EXPRESS is believed to be sufficient. The acquisitional efficiency of EXPRESS can be further enhanced using its graphical representation, EXPRESS-G.

3 *standardisation*

EXPRESS is an internationally standardised data definition language. The standardisation enables neutral storage of robot capability knowledge. Neutral storage of this knowledge enables communication of robot capabilities between contractors and subcontractors to promote the use of their robot in construction projects.

An example of a piece of an EXPRESS *schema* is shown below. This EXPRESS schema is part of the textual version which is generated from the EXPRESS-G models shown in figures 39 and 40. The schema includes the definitions of the entities *sand-lime element wall* and *sand-lime element*.

```

SCHEMA sand_lime_element_wall_construction_model;

ENTITY sand_lime_element_wall; --see EXPRESS-G diagrams fig. 39 & 40
  is located_at: position;
  OPTIONAL has_openings: SET[1:?] OF opening;
  has_shape: shape;
  is_connected_by: connection;
  OPTIONAL is_divided_by : expansion joint;
  is_built_of: SET[1:?] OF sand_lime_element
END_ENTITY;

ENTITY sand_lime_element;
  length : REAL;
  height : REAL;
  thickness : REAL;
  location : position;
  mass : REAL;
INVERSE
  is_part_of : sand_lime_element_wall FOR is_built_of;
END_ENTITY;

-- a lot of other entities are omitted from the schema for this example

END_SCHEMA ;

```

The above schema is used as a foundation for the representation of the robot capability knowledge. The EXPRESS language provides several *constraint modelling* constructs. The most suitable constraint modelling construct is the concept of *rules*. Rules can contain algorithms that describe the constraints to which all instances of some particular entity have to fulfil. An example of a rule is shown in the schema below.

```

SCHEMA robot_123_capabilities;

USE FROM sand_lime_element_wall_construction_model;

RULE robot_123_handable FOR (sand_lime_element);
WHERE
  robot_123_mass_limit:
    (mass < 300);
  robot_123_reach_limit:
    (is_part_of.shape.height - (location.z + height)) < 3.0;
END_RULE;

-- a lot of other rules can be added to model other constraints

END_SCHEMA ;

```

With the constraint knowledge such as modelled in the above EXPRESS schema, it is possible to evaluate a detailed wall layout, such as shown in figure 38, to evaluate whether the robot is able to build the wall. Optionally it can be established whether or not a wall can only partially be assembled by a particular robot. It is then up to the robot instructor to decide if it is acceptable that some elements have to be installed in a traditional manner.

7.2.2 Task Specification

In the project-model evaluation, all possible robot tasks have been identified. It is now up to the robot instructor to determine the robot assignment. The task specification subsystem assists the robot instructor by presenting him with a list of all possible robot tasks. In the case of the wall robot example, a list of all load bearing walls is presented. The robot instructor can select all the building parts that he wants the robot to work on.

The results of this task-assignment process are to be stored in the task-model database. Figure 42 shows an EXPRESS-G diagram of the representation of a robot task assignment. A task assignment consists of a number of task specifications. The output of the task specification process is an instance of a robot task assignment and a number of robot task specification entities in the task model database. The task planning subsystem will take care of the instantiation of a robot task plan that defines how a robot task will be fulfilled. This is discussed in detail in section 7.3.

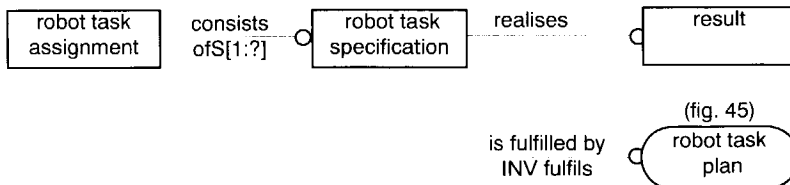


Figure 42 EXPRESS-G diagram showing the task assignment and specification in the task model database.

In case of the example wall robot, the robot task assignments are specialised to *wall robot assignments* which consist of *build wall* assignments which refer to a sand-lime element wall (see figure 43). The role of the task specification process is to instantiate the robot task assignment and robot task entities with the correct references to sand-lime element walls in the project model.

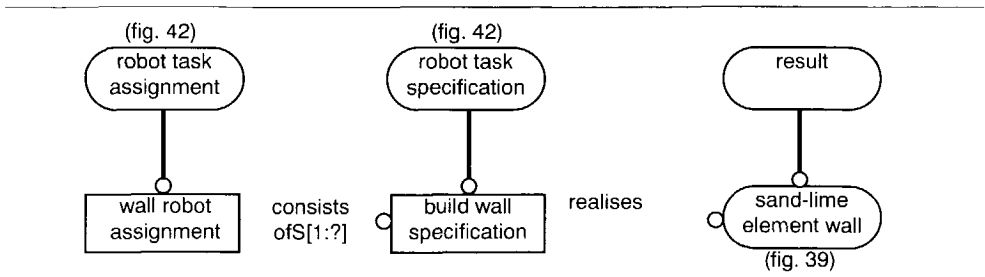


Figure 43 EXPRESS-G diagram of task specification for sand-lime element walls.

7.3 Task Planning

The purpose of the task-planning subsystem is to generate *task plans* that describe how the robot is to fulfil a task. A *task plan* is an information structure that specifies which operations are to be performed, and in what sequence. The building blocks of which a task plan is composed, are *primitive operations*. Primitive operations are operations that can directly be executed by the robot hardware.

As was discussed in chapter six, generic *process-type models* are used to generate task plans. A *process-type model* is a semantic knowledge representation describing how a process is organised for a class of processes. A *task plan* is an instantiation of a process-type model describing one specific process.

The generation of a task plan, requires knowledge that is contained in a process-type model. This knowledge can be classified into the following two categories:

- *ontological knowledge*
Ontological knowledge is the knowledge about what kind of entities exists, what their properties are, and how they are related. The ontological knowledge in a process-type model defines which types of construction processes are distinguished, how they are characterised, how they are related, and how are they decomposed. An example of ontological knowledge is the knowledge how a wall-construction process is decomposed into element pick-and-place operations, apply-glue operations, etc.
- *inference knowledge*
Inference knowledge is knowledge in the form of assertion-like rules that describes how knowledge can be derived from other knowledge, e.g. how proc-

ess-planning knowledge can be derived of product-design knowledge. An example of an inference-knowledge assertion is: 'If sand-lime element A supports sand-lime element B, then A is installed prior to B'.

The above division originates from the theory of knowledge representation in the field of Artificial Intelligence (See e.g. Rich et al. 1991 p. 298). Some implementations of knowledge based systems (e.g. CYC and KRYPTON) use separate knowledge representations for ontological and inferential knowledge. The ontological knowledge is represented in so called *strong slot-and-filler structures*. Inference knowledge is represented in first-order logic expressions which are formalised using some constraint language. The advantage of this division is that it is possible to combine the advantages of strong slot-and-filler structures (acquisitional efficiency and representational adequacy) with those of logic expressions (inferential adequacy and inferal efficiency).

The AI concept of *strong slot-and-filler structures* is nearly identical to the concept of a project model. Therefore it is possible to use the project-model information-structure also as an ontological-knowledge representation in the process-planning subsystem. The advantage is that the ontological knowledge can be included in the same task model that is used for the central storage of task-instruction system information. Section 7.3.1 discusses in more detail how ontological knowledge is modelled using PDT.

For the representation of inferential knowledge, no suitable PDT equivalent exists yet. The reason for this is that the objective in the development of PDT is focused at the storage, sharing and exchange of information. Reasoning with information is out of the scope of the PDT development community. Nevertheless some research projects have investigated the automatic evaluation of product designs. De Waard (1992) for instance, has investigated the realisation of automatic conformance checking using PDT. How inferential knowledge can be represented using PDT mechanisms is discussed further on in subsection 7.3.2.

The planning of a robot task itself is a relative uncomplicated reasoning process when powerful knowledge is used. Inference-knowledge assertions are applied to the task model to deduct a task plan from product design information. In section 7.3.3 it is discussed how ontological knowledge and inferential knowledge is used to generate a robot plan.

7.3.1 Ontological Knowledge Modelling

A process model is a model that describes how a process is organised. Essential process characteristics described in process-type models are:

- *process definition*
- *process decomposition*
- *process sequence relations*

How each of these process characteristics are modelled is discussed in this subsection.

Robot Process Definition

An important aspect in a project-type model is the process-product relationship. A construction process always has a *subject* it affects. This subject can be an object such as a sand-lime element, or it can be a substance such as paint, glue or concrete. Besides a subject there can be a number of *direct objects*. Direct objects are materials or substances that are also involved in the process, but that are not the subject. In the example of the installation of a sand-lime element in a wall, direct objects are the glue and the elements on/to which the installed element is glued.

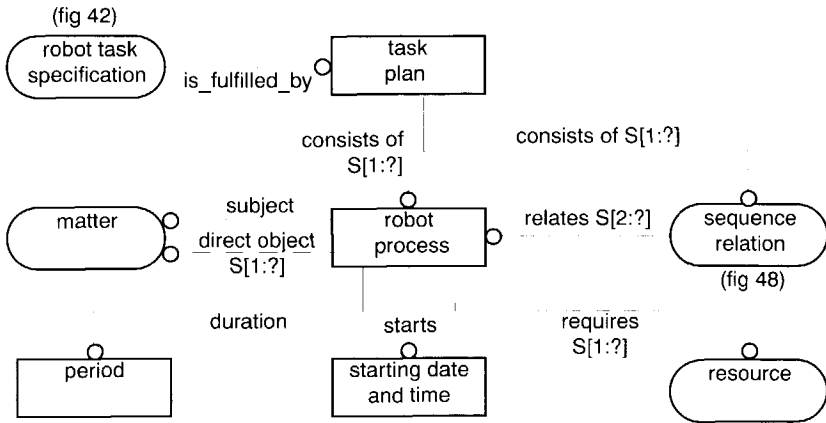


Figure 44 EXPRESS-G diagram showing how process data is modelled. Sequence dependencies between robot processes are modelled using the sequence relation entity.

Besides the process characteristics shown in figure 44, there are a number of other attributes that help to insure that the process plan can be executed without accidents or major problems. The most important of these attributes are discussed below.

- *process precondition*

Preconditions are the conditions that have to be fulfilled in order for the process to be executed without problems. An example of a precondition is that the mortar dispenser is functioning correctly before a sand-lime element can be placed in the wall.

- *process post-condition*

A process post-condition is a check to make sure that the robot process was actually completed successfully. E.g. is there actually a new element in the element wall after the completion of the installation process?

- *process invariants*

The process invariants are the conditions that have to be fulfilled at all time during the execution of a process. E.g. there should be no obstacles in front of the robot at all times when the robot is moving to a new location.

Robot Process Decomposition

Decomposition of processes is an important aspect of process-type models. The EXPRESS-G diagram in figure 45 shows how decomposition is modelled. The entity *robot process* has two subclasses, *primitive process* and *aggregate process*. Primitive processes are processes that are not further decomposed with the scope of the process-type model. E.g. *pick-up sand-lime element* or *apply glue to bottom of element* or at a lower level: *move to location P*. Aggregate processes are processes such as *build wall* that decompose into lower-order processes. *Aggregate process* entities have a *decomposes_into* relationship to *robot process* entities. Therefore aggregate processes can decompose into other aggregate processes or primitive processes.

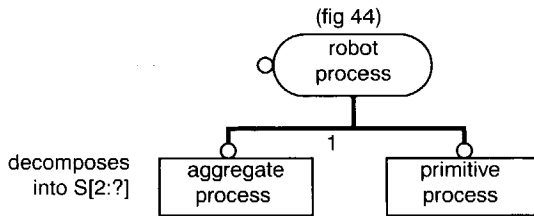


Figure 45 EXPRESS-G diagram showing how process decomposition is modelled. Robot processes can either be aggregate or primitive. Aggregate processes decompose into lower order robot processes.

Within the process decomposition structure in a process type model, task-abstraction layers can be distinguished. E.g in the wall construction process, two process model layers can be distinguished. A bottom layer where all element-handling tasks are specified and a second, higher task-abstraction layer where the wall-building process is defined using the element-handling tasks defined in the bottom layer. The advantage of this approach is that: (1) low-level tasks, that can be used in different robot applications, do not have to be remodelled for every application, and (2) low-level tasks can be tested separately during model development.

As a consequence of the distinction of model layers, the primitiveness of a primitive operation is a relative property. A primitive process can decompose into even lower order primitive processes in a lower model layer. Eventually all processes have to be composed until the processes can be executed by the robot hardware. Those primitive processes are called *operations*.

How the wall-building process can be modelled using the above presented approach is shown in the EXPRESS-G diagram in figure 46. In the model that is shown, *install-element* processes are modelled as primitive processes. These processes are defined in a lower model layer. The *decomposes_into* relation is redefined to model that a *build-wall* process is a process that is composed of *install-element* processes.

In a lower-order model the primitive install-element processes decompose into *handle-element* processes. How this is modelled is shown in the EXPRESS-G dia-

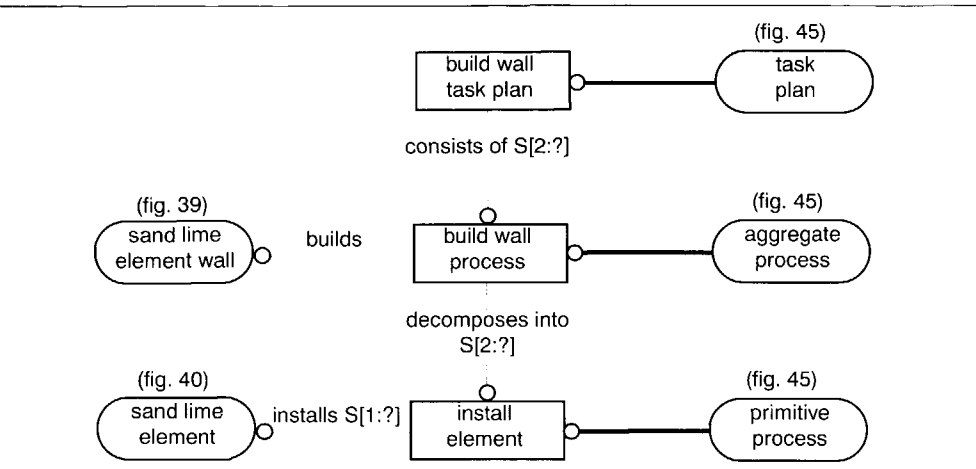


Figure 46 EXPRESS-G diagram of a process-type model for wall construction. Building a wall is a process that consists of 'install element' processes which can be one of three subtypes, according to the type of element to be installed.

gram in figure 47. Four types of handle-element processes are distinguished. These are *pick*, *place*, *transfer* and *apply mortar*. The first three processes are primitive processes, while the apply-mortar process is an aggregate process which is decomposed.

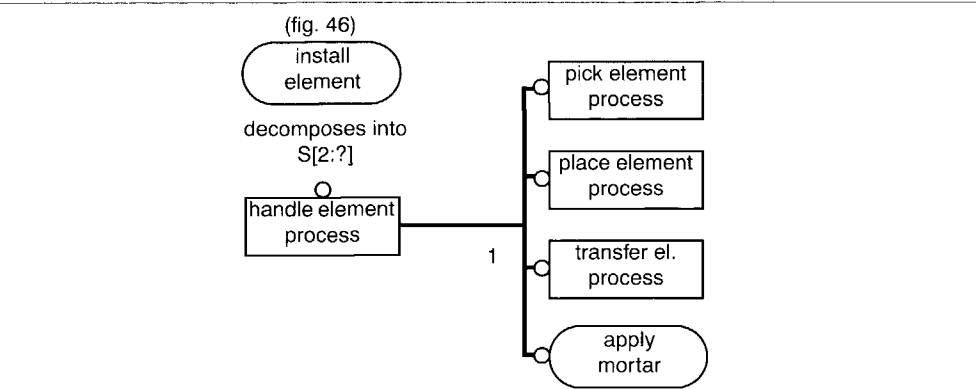


Figure 47 EXPRESS-G diagram of a process-type model for install element process.

Most of the time, process decompositions are related to product decompositions. When a wall is decomposed into elements, the build-wall process is decomposed into install-element processes. The instantiation of a process plan is a process that has to analyse the product-decomposition tree. How this can be realised is discussed in section 7.3.2. A significant difference between the product-decomposition tree and the construction-process-decomposition tree is that the product-decomposition tree stops at a certain level of detail, e.g. the layout of elements in a wall. The process decomposition (for the application of robot instruction) requires

decomposition to the finest level of detail. Therefore process models have to assume standard solutions for the smallest product details. An example of such an assumption is to assume that sand-lime elements are glued together using a special glue. This is not explicitly specified in the project model.

Robot Process Sequences

Another essential aspect of process modelling is the specification of sequence relationships. In the model shown in figure 48, these relationships are modelled as a separate entity *sequence relation*. This entity has a number of different subtypes according to the type of sequence relation. Three types of process relations are distinguished, which are:

- *precedes relations*
relations of type: A must be done after B.
- *succeeds relations*
relations of type: B must be done after A.
- *parallel relations*
relations of type: A must start at the same moment as B.

When two robot-process entities are not related by an explicit sequence relation of one of the above listed types, than they are implicitly related by a don't care sequence relation.

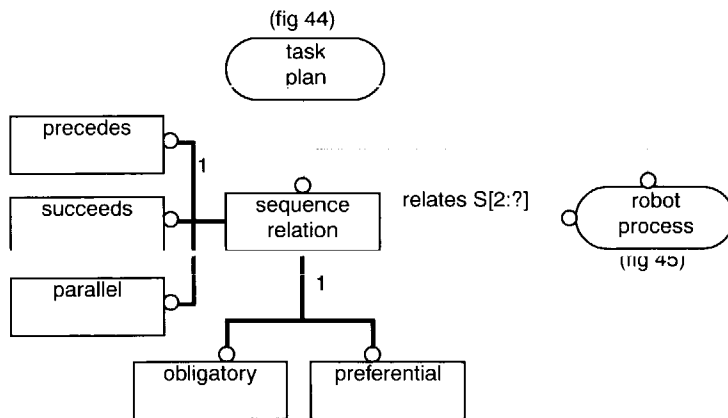


Figure 48 EXPRESS-G diagram of process model showing sequence relationship modelling.

Besides the three types of relations, there is also a distinction in the priority of the relationship. There are obligatory and preferential sequence relations. Obligatory relations are sequence relations that reflect physical laws. Preferential relations represent other sequence relations such as 'code of practice' or 'normally follows'. It is important to realise that the task planning does not produce a plan with a fixed linear sequence of processes. The obligatory and preferential sequence relations that always apply, are part of the knowledge contained in a process-type

model. During the operation sequence planning process the sequence relations in the process plan is further evaluated. This is discussed in section 7.4.

A special remark about parallel sequence relations has to be made. Parallel processes are generally avoided because they require two manipulators that can also coordinate their actions. Human beings are blessed with two arms and hands which can be used to perform two operations simultaneously. Even for human beings this is not always uncomplicated. Imagine the task where you have to hold a window in its frame and insert the pins in the hinges. Robots are generally equipped with only one manipulator to reduce robot costs. It is generally possible to adapt a product design in order to eliminate the need for parallel processes for the installation or manipulation of an object. In most cases this is much more cost effective than the use of a two armed robot. Especially in manufacturing industry they have a lot of experience with this process, where it is called *Design for Assembly*.

The generic modelling constructs that are discussed in this chapter and presented in various figures, are shown in one EXPRESS-G model in appendix A.

7.3.2 Inference Knowledge Modelling

Inference knowledge is the knowledge that enables the deduction of new knowledge from existing knowledge. In the context of robot task planning, the inference knowledge is the knowledge that enables the deduction of a robot process plan from project-model information. In other words: inference knowledge describes *how* a plan is made. This in contrast to the ontological knowledge which describes what a plan looks like.

Inference knowledge is knowledge that can be written in the form of *logical assertions*, such as: "All sand-lime elements are installed by an 'install element' process". The inference knowledge contained in process-type models, is strongly related to the ontological knowledge in the process-type model. Therefore the facts and predicates that can be used in logical assertions are those that are defined in the ontological knowledge representation. This means that the inference knowledge can only use information of which the existence and semantics is defined in the project type model.

In AI publications it is common to use predicate logic to represent logical assertions. Although the mathematical nature of predicate logic enables formal, unambiguous and compact representation, predicate logic expressions are generally regarded as complex and difficult to read for people that are unfamiliar with mathematical logic. For the storage of inference knowledge in process-type models, it would be convenient if the logical assertions could be represented in the EXPRESS language. The reason for this preference for EXPRESS is that it enables the use of a uniform representation language for both ontological and inference knowledge. However, EXPRESS is a language that is designed to define data types and constraints on data types, and not to represent knowledge. Nevertheless it is believed that it is possible to use the EXPRESS language as a base for the representation of inference knowledge.

The concept of *rules* in the EXPRESS language is a mechanism that allows representation of logical assertions. How this can be realised is shown in an example assertion that is related to the wall robot. For instance the logical assertion “*All sand-lime elements are installed by a corresponding ‘install element’ process*”. This assertion can be written in the following predicate logic *well formed formula’s* (*wff’s*):

$$\forall x:\text{sand_lime_element}(x) \rightarrow \exists p:\text{install_element}(p) \wedge p.\text{installs}(x)$$

This logical assertion can be represented in an EXPRESS schema. What this EXPRESS rule looks like is shown in the following fragment of EXPRESS code.

```
-- partially repeated from schema at page 102

ENTITY sand_lime_element;
  length : REAL;
  height : REAL;
  thickness : REAL;
  location : position;
  mass : REAL;
INVERSE
  is_part_of : sand_lime_element_wall FOR is_built_of;
WHERE
  wr1: SIZEOF(USEDIN(SELF,
    'PROCESS_TYPE_MODEL_SCHEMA.INSTALL_ELEMENT.INSTALLS')
  ) = 1;
END_ENTITY;
```

The above *where rule* actually specifies that every instance of the entity *sand_lime_element* should be referenced in exactly one instance of an *install_element* entity in the attribute *installs*. This representation does not model how new (process planning) knowledge can be deducted from existing (product design) knowledge because it is not specified what should be done if the *where rule* fails. EXPRESS does not provide an elegant syntax for that kind of assertions because it is a data definition language, designed for the representation of data structures and constraints.

In order to be able to support the deduction of knowledge from other knowledge, it is desirable that dedicated language constructs are available for expression of the knowledge. In the example below it is shown how a language construct for *assertions* could be included in the EXPRESS syntax.

```
ASSERTION is_installed FORALL sand_lime_element;
LOCAL
  used_in : BAG OF install_element;
  install_proc : install_element;
END_LOCAL
-- find out if the sand_lime element is already being installed?
used_in := USEDIN(SELF,
  'PROCESS_TYPE_MODEL_SCHEMA.INSTALL_ELEMENT.INSTALLS')
IF SIZEOF(used_in) = 0 THEN
  -- instantiate a new install_element entity and link it
  install_proc := install_element(SELF); -- create new instance
  SELF.is_installed_by := install_proc;
```

```

ELSE if SIZEOF(used_in) != 1 THEN
  -- something is not OK
  handle_error();
END_IF;
END_ASSERTION;

```

The above EXPRESS assertion is a mixture of a *where clause* and a *where rule*. Just like *where clauses*, the assertion applies to all instances of the specified entity and is declared globally instead of as part of an entity definition. This allows separation of the inferential knowledge from the ontological knowledge.

Most assertions in a process-type model will be different from the above discussed example assertion. A common form of assertion is a procedural assertion. This type of assertion describes a common sequence of operations in a decomposition of a task. Below, an example is shown with the procedure how to install a sand-lime element.

```

ASSERTION decompose FORALL install_element;
REQUIRES
  is_installed; -- this assertion is only of use when the 'is_installed'
                -- assertion is evaluated for all instances in the
model
END_REQUIRES
LOCAL
  from_loc,
  to_loc      : location;
  r1,r2,r3    : sequence_relation;
  pick_p,
  transfer1_p,
  apply_m_p,
  place_p     : robot_process;
  subject     : sand_lime_element;
END_LOCAL

  subject      := SELF.installs;
  from_loc     := find_next_element_location();
                                     -- procedure that keeps
                                     -- track of the element locations
                                     -- on the stack of elements

  pick_p       := pick_element_process(from_loc);
                                     -- bring the element to the mortar
                                     -- dispensing unit

  transfer1_p  := transfer_process(mortar_dispenser.input_loc);
  apply_m_p    := apply_mortar(subject);
  to_loc       := subject.is_located;
  place_p      := place_process(to_loc);
  r1           := precedes_relation(pick_p,transfer1_p);
  r2           := precedes_relation(transfer1_p,apply_m_p);
  r3           := precedes_relation(apply_m_p,place_p);
  decomposes_into := [pick_p, transfer1_p,apply_m_p,place_p];
END_ASSERTION;

```

Besides the extension of the EXPRESS language with assertions, other facilities for inference knowledge modelling are needed. Some desirable extensions are: facili-

ties for object-oriented specification, mapping constructs, preconditions, invariants and post-conditions. A separate EXPRESS dialect could be developed to provide all the required facilities for inference knowledge modelling. A similar approach has been adopted in the ESPRIT project PISA. Within this project, three EXPRESS dialects have been developed, including a version for the specification of object-oriented data structures (Gielingh et al. 1996 p. 240). It is beyond the scope of this research to develop an EXPRESS dialect for inference knowledge modelling. Further research is needed to make sure that the all desirable inference knowledge assertions can be represented in an EXPRESS dialect.

