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TNO report

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Task analysis and decision support requirements for Dynamic Positioning operators

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Summary

The present research was conducted as part of the Early Research Program Human Enhancement in the domain of Adaptive Maritime Automation, which strives to develop knowledge regarding the support of operators based on adaptively automated systems. To apply the developed knowledge about adaptive automation the use-case of Dynamic Positioning (DP) was chosen. The goal is to develop an Intelligent Operator Support System (IOSS) that can support the operator in his work to be safer, more efficient, and take over operator tasks during situations of underload so the operator can engage in additional tasks.
This report contains a task analysis of the activities of a DP operator aboard a Floating Production Storage Offloading (FPSO) vessel during stationary operations, and possible opportunities for operator support are identified.

To identify the various tasks and sub-task sets involved in a standard stationary FPSO operation of a DPO, a Hierarchical Task Analysis (HTA) was conducted.
It was found that the generic control tasks sense, assess, decide, act, and plan recurred while performing several different higher level DP tasks. This led to the distinction of seven generic DP control loops that each involve the steps of the generic control tasks but with a focus on different DP subsystems. The seven control loops are: position control, system functioning control, redundancy control, environmental control, collision control, grounding control and infra avoidance control. For each of the loops, and their subtasks, the information needs were identified and divided between information given by the DP system, and information potentially given by a future IOSS.

The relevance and intensity of a control loop is highly dependent on the type of operation, the location of the operation, and seasonal influences on the external environment such as hurricanes and sudden rapidly approaching waves. It was found in an interview with a DP operator that during some DP operations certain control loops are not performed at all, while others may require a lot of attention. This means that the HTA should be expanded with more formal workload measurements taking into account the great influences of external forces on the DP operation. This knowledge should be taken into account when designing the future IOSS. It has to be adaptive not only to the operator, but also to the varying conditions of the operation resulting in different information needs of the operator.

Contents

1 Introduction

Adaptive Maritime Automation (AMA) is a project within the Early Research Program (ERP) ‘Human Enhancement’. The ambition of this project is to develop a transparent (human-in-the-loop) adaptive automation platform, based on a computational human model to assess current and predicted human task load (Te Brake & Van Diggelen, 2015). To develop such a platform, a use case was selected to apply the research. The use-case focuses on the work of Dynamic Positioning (DP) operators. A DP system keeps a ship in a specified position, or moves it along a predefined path. This system is highly autonomous, however errors do occur. While the system can detect sensor defects, it is not aware of erroneous measurements, e.g. wind fluctuations due to helicopters or GPS drifts. Furthermore, it cannot anticipate future weather changes. This requires the constant monitoring of a human operator who needs to remain vigilant for possible threats to the DP functioning. As incidents are rare, there is a risk of underload for the human operator with a risk of reduced situational awareness possibly leading to detection failures or inadequate responses. To support the operator the Intelligent Operator Support System (IOSS) is proposed. The IOSS has two goals:

First, it should be able to take over operator tasks during situations of low cognitive task load. This gives the operator the opportunity to perform other (useful) tasks. As a result, the operator’s job becomes more interesting and the operator will be more productive by doing extra work. To make this possible IOSS must be able to monitor the DP system and other information to be sure that the vessel keeps its position as planned. If not, it should warn the operator in time to take measures and prevent or solve dangerous situations.

Second, IOSS should support the operator during situations of high cognitive task load. When too many tasks must be performed at the same time, or are becoming too complex, the system should be able to take over tasks, give support in finding the causes of disturbances or give advice about measures that can or should be taken. Before deciding on the IOSS requirements, we must know which tasks the operator performs, when overload and underload situations occur and what kind of task support is needed during these situations. As a first step, we performed a Hierarchical Task Analysis (HTA) to describe the operator tasks in a structured way. The next step is to determine the level of attention required during the various goals defined in the HTA. From that, the required information during the execution of these goals was analysed. This study has an exploratory character, the next step is to continue this study using a more formalised method. For example, by integrating it with the cognitive workload analysis (Neerincx, 2003). It allows to determine when operators are overloaded, when control loops are too complex or whether switches between task sets occur too often. This kind of information makes it possible to determine what kind of IOSS support is required during various modes of operation. For instance, it may be possible for the operator to become roaming, i.e. perform other tasks away from the DP console, if sufficient support can be provided. The IOSS can provide this support, or determine that under specific circumstances the operator should stay behind the DP desk.

2 Operator tasks

2.1 Human-machine teaming

Through increasing automation the role of the operator has changed the last few decades. The major change is the way in which computers have taken over the control and the role of humans has changed from manual controller to supervisor. Figure 1 shows the different types of human-computer collaboration. DP systems are highly automated systems. Most of the time they function fully autonomously. However, the operator continually monitors the system to ensure operation is as intended and the system does not, for example, base its actions on false sensor data (type (d) in figure 1).

Highly reliable automated systems need less involvement of the operator. As a consequence, operators get into a situation of cognitive underload and the danger is that they become out of the loop. The resulting out of the loop performance problems include reduced situational awareness, reduced vigilance for errors, and decreased task performance. To prevent cognitive underload an IOSS is proposed to monitor the system in place of the human operator. If the operator’s tasks can be trusted with the IOSS, the operator can become roaming, i.e. perform other tasks away from the DP console.

An important requirement for such an IOSS is that it can monitor for anomalous system behaviour or changes in the environment and alert the operator in time to take corrective actions. Sensor defects are already detected by the DP system itself, however sensor values may also provide false data as a result of, for example, sudden wind shifts caused by a close-by helicopter, or GPS values may drift near the poles. The DP system will attempt to counteract these anomalies, unaware of the cause. In such cases, the operator must recognise the problem, know what the situation is, be aware of the operational goals of that moment and know what measures to take to keep on track to achieve those goals (Tjallema, Van der Nat, Grimmelius, & Stapersma, 2007). Human-machine teaming may prove useful in supporting these processes.

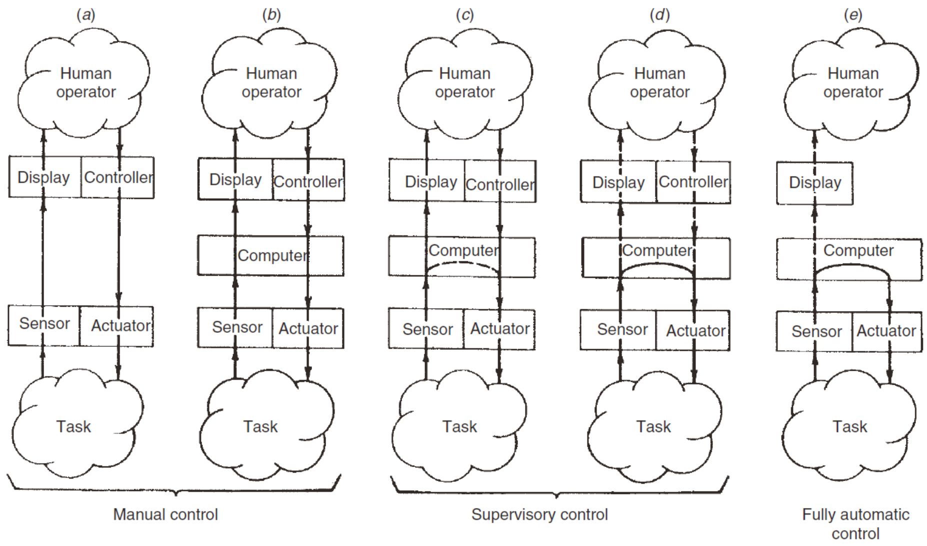

Figure 1. Types of human-automation collaboration (Sheridan, 2012)

2.2 Generic operator tasks

The DP system is an autonomously working control system that, given a set of goals (position, course, heading, etc.), automatically responds to sensor input values (e.g. position sensors, wind sensors, movement sensors) by adjusting actuator values (power, thrust, direction, etc., see figure 2 for a schematic depiction). In theory, especially in a stationary situation, no operator is needed to control the system. However, the system is not 100% reliable and does not have a complete conclusive fit to everything that can happen in the environment.
For example, sensors may not function or receive invalid data, thrusters may not function properly, power systems may be disrupted, or the control system may be out of order or use the wrong model. The DP system can detect a lot of errors, but not all, therefore the operator’s task is to monitor the functioning of the system and its components and take the appropriate actions when something goes wrong.

