Automatic inspection of railway overhead wires

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ABSTRACT

For the Netherlands railway company a system for inspection of the degree of wear of the contact wires is being developed. With an active sensor the reflective under-surface of the overhead wire is illuminated with a laserbeam and reflected radiation is detected by fast CCD detectors. With the sensor at a train speed of 90 km/hr. every cm of max. 4 overhead wires will be inspected, determining the wire thickness and the appearance of holes caused by local sparks. For illumination and detection a special optical system has been developed. From the railway inspection waggon measurements have been performed with a prototype system, demonstrating the feasibility of the measuring principe.

1. INTRODUCTION

One of the problems for railway companies is the unexpected fracture of overhead contact wires on electrified railway sections. These fractures lead to delay to the passengers and costly repair.

This wire breakage occurs, when the thickness of the wire has become too small, due to wear caused by the pantograph (current collector) scraping along it.
For periodical monitoring of the wear of the contact wires in most countries visual inspection at critical points takes place. This inspection however is very incomplete and gives only a rough insight in the condition of the contact wire network. Until now several inspectionsystems have been developed, based on the laser scanning principle or on the use of fiber optics, where the sensor is connected with the pantograph and follows the movement of the overhead wire.

For the Netherlands railway company the TNO Institute of Applied Physics is developing a new type of inspection system, with which contact wires can be inspected every cm in travel direction. This system is based on the application of fast linear Charge Coupled Devices (CCD) and makes no contact with the wire. The project has the acronym ATON, which stands for: Automatic Thickness measurement Overhead wires Netherlands railways.

The cross section of a weared contact wire is pictured in fig. 1. With the sensor the width of the reflective under-surface of the overhead wires is measured and from this the thickness is derived. This method can be applied in most countries, where the cross section of the wire has a circular shape.

The sensor is placed in a railway inspection waggon. The reflective underside of the contact wire is illuminated with a laser beam and the light reflecting part of the contact wire is imaged by a special optical system on a linear CCD array. By reading out the CCD signal the widht of the reflecting part of the contact wire and derived from it the thickness of the wire is determined and even holes in the surface (so called craters), that are caused by local sparks or large current collection can be detected. The measuring principle has been demonstrated in practice in a representative prototype experiment, while in laboratory experiments the reflection signals have been studied in detail.
At this time the final design of the instrument has been completed and the manufacturing is started. The instrument will become operational in 1989.

2. BACKGROUND

The application of CCD detectors makes it possible to develop an instrument with higher specifications, than is possible with a conventional mechanical scanning system.

The most important performance specifications of ATON are:
1. Measurement of the position of the contact wire:
Accuracy: ± 10 mm with respect to center of waggon
± 3 mm with respect to other wires.
This measurement must be performed every 10 cm in travel direction.
2. Measurement of the thickness of the contact wire:
Accuracy ± .25 mm.

This measurement must be performed every cm in travel direction and will be averaged over a distance of 1 m.

3. Measurement of occurrence of craters.
The size of craters can be rather small ($\leqslant$ 10 mm), so therefore every cm the reflection signal must be inspected. Craters can be recognized by a local drop of signal intensity. The presence of craters will be indicated by an alarm.

All measurements will be labelled with data from the train (speed, distance, etc.).

Besides there are a number of boundary conditions, that make the inspection problem extra difficult.

- The maximum speed of the train during inspection will be 90 km/hr. In this way the measuring campaign can be scheduled in between the normal railways activities, and is not influencing the train depart- and arrival schedule.
- The Field of view (FOV) in cross direction is 110 cm. The contact wires are mounted in a zig-zag pattern in order to distribute the wear over the whole width of the pantograph.
- The height of the contact wires can vary between 4.50 and 5.95 m above the rails.
- The slope of the overhead wires in height direction can vary between ± 1 degree. Due to the reflection properties of the wire surface this is an important factor for the system design.
- Within the FOV maximum 4 wires can be present.

Some other data of interest are:
Wire material: electrolytic Cu.
Diameter : ∅ = 12.0 mm (Circular with 2 grooves for mounting).
Voltage : 3000 V (DC).
Current : up to 1500 A.

Other conditions as available space for the sensor, temperature and vibration specifications, etc. are not relevant for further considerations and will not be discussed here.