7.3.3 Process Plan Generation

A process plan can be generated from a task-specification using the knowledge in a process-type model and the information in a project model. The inference knowledge rules have to applied to the information in the project model. The inference rules and assertions take care of the instantiation the process plan.

The use of a powerful and structured knowledge representation, such as the project-type models, enables the use of relatively universal and uncomplicated algorithms to generate a robot plan. The planning process is performed by evaluation of all inference knowledge assertions in the process-type model.

The generation of a correct plan, requires the inference knowledge to be complete, meaning that it produces a plan without omissions. Simulation systems can be used to verify robot process plans on their correctness and completeness.

The formalisation of task knowledge in process-type models is still a difficult and specialised task. The advantage of the approach is that the knowledge is re-used in every new robot task assignment. This is possible because the semantic definition of level storage of building design information enables the task planning system to produce the correct plan for the case such as described in the task model. The semantic information in the task model makes it possible to use inference knowledge in the form of (EXPRESS) assertions to deduct process planning information from the task model. In this section it was demonstrated how (a dialect of) the EXPRESS language can be used to model both ontological knowledge and inferential knowledge needed to deduct process plans from task model information.

7.4 Operation Sequence Planning

The purpose of the operation sequence planning subsystem is to determine the sequence in which each of the robot operations is to be executed. This involves the following two steps:

- 1 the collection of sequence planning boundary conditions
- 2 the search for a sequence that fulfils the planning boundary conditions.

Both steps are discussed in the following two subsections.

7.4.1 Collection of Planning Conditions

The process plan, generated by the process-planning subsystem, is a graph of robot-operation nodes, and sequence-relation links. In *collection step*, the decomposition hierarchy of operations is evaluated, to obtain a flat process plan graph. In the case of the wall-robot example the graph includes all handle-element operations. In this graph, it is no longer significant to which wall an installed element belongs.

The sequence relationships can originate from different sources. The three distinguished sources of sequence relations are:

- process-type model
- instructor input
- robot-capability model

All sequence relations are merged together, to form one complete sequence graph. Sequence conditions specified in the process-type model, have been discussed in the previous section. The sequence relations that originate from the instructor and from robot capability model, are discussed in more detail below.

Instructor Input

It is realistic to assume that the robot process being planned, will not be the only construction process that takes place at the construction site. Therefore it is possible that conflicts between the robot process and other processes occur or that preparatory processes are not yet completed. E.g. the robot can be hindered by scaffolding used for another construction task.

Due to the limited level of detail of the construction-process plans that are made, it is generally not possible to resolve all potential conflicts that can arise during construction. The most pragmatic solution seems to enable the robot instructor and also the robot operator to make scheduling changes in the task plan to resolve conflicts.

Robot-Capability Model

For reasons of performance and throughput, it is sometimes desirable to implement robots with multiple end effectors. E.g. a wall robot with an end effector that can hold two elements at a time or a tiling robot that handles two tiles. The operation planning for such multiple end effectors is of course very different because the plan has to be reorganised such that as much as possible operations can be executed in parallel to utilise the robot's capabilities. How operations can be grouped for simultaneous execution is primarily determined by the topology and geometry of the product being realised. For example a double element gripper requires elements to be next to each other, while a double armed robot requires the elements to be within a certain distance from each other.

Another situation occurs when a robot is capable of changing its end effector to perform different types of operations. Depending on the complexity of an end-effector change, it can be more efficient to carry out all operations using a certain

end effector before changing it. A consequence of this strategy may be that the robot has to relocate itself more often because it has to come to each location with each end effector separately.

7.4.2 Execution Sequence Planning

After the collection of all sequence relations, it is possible to start the search for a sequence of operation. This search requires an algorithm that can find a sequence that fulfils all sequence conditions. Such search problems are common in AI problem solving. Some general-purpose search algorithms that are often used are (Rich et al. 1991):

- depth-first
- breadth first
- A* algorithm

For some classes of problems the above listed linear planning-algorithms do not work. This is the case when the planning problem contains goal interactions. Goal interactions occur when a sequence of operations that achieves goal A excludes the achievement of goal B. Only when the operations to achieve goals A and B are mixed in the correct sequence, it is possible to achieve goals A and B. An example of such a goal interaction occurs when a wall erection robot has to unstack a pallet of custom-size elements before it can reach the element needed. Sheu and Xeu (1993) describe a nonlinear planning algorithm that can solve certain classes of sequence planning problems effectively. Whether such a nonlinear algorithm is needed in the presented task-instruction system architecture depends on the nature of the construction problem. In the case of the sand-lime wall robot, linear planning algorithms can be used. In general semi-unique tasks have a procedural nature for which linear planning algorithms can be used.

7.5 Motion Planning

Although, motion planning is not complicated for human beings, motion planning for robot manipulators is a complex problem for computers. Each robot motion accomplishes a specified mission while taking several kinds of boundary conditions into account. These boundary conditions include:

- the geometric and physical properties of the robot manipulator
- the geometric and physical properties of the objects to be handled
- the shape and location of obstacles in the surrounding of the robot
- physical effects such as gravity and friction

The development of efficient and effective motion-planning algorithms for computers is a complicated matter. Since the development of the first robot manipulators in the 1960s, researchers have been working on the problem of motion planning (Latombe 1991). Research on motion-planning algorithms has produced a number of useful algorithms. These algorithms tend to be computationally expensive. A comprehensive overview of path planning algorithms is presented by Latombe

(1991). Other key publications on the state-of-the-art in motion planning are: (Dean et al. 1991; Nnaji 1993; Sheu et al. 1993).

In the rest of this section it is evaluated what kind of motion planning algorithms are available for various kinds of motion planning problems that construction robots are confronted with.

First it is discussed which requirements for construction robots are relevant to motion planning. Relevant requirements are:

- *generation of safe motion paths*

At most building sites where robot are to be used, there will also be human beings. In order to reduce the risk of accidents with the construction robot, the robot motions should be safe. This means that the robot is required to have a predictable behaviour. E.g. if the robot moves a sand-lime element along a certain trajectory than it should use that same trajectory in similar circumstances. Also the robot should avoid motions where the objects will be subjected to large accelerations. Unfortunately, safe motions are not always the most efficient motions. Efficiency is of lower priority than safety, especially in the building industry.

- *support for mobile robots*

The size of the building-industry products, in combination with the requirements for transportability of a construction robot, requires these robots to be mobile (meaning: 'able to relocate themselves autonomously'). Motion planning for mobile robots is even more complicated because the motion planning problem has multiple solutions.

Motion planning is a process that has to be performed *on the fly*. The reason for this is that a large proportion of robot motions depend on local circumstances. Sensor feedback is essential to resolve differences that occur between planned locations and realised locations. This last statement refers to the location of the robot itself, as well as to the locations of building parts. Fixed motion patterns can only be used in fixed work-cell situations in factory environments. And even in those situations, sensors are often used to resolve differences between expected and actual locations.

In the rest of this section it is discussed which motion planning methods and techniques are available. A distinction is made in the following three areas of application:

- motion planning for tool end-effectors
- motion planning for object manipulation
- path-planning for mobile robots

Each of these three areas of application is now discussed in more detail.

Motion Planning for Tool Manipulation

A large proportion of the construction robots that exists today, are robots that perform some kind of treatment task for which they use a tool. These treatments are very often surface treatments. Distinctive for these tasks is that the end effector is some kind of tool that treats a surface or object. Some examples of treatment tasks are: cement floor finishing, paint spraying, vacuum cleaning or window cleaning.

The problem of motion planning for these types of tasks is to plan a motion path that covers the complete surface to be treated. (See figure 49). The problem is relatively uncomplicated for two-dimensional surfaces which are the most common. Motion planning problems are sometimes complicated because certain surface areas are to be avoided (e.g. stair openings in floors). Several effective planing procedures for this class of motion planning problems are available.

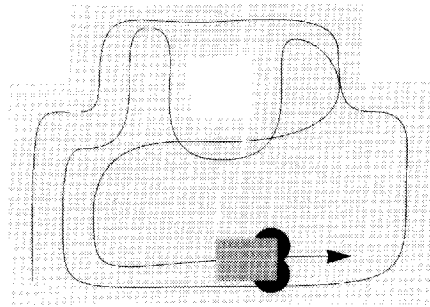


Figure 49 Example of motion planning trajectory for concrete surface treatment robot.

Motion Planning for Object Manipulation

The problem of motion planning for pick-and-place type manipulations is more complex than the previously discussed motion-planning problem because it is a three-dimensional planning problem. The problem has been a challenge for research groups for several decades (Latombe 1991). This research has delivered some effective, but computationally hard algorithms for pick-and-place motion planning.

Latombe distinguishes three aspects of motion planning for object manipulation (Latombe 1991), which are:

- 1 *grasping*; how an object is picked up
- 2 *transferring*; via which path the object is moved from A to B,
- 3 *positioning*; how an object is brought to its desired end position.

Two adverse strategies are distinguished to generate paths for grasping, transferring and positioning. The first strategy is called the *model based approach*. In this approach all relevant information about the work space is entered a priori into a world model which is used as an information source for the path planning. The opposite of the model based approach is the *non-model based approach* which relies on sensor systems to acquire information about the robot environment at

the time the environment information is needed (Sheu et al. 1993). Non-model based approaches require advanced (and sometimes expensive) sensing systems and complex data-interpretation algorithms to reconstruct knowledge about the robot environment. This approach is most suitable for robot applications in unstructured, unknown or frequently-changing environments such as may occur with robots for fire fighting or nuclear-disaster troubleshooting. Model based approaches avoid the complex problem of sensor interpretation, and currently use geometric models from external sources.

The model-based approach seems to be more appropriate for construction robot path-planning systems. The circumstances at building sites are not that unstructured or frequently changing to justify the extra complexity and costs of advanced sensing systems. Also the geometric data needed in the world model can be obtained from the project model.

Latombe (1991) has made an inventory of motioning-planning methods that produce motions plans for pick-and-place type operations. Existing motion planning methods are: configuration space (C-space), road-map methods, exact-cell decomposition and potential-field methods.

The road map method seems the most suitable method for most of the construction robots that manipulate objects, such as sand-lime elements. In the road map method, objects are only moved along predefined roads. The advantage of this approach is that robot motions are predictable. This is beneficial for the safety of the robot because humans can anticipate the motions of the robot. The drawback of the road map method is that motions are not as efficient as is possible. Figure 50 shows a top view on an example situation of a motion path for a sand-lime element along virtual transportation roads.

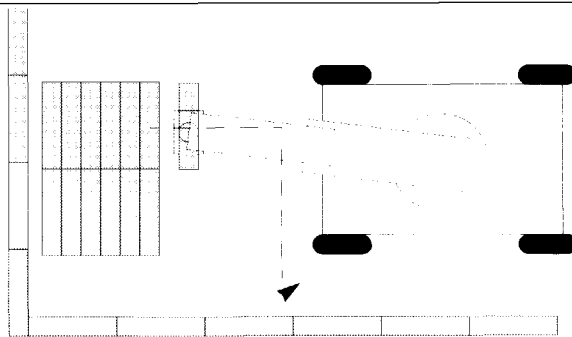


Figure 50 Motion paths along predefined roads. The dashed line indicates the motion of the sand-lime element along transportation roads orthogonal to the wall.

Motion Path Planning for Mobile Robots

Mobility is a very important property for construction robots. Many robots, including the example robot discussed in this chapter, need a mobile platform. An enormous advantage of using a mobile platform is that the work range of a manipulator can be enlarged when it is mounted on a mobile platform without making the robot too large or too heavy for the building it has to work in.

The difficulty of the use of a mobile platform is that it requires a complex strategy to plan both the motions of the mobile platform and the manipulator on top of it. Because there is a redundancy in the degrees in freedom of the manipulator and the mobile platform, the motion planning has to incorporate higher level of planning context to choose between alternative solutions in motion planning. Yamamoto (1993) discusses some possible strategies to deal with this problem.

The planning of routes for the relocation of a mobile robot to a certain location can be regarded as a subset of the problems of motion planning for robot manipulators in general. Therefore the same methods as mentioned in the previous sub section can be applied for mobile robot path planning problems. A special mobile platform motion planning problem occurs when the mobile platform uses an "automobile-like" *nonholonomic* wheel configuration that has indirectly controlled degrees of freedom. As all car drivers will know from experience, motion planning for non holonomic wheel configurations can be complicated (think of parking a car in line between two other cars). An overview of non-linear motion planning algorithms for mobile robots is given in (Canudas de Wit et al. 1993).

7.6 Plan Execution

The last in the chain of task-instruction subsystem is the plan execution subsystem. The primary function of the plan execution subsystem is to coordinate the execution of the plan produced by the four other subsystems. This coordination process involves the following functionality.

- 1 interaction with the robot operator
- 2 verification of plan assumptions / recording of 'as built' situation
- 3 dealing with contingencies

Each of the functions is discussed in more detail

Robot Operator Interaction

The robot operator is the person that takes care of a robot on the building site. He starts and stops the robot and deals with coordination of the robot task and other tasks executed at the building site.

In the situation where robots operate on a building site, simultaneously with other construction processes, it should be expected that planning conflicts occur. On the one hand these conflicts arise because human workers will (at least initially) have little consideration for robots. On the other hand conflicts can arise because robots are not flexible enough to adapt to small changes in plans which

are trivial to humans. To make the robot as flexible as possible, the robot operator should be able to make work-order changes in the prepared plans as long as these changes do not affect the end result. The use of conditional plans does allow for small changes in the work order to be made, as long as these changes do not affect the end result. For example it does not matter whether the sand-lime wall erection robot erects walls in a different sequence, as long as it is possible and it does not affect the end result.

Because the robot plan is defined in terms related to the task of wall building, the user interface of the plan-execution subsystem can use metaphors and concepts that the robot operator is familiar with. Industrial robot controllers generally use identifiers for programs, procedures and locations. These identifiers have no meaning to anyone except the writer of the program. Communication in terms related to the building task enables more meaningful and therefore more effective communication. In the example of the sand-lime element wall robot the concepts of *wall*, *element*, *opening*, *joint* can be used for communication. It is even possible to communicate with the operator in terms of schematic diagrams such as a floor plan or a wall layout.

Verification of Assumptions

By definition a plan is based upon assumptions. In case of a robot process plan these assumptions are about the robot and its environment. Preferably these assumptions turn out to be valid during the actual execution of the prepared plan. Nevertheless, contingencies can occur. Preferably contingencies are handled by the robot without help of a human being (the plan execution system). How contingencies can be handled is discussed further on.

Three types of assumptions can be distinguished, which are: boolean assumptions, value assumptions and location assumptions. Boolean assumptions are assumptions that evaluate to true or false, e.g. it is assumed that there are no obstacles near the robot. A value assumption expects some kind of parameter to be between certain tolerance limits. A contingency occurs when the parameter value is not within the tolerance limits, e.g. the temperature for the erection of sand-lime element walls has to be between 0°C and 30°C. Finally the location assumption requires objects to be at an expected location. In practice, objects are never found exactly at the locations you expect them to be. These differences are caused by inaccuracies in: the robot location measurement system, the placement of objects, in the dimensions of building objects itself, etc. Therefore it is necessary to include measurement procedures in the process planning. These measurement procedures replace *as expected* by *as measured* locations and dimensions. A location assumption expects objects to be at a certain location. A tolerance area limit defines how much deviation is allowed between *as expected* and *as measured* locations. This tolerance limit is the maximum deviation which can occur without causing an unacceptable degradation of the end result quality. When the tolerance limit is exceeded, a contingency occurs. The *as measured* and *as built* locations and dimensions are stored in the task model to be used in the motion planning for all remaining operations for other building tasks within the project and even for maintenance and renovation purposes long after the building has been finished.

Dealing with Contingencies

In the case that an assumption turns out to be invalid, a contingency occurs. Theoretically two solutions are available, either the plans are adapted to the new situation, or the situation is adapted to the original plan. Both approaches can be of use for a construction robot. On the one hand, if a contingency occurs due to some irreversible event, e.g. a sand-lime element breaks into pieces in the gripper, then the robot has to deal with the contingency and the plans must be altered. On the other hand when there is an obstacle in front of the robot which blocks the route, it is probably more effective to get help from the robot operator to remove the obstacle. As argued in chapter six, it is important that the task execution subsystem can resolve straightforward contingencies that occur relatively frequently, by itself.

In order to deal with contingencies, the task execution subsystem has to be able to establish the kind of contingency that occurred. The kind of contingency can be determined by the invariant, variant, precondition and post-conditions that are defined with each operation. As soon as the task-execution system has determined which operation has failed, it can decide whether the operation can be re-tried. E.g. when a sand-lime element breaks into pieces, or when an element is dropped, the robot can resolve the contingency, by getting a new element from the stack and continue. This requires the task execution system to jump back in the operation sequence plan.

When a contingency occurs that cannot be resolved by the robot, it is necessary to get help from the robot operator. However, it can be possible that the robot can continue working on other operations until the robot operator's help arrives. E.g. when placement of an element is obstructed by an obstacle, the robot can install other sand-lime elements within reach that are not near to the problem area. Because conditional plans are produced, it is not necessary to re-activate the operation sequence planning subsystem. The robot operation plan also shows which operations are not dependent on the problematic operation, and can therefore be executed until the problem is resolved by the operator.

7.7 Summary, Conclusions and Discussion

In the previous six sections, a reference architecture for task-instruction systems for construction robots is presented. The reference architecture distinguishes five subsystems that are part of every task-instruction system. These subsystems perform different functions that are needed for the *life cycles* of a task, from *specification* to *realisation*. The five subsystems that are distinguished are: task specification, task planning, operation sequence planning, motion planning and plan execution. The subdivision in five subsystems enables different aspects and sub-problems of task instruction to be controlled by different people and executed at the most appropriate moment and place. This separation in time, place and responsibility is essential for the organisational integration of task-instruction systems in the building industry. Different people control and supervise different aspects of robot task instruction.

The hypothesis formulated in chapter six is that product data technology (PDT) enables the implementation of task-instruction systems which: (1) use pre-cooked planning knowledge, (2) can communicate with humans in their jargon, (3) can exchange project data with other computer systems, and (4) can deal with contingencies.

In this chapter it was shown that it is not so much the technical solutions provided as part of PDT, but the conceptual approach using semantical information, that enables the implementation of task instruction as discussed in this chapter. Semantical information enables re-use of product information for the control of construction robots (and probably the construction process in general) and increases the flexibility of construction robots.

Some final remarks on the use of PDT in the proposed task-instruction architecture are:

- The use of a (virtually) centralised storage of information in a task model, enables open integration of the subsystems and open integration between the task-instruction system and its outside world. A prerequisite for the proposed PDT based architecture for task-instruction systems is that the fundamental concepts of product data technology (i.e exchange of semantic definition level information instead of representation level information) are accepted and used by the building industry. It may take much time before this is realised, but it seems realistic to assume that the building industry will be just as slow with the acceptance of robot technology, as it is with the acceptance of product data technology. Therefore, it is believed that this prerequisite does not hinder the acceptance of the architecture presented in this chapter.
- The technical solutions of PDT are designed for general integration purposes and not for special applications. Therefore it is no surprise that extensions are needed to use the EXPRESS language for knowledge representation purposes.
- The use of semantic information enables interaction between the task-instruction system and humans at a much higher semantic level than normally involved with robot instruction.
- The semantic information also enables the task-instruction system to establish the semantical context of contingencies (what has happened), which makes it possible to react more appropriately to the situation.

In the next two chapters the presented architecture for task-instruction systems is evaluated in two case studies. The first case study is about an autonomous drilling robot and the implementation of a prototype task-instruction system for that robot. The subject of the second case study is a control system for hydraulic excavators.

8

Case Study One: An Autonomous Drilling Robot

Chapter eight presents a case study about a prototype construction robot that can drill holes in concrete slabs and floors. It is explained how the robot works and how it is used. Also the implementation of a task-instruction system for the robot is discussed.

The subject of the case study is a robot that is capable of drilling series of holes in a concrete floors. There are two specific goals in this case study chapter. The first goal is to show a “close up view” of an example of an autonomous construction robot and apply the theory of chapters 2 to 5. The second goal in this case study is to show an example of task-instruction system and to demonstrate the benefits of such a system.

This chapter is divided into four sections. The first section describes the construction tasks for which the drilling robot is designed. In section 8.2 the drilling robot itself is described and discussed. Section 8.3 describes the implementation of a task-instruction system for the drilling robot. Finally in section 8.4 the case study is evaluated and the main conclusions are summarised.

8.1 General Description

With the increasing urbanisation in the western half of the Netherlands, more tunnels are constructed for roads and railways. One of the sites where a new railway tunnel is being constructed is Amsterdam's Schiphol airport. In this project an experiment with the drilling robot was carried out. Figure 51 shows the drilling robot in action in the railway station beneath Schiphol.

At Schiphol, the existing underground railway station and tunnel are being doubled in capacity to accommodate the forecasted growth in passenger traffic. The Dutch railway authorities (NS) were asked to extend their underground infra-



Figure 51 The Autonomous drilling robot at work in the railway station at Schiphol.

structure before the start of the construction of the a terminal-building above the railway station and tunnels. The extension of the railway infrastructure consists of 5 km double track tunnel and an extension of the existing railway station with three new platforms.

The construction of the railway tunnel involves several construction processes in which large numbers of holes are to be drilled. Two processes attract the attention because of their repetitive nature. These are: (1) the drilling of holes for the anchor bolts that fasten the rails to the concrete floor of the tunnel, and (2) the drilling of holes for re-inforcement starter bars for the construction of the footpath edge that runs along the tunnel. Both tasks are explained in more detail in the following two subsections.

Holes for Rail Fastening

In general most railway tracks are built using a ballast bed system. In this system the rails are fastened to concrete or wooden sleepers which are laid in a gravel bed. However, in stations this system has its drawbacks. The metal particles, produced by the wear of the rails and wheels, collect in the gravel bed and are blown around when trains pass causing rust stains in the station. Also the acceleration and deceleration forces on the rails increase the maintenance on ballast bed systems in stations.

In the Schiphol railway station a ballast-less system, called *slab track system* is used. In this system the rails are fixed to concrete slabs on the tunnel floor using steel baseplates. The rail fixtures have an intermediate distance of approx. 60 cm. The slabs are approx. 85 by 345 cm in size. Between every slab there is a space of approx. 15 cm. Every six slabs there is an expansion joint between sections of the concrete tunnel. Figure 52 shows a plan and a cross section of the tunnel.

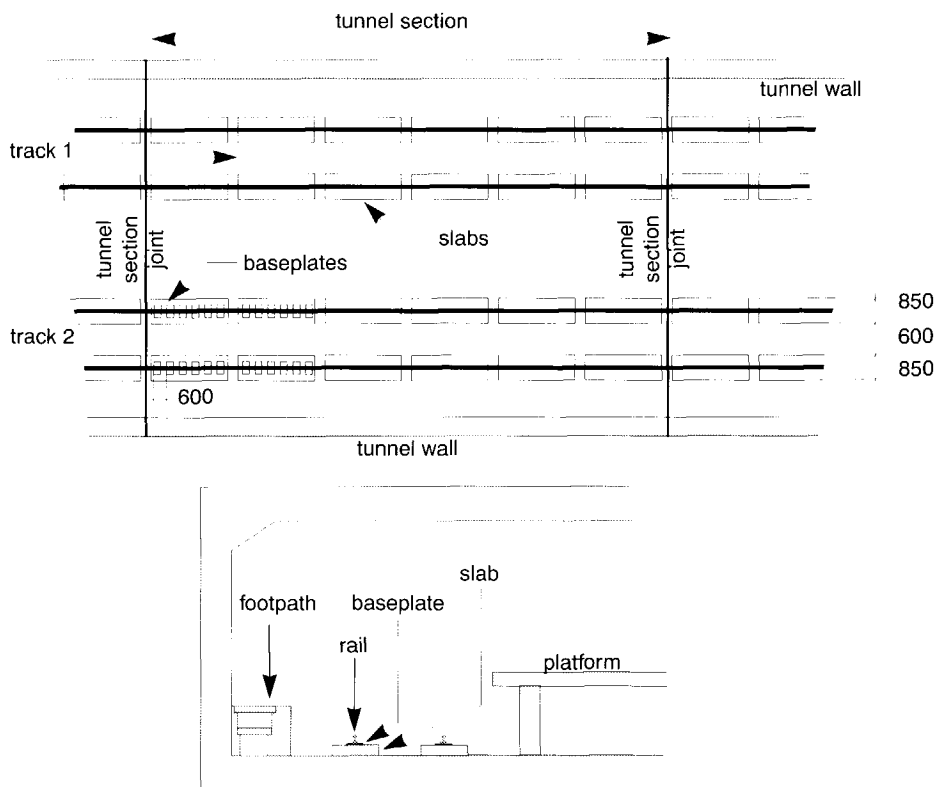


Figure 52 Top view on tunnel section (above). Cross section of tunnel (below).