In addition to the current state, future states may threaten the functioning of the system as well. Indications of the malfunctioning of sensors, actuators and control system may require actions from the operator to prevent a drift-off or other position deviations. Besides that, future external circumstances, like extreme weather conditions or approaching vessels, may threaten the operation as well. So besides monitoring the current situation, the operator must also anticipate the future situation. Also, the operator must respond adequately to current and future threatening states.

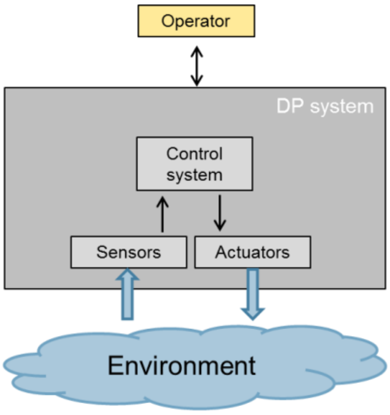

Figure 2. Generic functions of DP system

To describe the generic tasks involved in process control the decision ladder model by Rasmussen (1986) is adopted. From this model five generic operator tasks are identified that are relevant to a DP operator: sense-making, assessing, deciding, planning, and acting (Figure 3). Rasmussen (1986) discusses that it depends on the level of information processing; skill-, rule-, or knowledge-based, which of these five steps are executed. Generally, only in knowledge-based information processing are all the steps executed. In skill-based processing the operator goes straight to acting upon detection of an undesired system state. Rule-based performance is characterised by taking shortcuts, i.e. leaps, between the five steps, by for instance skipping the 'decision step' when rules already dictate the correct course of action.

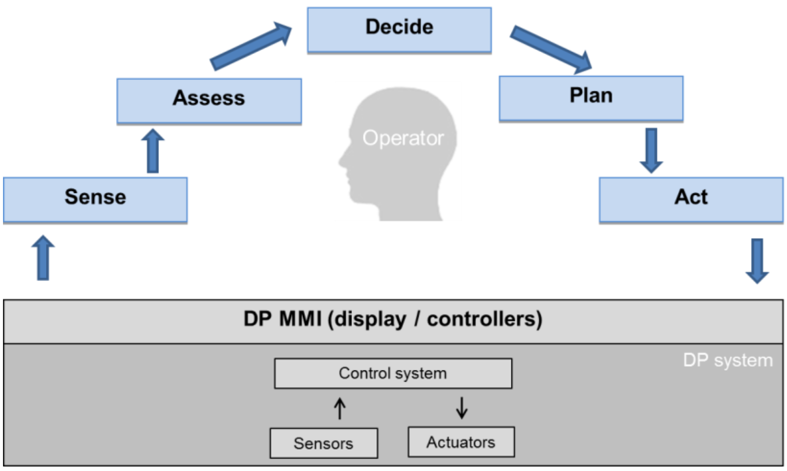

Figure 3. Generic operator tasks

Sense. Sense refers to the creation of a situation awareness of the operating environment by using sensor and other information. The operating environment includes the external state (e.g., weather, current, other ships or platforms) and internal state (e.g., thrusters, power, direction) of the DP system.

Assess. Operational goals determine what the situation should be. Assess refers to identification of (potential) deviations between the actual state and the preferred state.

Decide. If there are potential threats interventions must be made to achieve the operational goals. Given the available means a decision must be made about how to intervene.

Plan. A plan must be made about the way decisions are carried out. What actions have to be done by what/whom in what order? Especially when many interdependent interventions must be made, planning is very important.

Act. Act refers to the actual execution of decisions and/or plans.

The whole set of tasks is a control loop that is continuously performed by the operator.

2.3 Hierarchical Task Analysis

A task performed to achieve a certain goal usually consists of a multitude of lower level sub-goals that all contribute to the execution and completion of the main goal. To systematically order all the various goals of a task, and get insight into their interdependencies, a Hierarchical Task Analysis (HTA) was performed. A HTA results in a diagram displaying at the top level the main goal of an operation, and on the subsequent levels the sub- and sub-sub goals that need to be completed in order to achieve the main goal.

The HTA method was chosen because it fits the specific domain of a DP-operator. The work of a DP-operator consists of sub-goals which do not always occur in the same order or frequency. Also, different goals and actions may become important at varying moments in time. The HTA does not assume any chronology between the sub-tasks and allows them to be structured according to their interdependencies without making assumptions about how or when the tasks should be executed.
The HTA method was created by Annett & Duncan (1967) and serves to systematically organise all the sub-goals to illustrate what the prerequisites are of a higher-level goal. It was developed out of a necessity to deconstruct complex tasks into smaller chunks to identify sources of problems and the opportunities for improvement.
The HTA does not specify a chronological order in which the sub-tasks have to be executed, however to complete a higher-level task, all of its sub-tasks must be completed. Furthermore, the HTA also does not indicate a relative importance between tasks, as one sub-task may be far more complex and time-consuming but not necessarily more important.

The HTA is also very useful as a basis for subsequent analyses to be performed as discussed by Stanton (2006). The notion is illustrated using a comparative study of the usability of two cassette players for which a HTA was performed that in itself did not indicate which of the two was better but set the stage for other analyses into, for example, the error potential or time occupied for various sub-tasks in both HTA's. For an accurate error potential analysis to be performed it is necessary to have a complete overview of all the different steps, i.e. sub-goals, needed to achieve a goal. This means that a HTA will show all the different activities a DPO engages in, and then subsequent analyses can take each of these activities and study their variability between different situations, levels of workload, and combinations with other tasks.

While it can be necessary to have a detailed decomposition of a task, it is important to identify the necessary level of detail for the HTA to be able to answer the research question. It is tempting to continue decomposing tasks further and further which can turn out to be very time consuming and is not necessarily beneficial for the understanding of the task. It is often chosen to end the decomposition of tasks when the potential for variation in the execution of a task diminishes. This is the case when tasks become procedural and are always executed the same way.

2.4 Workload

An important consideration when looking at the work of a DP operator is his/her level of cognitive workload. Neerincx (2003) presents a three-dimensional model of cognitive workload in which four problem regions are defined, as displayed in figure 4.

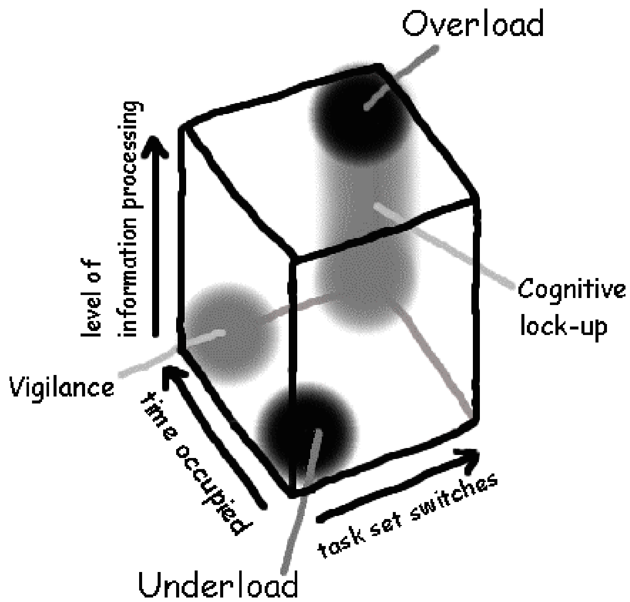

Figure 4. Three-dimensional model of cognitive task load (Neerincx, 2003)

The four problem areas are marked in figure 4, when the three dimensions of task load cause operator workload to enter one of the problem areas this will have consequences on operator performance, which is likely to deteriorate. One of the dimensions of cognitive task load is the level of information processing which entails the amount of knowledge-based actions, based on the Information Processing paradigm by Rasmussen (1983) which distinguishes skill-, rule-, and knowledge-based actions, varying in their cognitive demand.

DP tasks are highly automated and critical events rarely occur. In order to determine where and especially when the IOSS system should offer support to the operator it is important to determine the operator state within the three-dimensional model during various DP operations.

A report on DP incidents identified three general situations where operator workload is significantly different (Tjallema et al., 2007). The first is normal operation which the report identifies as potentially problematic as operator workload is very low and therefore resides in the 'underload' problem area of the three-dimensional model of cognitive task load. The second is Alerted operation where the operator will be more actively engaged with the DP task. Finally, emergency situation where the operator is generally overloaded as a system fault has to be identified quickly to prevent substantial losses.