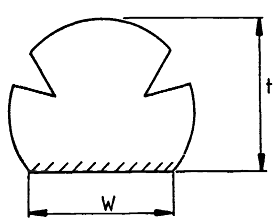

Fig. 1.

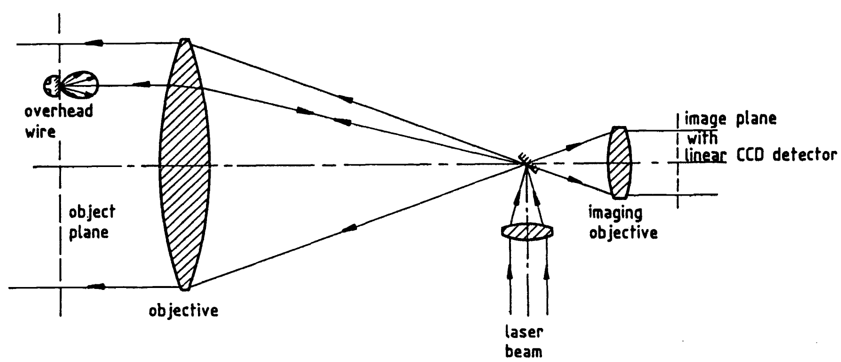

Fig. 2.

3. SENSOR DESCRIPTION

3.1. General principle

After balancing various technical possibilities the use of fast linear CCD arrays to solve this inspection problem was chosen. The measuring concept is schematically pictured in fig. 2.

Starting point for the concept is, that as a result of the scraping of the pantograph along the overhead wire the underside of the wire becomes reasonable flat and reflective. This means that by illuminating this surface a part of the reflected light can be detected and the surface can be inspected.

With an optical system a laser beam is made parallel in cross direction and is imaged on the contact wire with an aperture of more than 4 degrees in travel direction. The choice of this illumination configuration is based upon the reflection characteristic of the flat surface of the contact wire. Measurements showed, that in travel direction the reflection is almost specular, while in cross direction the light is scattered over some degrees, caused by small grooves in length direction as a consequence of the scraping of the pantograph. In cross direction a maximum amount of light is reflected back into the optical system for detection, while in travel direction within the slope of the overhead wire that can occur always a part of the light is reflected back to the imaging optics.

The imaging system is a telescope configuration, which has a constant magnification independent of the object distance. In the focal plane a linear CCD array is positioned with which the width of the reflecting surface can be measured. Movement of the contact wire in a horizontal direction perpendicular to the travel direction leads to displacement of the image over the detector array while movement in vertical direction makes an active focussing necessary. The amount of focussing depends on the magnification of the configuration and is small with respect to the height variation. The magnification is determined by CCD detector element size and required resolution.

Between telescope and CCD a narrow bandfilter is positioned to suppress straylight and background light in order to improve signal to noise ratio.

3.2. Optical system

Fig. 3 gives a perspective drawing of all optical parts of ATON.