The baseplates are fastened to the slabs with two anchor bolts. These anchor bolts are glued into holes, drilled in the concrete slabs. A pre-loaded spring and nut hold the baseplate to the floor. The holes needed for the anchor bolts have a diameter of 37 mm and are 130 mm deep.

In total, three railway tracks of each approximately 1000 m length are installed using the slab-track system. This adds up to a total of approx. 20 000 rail-fixture holes in this project.

Holes for Starter Bars

Another construction process that involves drilling of holes is the construction of the footpath along the tracks (See also cross section in figure 52). The railway station and tunnel at Schiphol are constructed using the *cut and cover* method. The basic principle of this method is that a trench is excavated, a concrete tunnel is cast in this trench and afterwards the tunnel is covered with soil. After the construction of a concrete tunnel floor the tunnel walls and roof are cast using steel formwork inside the tunnel. Because the formwork has to be retracted afterwards, the tunnel floor has to be free of obstacles (See figure 53) and therefore the footpath edge has to be constructed at a later stage. It is necessary to drill holes for starter bars afterwards. These holes are approximately 35 cm deep and have a diameter of 20 mm.

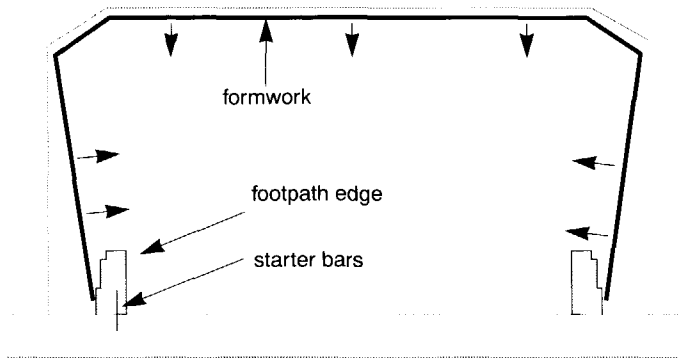


Figure 53 Cross section of tunnel showing obstruction of footpath edge during release of inner formwork in tunnel.

The distance between the starter bars is approx. 15 cm. The footpath is constructed throughout the complete length of the tunnel. In total there are approx. 55000 starter-bar holes needed for the construction of the footpath.

8.2 The Drilling Robot Design and Development

This second section explains how and why the robot was developed. It is divided into four subsections. The first subsection describes why the robot development was started and who were involved. The second subsection describes how the robot development process. Subsection 8.2.3 describes how the robot works. Subsection 8.2.4 discusses how the robot is integrated in the rail installation process. Finally in subsection 8.2.5 the robot application, design and performance are analysed.

8.2.1 The Background

In 1991, the Dutch civil engineering contractor Hollandsche Beton en Waterbouw (HBW), together with TNO Building and Construction Research started a joint development project for a prototype construction robot. Both partners were interested in gaining experience and knowledge on the benefits and costs for construction robots.

In a series of brainstorm sessions between researchers, designers, construction managers, site superintendents and equipment engineers, a list was made of potential applications for successful construction robots. Construction robot applications have to fulfil characteristics that are in-line with the interests of both parties in order to be selected. These interests are:

- There should be a potential for commercial benefits of robotisation.
- The development has to take place in cooperation with the eventual users at the building site.
- The robot development has to be in line with both partners' business activities, being:
 - robotisation of a construction task performed in civil engineering projects carried out by HBW
 - demonstrating TNO's technology, in particular the position measurement sensor CAPSY (Computer Aided Positioning SYstem)
- The robot development should provide technology that enables further robot developments.
- The robot has to show perspective for use in more than one project.

After evaluation of all candidate applications, the drilling of holes for the construction of the railway tunnel at Schiphol was selected as the application for the development of a prototype construction robot. At that time other partners were invited to join the development project. Eventually a joint venture of three parties was formed for the development of the prototype drilling robot. The joint venture is called Foundation 'Robouw'. The participants are:

- HBW B.V.: a general contractor part of the Hollandsche Beton Groep, also member of the Schiphol Tunnel joint venture,
- Strukton Groep N.V.: a general contractor, specialised among other activities in rail road construction; member of the Schiphol Tunnel joint venture,
- Hilti Netherlands B.V.: the Dutch sales representative of the drilling machine and mounting devices manufacturer Hilti in Liechtenstein.

The robot engineering is carried out by TNO Building and Construction Research.

8.2.2 The Robot Engineering

The engineering of the robot was carried out in three steps, which are:

- specification of the required robot performance
- investigation of the feasibility

- detailed design of the prototype robot

Each of these stages is now discussed.

Required Specifications

As mentioned in section 8.1, the drilling robot is to be used for two types of tasks, both with different requirements. The required robot specifications for the task to drill holes for rail fixtures, are:

- *location accuracy of a pair of holes of ± 2 mm*

The allowed tolerances on the railway track gauge are ± 2 mm at the time of installation of the tracks. There is an eccentric adjustment mechanism to allow fine adjustment of the baseplates to accommodate tolerances in the hole locations and the rail and baseplate dimensions. Although the adjustment mechanism allows compensation of larger tolerances, the railway authorities require that the adjustment possibilities remain useable for maintenance and replacement of the rails. Therefore the location accuracy demands are ± 2 mm in transversal direction. In longitudinal direction the accuracy demands are much lower (up to 2 cm is allowed). The accuracy demands on the relative locations of the pair of holes for one baseplate are more strict and are required to be better than ± 0.5 mm.

- *ability to deal with concrete slabs*

The concrete slabs form an inconvenient obstacle for a mobile robot. Either the robot has to drive on top of the slabs (which are 80 cm wide) or the robot has to drive besides the slabs. The first approach requires that the robot's wheel gauge is limited to the slab width and that the robot is capable of crossing the gaps between the slabs. The second approach requires a minimum gauge and the ability to deal with the varying slab height and transversal gradient.

- *ability to verify the absence of re-inforcement steel at the hole locations*

An important requirement for the slab track system is that there is no electrical contact between the rails and the concrete re-inforcement. Therefore the re-inforcement grid has extra large openings at the baseplate locations. It is the responsibility of the drilling robot to verify that there is no steel at the locations where the holes are to be drilled. A complication is that a hammer drill cannot drill through steel re-inforcement rods.

- *ability to clean the drilled holes.*

To improve the working conditions in the railway tunnel, it is desirable that the drilling robot removes the bore dust. The holes have to be clean before the anchor bolts can be glued into the holes.

Although the task of drilling holes for starter bars is very similar, there are different requirements related to both tasks. The requirements for the drilling of holes for starter bars are:

- *location accuracy of a pair of holes of ± 2 cm*

The accuracy demands for holes for starter bars are much lower than for the previously discussed application.

- *ability to avoid re-inforcement bars*

During the drilling of the holes for starter bars there is a significant chance that the drill will hit a re-inforcement rod because of the high density of re-inforcement near the tunnel walls. To avoid loss of time and unnecessary wear of the drills, it is required that the robot scans the floor to check for the presence of re-inforcement rods before any drilling is done.

- *ability to drive near a tunnel wall (approx. 60 cm)*

The holes for starter bars are needed relatively close by the tunnel walls. Therefore the robot should not be too wide.

Both applications result in different requirements which do not seem to result in conflicting robot properties. The application of drilling holes for starter bars was regarded as an application that can be used as a fall-back option when the requirements for the rail-fixture application prove to be unfeasible.

Besides the application specific requirements, there are a number of general requirements for the robot. These are:

- *electric power supply*

The robot is required to use electricity for its power supply. The robot is not allowed to produce exhaust fumes because it is to be used in tunnels. Also compressed air is to be supplied internally.

- *environmentally friendly*

Especially in the tunnel environment the noise production of the robot should be as low as possible. In an echoing tunnel drilling noises are very unpleasant for other workers. At Schiphol station this is also uncomfortable for train passengers that use the existing half of the railway station.

- *building-industry proof*

The robot should be robust. Construction equipment is generally not treated very delicately. For transportation of the robot there should be facilities for cranes to lift the robot. The robot should be rigid enough to withstand shocks when the robot collides with obstacles during hoisting operations and no parts should stick out at the sides of the robot.

- *vandalism and theft proof*

Because the robot is used in an area that is accessible to everyone, precautions against vandalism and theft have to be taken. First of all the robot must look uninteresting. Cladding and locks should prevent theft or vandalism of components of the robot (e.g. the control computer of the drills).

The Feasibility Studies

To prove the feasibility of the implementation of the drilling robot, two feasibility studies were carried out before the engineering of the robot was started. These feasibility studies had the purpose to demonstrate the feasibility of the following two subjects:

- automatic drilling of large diameter holes using a hammer drilling process
- the accurate position measurement of the holes to be drilled

The use of a hammer drill for the drilling process is preferred because of the advantages of hammer drilling compared to the alternative of the hollow core diamond cutting. The advantages of hammer drilling are:

- Hammer drilling does not “pollute” the tunnel with water which is inconvenient in a railway tunnel.
- Hammer drilling can produce holes with the exact desired depth. When a hollow core diamond cutting method is used, the bore cores have to be broken out of the drilled holes. This produces two problems: (1) breaking process is difficult to automate and (2) the produced holes have an unpredictable depth because the point where the core breaks, varies.
- The operational costs of hammer drilling (the drill bits) are lower than the hollow core drills that contain diamond particles.

Another challenge is the accuracy of the hole locations. At the time of the feasibility study there were some uncertainties about the accuracy behaviour of the CAPSY position measurement sensor. Especially the long and narrow shape of the tunnel work environment provided some uncertainties about the achievable accuracy of the position measurements.

Two feasibility studies were started with the objective to answer the following two questions:

- Is it possible to build an automatic drilling unit that uses a hammer drill and is able to produce 37 mm diameter holes accurately and reliably?
- Is it possible to perform position measurements with the required accuracy of ± 2 mm using the CAPSY position-measurement sensor?

For both feasibility studies, experiments were carried out. Figure 54 shows the test set-up of the prototype hammer drill unit. The feasibility studies are described in more detail in (Krom, Klok and Vos 1993). After it proved to be feasible to build a robot that would fulfil the formulated requirements, a the robot engineering was started.

8.2.3 The Robot Design

The robot has a modular structure. The main functional units of the drilling robot are:

- robot vehicle and frame
- drilling unit
- position measurement sensor
- concrete re-inforcement bar detector
- control computer

Each of the main functional units is discussed in more detail below.

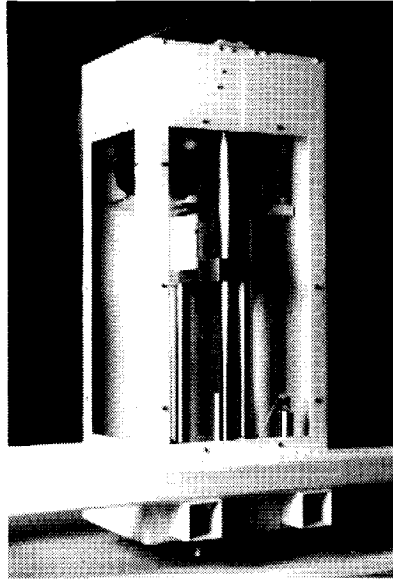


Figure 54 Hammer drill test unit.

The Robot Vehicle

The robot vehicle integrates all components within a frame. The frame is made very robust to protect all robot components against damage during robot transportation. The vehicle is 2.3 m long, 0.9 m wide and 1.4 m high. The total weight of the robot is approximately 1000 kg.

At the back of the robot vehicle two sets of four wheels are mounted. At the front of the vehicle a single, electrically driven wheel is mounted for traction and steering. A special steering mechanism has been used, designed for operation of the robot vehicle in nearly straight lines. Except for the rotation of the wheel itself, the front wheel only has two translational degrees of freedom: it can be moved sideways (left/right) and vertically (raised/lowered). The wheel *cannot* rotate about a vertical axis. This special steering mechanism has two functions:

- 1 It can turn the robot vehicle to the required orientation (heading)
- 2 It can accurately adjust the position of the drilling unit in transverse direction (left/right).

With the front wheel in lowered position, the front of the vehicle can move 40 mm to the left or to the right. Consequently the orientation (heading) and position of the vehicle changes. When the required orientation/position of the robot vehicle has been reached the wheel is raised, set in the centre position and lowered again. This cycle can be repeated as often as necessary to bring the vehicle into a desired orientation. During the drilling the front wheel is raised and the vehicle rests on its back wheels and two fixed supports near the drilling unit.

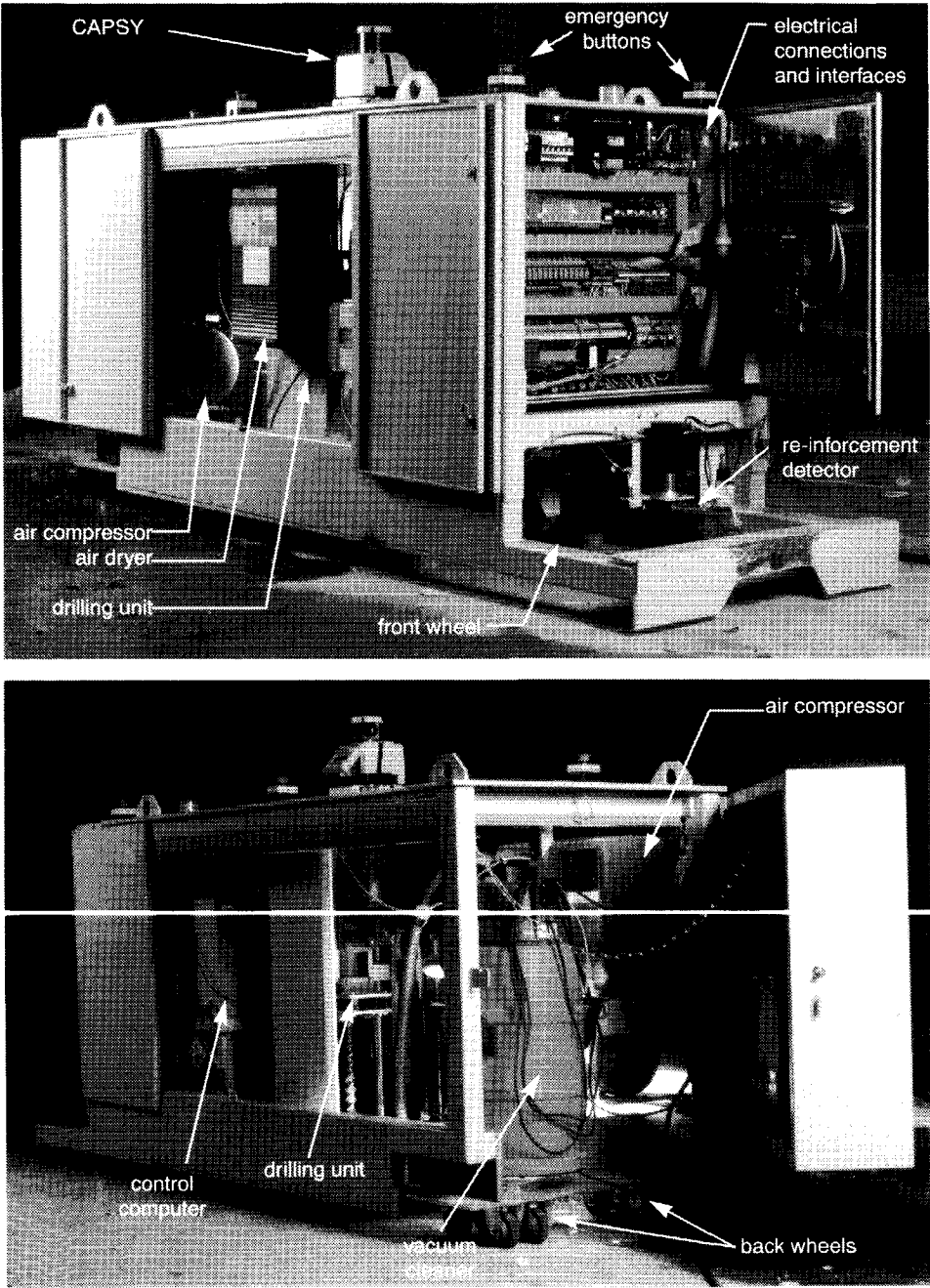


Figure 55 Front view (top) and back view (bottom) of drilling robot.

Drilling Unit

The drilling unit is placed in the centre of the vehicle. The unit contains two hammer drills which can drill two holes simultaneously. The hammer drills are set in position corresponding to the distance between the holes in the baseplates which fasten the rails to the concrete floor. Each hammer drill has its own guidance and control system. The cladding of the drilling unit reduces the noise level and provides stability for the drill guidance mechanism.

Figure 55 shows the front and back views of the robot. In the back view the inside of the drilling unit is visible. The drilling unit contains the following components:

- two standard hammer drills
- vertical guidance mechanism
- pneumatic cylinder for vertical movement of the hammer drill
- pneumatic safety brake

The drilling process is controlled by a personal computer. It activates the drill and controls the drilling forces. The power consumption and the vertical position are measured and fed-back into the control computer where a software control loop controls the drilling process. This drilling process is position and force controlled.

Position Measurement Sensor

For the positioning of the drilling robot the CAPSY position measurement sensor is used (Vos et al. 1989; Vos et al. 1993). This sensor uses a rotating laser to locate itself relative to a set of bar-coded reference reflectors around the work area. The position measurement principle used by CAPSY is triangulation. The positions of the reference reflectors are to be measured before operation of the robot vehicle. The feasibility studies proved that CAPSY achieves the required accuracy.

CAPSY is mounted on top of the robot vehicle (See figure 55) right above the drilling unit. The position measurements of CAPSY are corrected for the roll and pitch motions that the robot can make when it drives over small unevennesses or when the concrete slabs have a transversal inclination for the track camber.

Re-inforcement detector

A re-inforcement detector is placed at the front of the vehicle in order to avoid that re-inforcement rods are hit by the drills. As mentioned before, electrical contact between the rails and the re-inforcement bars is not allowed. If necessary, the positions of the holes to be drilled are to be changed. Re-inforcement bar detection is carried out simultaneously with drilling. This is possible because the distance between the drilling unit and the re-inforcement detector is equal to the distance between rail fixtures in longitudinal direction.

The Control Computer

All the components of the drilling robot are controlled by a single control computer. This computer is an off-the-shelf PC with a 80486 processor. The computer is equipped with a general-purpose input/output interface board which enables con-

trol of the robot hardware through a set of relays and amplifiers in a separate box at the front of the robot. (See figure 55) The operating system running on the computer is MS-DOS.

Auxiliary equipment

In addition to the discussed main components, the drilling robot is also equipped with the following devices:

- a vacuum cleaner to exhaust the holes and collect the bore dust
- two air compressors for the air supply used for the vertical motion of the drills and the raising and lowering of the front wheel
- a slope sensor that measures roll and pitch angles of the robot vehicle
- several safety devices, such as:
 - light and sound warning signals
 - emergency buttons
 - safety bumpers with tactile sensors

8.2.4 Integration of the Drilling Robot in existing Work Methods

From a functional point-of-view, the drilling robot performs two functions. These functions are:

- surveying of the baseplate locations
- drilling of holes

Both functions are fulfilled in one operation cycle of the robot. Because the robot is able to do the surveying as well as the drilling, the rail installation process has to be organised differently than in the conventional installation procedure. The conventional installation procedure consists of the following process steps:

- 1 The surveyor roughly indicates the baseplate locations using spray paint and a template (Figure 56, step 1).
- 2 The rails including baseplates are laid out on the indicated locations.
- 3 The rails are aligned along the desired alignment at the correct gauge (Figure 56, step 2 & 3).
- 4 The baseplate anchor bolt holes are drilled using the baseplates as a template. A special drilling rig is used that runs on the rails (Figure 56, step 4).
- 5 The baseplates are shifted to allow access to the drilled holes (Figure 56, step 5).
- 6 The holes are cleaned, and anchor bolts are glued in the holes using a resin. The bolts are temporarily held into position by a special bracket.
- 7 When the resin has hardened, the rails are lifted to allow corkrubber pads and the baseplates to be placed over the anchor bolts sticking out of the concrete slabs.
- 8 The correct gauge and alignment is established using the eccentric rings around the bolts. The springs and nuts are installed on the anchor bolts.

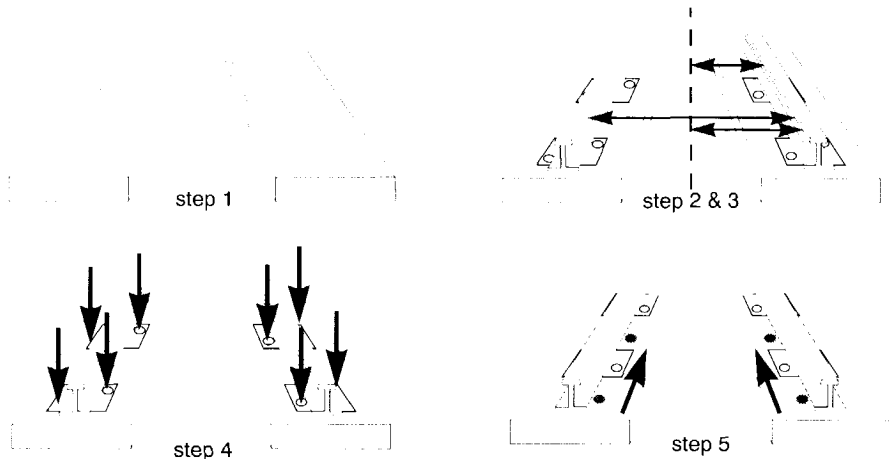


Figure 56 Illustration of steps in rail fixture process. The first step is to locate the approximate locations of the base plates. Next, the rails are placed and aligned. The base plates are used as a drilling template (step 4). Finally the base plates are moved to allow the holes to be cleaned and the anchor bolts to be glued.

In the robotised process it is not necessary to use the rails and baseplates as a drilling template. The robotised rail-installation process consists of the following steps:

- 1 The surveyor places the position reference reflector around the track.
- 2 The robot is instructed about the location pattern of the baseplates.
- 3 The robot drills and cleans the holes for the anchor bolts.
- 4 The rails are placed with the baseplates besides their final location
- 5 Identical to step 6 in the conventional procedure.
- 6 Identical to step 7 in the conventional procedure.
- 7 Identical to step 8 in the conventional procedure.

The advantage of the robotised procedure is that a number of savings can be made. These are:

- 1 *robotic instead of manual drilling*
The most obvious saving is of course the replacement of the manual drilling by the robot drilling.
- 2 *less preparatory surveying work*
Instead of indicating the rough baseplate locations on the slabs, the surveyor's task in the robotised process is to position the sensor's reference reflectors. This task is less time consuming because there are only eight reference reflectors to be positioned, while there are 60 baseplate locations to be indicated in each section.

3 *alignment of tracks is only performed once*

In the traditional process the rails are installed in an early stage to use them as a measurement aid to drill the holes at the correct locations. In the robotised process this is no longer necessary. Therefore it is no longer required to align the rails twice (before drilling and at final alignment).

A new step in the robotised procedure is the instruction of the robot about the hole pattern that has to be drilled. This task is discussed in section 8.3. The instruction is a task that is the responsibility of the surveyor. Instruction mistakes are difficult to detect during drilling because it is not easy to detect deviations visually without the rails as a reference. Also it is difficult and expensive to correct mistakes.