The DP system and IOSS should strive to maintain operator workload at an optimal. To this end, the workload of the DP operator has to be investigated. The present report does not provide a formal analysis of operator workload, however a preliminary scenario-specific indication of workload was provided during interviews with an experienced DP operator.

3 Hierarchical Task Analysis DP operator

3.1 Approach

3.1.1 Inventory of operator tasks

Three resources were used to describe the operator tasks: documentation, interviews and training observations.

Documentation
DP system manuals and training documentation were studied for the initial description of the operator tasks and the DP system.

Interviews
Two operators were interviewed to describe the task performance during specific circumstances. A list of failure modes was used as a format structure for the interviews. A thinking out loud protocol was used to find out what tasks and activities the operators performed when failure modes occur.

Training observations
Observations took place one day during a DP training course. Two researchers participated as observers. One observed the DP operators in the simulator during the exercise. The second observer joined the instructor in the instructor’s room. The instructor explained what he did and why, and provided interpretation of the students’ actions.

3.1.2 Verification of initial HTA

Based on documentation, interviews and observations a first version of the HTA was presented to and discussed with a DP training instructor. The results were used to improve the HTA and make a final version.

3.2 Results

The main goal of the DPO is described as ‘Safe and efficient positioning of the vessel’. The three sub-goals are ‘Preparation operation’, ‘Performance operation plan’ and ‘Emergency Management’. Figure 5 shows the interrelation between the sub-goals.

Figure 5. Interrelation between sub-goals

Before the operation starts DP operators make an operation plan. The plan describes how the operation will be performed and contingency plans are produced in case the initial plan fails. During the operation the plan is executed. The plan allows room for adjustments within certain limits. However, when major deviations occur the plan has to be adapted. In practice, one of the contingency plans will be applied or the operation will be aborted. If there are major incidents, like a fire or a blackout, emergency management will take place using specific emergency plans. When the incident has been managed, the operation can return to the initial plan when the conditions allow. If not, a new plan must be created for repair and maintenance before the ship can operate safely again.

A full description of the HTA of the DPO can be found in appendix A. The HTA is partially presented in figure 6. The figure shows that at the level of control activities a set of control loops is identified:

- **Current position control**. This control loop is related to the actual position of the vessel in relation to the required position.
- **System functioning control**. This control loop is related to the functioning of the system components like sensors, actuators, power supply, etc. Operators must be aware of malfunctioning system components and take the necessary actions when needed.
- **Redundancy control**. When performing DP operations, the ship has to adhere to a predefined DP Class. There are several DP classes, and each has a particular set of requirements the ship must meet at all times. For example, some operations require the ship to have completely redundant power systems, and can therefore never exceed 50% of maximum power consumption. Similar requirements are made for other ship systems. If redundancy is insufficient the operation must be aborted.
- **Environmental control**. Environmental changes like wind speed, wind direction or current must be monitored to anticipate effects on the vessel and its position.
- **Collision control**. This control loop is related to possible encounters with other vessels in the environment. Threats must be detected and measures must be taken to prevent collisions.
- **Grounding control**. When waters become too shallow there is a risk of grounding. Therefore, sea depth must be monitored.

- **Infra avoidance control**. Cables or under water constructions may be present in the operational environment of the vessel. Encounters must be avoided to prevent damage to the infrastructure.

At a lower level, the generic process control tasks Sense, Assess, Decide, Plan and Act are embedded in all control loops. The generic process control tasks are subdivided in sub-tasks. There are a number of sub-tasks that can be related to more than one higher level control tasks. For example, *Monitoring position values* is a sub-task of the *Sense*-tasks of the *current position control*-loop, the *system control*-loop and the *redundancy control*-loop. From the sub-task level there is a connection with the system components represented in the system component level. One system component can support multiple sub-tasks. Appendix A shows the relation between the different layers of the HTA.

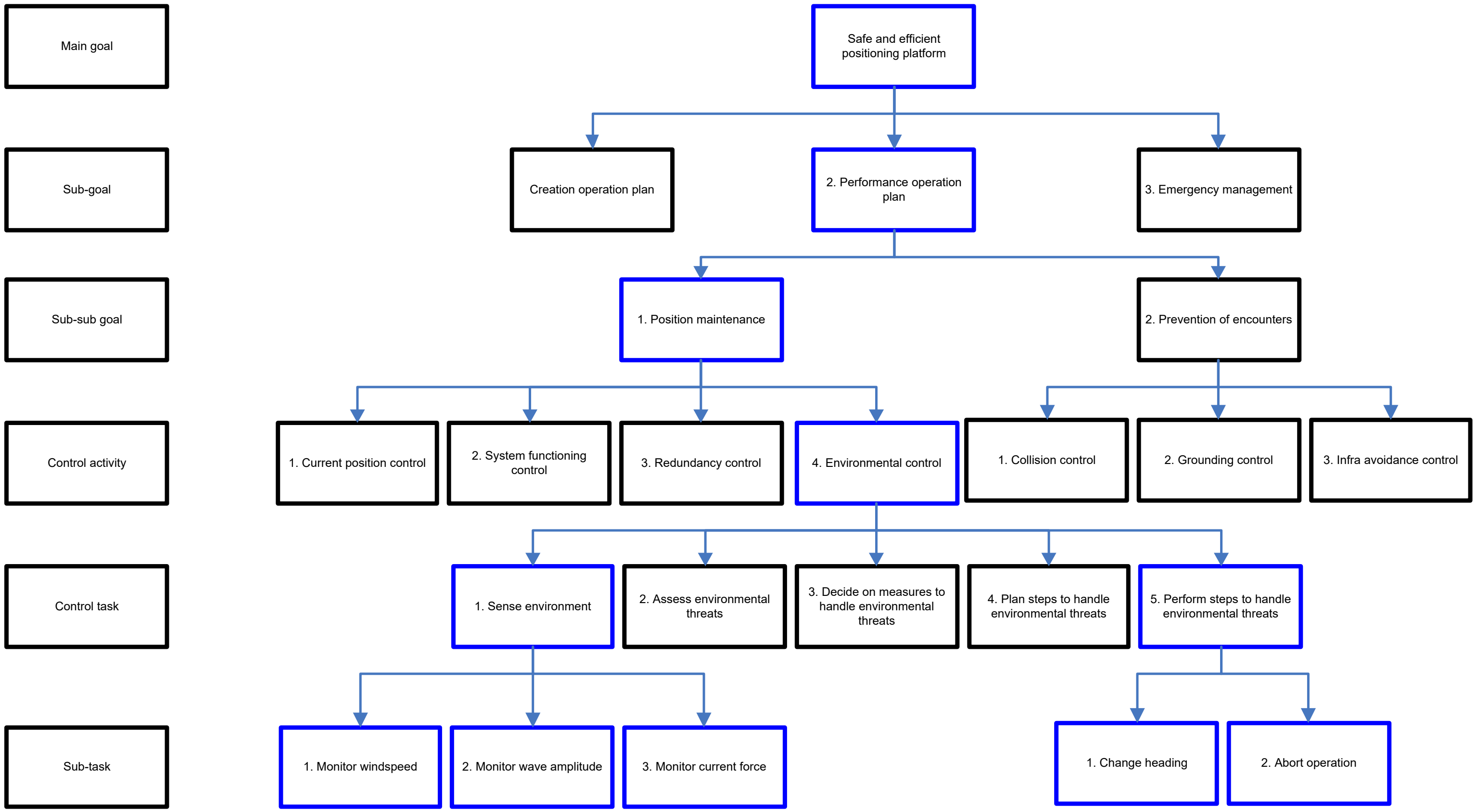

Figure 6. Hierarchical Task Analysis DPO. The HTA is only partly presented. The black boxes contain sub-goals and –tasks on a lower level that are not shown in the figure.

4 Operator support analysis

4.1 Expert session

4.1.1 Approach

Based on the task analysis the required operator support during roaming operations was identified in an expert session. Three TNO experts on supervisory control and Human-Machine Interface design were involved in the session. During the session a stationary DP scenario was used to analyse the user needs. A scenario was deliberately chosen in which the expected cognitive load was low, so a risk of cognitive underload exists. The situation was used as a context in which the operator could be active, i.e. in case of a fault, and to analyse what information is necessary to perform the tasks.