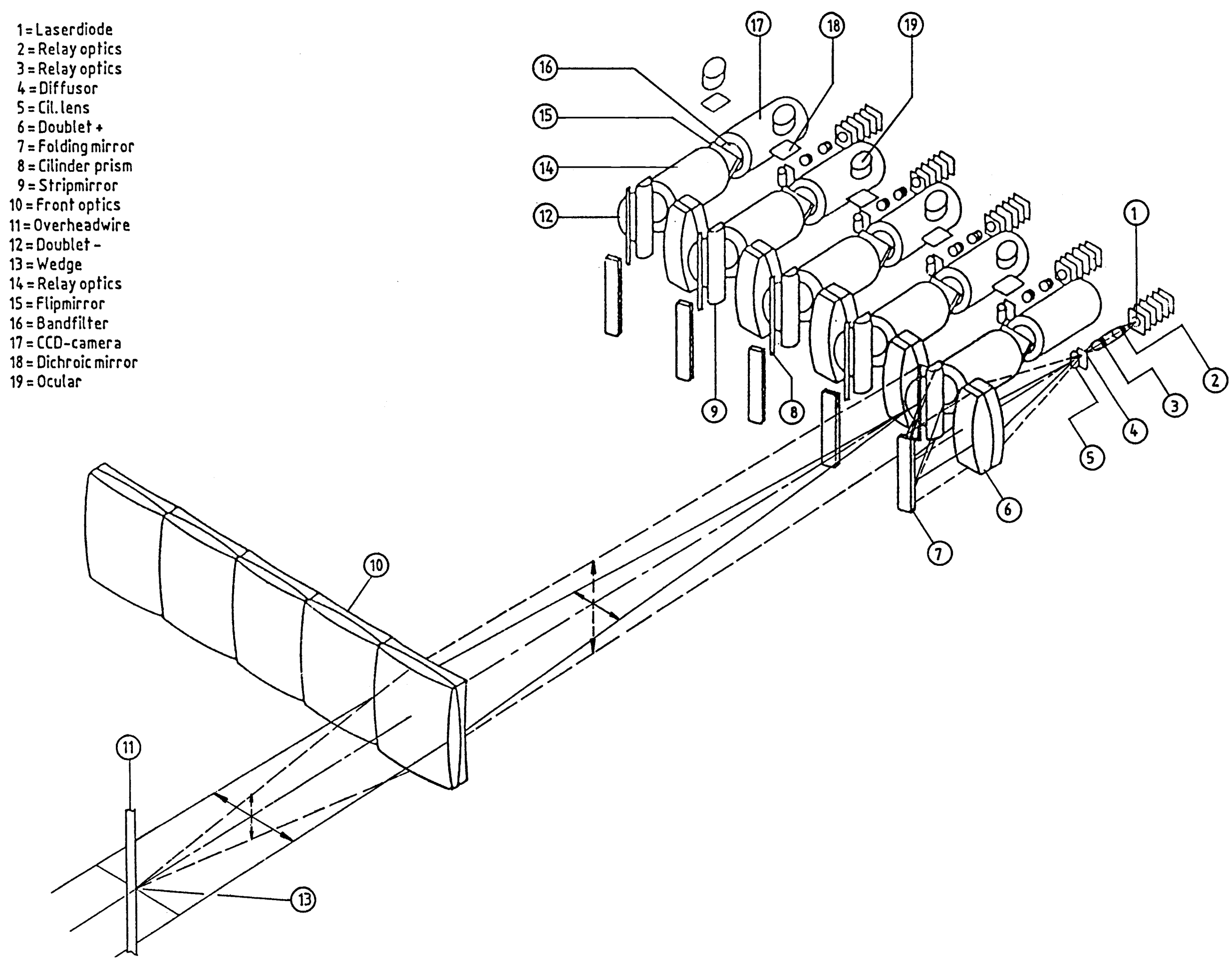

Fig. 3.

3.2.1. Detection optics

With respect to the basic configuration, as described in the previous section the final design is modified.

1. The FOV of 110 cm can not be scanned with adequate resolution by one system and/or one CCD detector. Considering the available space and after optimization of the optical configuration with one system finally a FOV of 220-230 mm in cross direction can be scanned.
Applying a modular construction this means, that the total FOV can be covered with 5 neighbouring modules with a small overlapping FOV.

2. To decrease vignetting over the FOV for the optical configuration a Galilean telescope has been chosen. This telescope gives a virtual image, that is reimaged on the CCD detector with a relay lens.