It can be concluded that the robot requires a different organisation of the rail installation procedure. This case supports the proposition that the introduction of the robot in construction requires *process re-engineering*. The benefits of the robot are primarily related to the more efficient organisation of the robotised rail installation process. A potential disadvantage of robotisation is that low skilled labour (drilling of holes) is replaced by high skilled labour (instruction of the robot).

8.2.5 Analysis of the Robot Performance

In this subsection the case study robot application is analysed using the theory such as discussed in the first half of this thesis (chapters two through five). The questions that are answered are:

- Is robotic drilling an opportunity for robotisation?
- Is robotic drilling a state-of-the-art application in the field of construction robotics research and development?
- Does the development of a drilling robot require much state-of-the-art or to be developed robot technology?

Finally the experiences with the performance of the robot during trials are discussed at the end of this subsection.

Is Robotic Drilling a Robotisation Opportunity?

Although the analysis method used in chapter 2 is meant to be used to compare different categories of construction processes, it is possible to use the method to assess the suitability of a particular robot application. The outcome of this assessment gives an indication of how the robotisationability of a particular application is in relation to the average robotisationability of all construction processes. In this subsection the robotisationability of the drilling robot's task is assessed. For this assessment the performance aspects such as identified in chapter 2, are discussed one by one.

- *costs of labour*

The costs of labour replaced by the robot is composed of two types of labour: (1) the drilling of holes, and (2) the surveying work for the layout of rails and hole locations. The labour costs of manual drilling of the holes, is below the average labour costs in the building industry. The costs of a surveyor are higher than

the average worker. Taking the relative amounts of both types of work into account, the costs of the labour replaced by the drilling robot (drilling + surveying) is estimated to be approx. 0.6 (i.e. somewhat higher than average).

- *task complexity*

The task performed by the drilling robot is not very complex. The robot design is of limited complexity, especially if it is compared to other third-generation robots such as discussed in section 3.3. There are only three degrees of freedom (drill up/down, forward/backward sideways left/right). The robot is also relatively uncomplicated because the task does not require a supply of materials. These facts together add up to the (conservative) assessment that the task complexity of the drilling robot's task is 0.3 (i.e. significantly below average).

- *repetitiveness per site and per task*

The repetitiveness of the task of the drilling robot is obviously relatively high. In total there are many thousands of holes to be drilled which is exceptionally high. The proportion of projects with a repetitiveness such as encountered at Schiphol, is low. All together the repetitiveness is assessed to be fairly high at 0.8.

- *value of the reduction of unhealthiness*

The use of the robot improves the labour conditions. The actual drilling work itself no longer requires manual labour and in the neighbourhood of the work area the amount of noise and dust produced by the drilling process is reduced. However, it is difficult to predict if the benefits in labour conditions are significant enough to provide financial benefits on the long term. The *value of the reduction of unhealthiness* is estimated conservatively at 0.5, i.e. average.

- *value of quality improvements*

The use of the robot does not prevent errors and mistakes to be made in the rail installation process. However, a possible improvement in quality is that the drill bits will have a longer life time because the robot drills the holes at optimal speed and pressure. In relation to other construction processes, the drilling robot does improve the end result quality when compared to the conventional process. Therefore the *value of quality improvements* is estimated to be below the average at 0.3.

- *level of mechanisation before robotisation*

The introduction of the drilling robot in the conventional situation requires a major organisational change because the interaction between surveying and drilling is completely different. Due to this significant difference in construction process organisation, the indirect costs involved with robotisation are assessed to be relatively high. Although the drilling process is mechanised in the conventional procedure, the effects related to the *level of mechanisation before robotisation* is estimated at fairly low. Therefore the value is assessed conservatively at 0.7.

In chapter two it has been explained how each of the above aspects contributes in the assessment of the robotisationability of a cluster of construction processes. In this section this approach is applied to the specific application of the drilling robot. The robotisationability of the application of drilling holes for rail fixtures, can be

assessed by substitution of the above discussed percentages in formula (IV) on page 21. The result of this substitution is:

$$Z = 16 \cdot 0.6 + 3 \cdot 0.5 + 12 \cdot 0.3 + 16 \cdot 0.8 - 48 \cdot 0.3 + 5 \cdot 0.7 = 16$$

The total robotisationability of the robot's task to drill holes for rail fixtures is assessed at 16. This outcome indicates that the application has a higher than average suitability to be robotised. The average robotisationability score is 2 (i.e. when all aspects are assessed at average, i.e. 0.5).

Is the Developed Robot State-of-the-Art?

In chapters three and four, the state-of-the-art in robot technology and construction robotics was discussed and analysed. The question to be discussed here is 'In what degree is the discussed drilling robot a state-of-the-art development?'. In order to answer this question a distinction is made between the robot functionality (is the robot state-of-the-art from construction robotics point of view?) and robot technology (is the robot hardware state-of-the-art?).

State-of-the-Art Robot Functionality

The drilling robot is a third-generation construction robot according to the classification introduced in chapter 3. The drilling robot is an autonomous robot that performs tasks that are carried out manually in the conventional situation. A special characteristic of the robot is that it combines the functionality of two tasks (i.e. surveying and drilling) in one piece of equipment. There are even opportunities to extend the functionality of the robot to further optimise the rail installation process. One easy to implement extra functionality, is to include a slab elevation measurement function to establish the desired thickness of the rubber pads to be installed under each baseplate.

A third-generation robot can certainly be valued as state-of-the-art from a construction robotics point-of-view. Maybe the step from 'non-robotised' to 'third-generation' is even beyond state-of-the-art because such a transition confronts construction workers with many changes at once. Too many changes does not improve the acceptance of robot technology because too much emphasis has to be put on the changes required for robotisation.

State-of-the-art Robot Technology

From a technology point of view the robot is believed to be state-of-the-art. The technical feasibility of the robot concept was not established at the moment the robot development was started. However, the robot application was selected because it seemed feasible to overcome the 'technological gaps' for which technical solutions were needed to build the drilling robot.

The technological gaps that needed to be resolved during the development of the robot, were the use of the position measurement sensor CAPSY for high-accuracy position measurement and the automation of the hammer-drilling process. At the moment of development of the robot, the position sensor CAPSY had not yet been used in an application where an accuracy of ± 2 mm was required. Automatic hammer drilling of large diameter holes had also never been automated before. A fea-

sibility study on both gaps was conducted before the robot development was started. An unanticipated problem that emerged during the development and testing of the robot was the detection of re-inforcement bars in concrete. Reliable detection of re-inforcement bars in concrete proved to be a difficult technical problem. All magnetic field based detection methods have the problem that the signal to noise ratio of sensor signals is very poor. This makes it very difficult to implement an affordable and reliable system that is able to detect where re-inforcement bars can be found in the concrete. New techniques such as *micropower impulse radar* enable much better detection of re-inforcement bars (Warhus, Mast and Nelson 1996; Azevedo and McEwan 1996). However, this technology is not yet available in the form of an affordable standard component that can be built into the robot.

Performance in Practical Situation

The use of a drilling robot for the installation of railway tracks has been tested in a trial section of 60 meters. The Dutch railway authorities wanted to verify for themselves whether the position and gauge of the trial section would conform to their requirements. The reason for this is that they wanted to verify if the new process organisation involved with use of the robot, influences the accuracy of the track gauge and position in a negative sense. In the conventional rail installation process, tolerances in the rails and the baseplates are eliminated because the rails and baseplates are used as a template to indicate the hole locations for the drilling. In the robotised process the tolerances in rails and baseplates are not included in the measurement process. Therefore the correct position of the rails and correct gauge can only be realised when the tolerances in the rails and baseplates are smaller than the allowed tolerances in the rail positions minus the tolerances of the robot minus the tolerances in the anchor bolt gluing process. The geometry of the installed trial section was investigated to establish whether the new robotised process realises the same accuracy as the conventional process. The measurements, carried out by the Dutch railway authorities, confirmed that the accuracy of the robotised process is conform to the railway authority requirements.

Time measurements show that the robot needs approx. 5 minutes for drilling a pair of holes and relocating itself to the next position. This cycle time is dependent on the wear of the drill bits, the local concrete quality and the curvature of the alignment. The more curved the alignment the more side-step steering motions the robot has to make. These side step motions are relatively time consuming, and therefore the curvature of the track influences the robot cycle time.

For production-optimization purposes it is desirable that the robot is able to work as long as possible without operator assistance. An accuracy analysis of the CAPSY position sensor indicated that it is possible to make a reflector set-up around two sections. With a cycle time of approx. 5 minutes, required for each rail fastening, this enables the robot to work approx. 5 hours without operator assistance. When the robot can continue working in the evening, it is possible that the robot drills holes for fasteners of two rails in two sections per day. During the robot trials, the

reflectors were set-up around single sections and the robot was not in operation outside normal work hours.

The application of the robot to drill holes for starter bars, imposes much less stringent demands on the robot performance. The position accuracy of the holes is ± 1 cm. This makes it possible to set-up the reference reflectors at much larger distances, which allow the robot to work longer without operator assistance. It is possible to adapt the distance between reflectors, to the desired work period of the robot. The lower accuracy demand and the smaller diameter of the holes, both decrease the cycle time of the robot operations. The lower the accuracy demands, the less time is needed for manoeuvring operations of the robot.

8.3 A Drilling Robot Task-Instruction System

This section discusses the realisation of a task-instruction system for the drilling robot according to the reference architecture presented in chapter seven. The discussed task-instruction system supports the instruction of the robot for the task of drilling holes for rail fasteners.

Subsection 8.3.1 explains the relevance of a task-instruction system and the objectives of the prototype implementation. Subsection 8.3.2 discusses what the drilling robot's task-instruction system looks like. In section 8.3.3 the presented architecture is evaluated.

8.3.1 The Robot's Task

At first sight, one might conclude that a task-instruction system for the drilling robot is a luxury because of the uncomplicated and repetitive nature of the task. However, this is not the case. The instruction of the robot task is complicated and involves a substantial amount of time because the pattern of the holes to be drilled is in fact irregular. A significant proportion (approx. one-third) of the base-plate locations is irregular. The irregularities are caused by two phenomena:

1 *track curves*

A relative large proportion of the tracks in stations has a curved horizontal alignment. In curved alignment sections, the fixture locations have to follow the alignment which makes the fixture locations shift in a transversal direction.

2 *crossings of tunnels section joints*

The concrete tunnel is divided into sections of varying length. Rail fixtures cannot be installed too close to the section edges. Therefore the spacing between fixtures is reduced near the section ends such that a section joint is centred between two rail fixtures. This makes fixture locations shift in longitudinal direction (See fig. 57)

The design of the railway-track alignment for the slab track system is a process in which there is an iterative interaction between design and construction. After the construction of the tunnel shell, the 'as built' dimensions of the tunnel are measured. Using the as built dimensions, the concrete slabs are designed. Each slab has its location and height. The height is important for the vertical alignment and

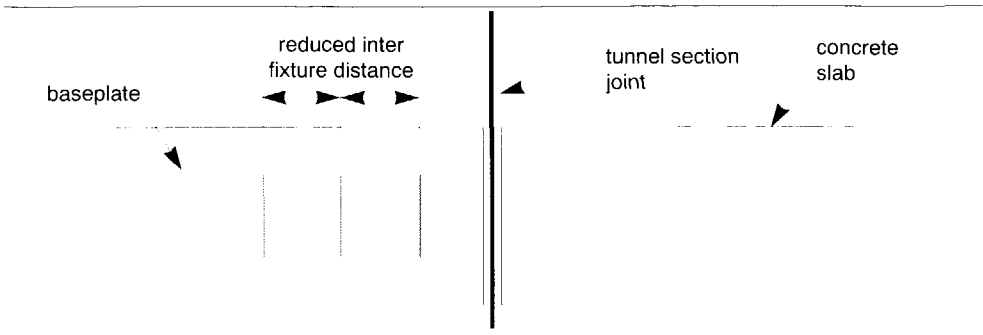


Figure 57 Top view on slabs near tunnel section joint.

the track camber in curves. Also the re-inforcement of the slabs has gaps at the planned locations of the baseplates to avoid interference between the re-inforcement and anchor bolts. After the construction of the slabs, their 'as built' elevation is measured. These 'as built' measurements are used to perform a fine-tuning process on both the horizontal and vertical alignment of the tracks. In this fine tuning process it is determined what the thickness of the cork rubber pads under each of the baseplates will be. The variance in thickness of the cork rubber pads allows tolerances in the slab heights to be resolved. If necessary the slabs are ground to reduce their height.

In the as-is situation the designs of the slabs and the rail baseplate locations are communicated in the form of technical drawings. The designs and drawings are made by the engineering department of the Dutch railways and are provided to the contractor.

In the situation where the drilling robot is used (referred to as the 'to-be' situation), it is assumed that the robot task-instruction system is part of a *Computer Integrated Construction (CIC)* infrastructure. In this CIC infrastructure, all information about the tunnel and track design is available in a project model database.

The drilling robot task-instruction system should enable the instruction of the drilling robot to be executed with as little as possible manual instruction work. This requires that the system obtains its required task information from the provided project model and that general task knowledge is applied to produce a process plan. In the next subsection it is described how this can be realised using the reference architecture presented in chapter seven.

8.3.2 The Task-Instruction System Design

In this section each of the subsystems, distinguished in the reference architecture in chapter seven, is discussed.

Task Specification

The task-specification subsystem performs three functions, which are:

1 *import of project model information*

The first function of the task-specification subsystem is to obtain the relevant project information needed by the task-instruction system.

2 *analysis of possible tasks for the robot*

The second function of the task-specification system is to analyse the imported design information and find the tasks that can possibly be performed by the robot using knowledge about the robot's capabilities.

3 *interaction with robot instructor for selection of robot tasks*

The third function is to take care of the interaction with the robot instructor. This interaction is required to be at the abstraction level at which construction experts normally communicate.

The implementation of the above listed functions is discussed below.

Import of Project-Model Information

The drilling robot needs information about the railway track design, the tunnel design, and the detailed design of the track fixture. Several experts in the project at Amsterdam airport have been interviewed to establish which information is needed to let the task-instruction system know everything it needs to know to prepare the drilling of the rail fixtures. The result of the study has provided a model of the information that is to be communicated between the design office and the task-instruction system in order for the system to be able to have the information that is required. Figure 58 shows an EXPRESS-G diagram of the model.

The model in figure 58 contains the information that is transferred from the design department to the task-instruction system. The upper right corner of figure 58 shows the entity *railway tunnel* which is segmented in a number of *tunnel sections*. A railway tunnel also accommodates a *railway track section*. The division in sections of railway tracks and of the tunnel are both different ones. The shape and position of a railway track is specified by its *alignment*. Also a track section has two *rails*, a left rail and a right rail. A *railway track* crosses tunnel section joints at a *track section joint crossing*. Locations related to the railway track are specified in terms of a *chainage* which is a one dimensional coordinate indicating the distance from an origin measured along the track. The pair of rails (a left and right rail) is each fixed individually by *rail fixtures* (See also figure 52 on page 125). The rail fixtures are the most important entities for the robot. The locations of the rail fixtures are specified by a chainage. The chainage together with the track alignment can be converted into an X, Y, Z coordinate which can be related to the tunnel locations (not shown in the EXPRESS-G model).

Analysis of Possible Tasks

Because of the specialised nature of the drilling robot there is only one type of task for which the project model has to be evaluated, which is the drilling of holes for rail fixtures. The task-specification subsystem has to find out which rail fixtures there are, and if they can be handled by the robot. In the prototype implementation a query is made for all rail fixtures as possible candidates.

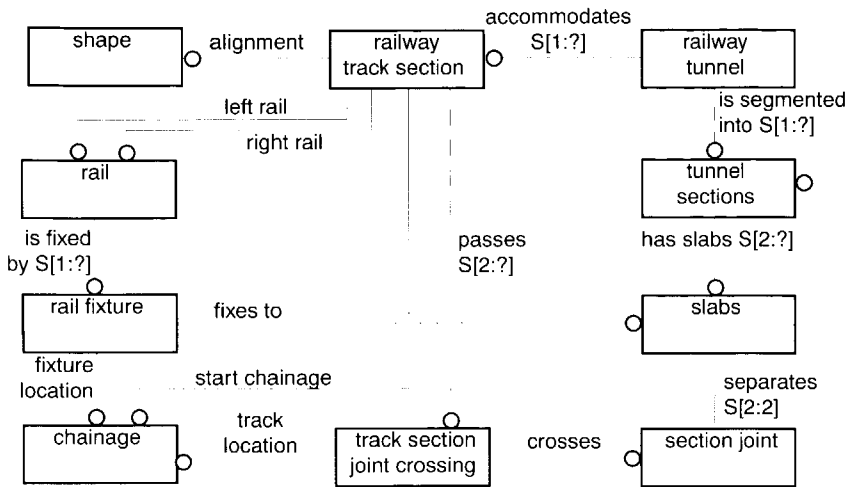


Figure 58 EXPRESS-G diagram of design information structure supplied from the tunnel and track design to the robot planning.

There are however, situations where the robot is not able to drill the holes for the fixtures. This is the case when the robot has to follow sharp curves. Such situations occur near track switches. The judgement whether the holes for fixtures near switches can be handled by the robot, is probably best left over to the robot instructor.

Robot Instructor Interaction

The task-specification subsystem presents the candidate rail fixtures in aggregations related to the *tunnel-rail sections* they belong to. A tunnel-rail section is the intersection of one rail and a tunnel section. A rail section is a section of a rail which the start and end correspond to the points where the rail crosses the tunnel-section joints. The aggregation to tunnel-rail sections is related to the usage of the robot which requires the reference reflectors for the position measurement device to set-up around a tunnel-rail section. Also the segmentation in tunnel sections is a general method of identification of locations in the railway tunnel construction project at Schiphol.

Figure 59 shows a prototype implementation of a user interface for the construction robot task specification. The program presents a schematic overview of the sections in which the tunnel and tracks are divided. The robot task assignment is made by selecting the sections that have to be drilled by the robot.

The output of the task-specification subsystem is basically a list of references to rail fixtures for which holes have to be drilled. The EXPRESS-G diagram in figure 60 shows the information contained in the task specification. On the right half of the EXPRESS-G diagram the generic entities *task specification* and *task plan* are specialised for the drilling robot. In the left half of the diagram the expected result of the task assignment is specified. The *drilling-robot task-result* is specified

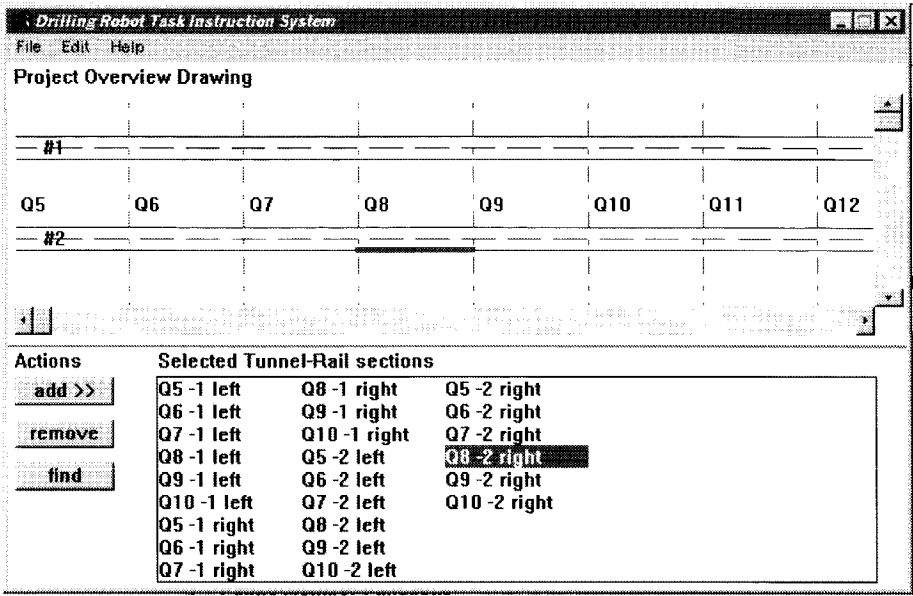


Figure 59 Dialogue window of task-specification system user interface.

by a set of *tunnel rail sections* in which all the holes for the rail fixtures have to be drilled.

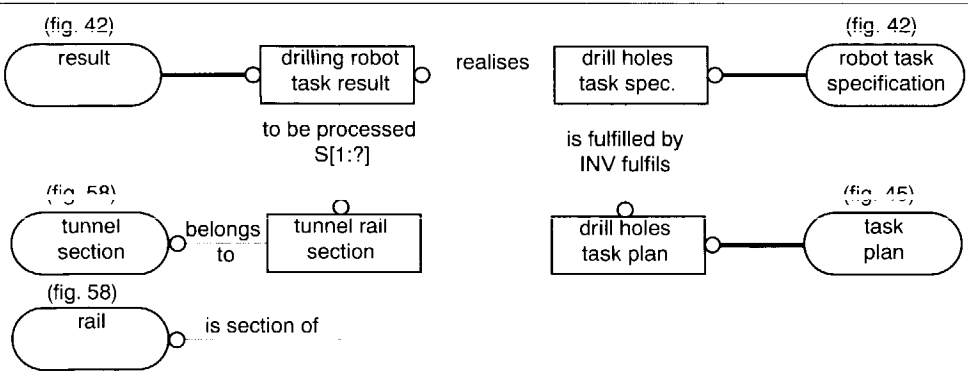


Figure 60 EXPRESS-G diagram of specification of robot task as produced by the task-specification subsystem.

Task Planning

The key component of the task-planning process is the process-type model. As explained in section 7.3, the process-type model contains knowledge how a type of task is to be performed. In this case this knowledge expresses how the process to drill rail fixture holes in a tunnel rail section is organised.

The knowledge in the process-type model is separated into two types: *ontological knowledge* and *inference knowledge*. The ontological knowledge describes which types of primitive operations can be performed by the robot, and how higher level processes decompose into primitive operations. The inference knowledge describes how the plan is deduced from the provided tunnel rail section design specification. The modelling of both types of knowledge is discussed below.

Ontological knowledge

The ontology of the process-type model for the drilling robot is shown in the EXPRESS-G diagram in figure 61. This EXPRESS-G diagram shows that there are three types of primitive processes that can be performed directly by the drilling robot hardware. These are: *relocation*, *drill hole pair* and *change section*. The subject of a *drill hole pair* operation is a *rail fixture*. The information that is of primary relevance to the *drill hole pair* operation is the *location* of the fixture. This location has to be deduced from the *fixture chainage* in combination with the *rail alignment*. Standard numerical procedures exist to make this conversion.

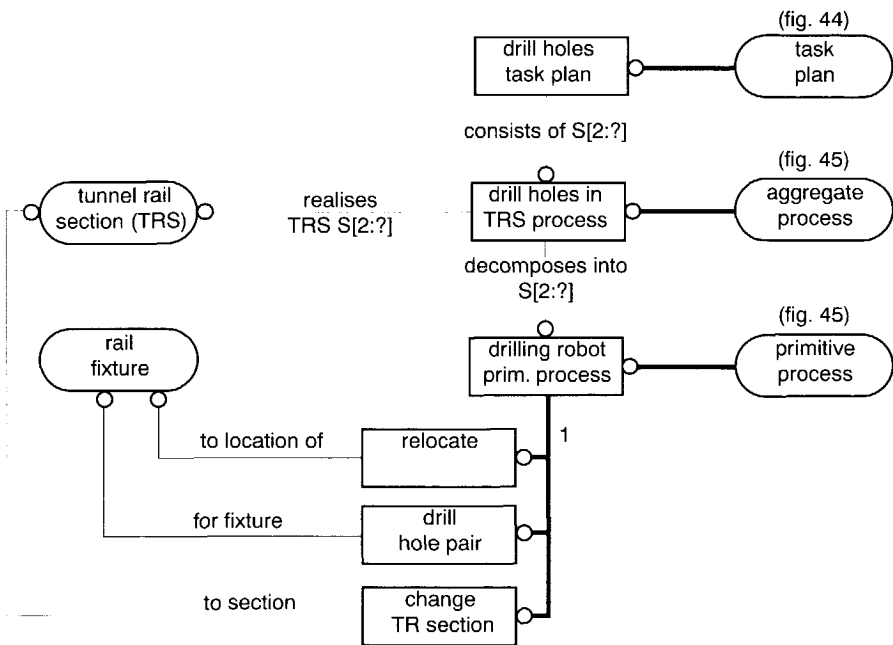


Figure 61 EXPRESS-G diagram of process model for drilling robot.