The seven control loops that were identified through the HTA all consist of the same generic control tasks, sense, assess, decide, plan, and act. It was found, based on the expert interviews, that each of these control tasks can be demanding on the operator. The operator may struggle with *assessing* why a certain position drift is occurring in some situations, and in others it may be clear what the situation is but the difficulty may lie in *deciding* how to resolve the undesired system state.

The operator support system should therefore be able to give support to all generic control tasks when necessary, i.e. when operator workload is too high, or too low (see figure 7). The system should not only give information about values and a panel to control the systems. It must help identify threats and provide decision support so the operator is aided in making the right decisions. Planning and/or procedural support help the operator to plan the actions that must be taken. This should be possible for all of the seven control loops.

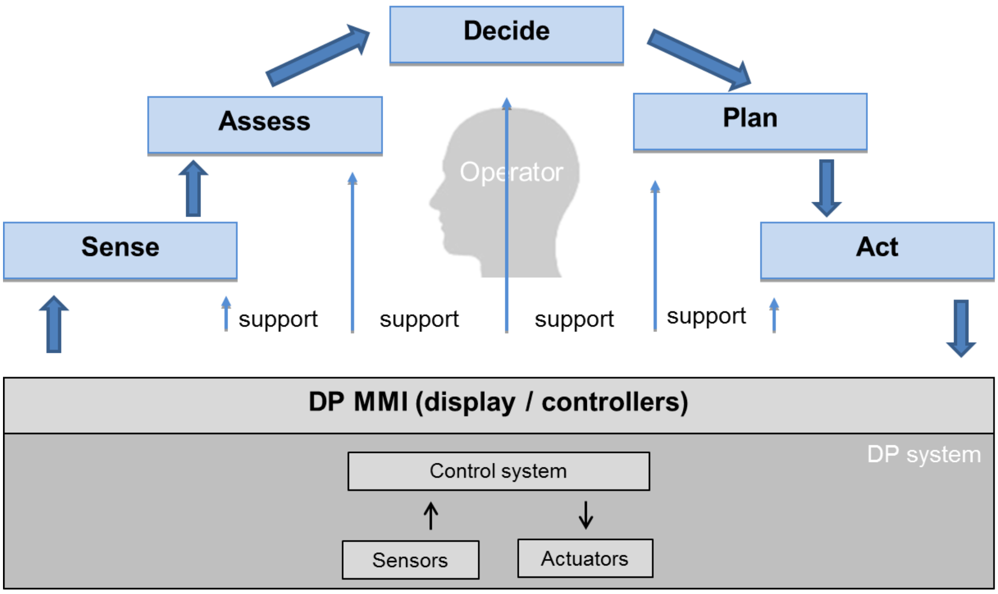

Figure 7. The DP MMI should support all generic control functions

During the expert session the control loops (control activities in the HTA) were identified that are relevant in stationary DP operations. For every control loop the five control tasks were analysed and the information needs were identified. In a previous session an inventory was made of available support already present in the current DP system (see Appendix B). This information was used to determine which additional information could be provided by the IOSS that could be beneficial to operator performance when he/she is suffering from cognitive under- or overload.

4.1.2 Results

Table 1 shows the results of the expert session and displays the information needs for the identified control loops. The information needs have been separated into information already provided by current DP systems, and information that could be provided by the future IOSS.

Table 1. Results of the expert session

Information needs	**Information from DP system**	**Information from IOSS**
General		
Information about failures related to control loops. Insight in the reasoning behind system decisions		- Show in which control loop(s) a problem originates - Inform about decisions that were made autonomously (optimal heading; LOA)
Current position control		
Proactive: what is future position	Position offset	Position information
Reactive: information about deviant position and its cause	Alerts / Alarms	Root cause of alarms
System functioning control		
Sensors: information about sensor failures and causes	Sensors in use	Info about (de)selection of sensors + explanation
	Sensor drift	Display unexplained drift
	Sensor heartbeat	Display sensor failure
Engines: information about engine failures and causes	Engine output	
	Discrepancy required output / actual output	Display possible causes of discrepancy
Power consumption: information about used and available capacity	Engine capacity	
	Notify when engine approaching maximum	
	Power Bus capacity	
	Notify when power bus approaching maximum	

Redundancy control		
Compare to DP class requirements: information about actual and required redundancy	Sensor redundancy	
	Power Bus redundancy	
	Thruster power redundancy	
	Capability plot	
	Notification when DP-class is no longer met	
Environmental control		
Ship movement: information about ship movement in relation to movement limits	Roll/pitch/heave	
	Roll/pitch/heave exceed set limits	Provide suggestion to reduce roll/pitch/heave
Current weather	Wind speed	Wind speed compared to capability plot
	Wind direction	wind direction compared to capability plot
	Wave height	
	wave period	
	Water current	
Upcoming weather changes: information about upcoming weather and possible threats in relation to the operational goals		Wind speed compared to capability plot (limits)
		wind direction compared to capability plot
		Water currents
		Provide suggestions to anticipate on future weather changes
Collision control		
Detect other vessels: information on collision risks with other vessels in the environment	-	Alert on close (expected) proximity ((ARPA information)
Grounding control		
No issue in this scenario		
Infra avoidance control		
No issue in this scenario		

In the stationary scenario it became clear that not all the identified control loops were equally relevant. Grounding control and Infra avoidance control were found not to be of importance during a stationary FPSO operation. The other control loops play a significant part in the operation, however not always does the human operator have to interfere in these processes. Information can currently already be independently processed to a certain extent by the DP system.

The information needs that can be fulfilled by the IOSS have to do with comprehension of the information presented by the DP system. The DP system is very advanced in showing complex sensor values and relating those to other sensor values. The IOSS, however, could support the operator by providing root causes of certain sensor values. This can be further expanded by adding the ability to analyse these causes and suggest solutions to ensure an optimal operation. For example, the IOSS could provide explanations for the decisions it makes automatically.
The DP system currently makes simple decisions in the background that often go unnoticed, however these changes may be undesirable in certain situations or even erroneous. The IOSS could provide insight into why certain decisions are made so the operator can verify that they are appropriate. In essence the IOSS supports the operator in monitoring the system. It is important that information collected by the IOSS is presented in a comprehensible way. As the human operator will rely on the agent in times of high workload it must not add to the workload by requiring intensive processing of information. It is therefore suggested that information provided by the IOSS is presented in a way that is comparable to the existing mental models of the DP operator that were formed by using the DP system (Loeffler, et al., 2013). Operators have received great training to be able to handle the DP system and the displays are easy to interpret for them. An IOSS that takes advantage of those skills will most likely be experienced as easy to use.

4.2 Interviews

4.2.1 Approach

In order to get an idea of the implications of an FPSO related DP operation, an interview was conducted with an experienced FPSO DP operator. During the interview an offloading scenario was discussed. Offloading is one of the tasks of an FPSO vessel which involves transferring the oil to a shuttle tanker which then takes it back to shore. The goal was to get information regarding the possible risks of various stages during an offloading operation, the involvement of the DP operator, and in specific his/her tasks. The previously identified control loops were presented to the expert operator for verification.

4.2.2 Results

4.2.2.1 Scenario analysis

The FPSO operator provided valuable insight into the various tasks preceding and during an offloading operation. One thing that became clear, is that the nature of the operation varies depending on whether or not the shuttle tanker is also equipped with a DP system. When a shuttle tanker is not equipped with a DP system, the approach and offloading procedures require more manual input from the FPSO DPO. The majority of shuttle tankers is currently not equipped with a DP system, more detailed implications are discussed in the next paragraphs.
For the offloading process, the following general phases of the operation have been identified:

Long distance approach
During the final 24 hours before the offloading is scheduled to commence the FPSO vessel and the shuttle tanker are already in contact. They discuss the weather forecast and other ships that are, or will be, in the area. The FPSO vessel receives four of these notices during the final 24 hours before offloading

Close distance approach
When the ships are at a distance of 1000 meters the offloading checklist is completed and the equipment on deck required for offloading is tested. At this point the operation might slightly differ depending on whether the shuttle tanker is equipped with a DP system or not.
A DP shuttle tanker will be required to communicate with the FPSO vessel to activate several close-proximity DP systems and run trials to test their functioning. When the systems are tested and working the approach mode is activated bringing the shuttle tanker to a distance of roughly 80 meters from the FPSO vessel where it automatically keeps its position. If the shuttle tanker is not equipped with a DP system, however, the approach is done manually. The shuttle tanker is visited by a mooring master sent by the FPSO tanker to assist in the approach. A non-DP shuttle tanker remains at a slightly larger distance of roughly 120 meters.
The distance between the vessels is measured using a laser beam.