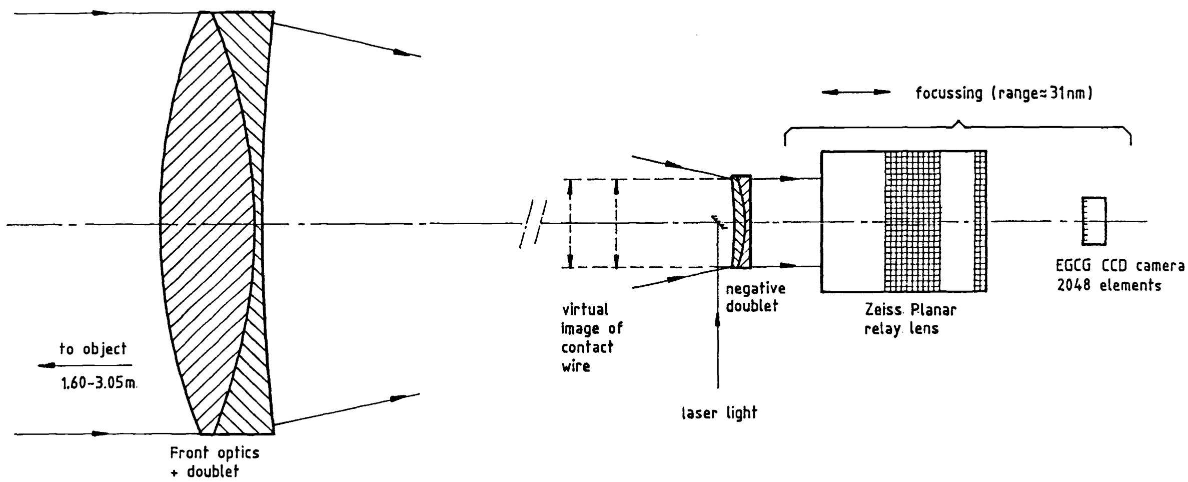

Fig. 4.

The final detection system is pictured in fig. 4. Some data are given in table 1. The configuration consists of the following parts:

- The Galilean telescope
This telescope consists of a positive doublet (the front optics) with a dimension of 220 x 240 mm and a negative doublet with a diameter ø = 35 mm.

The doublets are cemented and optical glasses are selected with almost equal thermal expansion. During the design phase it is tried to use a single large front component, but sufficient optical quality only was possible using 2 components.

- The relay lens
The virtual image of the telescope is reimaged by a standard relay objective from Zeiss (Macro Planar S, f = 86 mm).
The magnification of this relay imaging is 1.76 x . For focussing both the relay lens and the CCD detector are shifted along the optical axis. The direction and amount of shift is derived from the available pantograph height data.

Magnification:	
Telescope	6.8 x
Relay lens	1.76 x
Total	12 x
Focussing range (Relay lens + CCD)	31 mm
FOV (in object space)	230 - 240 mm
Number of pixels used	1420-1480
Scale factor	1 pixel = 0.155 mm
Physical dimension of front optics	220 x 240 mm
Number of modules	5
Totaal FOV	5 x 220 = 1100 mm

Table 1
Some relevant data of detection optics

The relative aperture of the imaging beam is F/4.5. This leads in object space to a depth of focus of about ± 8 mm, being in conformity with the accuracy, with which the height of the pantograph is measured.

- The CCD camera
The image of the contact wire is detected with an EG & G line scan camera. The camera containes a 2048 elements linear CCD with a pixel size of 13 µm x 13 µm.
This camera was chosen because of high speed operation (up to 20 MHz), excellent detection properties and small dimensions.

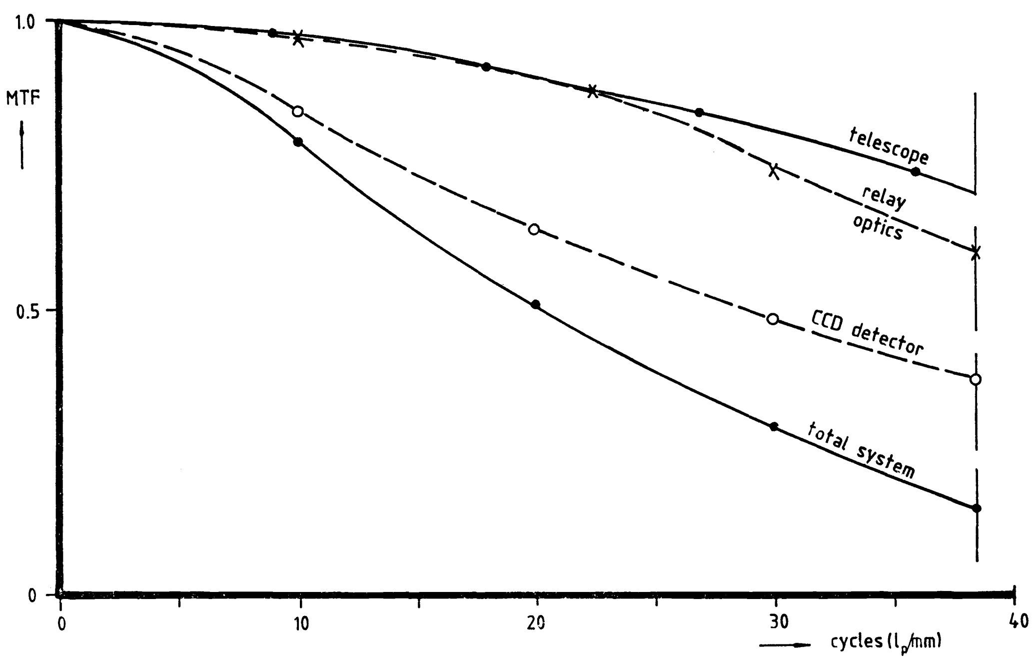

Fig. 5.