Inference knowledge

The inference knowledge assertions describe how the process-type model ontology is instantiated such that the instantiated model realises the specified result. There are a number of assertions that specify how process-type entities relate to product-type entities. In the case of the drilling robot the most important assertions are:

- 1 For every *tunnel-rail section* there exists a corresponding *drill holes in tunnel-rail section* process which contains all sub-processes needed to the drill all holes for fixtures in that section.
- 2 All processes that work on parts of a *tunnel rail section*, are sub-processes of the corresponding *drill holes in tunnel rail section* process.
- 3 For every *tunnel rail section* there exists a corresponding *change section* process which has the purpose to make sure that the robot gets to the tunnel rail section it is supposed to work in.
- 4 For every *rail fixture* there exists a corresponding *drill hole pair* process which realises the holes for the fixture.
- 5 For every *drill hole pair* process there exists a corresponding *relocate robot* process which makes sure that the robot moves itself to the correct location for the *drill hole pair* process.
- 6 For every *drill hole pair* process and corresponding *relocate robot* process there exists a *precedes relation* between those processes.
- 7 All processes that deal with components of a particular *tunnel-rail section*, are sub-process of a the *drill holes is tunnel-rail section* process.

Assertions 1 to 5 specify how process-type model entities are to be instantiated and related to product entities. Assertions 6 and 7 specify the relations between process-type model entities.

When an assertion is not true in the process model, the process planning subsystem instantiates the entities and relations that are needed to make the assertion true. This process is repeated until all assertions are true and the process-plan ontology is complete. A robot process plan according to the structure specified by the process-type ontology model, is produced when all assertions are evaluated.

The assertions can be formalised using the EXPRESS language such as shown in chapter seven. In the prototype implementation the assertions are not formalised in a neutral language such as EXPRESS. For pragmatic reasons the assertions are formalised in C++.

Operation Sequence Planning

The reduction process of an abstract task assignment into primitive operations produces an operation plan. Although many sequential relationships between operations are specified in the process-type model, there are still many sequence options available in the operation plan.

Theoretically all holes in any section can be drilled at any moment because there is no strict dependency between each of the operations. However, most of the possible sequences of execution are not efficient. The most efficient sequence of operation can be determined by elimination of all unnecessary robot motions. This can be done using the topological relationships in the product design (Which rail fixture is adjacent to what other rail fixture?).

In the situation of the railway-station tunnel this means that the robot will work from one end to another. A small complication is that the robot requires reference reflectors for its position measurement to be set-up around its work area. Because the set-up of these reference reflectors has to be performed by a surveyor, the most efficient sequence can be somewhat different. These optimisations are determined by the interaction with other construction processes and local circumstances at the location of drilling.

The planning, generated by the sequence planning algorithm, is presented in a Gantt chart such as shown in figure 62. The use of Gantt charts presents the robot action schedule to the work order planner in a presentation format that he is familiar with. The presentation shown in figure 62 is made using a standard software package. The task-instruction system generates a file that can be imported by the software package.

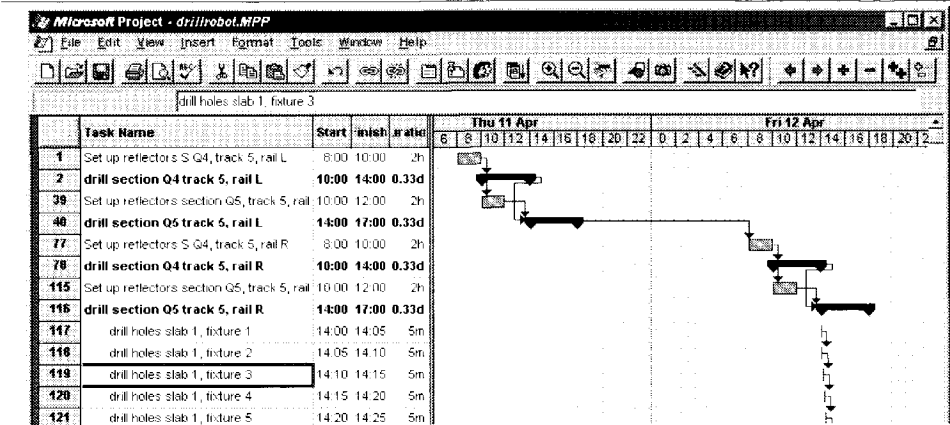


Figure 62 Gantt chart of operation sequence planning of robot actions of the drilling robot. The application MicroSoft Project™ was used to present the above planning.

Motion Planning

The motion planning subsystem plans the robot relocation-motions. The motion planning of the relocation operation uses a very hardware-specific algorithm because the drilling robot is equipped with a special steering mechanism. The front wheel of the robot can only be moved sideways by a linear actuator. When the front wheel is moved sideways, the orientation of the robot is changed by a few degrees. Because the front wheel can also be retracted, in which case the front of the robot will rest on the ground, the front wheel side steps can be repeated when larger changes in orientation are required (See also section 8.2.3).

In order to bring the robot's drilling unit at a specified position in a specified orientation, planing of the relocation motions is required. Figure 63 shows what steps (indicated as step 1, 2 and 3) are required to move from one location to another along the arc-formed alignment of the tracks.

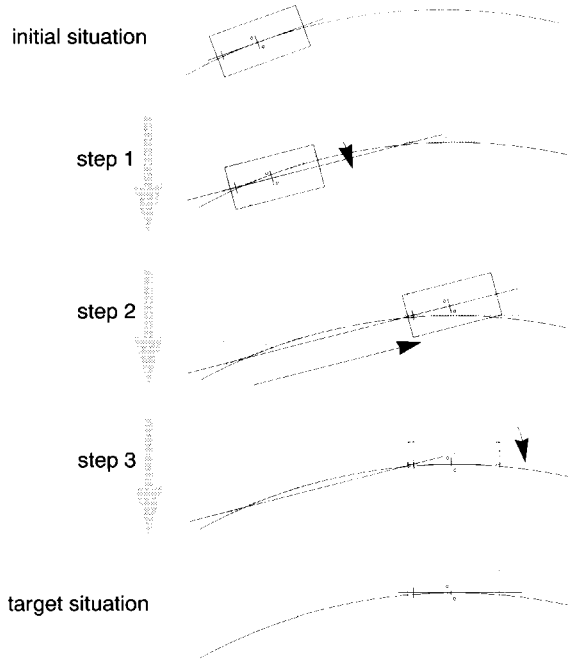


Figure 63 Motion planning principle of drilling robot.

Task-Plan Execution

In the previous steps, all information needed to control the robot hardware has been collected and deducted.

Depending on the level of detail of the plannings made of the construction process, these sequence plannings can be performed by the construction planner or by the robot operator. In many construction projects there are several subcontractors working at the same time. This makes it difficult to coordinate all processes down to the smallest details. Therefore, it is often more efficient to follow a pragmatic approach where the robot operator can change the sequence of operation of the drilling task to resolve interferences with other construction work going on. This responsibility can be delegated to the work floor because the robot already has the correct baseplate locations for the complete project. It is the responsibility of the robot operator to specify the correct track-section identification of the robot position.

During the execution of the prepared robot operation plan, many things can go wrong, causing the system to stop and adjust the process plan if necessary. Some possible contingencies are:

- the robot drill bits can become damaged or worn out
- the drill can hit a re-inforcement bar

- the robot can bump into an obstacle in front of the robot
- one of the position measurement reference reflectors can be knocked over

Some of these contingencies can be classified as 'recoverable'. An example of a theoretically recoverable contingency is when the drill hits an re-inforcement rod. In this case the robot can drill a new pair of holes for one rail fixture baseplate 5 cm along the alignment. Contingencies that can be the result of human errors or interference (e.g. obstacles or relocation of a reflector) require the assistance of the robot operator. Using a wireless communication device, the robot can inform its operator any time and anywhere.

8.3.3 Summary & Evaluation

In the previous subsection it is described what a task-instruction system for the autonomous drilling robot can look like. The described task-instruction system architecture is based on the reference architecture described in chapter 7.

A precondition for the realisation of an effective task-instruction system is that all the required information needed for the planning of the robot task is available in a computer interpretable form. In the case study this means that the engineering department of the railway authorities have to provide their track designs in the form of a project model instead of in technical drawings.

The very procedural nature of the robot's drilling tasks, enables the task knowledge to be captured in a process-type model without problems. It should be noted that the drilling robot's task is an example of a relatively uncomplicated task.

The presented approach does provide several benefits:

- 1 The generated plans are not fixed sequence process lists, but structured process graphs, that enable modification of execution sequence in case changes are required or contingencies occur.
- 2 The presented task-instruction architecture supports the separation in responsibilities that traditionally exists around the drilling task. The railway authorities are responsible for the design of the layout pattern of the rail fixtures and also provide this data to the robot. The construction manager, is responsible for the assignment of tasks to the robot, and the sequence of execution of the tasks. Finally the project surveyor, is responsible for the correct measurements locally around the robot. This separation in responsibility helps to reduce the number of changes in responsibilities that are needed for the introduction of the robot. This is an important benefit because none of the people involved is a robot expert and no one has to take over responsibilities that originally were someone else's.

8.4 Evaluation

In chapter one, it was concluded that somehow, construction companies see too many problems in construction robots, to start experimental use of robot technology. In the case study in this chapter, an example of an application is shown which

can successfully be robotised, both in a technical sense as well as in a practical sense. Construction robot users, together with robot developers, have looked for an application which seemed attractive for robotisation from both a construction company point of view as well as a robot developer point-of-view.

Regardless of all feasibility studies, the development and use of the robot has provided lots of valuable knowledge on robotisation. The project participants have gained hands-on experience with the requirements and effects of robotisation of a particular task. But also the project has been a very interesting case for the research presented in this thesis. The main lessons learned from the case study are:

- The costs of the development of the robot are a multiple of the costs of manufacturing the robot. This observation, together with the short term management strategy, common in the building industry, virtually eliminates the chances that the building industry takes the first steps in the development of robot technology. Third party investments are essential for innovative developments.
- The method for assessment of robotisationability discussed in chapter two, assesses the robotisationability of the task of drilling holes for rail fixtures is above average.
- Like in manufacturing industries, the introduction of robots in the building industry, requires a re-organisation of the production processes. The productivity increases of robotisation in combination with process re-organisation, enables commercially attractive robotisation.
- The drilling robot that is discussed in this chapter, shows how innovative new robots can be developed by a combination of available technical solutions.
- The case supports the thesis that instruction of construction robots is a fundamental problem related to the nature of the building industry production process. Using conventional motion oriented programming methods, the programming of the drilling robot is a complicated, time consuming task due to the many irregularities in the rail fixture pattern.

In chapter six, the hypothesis is presented that task-instruction systems for construction robots can be realised easier than for manufacturing robots. This chapter shows how a task-instruction system for a drilling robot can be implemented using a relatively uncomplicated process-type model. In combination with a project model, containing the tunnel design and the track design, the robot has sufficient information and knowledge to know what has to be done. In section 8.3 the implementation of a task-instruction system for the drilling robot is explained. Special features of this implementation are:

- The use of open interfaces for exchange of information, enables importation of design information into the task-instruction system. Internally all information in the task-instruction system is stored in a task-model database which is open to other applications that can be interested in the information.

- By using semantical information in the task-instruction system, the communication with human beings can take place at a more abstract and powerful level (e.g. technical drawing, Gantt chart etc.), which is more efficient and less error prone than lower abstraction level communication.
- The use of semantic information also enables powerful reasoning by the task-instruction system. The knowledge that is stored in process-type models enables automatic generation of robot task plans from product design information. A condition for this is that the provided design information is formalised at a semantical level.
- The use of the least commitment strategy helps to improve the robot productivity. The fact that the robot or the robot operator can re-order the sub tasks in the task plan, enables the robot to continue working at other locations when there is a problem or obstacle at a location.

9

Case Study Two: An Earthwork Robot

This chapter describes a case study about an earthwork robot. This case deals with the conversion of an existing hydraulic excavator into an earthwork robot which is controlled by a task-instruction system. The earthwork robot potentially increases productivity and accuracy by the automation and integration of surveying and operator control.

9.1 Introduction

The most popular piece of equipment for earthwork is the hydraulic excavator. Hydraulic excavators are *construction manipulators* that are developed and designed for the manipulation of bulk goods such as soil. The basic functionality that is fulfilled by these types of machines is the amplification of human power. This basic functionality has a very universal nature. The productivity of human beings is increased enormously without sacrificing too much of the versatility of a human being. These properties have made excavators popular machines that are used for a variety of different tasks such as:

- *excavation*
- *trimming of surfaces*
- *loading and unloading of bulk goods into trucks, ships etc.*
- *demolition*
- *hoisting*
- *dredging*

There is however one aspect of the functionality in which hydraulic excavators do not particularly excel. This is the aspect of accuracy. Although it is possible to control the motion of the excavator arm precisely, much experience of the operator is required.

From a mechanical engineering point-of-view, the current design of hydraulic excavators is perhaps nearly optimal, but from an ergonomic point-of-view the current method of controlling the motions is not optimal. The operator controls are one to one related to the configuration of the arm. Every hydraulic cylinder on the arm is controlled by one joystick motion. To perform excavation tasks, the operator has to translate his desired bucket motion-path into cylinder motions. When the operator wants to make a linear excavation motion, he has to control the joysticks such that the boom, the bucket arm and the bucket actuators all move simultaneously in the correct relative speeds (See figure 64). In order for a human being to perform this motion planning translation, much training is required. But even an experienced operator cannot excavate at ± 1 cm accuracy at full speed.

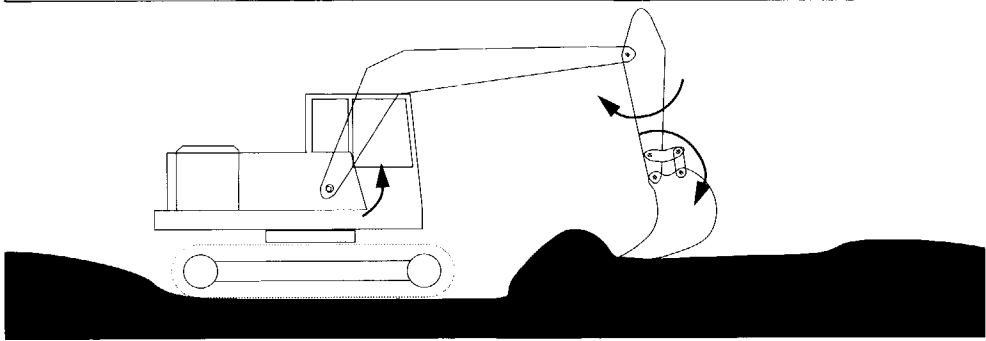


Figure 64 Linear trimming motions require simultaneous control of the three degrees of freedom of the excavator arm.

Computers are potentially much better in motion control. Independent of the chosen kinematic robot configuration, the computer controller is able to let the robot end effector move along any desirable path with high velocities. The use of a control system on excavators can provide significant benefits in terms of improved quality and/or productivity.

The control system of the earthwork robot which is discussed in this chapter, enlarges the versatility of the hydraulic excavator by improving the accuracy of motions. A robot control system built into an excavator provides both short term and long term opportunities. On the short term, the robot control facilities enable fast and accurate motion control supporting the operator to trim surfaces with both a higher precision and a higher speed. On the long term, the robot control facilities enable automatic execution of (simple) earthwork tasks. Also a robot controlled excavator can be used as a medium-scale robot manipulator for construction applications where heavy objects need to be manipulated with precision. The development described in this chapter focuses on the short-term objective to support the operator with accurate earthwork.

This case study is closely related to a research project carried out at the Centre for Mechanical Engineering of TNO Building and Construction Research. This research project aims to develop an Excavator Control System (ECS). The ECS is a

system that assists the excavator operator for accurate trimming work by automatically controlling two arm motions during trimming operations. The ECS project provides the technology that enables standard hydraulic excavators to become computer controlled. The results of the ECS project form the base of the earthwork robot development discussed in this chapter.

The initial implementation and application of the system (i.e. the ECS) is not a robot according to the definition in chapter 1. Nevertheless the term earthwork robot is used. The reason for this is that the system that is discussed in this chapter is technically not different from a robot and can be used as a true robot. The full potential of all robot functionality is not used because of the robot-environment interactions that complicate full robotisation. However there exist earthwork applications where fully autonomous operation is desired. E.g. toxic soil handling or radioactive object handling.

The case study discussed in this chapter pursues two objectives. The first objective is to show how it is possible to implement a low-cost robot control system and hook this up to a standard excavator. The second objective is to evaluate how the presented theory on task instruction (chapter seven) can be applied for an earthwork robot.

The earthwork robot is to become an intelligent machine that knows *what to do where*. This *know what to do where* functionality supports the use of hydraulic excavators for accurate work. When a control system takes over the task of accurate motion control from an operator, the control system has to be informed about the desired excavation motions. Therefore earthwork design and earthwork robot control have to be integrated otherwise the problem is relocated but not solved.

The use of an earthwork robot provides several advantages over the conventional procedure.

- 1 A higher productivity and accuracy can be achieved because operations which require accuracy are performed automatically.
- 2 Communication and exchange of information between supervisor and operator can be made more efficient and less error prone because the operator can see the assignments on his cabin display.
- 3 It is no longer necessary for a surveyor to set out reference lines and surfaces from the design because the control system knows where the machine is relative to the design.

Given the advantages and potential benefits, the question that arises is "Why is computer control not yet used on excavators?". The main reason for this situation is the gap between the excavator robots and the industrial robot system. Significant differences are:

- *system characteristics*

Industrial robots are equipped with high quality servo type valves which have features such as actuator velocity feedback and load compensation built in. The hydraulic actuators on most older excavators do not have such features.

- *price level*

An industrial robot controller roughly costs between a quarter and half the price of an excavator. Including interfaces and installation these costs are even higher. These costs are not in proportion with the costs of an excavator. Commercial robot controllers are too complete and luxurious for use on excavators.

This chapter contains three sections. Section 9.2 describes the implementation of a computer controlled excavator, such as is developed in the ECS project. Section 9.3 describes what a earthwork task-instruction system looks like. Finally in section 9.5 the case is evaluated.

9.2 Prototype Hardware Implementation

The hardware development is part of the ECS project that is carried out by TNO Building and Construction Research. The primary function of the ECS system is to support the excavator operator with trimming operations, by automatic control of two of the three actuators. The operator controls the motion of the bucket arm, while the ECS controls the motion of the boom and the bucket. The boom motion is controlled such that the depth of excavation remains at the desired value. The bucket motion is adjusted such that the bucket cutting-edge remains at the desired angle relative to the trimming surface. This configuration allows the operator to control the speed of excavation, while the ECS controls the depth of excavation.

Within the prototype ECS implementation three subsystems are distinguished. These three subsystems are:

- an arm-pose sensor system
- an electric-hydraulic interface
- a motion-control system

Each of the subsystems is discussed in the following three subsections.

9.2.1 The Arm-Pose Sensor System

The principle of the arm-pose sensor used in the ECS is rather unconventional. A non-contact optical sensor is used to measure angles from a distance using a laser beam. Figure 65 shows the configuration. The transducer is mounted on the boom. The transducer emits a laser beam that rotates in a vertical plane parallel to the arm. On the cabin, the bucket arm and the bucket mechanism, reflectors are mounted. The reflections of the laser beam on the reflectors are received back in the transducer. The hardware of the transducer is identical to the CAPSY position measurement sensor, used in the drilling robot (see also page 133).

The transducer measures the angles at which reflections are seen. (α_1 , α_2 and α_3 in figure 65). The pose of the arm is calculated from the measured angles. The arm pose is defined by the three angles between respectively the excavator frame, the boom, the bucket arm and the bucket. The location of the reflectors and the sensor are additional parameters in the arm pose calculation.

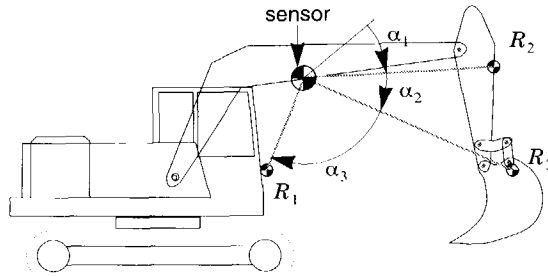


Figure 65 The principle of the arm pose sensor system. An angle sensor mounted on the boom measures the angles to a set of three reflectors (R_1 , R_2 , R_3) which are mounted on the cabin, the bucket arm and the bucket.

The reflectors are made of plastic tubes with a diameter of 5 cm. The tubes are covered with waterproof retroreflective material. The plastic tubes are connected to the excavator arm in a rigid metal clamp. When a reflector tube is damaged, a new tube can be installed in a few seconds.

The conventional method to measure the pose of a manipulator arm is to install angle encoders on each of the arm joints. The approach to use an optical sensor system has several advantages and disadvantages compared to the conventional encoder approach. The most significant advantages and disadvantages of the optical sensor are discussed below.

- The use of only one active sensing component on the excavator arm provides the advantage that there is no need for cables on the bucket arm. Although this may seem a insignificant advantage, practical experiences have proved that cabling on the outer end of the arm is sensitive to damage and wear. Although the reflector rods may seem very vulnerable to damage and dirt, experiences have proved that there are locations at the back of the bucket which seldom get dirty or damaged. The use of simple, easy to replace, plastic reflector rods, enables quick replacement in case of damage.
- An advantage of the optical system is that it can be installed and removed quickly. This is important to protect the system against theft and damage. It also enables the sensor system to be used on more than one excavator.
- An advantage of the optical system is that the measurement of arm member angles is less affected by clearances in the joints. When the angles are measured from a relative long distance, displacement of the arm pivot point has no significant effect on the measured angle. This in contrast to encoders which have their reference close by.
- A disadvantage of the optical approach is that the set-up of the system requires more parameters of the installation to be determined. Besides the length of the arm members, the locations of the reflectors and the sensor on the arm members have to be determined.

- A disadvantage of the optical system is that optical systems are delicate instruments that are generally not resistant to the severe shocks and vibrations that can occur on an excavator arm. Damping of the shocks and vibrations is needed.
- The disadvantage of the optical system is that it is not suitable for underwater excavation applications such as dredging. However, there does exist a solution that enables underwater excavation up to a limited depth. This solution uses a bucket angle reflector at the upper end of the bucket arm which is connected to the bucket by a rod or cable.

The performance of the laser sensor system has been investigated and demonstrated in a separate feasibility study preceding the development of the ECS. The feasibility study proved that an accuracy of the sensor system better than ± 1 cm standard deviation is realised in a prototype installation. In the study it was also demonstrated that vibrations and shocks that can occur on the excavator arm can be dampened effectively without sacrificing accuracy in normal use.

In order for the ECS to enable excavation to an absolute level, it is required that the elevation of the excavator itself is measured. This requires an additional measurement system. This measurement system can be a one-dimensional level-reference laser/receiver combination. A laser beam, rotating in a horizontal plane provides an elevation reference which is picked up by a receiver on the back of the excavator (See figure 66). In combination with an inclination sensor on the excavator body it is possible to calculate the absolute depth of excavation.

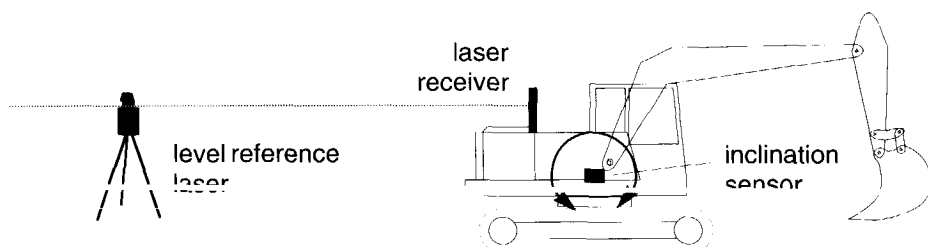


Figure 66 Digging depth measurement.

An alternative, more advanced approach is to use a three-dimensional position measurement system such as a Global Positioning System (GPS) receiver or a auto-tracking total station. Three-dimensional position measurement is essential when 3D terrain shaping tasks are to be carried out.

Figure 67 shows a picture of the prototype system installation on an Akerman H7Mc excavator with all system components labelled.