Docking
During the offloading procedure the ships are positioned bow to stern in the direction of the wind/current, where the shuttle tanker takes the aft position.
The docking procedure differs between a shuttle tanker with DP and without DP.
A DP shuttle tanker is connected to the FPSO vessel through a hose spanning from the tanker's bow to the FPSO's stern. When a shuttle tanker is not equipped with DP a floating hose is connected from the FPSO's stern, to the tanker's mid-ship. The docking of the hose is out of the scope of the DPO's work and is handled on deck. The DPO does monitor the status of the connection by monitoring the so-called telemetry which provides information about the pipe, the pump, the tank, and the quality of the connection between the two ships. If any of the variables are no longer within the required parameters the pumps are halted to prevent spillage.
In case of a floating hose the DPO is faced with an additional challenge of watching out for other ships that might want to cross in between the FPSO vessel and the tanker thereby sailing over or through the hose.

Offloading
Once the pre-checks are complete, the actual offloading commences. The DPO's role is to maintain the correct position between the ships. In case of a DP shuttle tanker this happens automatically but the DPO's on both vessels are in frequent contact to discuss external influences and changes to the optimal heading of the tandem. For example, as oil is pumped from one ship to the other their weight and draught changes. As a result, the influence of the elements such as wind changes as well and heading adjustments have to be made.

When the shuttle tanker is not equipped with a DP system it becomes a little more complex. As the hose between the ships floats and extends past the aft of the FPSO vessel, it is impossible for the FPSO ship to use the main engines in reverse as the hose might get caught in the ship propellers.

The DPO will generally disable the main propellers during these types of operations. This is something that must be considered when monitoring the position and making corrections.
In addition, to ensure a correct position, the DPO checks the telemetry of the offloading equipment and makes sure the offloading process is proceeding correctly. Technicalities regarding offloading, like for example speed of the pumps and hose tension, are managed on deck.

4.2.2.2 *Implications for support system*

The expert FPSO operator mentioned that there is a difference between the cognitive workload of the operator in the various phases of the offloading operation. He described the actual offloading phase as a period of low activity for the DPO. As discussed previously, low cognitive workload may result in underload issues associated with few task-switches, little time occupied, and low level information processing. To prevent operator errors due to cognitive underload, it may be desirable to assign additional tasks to the operator to keep him/her within the optimal range of cognitive workload.

4.2.2.3 *Verification control loops*

In order to organise the various DP tasks we proposed several control loops that recur during generic DP tasks. These were presented to the DP operator for verification. The verification was done in relation to the offloading scenario.
The expert provided very useful information into the relevance and intensity of the various control loops.

Firstly, the DPO confirmed that not all loops are equally important during an offloading operation, and that the *grounding control* loop, and the *infra avoidance* loop indeed receive no attention from either the human operator or the DP system. The operation occurs in areas with deep water where there is usually no infrastructure. Nevertheless, there may be particular DP operations where these loops may play a vital role so they should not be disregarded when developing a future IOSS.

The *system functioning* and the *redundancy control* loops are executed during the offloading operation. However, these are executed by the DP system itself.
The human operator is not as involved in these control loops. Instead, the operator is vigilant for the alerts given by the DP system which detects any issues. It is the operator’s job to set alerts and alarms in such a way that they provide a timely warning given the current and/or future operating conditions. The DPO expert mentioned that even though the system may provide warnings regarding faulty system functioning, it is not always clear what the root cause is of a malfunction. He gave the example of a ship having trouble keeping position. It turned out that one of the thrusters was operating under the wrong angle, which was the result of the feedback mechanism malfunctioning due to worn cogwheels. The expert stated that even though this problem was listed as a known issue in extensive manuals of the various subsystems, these manuals are usually not known by heart. As a consequence, diagnosing these problems requires a considerable amount of time and effort to either discover the fault or to work through the extensive manuals.

Therefore, even though this loop is performed by the system in most cases, operator involvement will likely still be required when certain less frequent malfunctions occur. Interestingly, other experts that had experience with DP systems, but not with FPSO operation, mentioned that system functioning is in fact not left completely to the DP system. Sensor drifts may occur that are not recognised as such by the DP system, these must be recognised by the human operator.

Three loops that require active engagement by the human operator are *position maintenance*, *environmental control*, and *collision control*. The position maintenance loop is monitored by both the DP system and the operator. Constant monitoring by the operator is not required as the DP system can give notifications when the position moves beyond certain thresholds that are set by the DPO.
In more variable weather conditions the operator may also actively monitor for deviations in the position, but more importantly the heading. External influences have to be countered by using the ship’s engines. As the engines have a limited amount of power, it is the operator’s responsibility to make sure the ship can counter external forces as efficiently as possible, usually by changing the heading so the ship faces the direction of the external force, provided the operation allows heading changes. This is the reason that even though maintaining the position is the main goal, monitoring the heading is more important than monitoring the position. The expert said that when you lose your heading, you will most likely lose position as well. To change the heading appropriately, the operator has to know the direction of the external forces, which is when he engages in the environmental control loop.

The environmental control loop entails the operator monitoring current and future weather states and calculating the best predicted position for the ship to handle the forces or, in extreme cases, whether the operation has to be aborted when there is no way the ship can handle the external force. Information gathered here includes wind direction, wind speed, but also properties of the waves and water currents. The expert mentioned that this loop is likely the most active of all, as the environment is the most variable. Two factors that impact the amount of work involved in monitoring the environment are the location and time of year the operation takes place. Whereas in some parts of the world the weather can be relatively stable and predictable, there are also regions where storms form in less than half an hour, or where anomalies in the water current can cause a ship to drift off without warning. In such conditions, the DPO is constantly engaged in the *environmental control* loop, monitoring the weather sensors in an attempt to detect anomalies as early-on as possible among a large array of ambiguous data, resulting in a high level of workload.

The third loop that requires operator attention is the collision control loop.
The operator has to monitor the radar and make sure there are no other vessels that are on an intercept course. Preferably third party vessels have to stay outside of a 500 meter radius of the FPSO vessel. Similar to the environmental control loop, the amount of required engagement in preventing collisions is highly dependent on the location of the operation. When this takes place in a remote part of the ocean where there are few to no ships that could potentially collide, however there are areas where dozens of small fishing boats clutter the area and constant attention is required.

5 Conclusions and recommendations

5.1 HTA

In the HTA several control loops were identified at the control activity level.
An interesting observation regarding this HTA is that it has an uncharacteristic diamond shape instead of the more traditional pyramid shape. This is the result of the HTA demonstrating that the control loops are dependent on the same generic tasks at the control task level. The control tasks are in turn related to a limited set of sub-tasks, and the execution of a particular sub-task can serve multiple different control tasks instead of just one. The same goes for the relation between sub-tasks and system components, where a system component can provide input for multiple different sub-tasks. The fact that lower level tasks serve multiple higher level tasks causes the shape of the HTA to narrow down towards the bottom levels.
This observation might be applicable for other highly automated control environments as well. From a top-down approach, even though the goals and sub-goals may be completely different, the identification of control activities sub-divided in generic control tasks could work for other supervisory control domains as well. From a bottom-up approach, a limited set of system components can serve a larger set of sub-tasks that may serve a variety of control tasks.

From the point of cognitive task load this means that the observation of an operator watching particular instruments may serve different tasks or goals. For example, watching sensor values could mean that the operator wants to check the current position, or compare it with other sensor values to check the functioning of the system. And changing the thruster settings could mean that the operator is changing heading to keep position or tries to avoid a collision with another vessel.

5.2 Operator support analysis

The goal of the operator support analysis was to identify periods during the work of a DPO where he/she experiences cognitive under- or overload. During these periods the operator could benefit from additional support provided by an IOSS.
In order to determine this, the operator’s information needs were identified during an expert session, and the phases of a typical FPSO operation were discussed with an experienced DP operator. During the interview with the DPO it was found that during an offloading operation the operator experiences situations both where the level of workload is high, and where it is low. Periods of high workload occur especially during the approach and docking phase of the operation where the operator is faced with several additional tasks on top of keeping the vessel in position. These additional tasks are comprised mostly of communicating with the shuttle tanker about the planned approach and the docking procedure. It was identified that the amount of additional workload during these tasks is to a large extent dependent on the type of shuttle tanker. Where a shuttle tanker equipped with DP can perform the approach largely automatically, a shuttle tanker without DP requires a lot of manual input and communication regarding the distance between the ships. This may lead to reduced performance on the generic DP tasks such as monitoring the weather and system functioning.