Besides of these 3 main parts the detection system is supplied with:

- A narrow bandfilter (background reduction).
λc = 800 ± 2 nm
$\Delta\lambda$ (FWHM) = 10 nm
Transmission: 75 - 80% (peak).

- Circulair linear-wedge neutral density filter.
The angular position of this filter is coupled to the speed of the train. At maximum speed (90 km/hr) the transmission is about 100%, at half speed (45 km/hr), when the integration time of the CCD is doubled to have still the 1 cm resolution in travel direction, the transmission is about 50%.
In this way the signal/background ratio remains optimal

- A viewing system.
For visual inspection between relay lens and camera a viewing system is positioned. Via a flip mirror and by means of an ocular the overhead wires can be seen. A dichroic filter with reflection at 800 nm protects the eye against the reflected laser light.

The image quality of the detection system has been determined. Therefore in the first place the Modulation Transfer Function of the telescope has been computed. Of the relay lens the MTF has been measured and also the MTF of the CCD detector, including the influence of channelstop, crosstalk and element size has been determined. For the total system we find:

$$MTF_{TOT} = MTF_{TEL} \times MTF_{Relay} \times MTF_{CCD}$$

The MTF of the telescope is an averaged value over the FOV and for various object distances. From fig. 5 it is clear, that the contribution of the CCD detector to the final MTF is significant. The optical parts (telescope and relay lens) have amost an equal contribution to the MTF.

3.2.2. Illumination optics

The illumination configuration is schematically outlined in fig. 6.