9.2.2 The Electric-Hydraulic Interface

Electrically-controllable hydraulic valves are needed in the excavator to allow the control computer to take control of the machine. Such valves have to be installed on many types excavators. On most excavators, including the used Akerman exca-

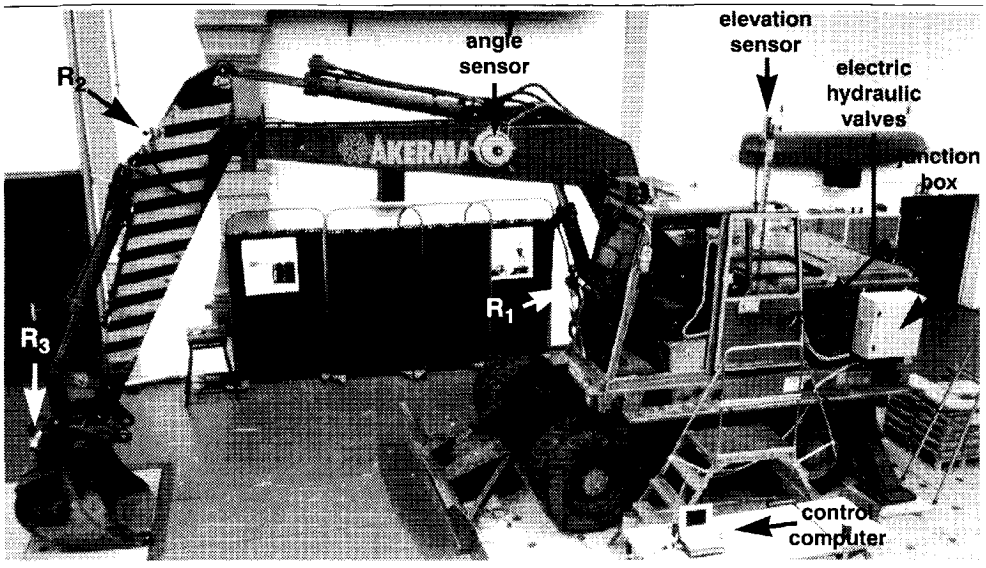


Figure 67 Installation of the ECS on an Akerman H7Mc excavator.

vator, the joysticks regulate control pressures which regulate the opening of the main hydraulic valves. The main valves regulate the oil flow from a pump to the hydraulic cylinders on the arm. Such a system is called a pilot-pressure operated system. Figure 68 shows a schematic diagram of such a system for one actuator.

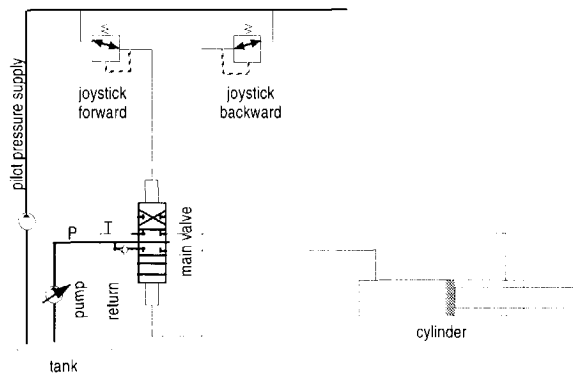


Figure 68 Schematic diagram of pilot pressure operated hydraulic system such as used in most small to medium sized excavators.

The latest, larger model excavators already have electrically operated valves. In these machines electric signals from the joysticks control a solenoid on the main hydraulic valves. External control of such excavators is much simpler because modifications to the hydraulic system are not needed.

All excavators, using the pilot pressure operated valve control, can be modified in a similar manner, to add electrically-operated valves. Off-the-shelf electrically-operated pressure-regulating valves can be built in parallel to the joysticks. To avoid conflicts between the joystick and the electrically-operated valves, switch valves are used. One pair of switch valves switches between joystick control and automatic control, while a third valve determines the direction of motion. The schematic diagram in figure 69 shows how the electrically operated valves can be included in the system.

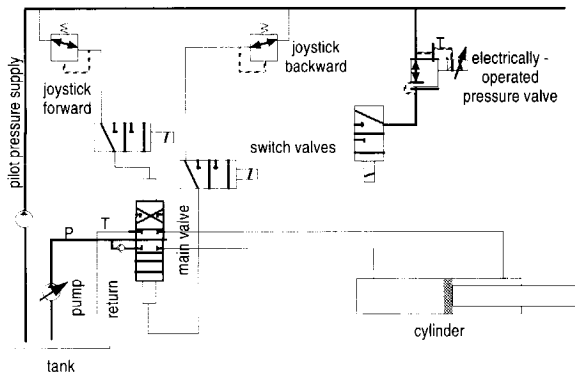


Figure 69 Schematic diagram of hydraulic system with electrically operated valves included.

For each motion function (boom, bucket arm, bucket), a set of electrically-operated valves is needed. In the ECS prototype installation where the boom and bucket motion are controlled, two pressure regulating valves and six switch valves are used. The picture in figure 70 shows the installation of the valves on the excavator.

On many excavators the actual hydraulic system is more extensive than explained in figures 68 and 69. Parallel-switched valve banks are used to divide the available hydraulic power from three pumps. The system is designed to provide, both operating speed and operating power without wasting fuel. Unfortunately these optimizations cause mutual interferences between actuator motions. This is undesirable for automatic control. Therefore the excavator hydraulic system has to be set in the correct mode in which oil-pump supply optimization is inactive.

9.2.3 The Low-Level Control System

The computer hardware for the low-level control system is an off-the-shelf PC with a 90 MHz Pentium™ processor. This PC is equipped with a multi-purpose input/output interface board. The signals to and from the interface board are conditioned, amplified and optically isolated in a separate interface and junction box (see figure 67).

The PC runs the Windows '95 operating system and a special control program called 'eXcavator Control Program' (XCP). The XCP program performs the following functions:

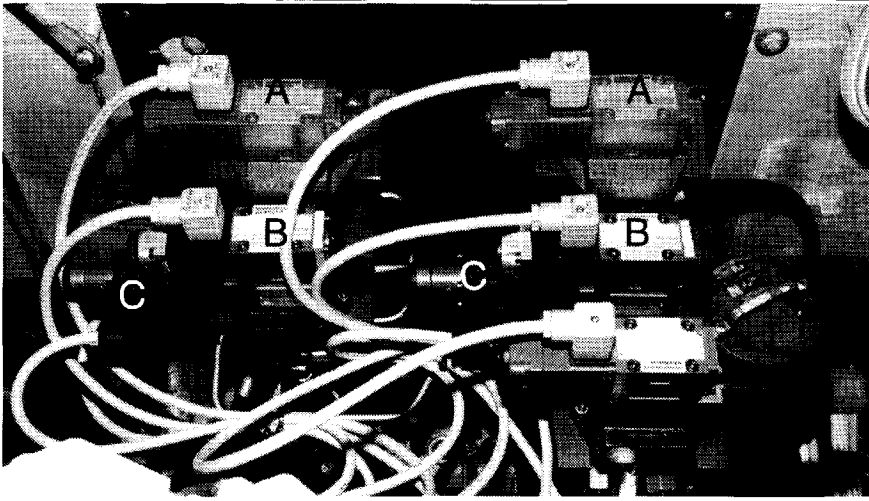


Figure 70 Picture of electrically operated valves installed in prototype ECS system on Akerman excavator. Valves A switch between automatic and manual. Below the two A-valves there is another pair of A valves which is not visible. Valves B switch the direction of the actuator motion. Valves C are the proportional pressure regulating valves.

- *input/output-signal processing*

Measurements from the angle sensor are communicated through a serial communication protocol. Other sensor readings are available through analog to digital interfaces.

- *signal conversion*

Some of the signals that are measured need to be converted into the signals that are required for the control. The XCP program converts the measured arm member angles and rotational velocities into actuator lengths and velocities using the arm geometry.

- *actuator control*

The primary function of the XCP program is to control the boom and bucket actuators to realise a straight line excavation motion of the arm. In a feedback loop, the boom and bucket pilot-pressure valve outputs are updated to control the motion as accurately as possible. How the motion control is implemented is discussed further on.

The state of the control program and the readings of the sensor systems are displayed in the graphical user interface of the XCP program. Figure 71 shows what this graphical user-interface looks like. This user interface is only for development purposes and is not meant to be seen by the operator.

The principle of the control strategy is shown in the diagram in figure 72. The pose of the excavator arm is measured by the angle sensor. The measured angles are converted into actuator lengths. The bucket-arm actuator length is fed back to the *motion planner* where the desired boom and bucket actuator lengths are calculated. The function of desired excavation depth is input of the motion planner. The

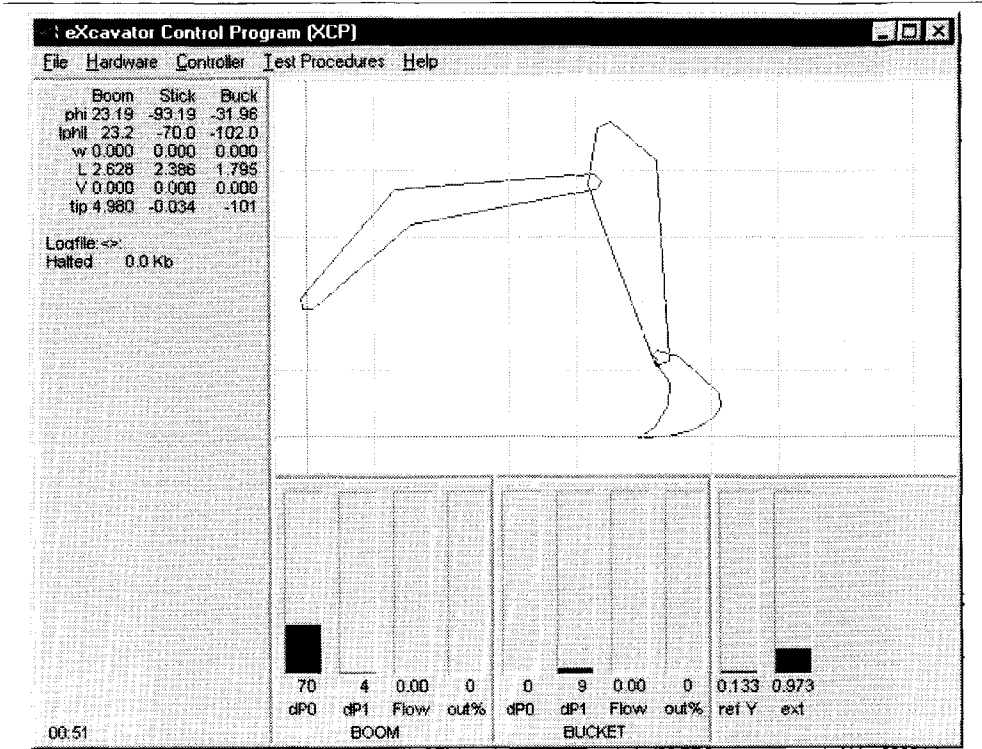


Figure 71 Screen snap shot of eXcavator Control Program status presentation. This user-interface is only for development purposes and is not meant to be seen by the operator.

(measured) boom and bucket actuator lengths are fed back to the *boom actuator controller* and the *bucket actuator controller*. These controllers control the motion of both actuators through the electric hydraulic interface.

Because of the power in a hydraulic excavator, care must be taken to avoid erroneous abrupt motions of the arm. Such abrupt motions can injure people and cause damage to objects. The system has been designed to be safe. The operator has to hold the activation button during use of the system. As soon as he releases the button, the system switches back to manual control mode. The risk of accidents caused by technical problems in the control software or control computer is reduced to an acceptable level.

9.3 Earthwork Task Instruction

As mentioned earlier, the type of tasks for which the earthwork robot is to be used, are tasks where accuracy is important. Most of the tasks which require a high accuracy, are finishing tasks such as the trimming of surfaces. These surfaces can be part of an embankment slope, road, ditch, canal bank, construction pit etc. The

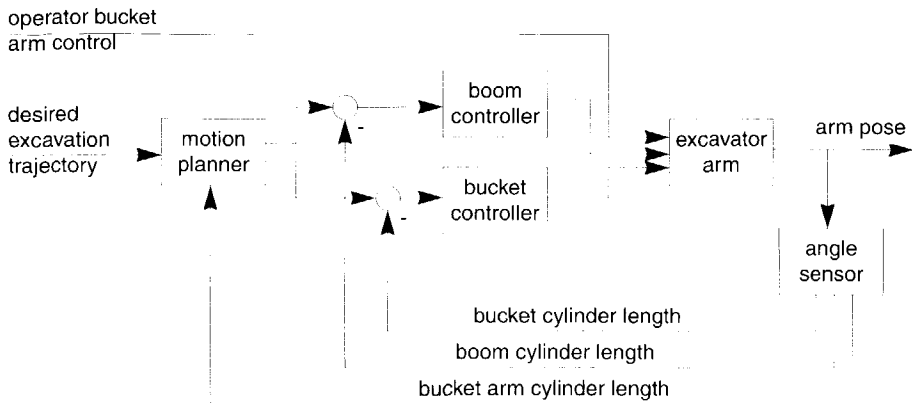


Figure 72 Diagram of control loop of excavator arm motion. The pose of the arm is measured by the laser sensor. This measurement is fed back to the motion planner which calculates the desired boom and bucket cylinder lengths. These values are compared with measured bucket and boom cylinder lengths to control the motion of the cylinders.

primary function of the earthwork task-instruction system is to manage the (design) information that is needed by the control system. This information is primarily the shape of the terrain to be realised.

This section discusses what an earthwork task-instruction system should look like. Due to the status and objectives of the hardware development project, there is no operational prototype implementation of the task-instruction system discussed in this section.

Earthwork Tasks

In this chapter the term *earthwork* is used to refer to the set of activities that realise some three dimensional shape of a terrain. Just as any other construction activity, earthwork tasks require preparations in the form of design and planning. In general an earthwork project involves the following activities:

- The 'as is' terrain is surveyed and digitised and stored.
- The design of the desired terrain is compared with the surveyor data to calculate the amounts of soil to be removed, filled out or relocated. These quantity calculations are used to assess the project costs.
- At the site, the significant terrain reference points and lines are surveyed and marked using stakes.
- The rough shape of the terrain is realised. Soil is removed or supplied where needed.
- The terrain shape is finished. Important terrain elements such as edges are indicated using stakes and poles. Rotating-laser systems are used as a reference for surfaces and elevations.

The earthwork robot simplifies the last task, making it more efficient. Operator will remain indispensable for *unstructured operations* that are part of earthwork tasks. Unstructured operations need some form of improvisation to deal with unpredictable circumstances that can occur. E.g. digging a trench without damaging pipes or cables. With the current state-of-the-art in robot technology it is not realistic to try to automate such unstructured operations.

The earthwork task-instruction system is a system that knows what *knows what to do where*. In order to realise this functionality, the system has to be able to:

- 1 import terrain shape designs (from a project model)
- 2 let the operator select which part of the design he is working on
- 3 set the motion control system at the correct depth of excavation given the location of the machine.

The earthwork task-instruction system is envisioned as an on-board system which has a display in the excavator cabin which shows the operator technical drawing-like presentation of the site. On this drawing he can see what his current position is, what has been done, and what has to be done. The presentation can include several views allowing the machine operator to see all relevant information. Figure 73 shows an example of such a visualisation.

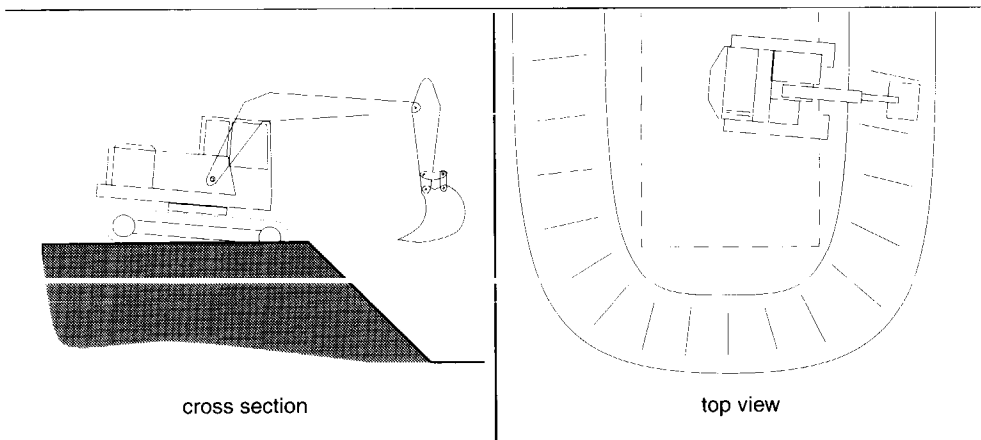


Figure 73 Sample visualisation of the display of the task-instruction system. The display should show a number of different views of the current location of the excavator in relation to the desired terrain shape.

Depending on the location of the excavator and the direction in which the arm is pointing, the task-instruction system figures out what the cross section of the terrain is and what motion trajectory is to be made by the excavator bucket.

An earthwork task-instruction system provides several benefits which make the system worth its investment. The primary benefit is that work methods are simplified because surveying and earthwork are integrated. Some advantages of an earthwork task-instruction system are:

- 1 It is no longer necessary for surveyors to mark points in the field using stakes. The task-instruction system measures the 3D-position of the machine and shows terrain markers to the operator on a display.
- 2 Because stakes are no longer needed, a potential source of errors caused by stakes getting relocated or lost, is eliminated.
- 3 The trimming operations that are performed by the control system, are carried out faster and more accurate by the automatic system than by hand.
- 4 There is no need for manual setting or programming of the excavator control system which eliminates potential errors and saves labour.

In this section it is discussed how a task-instruction system with the above discussed functionality can be implemented using the reference architecture presented in chapter seven. In section 9.3.1 it is discussed what the task-instruction system architecture looks like. In the succeeding subsections the subsystems in the task-instruction system are discussed.

9.3.1 Task-Instruction System Architecture

The architecture of the earthwork task-instruction system is a partial implementation of the reference architecture presented in chapter seven. Because the earthwork robot is not a fully autonomous system, the task-instruction system does not need to prepare a plan how the task is to be fulfilled. Therefore the *task planning* and *operation sequence planning* subsystem are not part of the earthwork task-instruction system.

The IDEF₀ diagram in figure 74 shows the overview of the earthwork task-instruction system. The first subsystem is the *task specification* subsystem. The second subsystem is the *arm motion planning* subsystem. Part of the function of this subsystem has already been discussed in section 9.2. Finally the *plan execution* subsystem continuously establishes the current situations, and activates the motion planning subsystem to produce the correct control commands for the low-level controller. Each subsystem is discussed in more detail in the following subsections.

9.3.2 Earthwork Task Specification Subsystem

The earthwork task-specification subsystem performs two functions: (1) import of project model information, and (2) selection (by task instructor) of a terrain section and/or earthwork feature to be realised. How both functions are to be fulfilled is now discussed.

Import of Project Model Information

Information about the desired end result is essential for all task-instruction systems. It is assumed that design information is accessible in a project model database. In other words, the task-instruction system has all the needed semantical information about the design of the earthworks.

The project-model database contains the designed shape of the terrain to be realised. The conceptual model of the information that can be stored in a earthwork

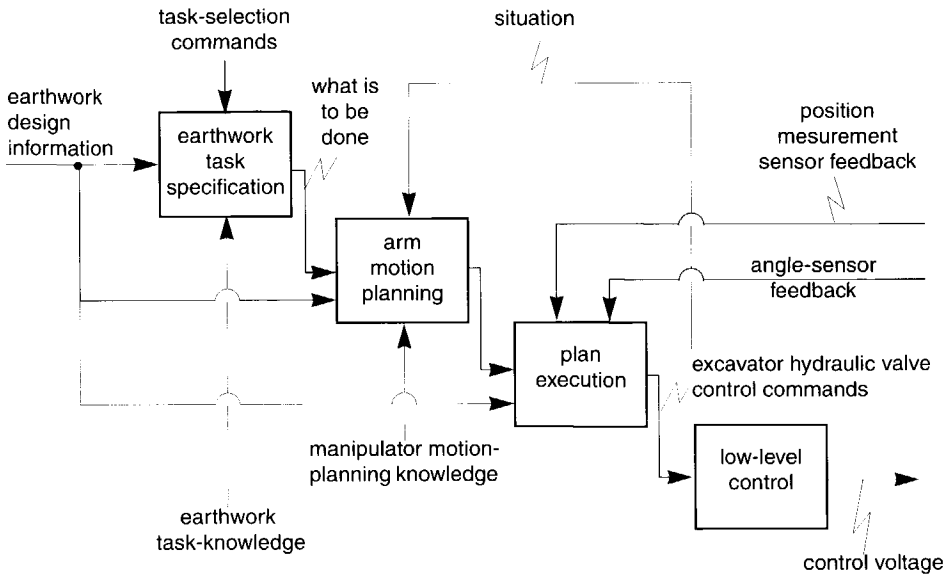


Figure 74 IDEF₀ diagram of earthwork task instruction sub processes and information flows.

design project model is shown in the EXPRESS-G diagram in figure 75. An earthwork task-result is composed of a number of earthwork surfaces to be realised. The shape of each earthwork surface is described by a bounded surface. The representation of product shape is standardised in part 42 of the ISO standard 10303 (STEP) (ISO 1994c). This standard provides a generic representation for storage of topology and geometry information.

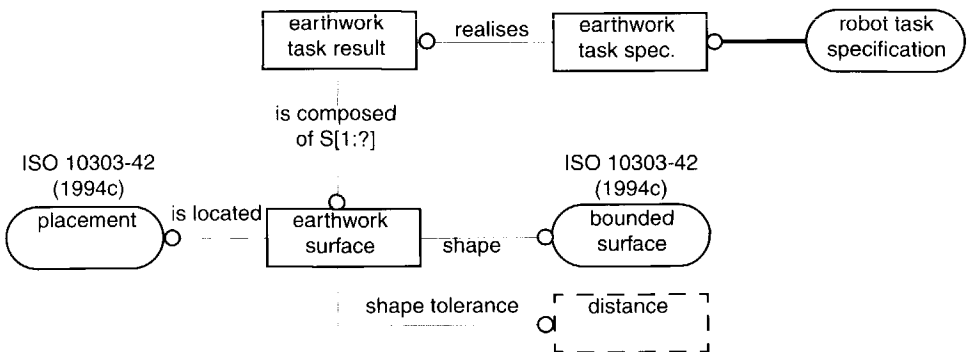


Figure 75 EXPRESS-G diagram of earthwork design information in project model.

The accuracy required for earthwork surfaces depends on the type of project. An attribute *shape tolerance* specifies how much deviation is allowed between the ‘as

designed' and 'as realised' shape of the earthworks. This tolerance can be different for each earthwork surface to be finished. E.g. the tolerances on a road foundation are much lower than for a ditch embankment.

Specification of Terrain Shaping Task

The assignment of tasks can be made by a selection one or more earthwork surfaces to be shaped. Earthwork objects can be composed of different layers of sand and soil each of the surfaces between layers can be selected. Each earthwork surface can be selected by point-and-click actions on a display. It is the function of the task-specification system to present the earthwork surfaces on a display in an easy to understand manner. A suitable presentation form is probably a technical drawing with several 2D views. It is important to keep the task-instruction interface as simple as possible because the machine operators in the field have little or no experience with computer screens and user interfaces.

The project-model information is down loaded into the task-instruction system on the excavator by the project manager. The communication medium can be a magnetic storage medium such as a removable disk or it can be some kind of wireless link. In his machine, the operator selects the correct earthwork surface to be finished. On his display he can see the location of his machine in relation to the earthwork design. When he activates the robot controller, the machine automatically follows the correct cross section.

The task-instruction system also supervises the product quality. A log of the 'as realised' earthwork-surface shapes can be kept to prove the product quality to the client.

9.3.3 Motion Planning and Plan Execution

Motion planning is performed 'on the fly' because the current position of the machine is needed to calculate the correct excavation trajectory. This position and orientation of the machine is controlled by the operator. The plan-execution subsystem invokes the motion-planning subsystem to update the excavation trajectory as the machine changes its position and orientation.

The EXPRESS-G diagram in figure 76 shows the data structure which is updated by the plan execution subsystem. Every excavation situation is characterised by a *machine position* and *machine orientation*. An *excavation trajectory* is derived using the specified earthwork surface. The 'excavation plane' that is defined by the machine location and orientation is intersected with the earthwork surface shape to produce the excavation trajectory.

The excavation trajectory is converted into actuator velocity and length set points using the inverse kinematic transformation of the machine such as discussed in section 9.2. This inverse transformation is dependent on the configuration and geometry of the excavation arm.

Because the plan-execution subsystem establishes the current situation it is possible to produce an activity log which enables the feed back of earthwork produc-

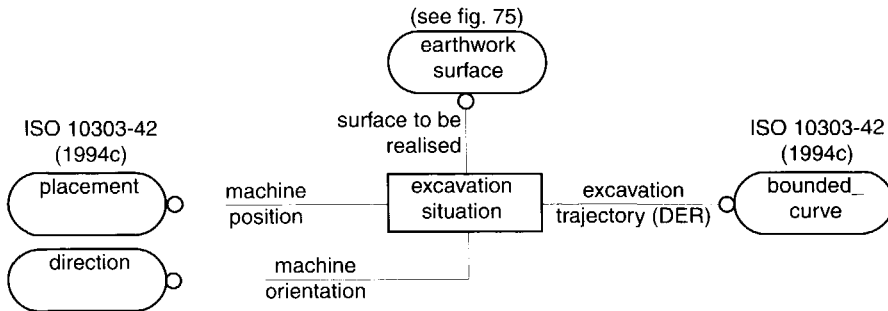


Figure 76 EXPRESS-G diagram of information that describes an excavation situation for which motion planning is performed.

tion experience information to improve the accuracy of costs estimation for future projects.