Once the ships are docked and offloading, the operator experiences a low level of workload. However, anomalies may occur that are usually related to changes in the external environment. Consequently the environmental control loop that was identified in the HTA is also considered to be the most active and the most variable in terms of demanding operator attention. It was found that the intensity of the environmental control loop is to a large extent dependent on the location of the operation, and the time of year, i.e. the impact of seasonal weather changes.
The DPO expert explained that during certain times of year in certain parts of the world storms can form within 15/30 minutes, and anomalies in the water currents, such as solitons, can approach in an equally small amount of time. Interestingly, the control loops that were identified as being the most demanding on the operator, e.g. environmental control, will be demanding regardless of the type of operation. Therefore, for stationary DP operations with the aim of relieving the operator and possibly allowing him to become roaming and engage in other tasks, it is imperative that the most active control loops, i.e. position control, environmental control, and collision control, are sufficiently monitored by the IOSS. The IOSS needs to provide problem detection early enough for the DPO to be able to respond in time, which can be within a timeframe shorter than 15 or 30 minutes depending on the variability of the situation.

Furthermore, the IOSS should support the operator during times where he/she is engaged in additional tasks such as communicating with a shuttle tanker, resulting in a high level of workload. The IOSS could take over some of the generic DP tasks and alert the operator to sudden changes in either the internal or external environment. Another opportunity for additional support is based on the example given by the DPO regarding the missed defects. The IOSS could support the operator in recognising errors or abnormal system behaviour and provide the operator with a possible diagnosis and resolution.

Based on the analyses presented in this report it has become clear that an IOSS should not only be adaptive to the operator state, but also to the variability of the operation. Since some control loops may require a lot of operator involvement in certain conditions, and be irrelevant in others.

5.3 Limitations

The results presented in this report are subject to several limitations. First it must be noted that the information presented and the conclusions are based on interviews with a rather limited number of domain experts. Even though the information has been cross-checked between the experts and was revised several times, it is possible that additional experts will provide new insights or nuance the existing information. Further investigation of the FPSO task might be required, as non-FPSO DP operators have mentioned aspects of their work that has not come forward during the interview with the FPSO operator, e.g. consideration of internal system failures by the human operator rather than to leave it to the system. This aspect has therefore received little attention so far.
The task-analysis that has been presented here may be further expanded based on new information. It should therefore not be regarded as definitive and should serve as a basis for further research.

5.4 Recommendations

From the interview with the FPSO operator it became clear that during the offloading operation the DPO has to perform several operation-independent tasks to ensure safety and normal functioning of the DP system. Thus far, these functions have not received a lot of attention during the inventory of the operator tasks and corresponding workload.

One of these functions is that prior, during, and after the operation, checklists have to be completed where key system settings, sensor values, and future decisions have to be recorded for future reference. The FPSO operator indicated that a support system to make the completion of the checklists easier could be useful. This was not included in the current analysis but may be worth investigating further. Another task that falls on the shoulders of the DPO is communicating with other vessels about position, trajectories, and decision-making. Future research should include these tasks in a time-critical situation and investigate how often these tasks are performed, how demanding they are, and how they may influence the performance.

Two of the identified control loops were found to be irrelevant for the current offloading scenario, however, for the development of an IOSS it is important to also evaluate other types of DP operations where these control loops are relevant to get a complete picture of the demands placed on the operator during various types of operations.

A further recommendation for future research is a more formalised assessment of cognitive workload. The current information is based on expert evaluation and the input of one domain expert, but no simulated or real-world tests have been conducted and no measurements have been made. Before the necessity and the usefulness of support systems can be determined it is first necessary to conceive a method to make the DPO’s workload quantifiable and to measure performance increases as a result of the implementation of support concepts.