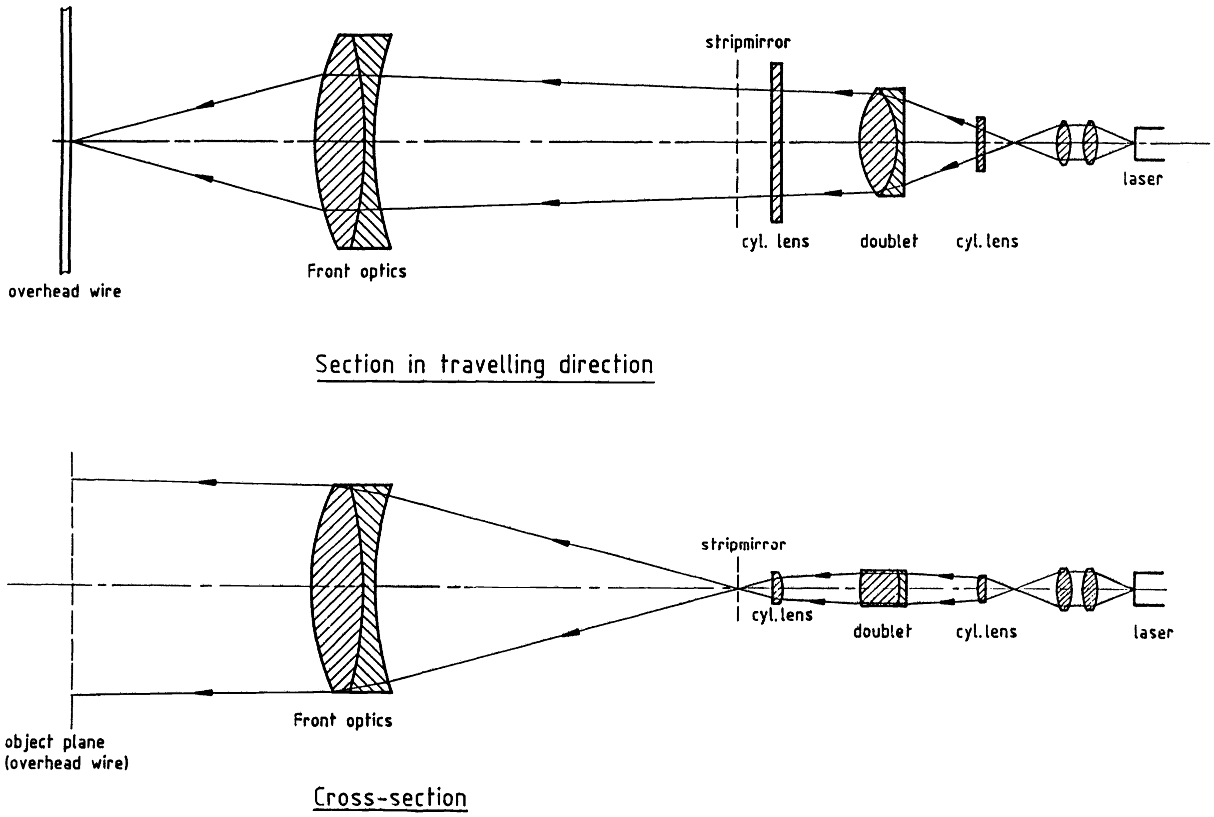

Fig. 6.

Although prototype experiments for demonstration of the feasibility have been performed with a conventional He-Ne laser (633 nm), for the final design a high power laser diode, emitting at a wavelength of 800 nm has been chosen.

The reasons for this choice are obvious:

- Long life time.
- Almost optimal location of wavelength, considering skylight, CCD sensitivity and wire reflection.
- Small dimensions.
- High efficiency.

With the optical system the laser point source is projected as a line on the overhead wire, perpendicular to the travel direction. With some cilindrical lenses and a spherical doublet the light is reflected in the telescope system via a small strip mirror. This mirror is located just in front of the negative doublet of the telescope, where a line shaped intermediate image is created. Some characteristic elements of the system are:

1. In travel direction the light is imaged on the contact wire with a beam aperture of more than 4°.

2. Focussing in this direction on the wire is performed by moving a relay- and a cilinder lens.
The optical system is dimensioned in such a way, that focussing movement of the illuminating system is equal to the focussing of the detection system.

3. Perpendicular to the travel direction the light is slightly diverging, because the strip mirror is located within the focal distance of the front optics. This diverging is necessary because of the overlap of FOV between adjacent modules.

4. Most of the optical surfaces are supplied with an anti-reflective coating for 800 nm. However to prevent the direct rest reflection at the rear surface of the front

doublet from entering the camera system, the radius of curvature is adapted in such a way, that the strip mirror is located in the center of curvature of this rear surface. In this way all of the light, coming from the strip mirror and being the rest reflection of the rear surface of the front doublet, is reflected back into the illumination system and cannot enter the detectors relay optics.

5. The radiation pattern of the laser diode is not uniform. In the arrangement 2 methods can be applied to make this pattern homogeneous.

- The laser can be supplied with a fiber stub or pigtail.
- Near the location of reimaging a diffusing plate can be positioned.

A final choice will be made in a later stage.

The total width of the line image of the laser at the location of contact wire varies between 1.3 - 1.8 mm, depending on the wire distance.
Between the modules the FOV has an overlap of $>$ 12 mm, this being the maximum width of the worn surface of the overhead wire.

3.3. Mechanical system

1. The complete optical system, consisting of 5 imaging systems, 5 CCD camera's and 5 illumination systems will be integrated on a modified, commercially available optical breadboard.
The dimensions of this breadboard are: width 1219 mm, height 1524 mm and thickness 50 mm. The weight of the breaboard alone is approximately 155 kg.
the estimated weight of the whole optical system to be built on the breadboard is around 200 kg.

2. For the mounting of the optical system in the inspection waggon a special frame is designed. This frame stands on the floor of the waggon on vibration dampers and is also secured to a vertical mounting frame in the waggon. The vibration dampers are adjustable in height and the breadboard is in one direction angular adjustable within this frame.
As a result of this mounting as a whole, the optical axes of the systems can be adjusted to be nominally perpendicular to the reflecting surface of the overhead lines.