9.4 Benefits

The robot control system as discussed in the preceding sections, is a system that helps excavator operators to control their excavator. Because the robot controller takes over the motion control of the excavator arm, accurate excavation along pre-determined excavation trajectories is a simple task.

Benefits of the earthwork robot control system are:

- *increased productivity in earthwork finishing operations*
- *improved quality by more accurate earthwork surface shape*
- *reduced risks of mistakes because stakes are not needed*
- *possibilities for realisation of more complex earthwork shapes*
e.g. golf course.
- *possibility to use less experienced operators for more complex tasks*
Experienced excavator operators will probably be able to work as fast and accurate without the help of a control system. However, experienced operators are expensive and sometimes difficult to find. The availability of an earthwork robot enables contractors to use less experienced, and less expensive, operators for their projects.
- *less error prone communication between supervisor and machine operator*
Because ambiguous references such as stakes and marker poles are not longer needed and because interpretation of drawings is no longer needed, a potential source of errors is eliminated.

Special applications provide the best opportunities for the introduction of such control systems. Such applications are the applications where a control system is essential. Such applications are applications where the operator is not able to see the surface which he is finishing, e.g. underwater excavation, dredging.

Another class of applications for an autonomous robot, based on the earthwork robot hardware are applications where operators are undesirable because of the environment. Such environments exist in a number of areas:

- excavation in pressurised underground construction, e.g. tunnels, basements etc.
- handling of soil at contaminated sites or at treatment plants.
- military applications. e.g. excavation of undetonated explosives, repair of roads and runways in dangerous areas
- handling of radioactive objects or objects in radioactive environments, e.g. nuclear plant disassembly

In these applications, the use of human being as operators is only possible using remote control facilities. Such facilities complicate accurate control in such a degree that robot control (in combination with remote control) is indispensable. In such applications costs are not so much an issue. These applications can provide a sales momentum for robotic excavators.

9.5 Evaluation

The case study described in this chapter shows an example of a robot development project where currently available technology is used and applied on a piece of equipment that is used in almost every building project. This case study has provided valuable knowledge and experience about the conversion of existing equipment into a mechatronic manipulator. The main lessons learned from this case study is that it is technically possible to convert a mechanical excavator into a mechatronic manipulator using available sensor and control system technology. In the analysis of the technological gap between the construction industry demands and the available robot technology (chapter 5), it was concluded that manipulator design is one of the problems that hinders the implementation of construction robots. The case study in this chapter demonstrates how this gap can be resolved using standard building machines and off-the-shelf industrial components.

It was also demonstrated that task instruction is not only for autonomous robots. Also less advanced operator-controlled systems need some form of instruction system to manage the information needed by the robot controller. It is unavoidable that every automation step requires more information to be transferred to be available to the robot. The more advanced and autonomous a system is, the more information is needed. The theory of task instruction as presented in chapter 7, provides a strategy for the integration of design and construction. This integration is an essential ingredient for construction robotisation because without this integration construction tasks are only substituted by programming tasks.

This second case study also shows that an inherent side effect of construction automation, is that work methods and responsibilities change. The earthwork

robot discussed will eliminate the need for stakes and change the division of responsibilities between machine operator and site superintendents.

In section 9.3 an implementation of an earthwork task-instruction system is described. This implementation is not a full instantiation of the reference architecture presented in chapter seven. Not all subsystems distinguished in the reference architecture are present in the implementation for this case study. Some additional remarks about the implementation discussed in this second case study are:

- The use of an open, standardised representation for earthwork designs is essential for efficient transfer of design information between the engineers to the earthwork robot at the site.
- The use of semantical project information enables interaction with the machine operator at a higher abstraction level (embankments ditch, etc.). This makes the interaction more effective and therefore less error prone.

10

Conclusions and Recommendations

The building industry is undergoing several changes that affect the industry's production. The complexity and scale of newly designed buildings keeps increasing, while construction processes are required to become more efficient, less time consuming, more environmentally friendly and less dangerous and unhealthy. Several methods and technologies can be adopted to cope with these changes. Robot technology is one of the technologies that might play a role. Some of the potential benefits of robots are:

- robots can produce at lower costs than humans
- robots can work longer hours per day
- robots deliver work of a high and constant quality
- robots can do work that is dangerous or unhealthy for humans
- robots can do work for which it is difficult to employ workers

Regardless of these benefits, robots are not used in construction processes, except for some (Japanese) experimental projects. The reason why robots are not used in the building industry, can be found in the following special characteristics of construction processes and projects:

- building industry products are assembled at sites and not in factories because the products are large and heavy which makes them difficult to transport
- robots have to work along their workpiece because the production takes place at building sites
- building industry products are one-of-a-kind products
- the responsibilities in construction projects are divided amongst different partners, i.e. the client, architect, contractor, subcontractor and governmental organisations.

The currently available commercial robots are designed to be used in mass production in factories for small to mid size products. These robots cannot easily be used in construction processes. Results of technology forecast surveys held in Japan and Germany show that 71%, respectively 60% of the construction experts believes that the use of robot technology in construction processes is hindered by technical problems (BMFT 1993; NISTEP 1992).

This thesis analyses in which technological areas, additional R&D is most needed. Section 10.1 summarizes the conclusions from this research. One particular topic was studied in depth, namely the instruction of construction robots. Section 10.2 discusses the main topics of the developed strategy for realisation of task-instruction systems. The analysis and developed strategy are evaluated in two case studies which are discussed in section 10.3. Section 10.4 contains an additional discussion about the future of construction robotics. Finally, section 10.5 summarizes the recommendations for further research.

10.1 Technological Problems for Construction Robotics

The first question formulated in this thesis was: which technologies are demanded for realisation of successful construction robot applications? To find an answer to this question, the subject of construction robotics is examined from the following two points-of-view:

1 *building industry point-of-view*

Where are the best opportunities for the application of robots?

2 *(construction) robot technology point-of-view*

Which technologies are available and what lessons can be learned from existing experimental construction robots?

The results of both investigations are discussed below.

Opportunities for Robotisation

The *robotisationability* of seven clusters of construction subprocess are analysed. These seven categories (as distinguished by CI/SfB Ray-Jones et al. 1976) are:

- ground and substructure works
- erection of building carcass (primary elements)
- completion of building structure (secondary elements)
- finishing of building structure
- installation of piped services
- installation of electrical services
- installation of fittings

The robotisationability of each clusters is evaluated using six aspects, believed to be of influence. The performance-grade assigned for each aspect is multiplied by an aspect weight factor to determine the overall score of a cluster. The aspects that have a positive contribution to the robotisationability, are:

- low task complexity (weight 48%)
- high costs of manual task execution (weight 16%)
- tasks are dangerous or unhealthy for humans (weight 3%)
- tasks involve repetition of similar operations (weight 16%)
- high and/or constant quality is required (weight 12%)
- the process is already mechanised (weight 5%)

The analysis results indicate that the *erection of the building carcass* is the category that provides the best opportunities for robotisation. Second best scores *ground and substructure works*. *Installation of services and fittings* is the least suitable for robotisation.

The State-of-the-Art in (Construction) Robotics

Since 1983 experiments with construction robots have been carried out. Four generations of construction robots are distinguished. These generations differ from each other by the influence of the robotisation on the construction process. The four generations are:

- 1 existing machines equipped with sensors and control systems
- 2 new machines for support of conventional work methods
- 3 autonomous machines (robots)
- 4 new construction methods specially adapted for the use of robots

Of each generation several prototype robots exist. Since a number of years, the large Japanese contractors are putting lots of effort in experiments with fourth-generation building systems for the erection of high-rise buildings. These fourth-generation systems demonstrate a top-down strategy in which the design, construction methods and planning are adapted to efficient and effective use of available robot technology.

The experiences in trial projects show that construction-process changes are needed to be able to use available robot technology. Enhancement of the available robot technology is desirable. The performance of a robot in general can be defined using the following six robot performance aspects:

- robot manipulator performance
- robot end-effector characteristics
- material feeding
- control
- sensing capabilities
- mobility

Limitations in the state-of-the-art robot technology are encountered in the fields of manipulator technology (lightweight in relation to the load-carrying capacity), control (efficient instruction) and sensing (position measurement).

Conventional robot manipulators have a limited load-carrying capacity and work range, but a relative high mass. This is because the manipulator is required to be rigid to eliminate unwanted dynamic effects. This approach is not suitable for construction robots. Construction robot manipulators are required to have a long reach, high load-carrying capacity and limited mass. An approach to this problem is to use non-rigid manipulators in combination with sensors and new control strategies to obtain the desired accuracy.

Robot operations in construction applications do not consist of repeated, fixed motion patterns as in manufacturing industry applications. The combination of the facts that construction robots move along the product, and that the construction industry produces one-of-a-kind products, makes current motion-oriented robot programming unsuitable. The building industry needs *task instruction*. Task instruction allows a robot to be instructed in terms of the problem to be solved or the goal to be achieved.

Position measurement is a sensing capability which is essential to most on-site robot applications. Especially autonomous mobile robots require position measurement sensors for their guidance. Process automation is virtually impossible without accurate position measurement of the machine which (automatically) performs tasks. Several types of position measurement sensors are available but their areas of application are limited.

Conclusion

The best opportunities for use of robots in construction processes, seem to be in the erection of building carcass. Recent Japanese fourth generation robot systems demonstrate how available robot technology can be used to implement factory like assembly of the building carcass of high rise buildings. The building design and the construction process are adapted such that available robot technology can be applied.

Limitations in the current state-of-the-art technology are in the areas: manipulators, sensing and control. The subject of task-instruction is selected for further research in the second half of this thesis. The research goal is to develop a concept for efficient task instruction for construction robots.

10.2 Task Instruction for Construction Robots

Available robot-programming methods are unsuitable for construction applications. The nature of the building-industry production requires an instruction method that allows a robot to know what has to be done, with the least possible instruction effort. Time-consuming instruction is costly and thus reduces the economic benefit for tasks where the repetition rate is limited. This is especially relevant for the building industry where one-of-a-kind products are made. Another aspect why available robot programming methods are unsuitable is because construction robots are required to relocate themselves around or through the product instead of the other way around, as in factories.

In contrast to the low repetition rate of construction tasks, there is the characteristic that most construction tasks are semi-unique. This semi-unique nature allows the operations of specific types of tasks to be specified in a template *process-type model*. Such template process-type models can be transformed into task-specific robot-process models, using information about the design of the product or part to be realised.

The hypothesis is that methods and techniques for the area of Product Data Technology (PDT) can be used to implement the above described idea to use process-type models. PDT is the technology that is being developed for exchange of product and process data between different computer systems and between different types of computer applications (design, structural engineering, cost calculation, energy calculation, etc.).

The primary reason to use PDT is because it provides a solution for the integration between the building design process and robot instruction. It is assumed that design information is available for a task-instruction system in the form of a project model. A project model is the PDT term for an application and system independent database, containing all technical information about a project.

A Task-Instruction System Architecture

The proposed task-instruction system architecture distinguishes the following five subsystems:

1 task-specification subsystem

In the task-specification subsystem it is specified *what* the robot has to do. This is done by selecting the building parts, that have to be realised or treated, from the project model. The task-specification subsystem verifies whether the robot is able to fulfil its assignment.

2 task-planning subsystem

The task-planning subsystem transforms the template process-type model into a project-specific process plan, containing all operations that are to be performed to fulfil the assigned task.

3 operation-sequence planning subsystem

The operation-sequence planning subsystem evaluates the generated process plan and determines in what sequence the operations are to be executed.

4 motion planning subsystem

In the motion-planning subsystem it is determined what robot motions are required for each operation. Information about the shape and locations of objects is used to generate motion patterns for each operation.

5 plan-execution subsystem

The plan-execution system monitors the correct execution of the prepared plans. Plans are, by definition, based on assumptions about situations. The plan execution subsystem verifies the correctness of planning assumptions, using sensor readings. If assumptions prove to be incorrect, the plan execution subsystem can re-activate the sequence-planning subsystem to try to resolve the problem. If this fails, operator assistance is needed.

The IDEF₀ diagram in figure 35 on page 92 shows which information flows go in and out of each of the subsystems. Also it shows what types of knowledge are used by the subsystems.

Representation of knowledge is an important aspect in the proposed architecture. Most important is the knowledge in process-type models which specifies how a certain type of task is to be fulfilled. The project-specific information in a project model is combined with the process-type model to produce the task-specific plan containing all operations needed to fulfil the task.

Two types of knowledge are distinguished in process-type models:

- *ontological knowledge*
knowledge about the types of objects and processes that are distinguished
- *inference knowledge*
Inference knowledge is knowledge that describes how information can be derived from other information, e.g. how process-planning information can be derived of product-design information.

PDT provides powerful methods and languages for the representation of ontological knowledge, namely EXPRESS and EXPRESS-G. However, PDT does not provide any methods for representation of inferential knowledge. This is no surprise, knowing the history and objectives of the PDT developments. Representation of inferential knowledge is possible using extensions of PDT methods and languages. A first step for such a development is described in this thesis. However, further developments are needed.

10.3 Two Cases of Construction Robot Developments

The proposed architecture for task-instruction systems has been evaluated in two cases. The first case concerns the development of an autonomous drilling robot. This case shows the development of the robot, its integration in the construction process, and the realisation of a task-instruction system. The second case concerns an earthwork robot. The case shows how the earthwork robot is implemented using a standard excavator. It is also discussed how earthwork tasks are handled by the task-instruction system.

Drilling Robot

The drilling robot is a prototype, third-generation robot that is specifically designed for one type of task, namely the drilling of holes in concrete floors. This type of task is used in the following two tasks that occur in the construction of a railway tunnel: (1) the drilling of holes for rail fixtures, (2) the drilling of holes for starter bars. A task-instruction system is developed for the first robot task.

The tasks of drilling holes for rail fixtures requires accurate position measurement and relocation by the robot. Information about the rail-fixture locations is essential. The process-type model in the task-instruction system distinguishes the following types of robot operations (ontology): (1) relocation of the robot from track

section to track section, (2) relocation from fixture location to fixture location, and (3) the drilling of a pair of holes for one fixture. The rail-fixture pattern is for a large part irregular because of the curves in the tracks and because of the segmentation of the tunnel in 20 m sections.

The implementation of a task-instruction system for the drilling robot demonstrates how the proposed architecture is to be used. The task-instruction system provides the benefit that different persons, responsible for different aspects of the robot's task, can set and change the aspects they are responsible for. E.g. the robot operator (responsible for the robot on site) can change the work sequence of the robot without being able to change fixture locations.

Earthwork Robot

The earthwork robot is a first-generation robot, based on a commercially available hydraulic excavator. Hydraulic excavators are very versatile machines. However, for accurate earthwork finishing they are not always the most suitable. Only more experienced operators are able to produce accurate earthworks at reasonable production rates.

Computer control systems are much better at motion control than human operators. A control system can take care of earthwork-finishing tasks autonomously, or the control system can assist the human operator. This case study demonstrates how a standard excavator is converted into a robot system which can fulfil both roles. The machine is equipped with a control computer, a sensor systems to measure the arm pose, and electrically controllable hydraulic valves that form the interface between the control computer and the excavator.

A task-instruction system is needed to inform the control computer to know what the desired earthwork shape is. This function is needed for both the autonomous operation and the semi-automatic operation. A terrain design contained in a project model, is imported into the task-instruction system. The task-specification subsystem allows terrain model areas to be selected for task specification. The control computer takes over the excavator control such that the excavation bucket follows the desired terrain shape during excavation operations. External markers, such as stakes, are no longer needed. This is also valuable in semi-automatic operation. In this mode, task planning and sequence planning is done by the operator instead of by the task-instruction system.

Both cases have demonstrated the implementation of construction robots using available technology. The second case has exemplified how existing machines can be converted into first and/or second generation construction robots. The robot control technology enables excavators to be used for tasks where accuracy is important. Task-instruction systems are needed for integration of the robot with its interacting design, planning and preparation activities.

10.4 Discussion

The presented architecture for task-instruction systems provides a strategy for integration in the so called *life-cycle dimension*. This direction involves integration of robotic construction with its preceding stages of design and planning. When robotisation becomes successful and more than one robot is used per site, new problems emerge. A need for integration between *islands of robotisation* will emerge (i.e. communication and cooperation between robots). The research in this thesis does not deal with this integration problem. Further research will be needed to cover integration in other directions than the life-cycle direction.

A recent development that stimulates the development of integration technology, is the Internet. Currently an increasing amount of software supports open, vendor independent Internet 'standards' for information exchange. Even system independent programming languages, Java and Javascript have been developed. These Internet technologies can be extremely useful in the integration in other areas such as the building industry. Further research on the use of Internet technology for building industry integration purposes is recommended.

The introduction of robotics in the building industry requires both a top-down and bottom-up strategy. A top-down strategy is needed to manage the required changes that are needed for successful robotisation. This management process includes the formulation of plans for the changes that are desirable for successful robotisation. These desirable changes include:

- organisational changes in work methods and responsibilities to change conventional construction into robotic construction
- design changes to allow building components to be handled by robots
- system integration to allow information to be exchanged between computer systems used within an organisation and within projects
- changes in the division of work and responsibilities between project partners
- social changes, to change the attitude towards automation, work methods, responsibilities, work hours etc.

Top-down introduction of robotics may not be successful in the European building industry. A *bottom-up* and *evolutionary* introduction is probably a better strategy. The reason for this is that top-down introduction of robotics requires many changes at once. There is a risk that changes are not understood and accepted. Small steps, one at a time are sometimes needed to let people get acquainted with new technology and see its possibilities and opportunities. Eventually these small steps forward should lead to a substantial increase of efficiency such as planned in a top-down strategy.

An opportunity for robot technology can be found in applications for special projects where human involvement is unacceptable or impossible because of the dangerous or unhealthy nature of the task. In such projects, the costs of robots are less significant because alternatives are not available. Such applications are scarce but they can be found in the building industry in underwater or under-

ground environments and in high rise buildings. Outside the building industry special opportunities for construction robot alike equipment can be found in dismantling of nuclear plants, treatment of toxic waste or military applications (undetonated explosives). New potential robot applications can be expected as a result of the tightening of regulations for labour conditions.

A particular bottom-up approach that is believed to be potentially successful, is the enhancement of the current construction equipment with electronic sensing and control equipment. The benefits of electronic sensing and control equipment are improvement of productivity and product quality. Such an approach does not directly result in robots, however it is the first (evolutionary) step from mechanical equipment to mechatronic equipment. The benefits of this approach are that it requires limited investments (compared to new types of equipment) and it allows workers become familiar with computers and robot technology.

An important role can be played by the material suppliers. In order to increase the market share of building products, material suppliers can use robot technology to lower the costs of handling of their materials and products with the objective to make them more competitive. For example, suppliers of tiles can offer their customers the services of a robot that places the tiles at a competitive price. Due to economy of scale, material suppliers have better economic perspectives for robot development initiatives. User-independent solutions for robot instruction and exchange of information are especially important in this area of application because many users should be able to work with such robots.

10.5 Recommendations

The leading standardisation efforts for product data technology (PDT) within the International Standards Organisation (ISO) do not provide a suitable representation for the storage and exchange of inference knowledge. Given the priorities in the development of this standard, this is no reproach. However further research and development of neutral, standardised inference-knowledge representation formats is recommenced. Standardisation of knowledge representations is not only of value for the implementation of task-instruction systems, but also for other purposes where exchange and formalisation of construction knowledge is desired, e.g. conformance checking or process control and planning.

The above recommendation is part of the larger scope of the objective to integrate construction processes and computer systems used in the building industry (i.e. computer integrated construction). Construction robots should become part of the computer-integrated-construction 'virtual factory'. Researchers currently working on the integration of computer systems in design and planning, should realise that this information is also to be used for construction robot instruction and control.

The task-instruction reference architecture presented in chapter 7 is only a first step in the development process of intelligent construction robots. Further research and development on this subject is recommended. It is believed that task

instruction is an essential aspect of construction robot technology. The subject of instruction should not have a lower priority than the hardware implementation.

The development of effective and efficient robots is a difficult engineering problem. Also the introduction of robots in construction processes requires many different aspects to be evaluated and issues to be resolved. Also the costs of failures in robotisation are high. It is believed that simulation systems are valuable tools to prove the feasibility of specific robot applications and to find solutions for robotisation issues. Some issues that could very well be investigated using simulation are:

- *robot configuration design*

Simulation at robot level allows a number of alternative robot designs to be evaluated on their performances. Such simulations help to find good answers to questions such as: What should a construction robot look like?, What is the best mechanical configuration for a specific task? etc.

- *robot-process interaction*

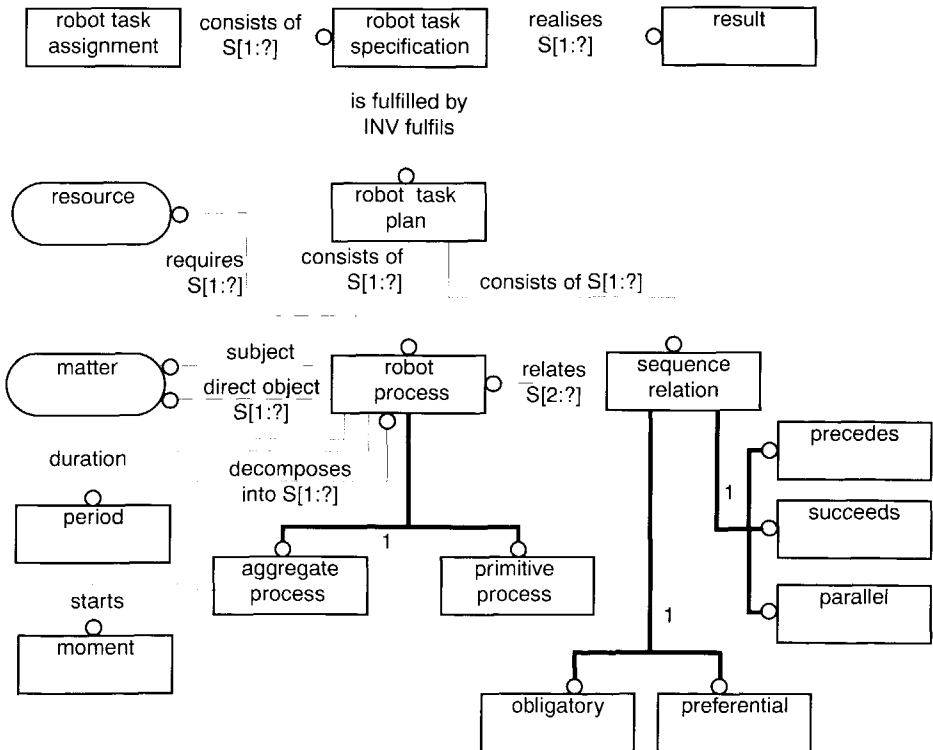
Another application of construction robot simulation is the evaluation of the interactions between the robot process and the 'outside world'. In other words find answers to questions such as: How does a robot process interact with other (manual) construction processes? How is the safety guaranteed? How can time losses in process interactions be avoided? etc.

- *construction-process re-engineering*

Simulation at a construction process level allows alternative work methods and task-delegation strategies to be evaluated on their performance, efficiency, cost and duration. Such simulation systems are essential for reliable quantification of the benefits of robotisation. An additional function of process simulation is the demonstration of the effects of robotisation. This demonstration functionality can be used to communicate new ideas and process-organisation designs within management and project teams.

Appendix A

Generic Process-Type Model



References

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Samenvatting

Robots in de bouw

Ronald P. Krom

Van de bouw wordt in toenemende mate gevraagd om complexere bouwwerken te bouwen. Tegelijkertijd wordt verlangd dat het bouwproces zo efficiënt mogelijk, zo snel mogelijk, zo milieuvriendelijk mogelijk, en zo arbeidsvriendelijk mogelijk uitgevoerd wordt. Verschillende technologieën kunnen worden aangewend om aan die vraag te voldoen. Robottechnologie is één van de potentieel beschikbare technologieën.