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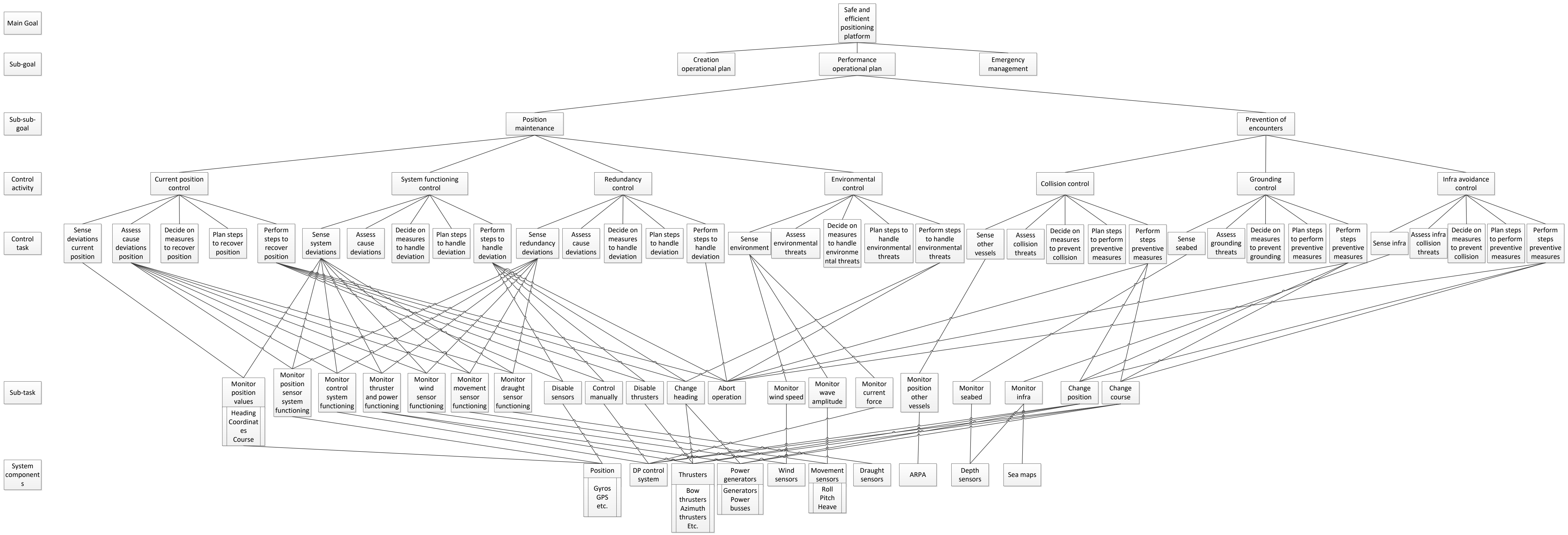
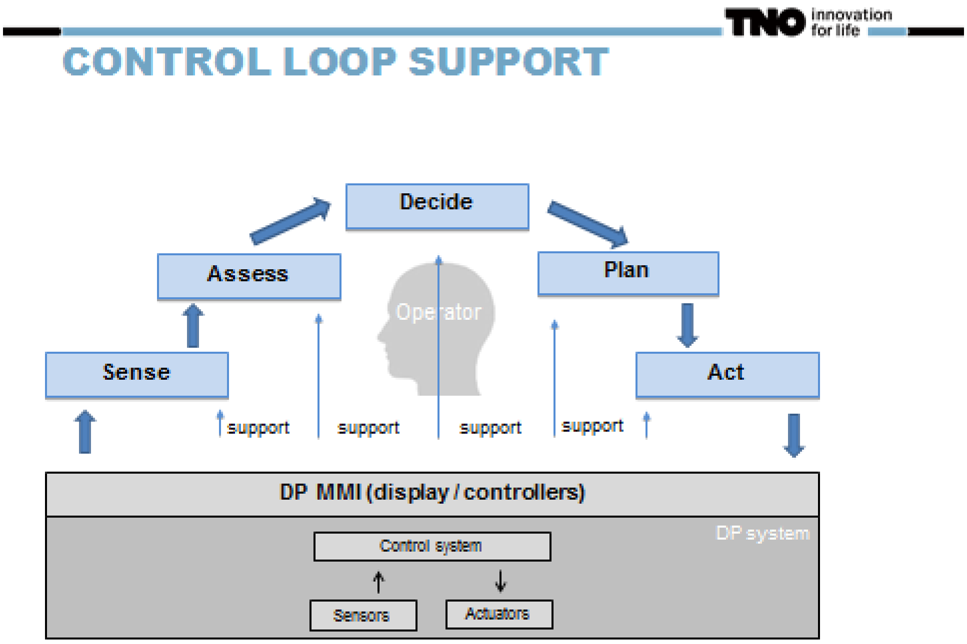
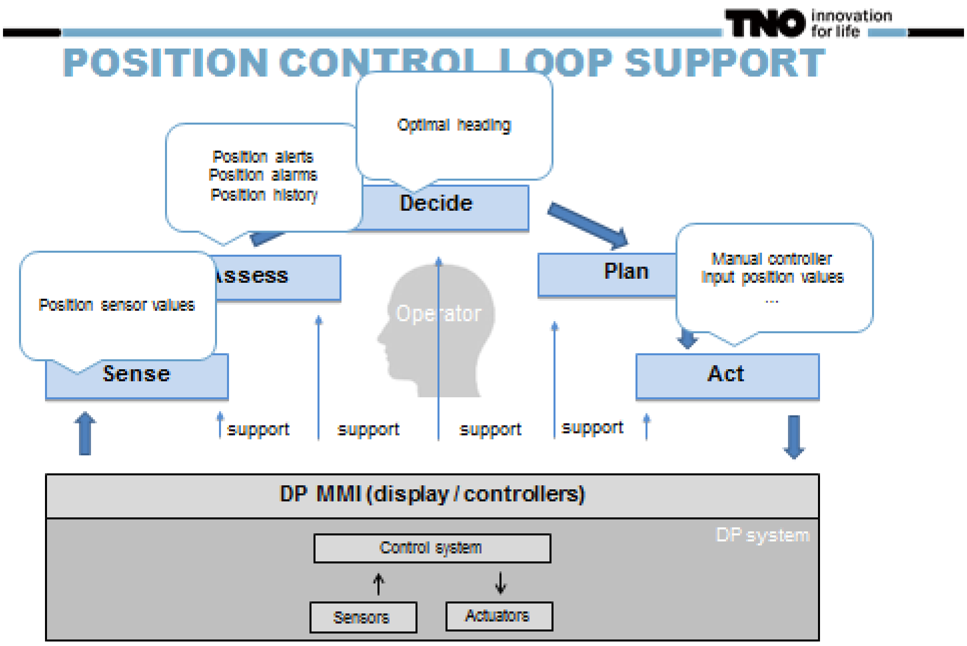
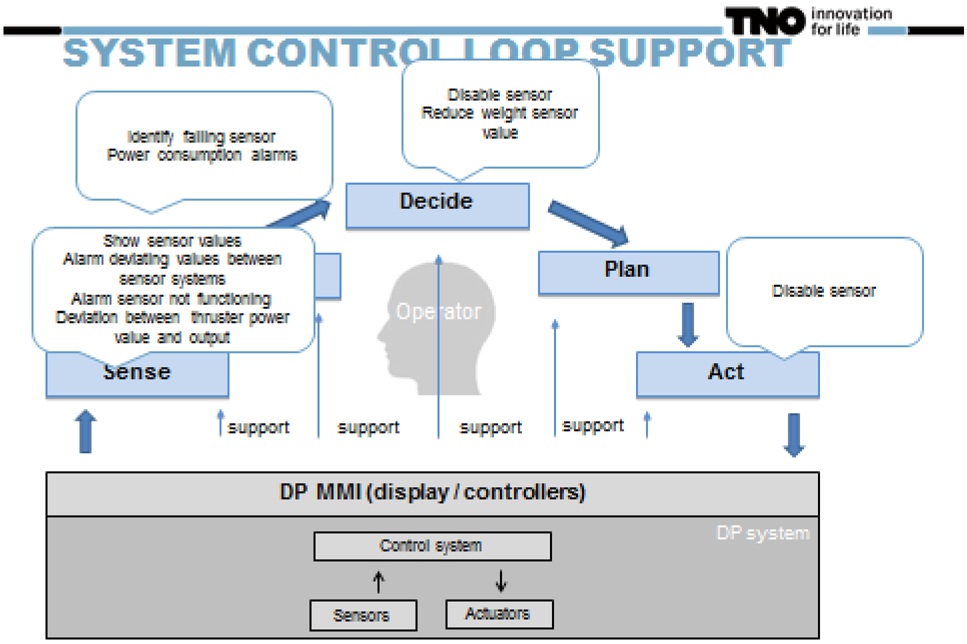
A Hierarchical task analysis of DP operator