3. In order to keep the light line on the overhead lines in focus, during the variation of the height of the overhead lines with respect to the optical system and to keep the detection system in focus, a dynamic focussing system is needed.
The optical components of the illumination system that have to be shifted are a re-imaging lens, a diffusor and a cylinderlens.
The part of the imaging system that must move for focussing is the combination of the relay-lens, viewfinder, interference filter and CCD-camera.
All these components for focussing must be shifted in the same direction and over the same distance for every change of the height of the overhead lines. This implies that all these components for one module can be mounted on a single linear translation stage. For the whole detection system 5 translation stages are used. All 5 stages are driven by a single DC motor-tacho combination powered by a four quadrant amplifier. Actual position of the stages is readout by means of a SLVC (super linear variable capacitor) transducer and compared with a set point input derived from the height of the pantograph of the inspection vehicle.
On the breadboard, temperature transducers are mounted. When the temperature of the breadboard changes and, as a result of that, the position of the image plane shifts along the optical axis, a correction for that shift is introduced on the focussing system.

4. Over the whole optical system a thermally insulated box is mounted which is sufficiently airtight to be able to maintain slightly higher air pressure in the box than the atmospheric pressure is. A selfsupporting air conditioning system feeds dry, filtered air into this box.
In one wall of the box large Peltier cooling/heating elements are mounted that have such a capacity that the dissipation of the electronic parts in the optical system can be removed by these elements and that the temperature extremes of the waggon can be smoothed out.

5. For the mechanical mounting of the system electronics a rack mount system is chosen, in which the system electronics are housed within vibration damped boxes.

3.4. Signal processing

The 5 CCD camera's produce an enormcus amount of data, from which a relative small amount must be extracted for determination of wire location, thickness, alarm for craters etc.

Therefore with the signal processing electronics a large data reduction is performed, reducing the data stream of 25 Mega words per second by more than 99%.

The general structure of the signal processing is pictured in fig. 7. This structure consists of the following parts:

- 5 CCD camera's

These camera's detect the overhead wire signal and each camera produces every second 2500 times the output of 2048 detector pixels. Each camera module contains correction and digitizing electronics.