De belangrijkste potentiële voordelen van robottechnologie zijn:

- robots kunnen goedkoper produceren dan mensen
- robots leveren werk van een hoge, constante kwaliteit
- robots kunnen werk doen wat voor mensen gevaarlijk en ongezond is
- robots kunnen werk doen waarvoor het moeilijk is om mensen op de arbeidsmarkt te vinden
- robots kunnen per tijdseenheid meer produceren.

Ondanks de bovengenoemde potentiële voordelen, worden robots nog niet ingezet in bouwprocessen, behalve in (voornamelijk Japanse) experimentele toepassingen. De redenen waarom robottechnologie niet in de bouw wordt gebruikt maar wel in andere industrietakken, moet worden gezocht in de verschillen tussen het bouwproces en industriële productieprocessen. Vier kenmerkende eigenschappen van het bouwproces zijn:

- producten van de bouw worden geassembleerd op bouwplaatsen in plaats van in fabrieken omdat ze groot en zwaar zijn, en transport moeilijk en kostbaar is
- doordat de assemblage op een bouwplaats gesitueerd is, moeten robots naar hun werkstuk toe komen in plaats van andersom zoals het geval is in fabrieken
- producten van de bouw worden geproduceerd in kleine series of als unieke ontwerpen

- de verantwoordelijkheden in het bouwproces zijn verdeel onder verschillende bouwpartners, te weten: opdrachtgever, architect, aannemer, onderaannemer en overheid.

De op dit moment commercieel verkrijgbare robots zijn ontwikkeld om in fabrieken te worden ingezet in massaproductie van kleine tot middelgrote producten. Het is daarmee verklaarbaar dat deze robottechnologie niet gemakkelijk kan worden ingezet in de bouw.

Vraaggesprekken met bouwrobotica-experts in Japan en in Duitsland (NISTEP 1992; BMFT 1993) laten zien dat 71%, respectievelijk 60% van de deskundigen meent dat toepassing van bouwrobotica belemmerd wordt door tekortkomingen aan de stand der techniek. In dit proefschrift is onderzocht in welke gebieden er behoefte is aan de ontwikkeling van nieuwe technologie ter implementatie van bouwrobots. Voor één specifiek onderwerp is ook gewerkt aan een nieuwe ontwikkeling, nl. de instructie van robots. Tenslotte zijn de analyse en de ontwikkelde oplossing getoetst in een tweetal case-studies, een boorrobot en een grondverzetrobot. De zojuist besproken driedeling is terug te vinden in de opbouw van deze samenvatting.

1 Probleemanalyse: Ontbrekende technologieën voor bouwrobotica

De eerste vraag die in dit proefschrift gesteld wordt, is: aan welke technologieën bestaat er behoefte voor de realisering van succesvolle bouwrobottoepassingen? Deze vraag is van twee kanten bekeken:

- 1 vanuit het gezichtspunt van de bouw om de toepassingen te vinden die de beste kansen bieden voor robotisering
- 2 vanuit het gezichtspunt van de robotica om te zien welke technologieën beschikbaar zijn en welke ervaringen er bestaan met de toepassing van robots in de bouw.

Beide gezichtspunten worden nader besproken.

Waar liggen de kansen voor robotisering vanuit de bouw gezien?

Binnen het bouwproces zijn de volgende zeven categorieën van deelprocessen onderscheiden die elk zijn beoordeeld op hun robotiseerbaarheid:

- grond- en funderingswerk
- bouw van de draagconstructie
- voltooiën van het gebouw en het plaatsen van secundaire elementen
- afwerken van het bouwwerk
- aanbrengen van klimaatbeheersingsinstallaties
- installatie van elektrotechnische systemen
- installatie van sanitair en keukens

Elk van de bovengenoemde categorieën is beoordeeld op een zestal aspecten die de robotiseerbaarheid bepalen. De totaalscore van elke categorie is bepaald door de score per aspect in te schatten en via een weegfactor te laten meetellen. Proceskenmerken (aspecten) die in positieve zin bijdragen aan de robotiseerbaarheid van een proces, zijn:

- beperkte complexiteit van de procestaak (gewicht 48%)
- hoge kosten voor arbeid voor handmatig uitvoeren (gewicht 16%)
- de uitvoering is ongezonder en of gevaarlijk voor mensen (gewicht 3%)
- de taak omvat veel herhaling van gelijksoortige handelingen (gewicht 16%)
- een hoge en/of constante kwaliteit is vereist (gewicht 12%)
- het proces is al gemechaniseerd (gewicht 5%)

Uit de analyse blijkt dat de bouw van de draagconstructie de beste kansen voor robotisering biedt. Het grond- en funderingswerk komt op de tweede plaats. Het aanbrengen van de installaties en het sanitair zijn het minst gemakkelijk robotiseerbaar.

Stand der techniek in de (bouw)robotica

Al sinds ca. 1983 wordt er met name in Japan, maar ook in de rest van de wereld, geëxperimenteerd met het gebruik van robots in de bouw. Er kunnen vier generaties van bouwrobots worden onderscheiden. De generaties onderscheiden zich door de invloed van de robotisering op het bouwproces. De generaties zijn:

- 1 *bestaande machines voorzien van computerbesturingen*
bestaande machines worden door toevoeging van computertechnologie slimmer waardoor er sneller en met een hogere kwaliteit gewerkt kan worden
- 2 *nieuwe machines voor ondersteuning van traditionele werkmethoden*
- 3 *autonome machines (robots)*
- 4 *nieuwe bouwmethoden speciaal aangepast voor de inzet van autonome robots*

Van elk van de robot-generaties bestaan prototype robots. Een aantal grote Japanse aannemers voert proefprojecten uit met vierde-generatie robotbouw-systemen. Deze robotbouwsystemen assembleren de draagconstructie van hoogbouw. Kenmerkend aan de vierde-generatie is de top-down benadering waarbij het gehele bouwproces zodanig georganiseerd is dat beschikbare robottechnologie efficiënt en doelmatig ingezet kan worden.

De ervaringen met prototype bouwrobots laten zien dat het bouwproces vaak ingrijpend moet worden aangepast om de beschikbare robottechnologie te kunnen inpassen. De prestaties van een robot kunnen worden gedefinieerd aan de hand van zes robotaspecten. Deze robotprestatieaspecten zijn:

- robotmanipulator-prestaties (reikwijdte, kracht)
- robotgereedschap-prestaties
- materiaal aanvoermogelijkheden
- besturingsmogelijkheden

- sensoren
- mobiliteit

De knelpunten voor de implementatie van bouwrobots lijken te liggen bij de technologie voor manipulators, sensoren en de besturing van robots. Manipulatorarmen zoals die worden gebruikt in de fabricage-industrie, kunnen niet in opgeschaalde vorm worden toegepast in de bouw omdat ze anders te groot en te zwaar worden. Lichtere manipulators zoals de nu al gebruikte armen voor betonverspreiding, hebben een lage nauwkeurigheid, een beperkt last-draagvermogen door hun beperkte stijfheid. Een alternatief voor grote manipulators is om manipulators mobiel te maken door ze op een onderstel met wielen of rupsbanden te monteren. Het wordt dan wel vereist dat de robot zijn positie t.o.v. het bouwwerk nauwkeurig kan bepalen. Plaatsbepaling is echter een aspect waar de mogelijkheden met de stand der techniek nog beperkt zijn. Tenslotte is de besturing van robots een probleem omdat robots worden geprogrammeerd in termen van bewegingen en niet in termen van de taak die moet worden verricht. De omzetting van een taak naar robotbewegingen moet handmatig worden uitgevoerd. Om robots efficiënt te kunnen inzetten voor bouwtaken, moet de instructie van een robot zo eenvoudig en doelmatig mogelijk zijn. Instructie in termen van de uit te voeren taak is dus gewenst. De vertaling naar robotbewegingen dient automatisch te geschieden.

Conclusie

De beste kansen voor de inzet van robots lijken te liggen in bouwprocessen voor de realisering van de draagconstructies. De recente ontwikkelingen in de Japanse bouw richten zich ook op deze delen van het bouwproces voor hoogbouw. In de Japanse experimenten richt men zich op de fabrieksmatige assemblage van hoogbouw-draagconstructies en de afwerking daarvan met behulp van robotkranen. In deze implementaties worden beperkingen van de stand der techniek van de robottechnologie ondervangen door beperkingen in het toepassingsgebied van de robotsystemen.

Voor een verbreding van het toepassingsgebied van de bouwrobotica is het wenselijk dat de stand der techniek van robottechnologie verder wordt uitgewerkt op het gebied van robotmanipulators, mobiliteit en instructie. Het laatst genoemde aspect is gekozen als onderwerp voor nadere studie in het tweede gedeelte van het proefschrift. De doelstelling is om een concept te bedenken voor efficiënte instructie van bouwrobots.

2 Synthese van een concept: Taak-instructie voor bouwrobots

De beschikbare robotprogrammeermethoden zijn niet geschikt voor de instructie van bouwrobots. Voor bouwrobots is er behoefte aan een methode om een robot te instrueren over zijn taak met een minimum aan instructie-inspanning. Tijdrovende instructie is funest voor het economisch rendement van een bouwrobot wanneer de herhaling in een robottaak beperkt is. Dit laatste is juist vaak

het geval omdat de producten van de bouw niet in grote series geproduceerd worden, dit in tegenstelling tot de massaproductie in andere industrieën. Een ander aspect is dat de robot langs zijn objecten moet werken in plaats van dat het object langs de robot komt. Hierdoor is een bouwrobotprogramma geen beschrijving van een bewegingspatroon dat voortdurend herhaald wordt, zoals wel het geval is bij robotprogramma's voor lopende band-werk, waarbij de robot vast is opgesteld.

Tegenover het afwijkende herhalingskarakter van bouwrobotprogramma's staat dat bouwrobottaken semi-uniek zijn. Het "unieke" van een bouwtaak zit in de project-specifieke parameters zoals afmetingen, locaties en aantallen. De uitvoeringsprocedure van een bouwtaak is steeds gelijk (bijvoorbeeld metselen, heipalen slaan of tegelen). Het semi-unieke karakter maakt het mogelijk om de benodigde handelingen voor een bepaald type taak vast te leggen in een sjabloon-procesmodel. Dit sjabloon-procesmodel kan, samen met een ontwerp van het te realiseren resultaat, worden vertaald in een op maat gesneden robotprogramma.

De hypothese is dat het mogelijk is om het idee van de sjabloon procesmodellen te implementeren met behulp van methoden en technieken uit het vakgebied van de Product Data Technologie (PDT). PDT is de technologie die ontwikkeld is voor de uitwisseling van productinformatie tussen verschillende computersystemen en tussen verschillende soorten computerapplicaties (ontwerpen, constructief rekenen, energieberekeningen etc).

De voornaamste reden om PDT te willen gebruiken is omdat daarmee de technische integratie tussen het ontwerp-proces en de robotinstructie grotendeels gerealiseerd wordt. Het probleem dat moet worden opgelost is, hoe een gebouwwontwerp kan worden vertaald in een robot-procesbeschrijving. Een belangrijke veronderstelling is dat ontwerp-informatie in de vorm van een zogenaamd projectmodel kan worden aangeleverd. Een projectmodel is een PDT-term voor een applicatie- en toepassingsonafhankelijke database waarin alle technische gegevens van een bouwproject zijn opgeslagen.

Een architectuur voor een taak-instructiesysteem

In een taak-instructiesysteem worden vijf subsystemen onderscheiden die verschillende deelfuncties vervullen:

1 taak-specificatiesubstysteem

In het taak-specificatiesubstysteem wordt éénduidig vastgelegd wat de taak van de robot is door te specificeren welke onderdelen van het bouwwerk door de robot moeten worden gerealiseerd of behandeld. Er vindt een toetsing plaats of de robot ook in staat is om de een taak te volbrengen.

2 taak-planningsubstysteem

Het taak-planningsubstysteem is het hart van het taak-instructiesysteem. In dit subsysteem wordt een sjabloon-procesmodel vertaald tot een taak-specifiek handelingenmodel aan de hand van de gegevens uit de taak-specificatie en het aangeleverde bouwwerk-ontwerp.

3 *volgorde-planningsubstelsysteem*

In het volgorde-planningsubstelsysteem wordt het handelingenmodel dat door het taakplanning-subsysteem is geproduceerd, geëvalueerd om tot een sequentiële lijst met uit te voeren handelingen te komen.

4 *bewegingsplanning-subsysteem*

In het bewegingsplanning-subsysteem worden de benodigde robotbewegingen voor alle handelingen uitgewerkt. Hiervoor is informatie over de vorm en locaties van alle onderdelen benodigd.

5 *plan-uitvoeringssubsysteem*

Het plan-uitvoeringssubsysteem zorgt voor de correcte uitvoering van de plannen. Plannen zijn per definitie gebaseerd op aannamen over situaties. Het plan-uitvoeringssysteem controleert met behulp van sensoren of de aannames geldig zijn. Zo niet dan kan worden gekeken of het plan op een alternatieve manier kan worden uitgevoerd door het volgorde-planningsubstelsysteem opnieuw in te schakelen.

In figuur 1 is in de vorm van een zogenaamd IDEF₀ diagram te zien welke subprocessen onderdeel uitmaken van het taak-instructieproces en welke informatiestromen er lopen.

De representatie van kennis is een essentieel aspect van de voorgestelde architectuur. Immers de kennis in het procestype-model beschrijft welke handelingen door de robot moeten worden uitgevoerd om een bepaalde taak te verrichten. De ontwerp informatie in een projectmodel dat aan het taak-instructiesysteem wordt aangeleverd, bepaalt hoe vaak, in welke volgorde en waar de handelingen worden uitgevoerd. Voor de representatie van kennis in het procestype-model wordt onderscheid gemaakt tussen twee soorten kennis:

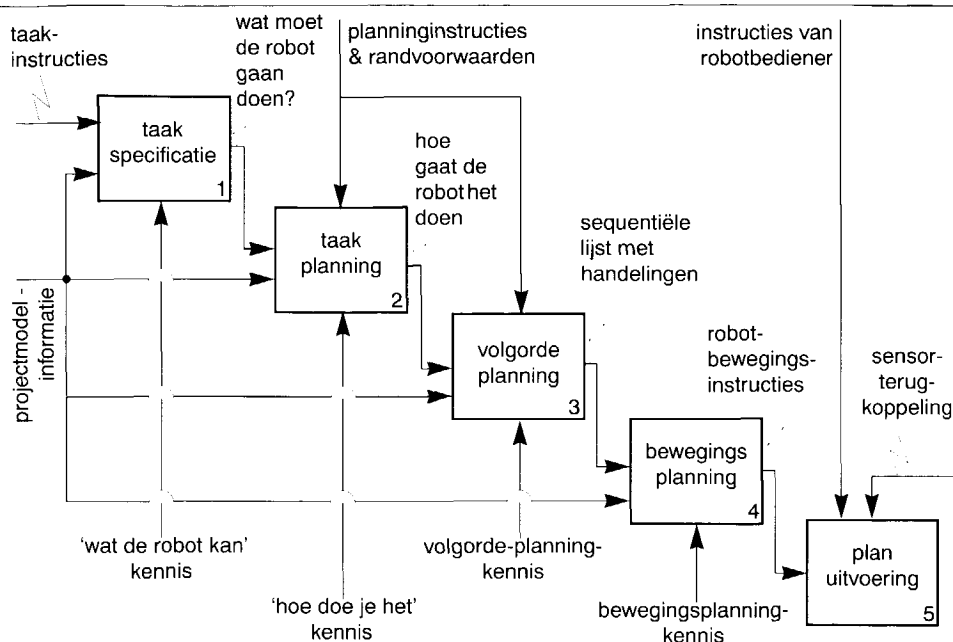
- *ontologische kennis*
kennis over de producten en processen die worden onderscheiden
- *afleidingskennis*
kennis voor het afleiden van nieuwe informatie.

Voor de representatie van ontologische kennis biedt PDT goede faciliteiten in de vorm van EXPRESS en EXPRESS-G. Voor de representatie van afleidingskennis ontbreken er echter goed representatie technieken. Dit is niet verwonderlijk gezien de historie en doelstellingen van PDT. Representatie van afleidingskennis is mogelijk met behulp van uitbreidingen aan PDT-gereedschappen. Een eerste aanzet hiervoor is gegeven. Verdere ontwikkeling is echter noodzakelijk.

3 **Evaluatie:**

Twee case-studies van bouwrobot-ontwikkelingen

De voorgestelde architectuur voor taak-instructiesystemen is toegepast in twee case-studies. De eerste case-study betreft een boorrobot. Deze case-study bespreekt hoe de boorrobot is ontwikkeld en hoe de robot is geïntegreerd in het bouwproces. Ook wordt het taak-instructiesysteem voor de boorrobot besproken.



Figuur 1 IDEF₀ diagram met daarin de opdeling van het taak-instructieproces in subprocessen met hun in- en uitvoer. In IDEF₀ worden subprocessen gerepresenteerd door rechthoeken; en materiaal- of informatiestromen door pijlen. Aan de linkerzijde van een rechthoek komt de invoer van elk subprocess binnen; aan de rechterkant gaat de uitvoer eruit; aan de bovenkant komt besturingsinformatie naar binnen en aan de onderkant worden benodigde hulpmiddelen toegevoerd. Aangezien het taak-instructieproces een informatieverwerkend proces is, representeren alle pijlen in dit diagram informatiestromen, namelijk invoer-, uitvoer-, besturings- en hulpinformatie.

De tweede case-study betreft een grondverzetrobot. In deze case-study wordt getoond hoe deze grondverzetrobot geïmplementeerd is op basis van een standaard grondverzetmachine. Ook wordt besproken hoe terreinafwerkings-taken aan het systeem opgedragen kunnen worden.

Boorrobot

De boorrobot is een prototype robot uit de categorie van derde-generatie bouw-robots. Figuur 2 toont de robot tijdens tests in de spoortunnel nabij het station van Schiphol. De robot is speciaal ontworpen voor één soort handeling, nl. het boren van gaten in betonvloeren. Deze handeling komt voor bij twee omvangrijke taken voor de bouw van een spoortunnel. Deze taken zijn: (1) het boren van gaten voor de bevestiging van spoorrails en (2) het boren van gaten voor stekeinden.

De taak van het boren van de gaten voor de spoorrailsbevestiging is op zich niet complex maar vereist wel correcte informatie over de ligging van het spoor en de locaties van de te boren gaten. Het procestype-model van de robottaak is relatief eenvoudig. De deelhandelingen die in de ontologie worden onderscheiden zijn: (1) verplaatsen van de robot van spoorsectie naar spoorsectie, (2) verplaatsen van



Figuur 2 Boorrobot tijdens proefnemingen op het spoorwegstation onder Schiphol.

bevestigingslocatie naar bevestigingslocatie en (3) het boren van een tweetal gaten. Door de combinatie van de bochten in de rails en de segmentering van de betonconstructie in delen van ca. 20 m lengte zijn de locaties van een groot deel van de bevestigingen onregelmatig.

De case-study laat zien hoe op basis van de voorgestelde architectuur een taak-instructiesysteem voor de boorrobot kan worden gerealiseerd. Een belangrijk voordeel van het gebruik van het taak-instructiesysteem is dat verschillende personen, ook die aspecten van de uitvoering van de robottaak kunnen beïnvloeden waar zij verantwoordelijk voor zijn. De robot-opzichter mag (en kan) de werkvolgorde van de robot veranderen zonder dat hij iets aan de locaties van de gaten kan veranderen.

Grondverzetrobot

De grondverzetrobot is een bouwroboticaontwikkeling die gebaseerd is op een bestaand type machine, nl. de hydraulische graafmachine. Hydraulische graafmachines zijn veelzijdige machines. Echter nauwkeurige afwerking is niet het sterkste punt. Alleen ervaren machinisten zijn in staat om grondlichamen nauwkeurig en snel af te werken.

Door gebruik te maken van robot-besturingstechnologie is het mogelijk om ook op het aspect van nauwkeurigheid, graafmachines goed te laten presteren. Een standaard hydraulische graafmachine is omgebouwd tot een grondverzetrobot door toevoeging van sensoren voor bepaling van de locatie van de machine en voor meting van de stand van de graafarm. Aan het hydraulische systeem zijn enkele

elektrisch aanstuurbare ventielen toegevoegd die bediening van de machine door de stuurcomputer mogelijk maken. In figuur 3 wordt de testopstelling van de grondverzetrobot getoond.



Figuur 3 Testopstelling voor computersturing van graafmachine-arm en sensorsysteem.

Aanvankelijk zal het systeem waarschijnlijk nog niet als autonome robot worden ingezet maar als semi-automatisch systeem ter assistentie van de machinist. Het doel van het semi-automatische systeem is om snel en nauwkeurig grondafwerkingstaken te kunnen verrichten. Zowel voor de autonome robot als voor het semi-automatische systeem is er behoefte aan een taak-instructiesysteem omdat het besturingssysteem moet weten wat voor terrein er gerealiseerd moet worden.

Het taak-instructie systeem maakt het mogelijk om in het ontworpen terrein-model die delen te selecteren die door de robot moeten worden afgewerkt. De sensorsystemen voor de meting van de machinelocatie en graafdiepte maken het gebruik van uitzethulpmiddelen zoals piketten en baken overbodig. In semi-automatische mode wordt de taak- en volgordeplanning door de machinist uitgevoerd, en deze subsystemen zijn dan in het taak-instructiesysteem inactief.

De case-study demonstreert hoe conventionele machines kunnen worden omgebouwd tot eerste- en tweede-generatierobots. De besturingscomputer in combinatie met het taak-instructiesysteem voegt (in semi-automatische mode) een nieuwe eigenschap aan hydraulische graafmachines toe, namelijk snel en nauwkeurig afwerken. Met de ontwikkelde strategie voor taak-instructie kan ontwerpinformatie (gewenste vorm en maatvoering van het terrein) op efficiënte en effectieve wijze worden overgedragen.

4 Conclusies en aanbevelingen

De belangrijkste conclusies van het onderzoek dat beschreven is in dit proefschrift zijn:

- De toepassing van robots in de bouw is een veelbelovende ontwikkeling. Net zoals bij de toepassing van robots in de automobiellindustrie, zijn het de Japanse bedrijven die het sterkst in robots geloven, en ook de toepassing in de praktijk onderzoeken.
- Voor de implementatie van robots voor de bouw zijn verschillende technische problemen te identificeren die de implementatie van eenvoudig bruikbare, universele robots hinderen.
- Robotisering van bouwprocessen vereist zowel een top-down als een bottom-up strategie. De top-down strategie is noodzakelijk om tot een optimale afstemming tussen robotmogelijkheden en bouwprocesorganisatie te komen. De bottom-up strategie is nodig om de mensen in de organisatie te laten wennen aan de veranderingen en deze geaccepteerd te krijgen. Hierin schuilt ook een fundamenteel verschil tussen de Japanse cultuur en die in Europa en in de VS.
- Door het semi-unieke karakter van de meeste bouwtaken is het mogelijk om taak-instructie voor robots te realiseren. De gereedschappen van Product Data Technology vormen een zeer geschikte basis voor de implementatie van taak-instructiesystemen. Voor de vastlegging van afleidingskennis schieten PDT-technieken echter te kort.

Aanbevelingen:

- De gepresenteerde aanpak voor de implementatie van taak-instructiesystemen is slechts een eerste aanzet die verdere ontwikkeling behoeft en dat ook verdient. Verder onderzoek op het gebied van taak-instructie voor robots wordt aanbevolen.
- Veel bouwrobot-ontwikkelingsprojecten richten zich op de ontwikkeling van de robot-hardware en verwaarlozen ten onrechte de technische en organisatorische inpassing van de robot. Juist de inpassing in de bestaande organisatie en koppeling met gerelateerde computersystemen is van grote invloed op het succes van robotisering.
- Om het bouwbedrijfsleven meer inzicht te geven in de kansen en problemen rondom robotisering, dienen de gevolgen voor hen inzichtelijker gemaakt te worden. Computersimulatiesystemen zijn een zeer bruikbaar gereedschap om de inzet van robots te evalueren. Simulaties kunnen inzicht geven in de presentatie van verschillende robotconfiguraties, de interacties van de robot met zijn omgeving en in de benodigde of gewenste aanpassing van het bouwproces voor de optimale inpassing van robots.

Curriculum Vitae

Ronald Peter Krom was born on the first of September 1965 in The Hague in the Netherlands. At the age of eleven he moved from The Hague to the village Sassenheim. He graduated for his Athenaeum at the Rijnlands Lyceum Sassenheim in 1983. In that year he started studying computer science at the Delft University of Technology. In 1989 he graduated on a thesis about the implementation of a programming environment for instantiation of product models. This research was carried out at the department for Computer Integrated Construction of TNO Building and Construction Research.

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