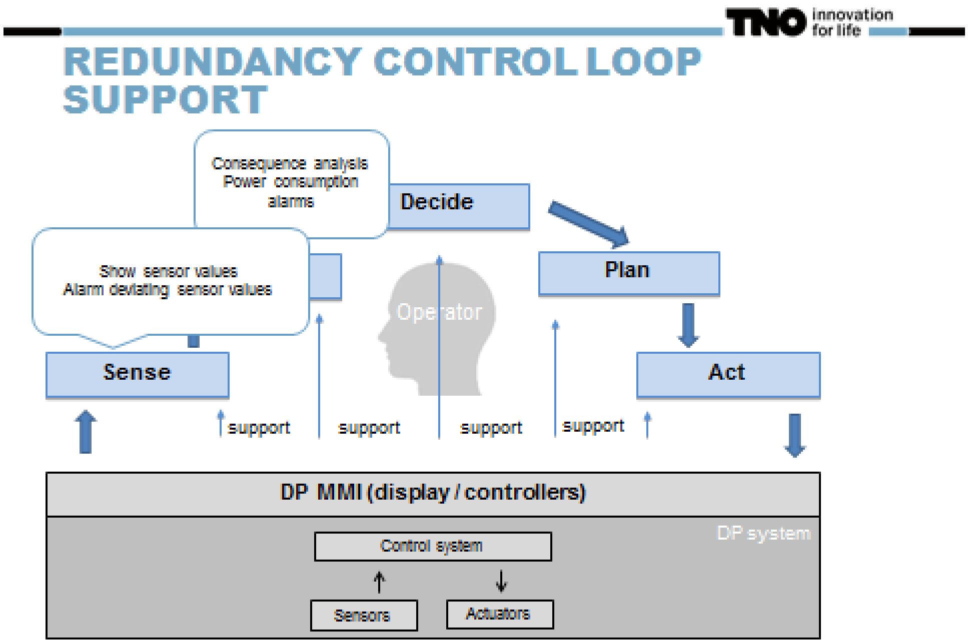


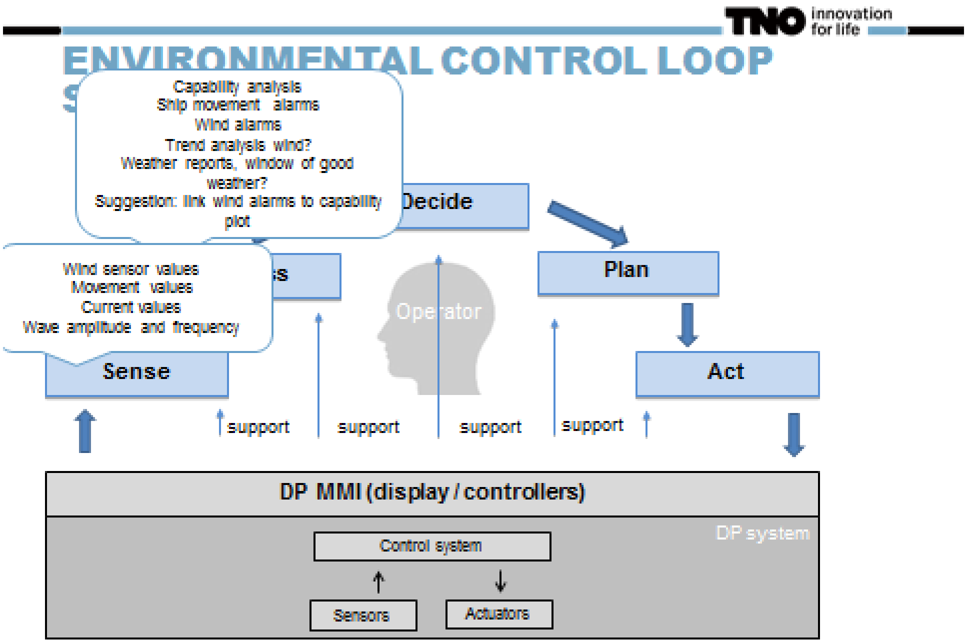
B Conning interface support

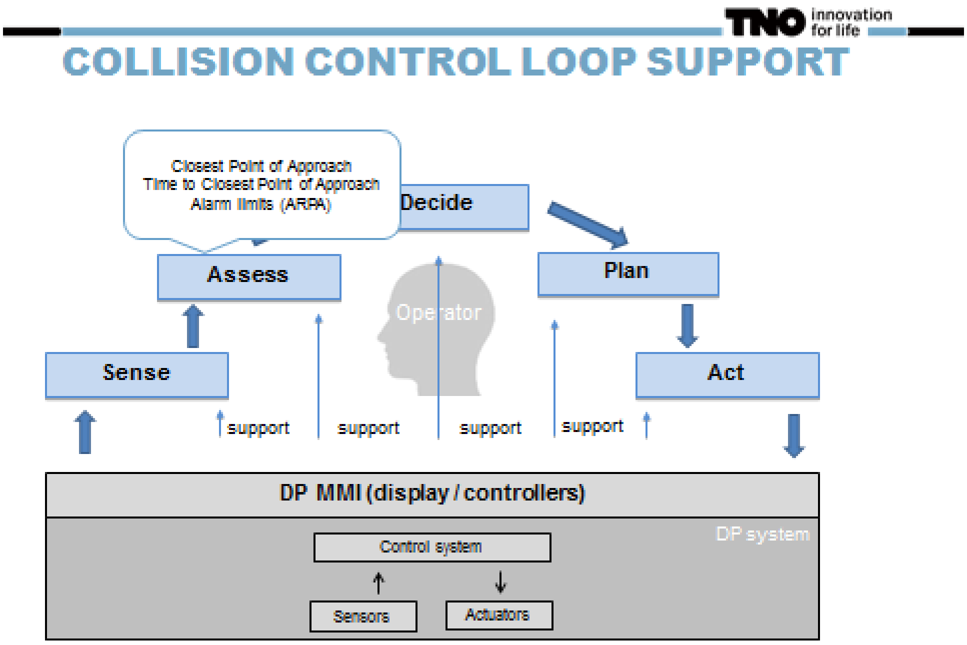


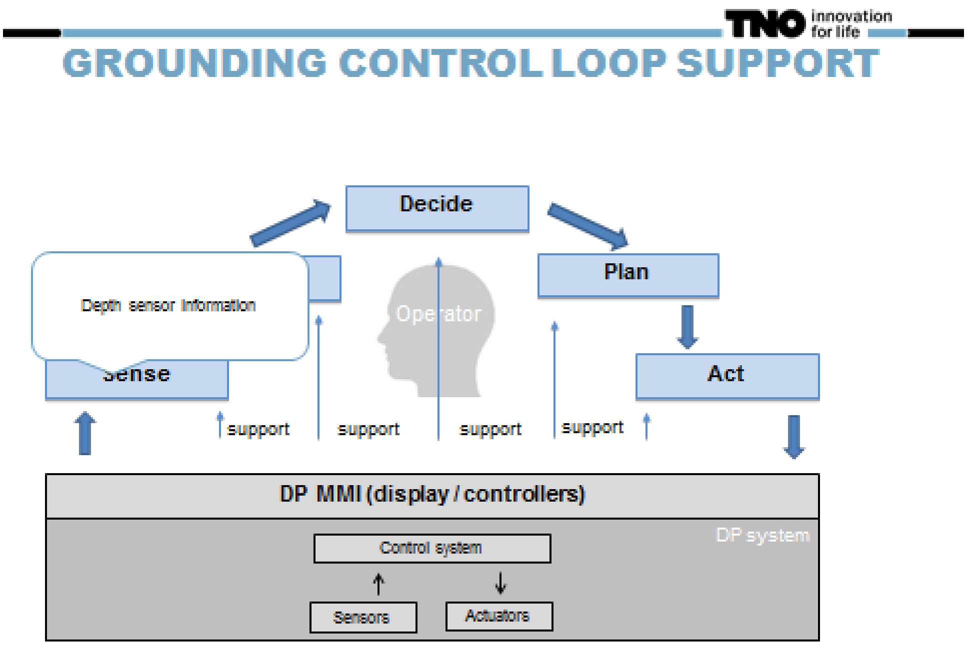


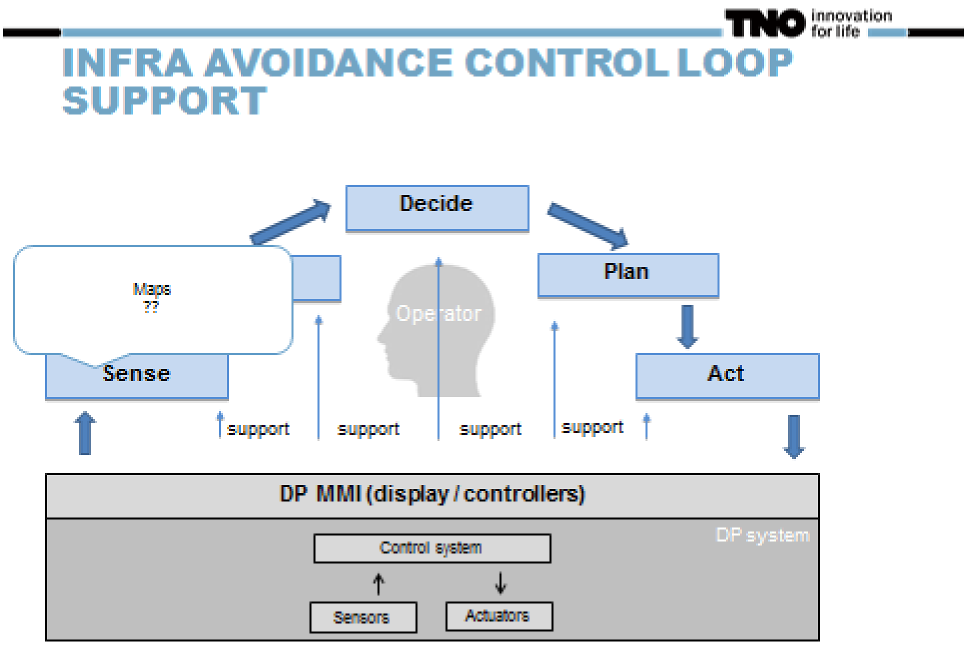

innovation for life
SYSTEM CONTROL LOOP SUPPORT
Identify failing sensor
Power consumption alarms
Disable sensor
Reduce weight sensor value
Decide
Plan
Show sensor values
Alarm deviating values between sensor systems
Alarm sensor not functioning
Deviation between thruster power value and output
Operator
Disable sensor
Act
Sense
support
support
support
support
DP MMI (display / controllers)
DP system
Control system
Sensors
Actuators


innovation for life
REDUNDANCY CONTROL LOOP SUPPORT
Consequence analysis
Power consumption alarms
Decide
Plan
Show sensor values
Alarm deviating sensor values
Operator
Sense
Act
support
support
support
support
DP MMI (display / controllers)
DP system
Control system
Sensors
Actuators


TNO innovation for life
ENVIRONMENTAL CONTROL LOOP
Capability analysis
Ship movement alarms
Wind alarms
Trend analysis wind?
Weather reports, window of good weather?
Suggestion: link wind alarms to capability plot
Wind sensor values
Movement values
Current values
Wave amplitude and frequency
Decide
Plan
Act
Sense
Operator
support
support
support
support
DP MMI (display / controllers)
DP system
Control system
Sensors
Actuators


TNO innovation for life
COLLISION CONTROL LOOP SUPPORT
Closest Point of Approach
Time to Closest Point of Approach
Alarm limits (ARPA)
Decide
Assess
Plan
Act
Sense
Operator
support
support
support
support
DP MMI (display / controllers)
DP system
Control system
Sensors
Actuators


innovation for life
GROUNDING CONTROL LOOP SUPPORT
Decide
Plan
Depth sensor information
Operator
Act
support
support
support
support
DP MMI (display / controllers)
DP system
Control system
Sensors
Actuators


innovation for life
INFRA AVOIDANCE CONTROL LOOP SUPPORT
Decide
Plan
Maps
??
Operator
Sense
Act
support
support
support
support
DP MMI (display / controllers)
DP system
Control system
Sensors
Actuators