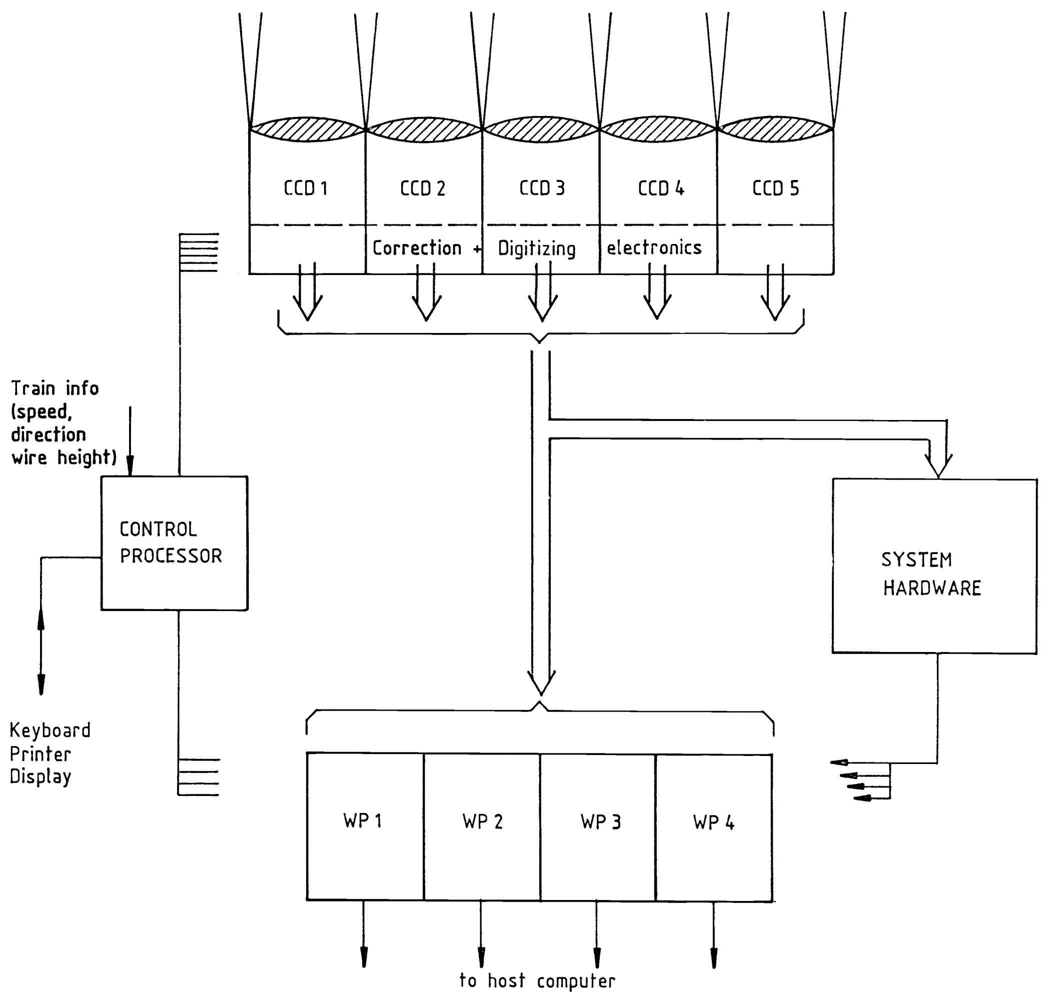

Fig. 7.

- System hardware part

This part, containing a special processor inspects constantly the CCD-signal for the presence of a new wire according to the following criteria:
1. The presence is detected when the signal exceeds a defined threshold.
2. A maximum of 4 wires can be detected.
3. Each recognized wire is followed.
After positive detection each wire is assigned to a wire processor.

- 4 wire processors
  These are digital signal processors connected to processors for data communication and computertasks.

A wire processor follows an overhead wire over the FOV and determines constantly the measuring data of interest (thickness, position, alarm, etc.).
Algorithms for determination the width of the reflecting wire surface have been determined. As soon as a wire is lost (end of wire) the status of the wire processor becomes 'not occupied' and the system hardware can assign a new incoming wire to that processor.

- Control processor
  This unit is for the overall control. It accepts data from the outside world, informs the operator about the system status and controls the operation modes (calibration, test, operation).

The system is completed with a keyboard, a printer and displays.
The signal processing electronics is built in one 19" wide, 24" high unit containing 18 printed circuit boards and power supplies for the processing electronics.
For housing of the power supplies for the lasers, Peltier coolers/heaters, focussing system etc. a second unit of the same dimensions is used.

4. EXPERIMENTAL VERIFICATION

4.1. Introduction

Before the development of ATON was started experiments have been carried out to demonstrate the feasibility of the measuring principle. These experiments consisted of 2 parts:

- Measurements in practice with a prototype inspection system.
- Measurements in the laboratory of the reflection characteristics of weared contact wires, simulating a travelling speed of about 45 km/hr.

These activities will be shortly described hereafter.

4.2. Prototype in situ measurements

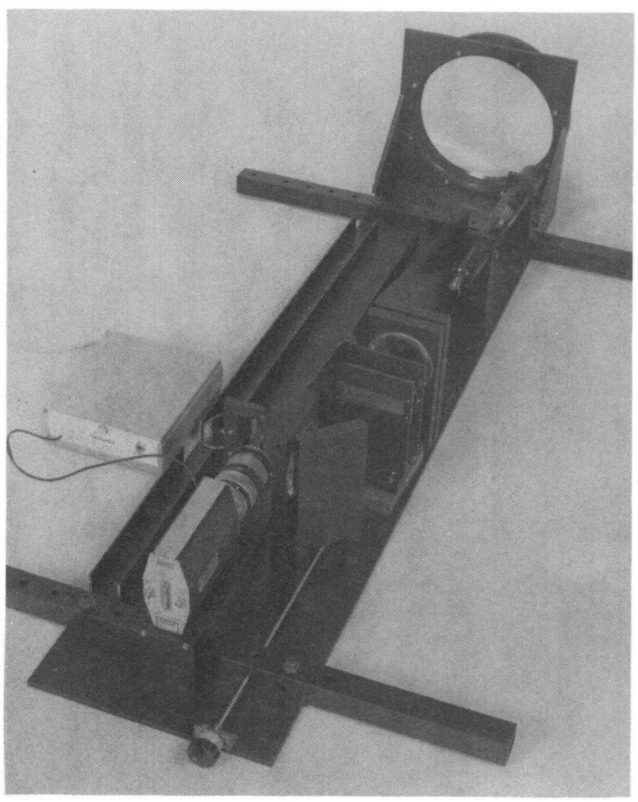

Fig. 8.

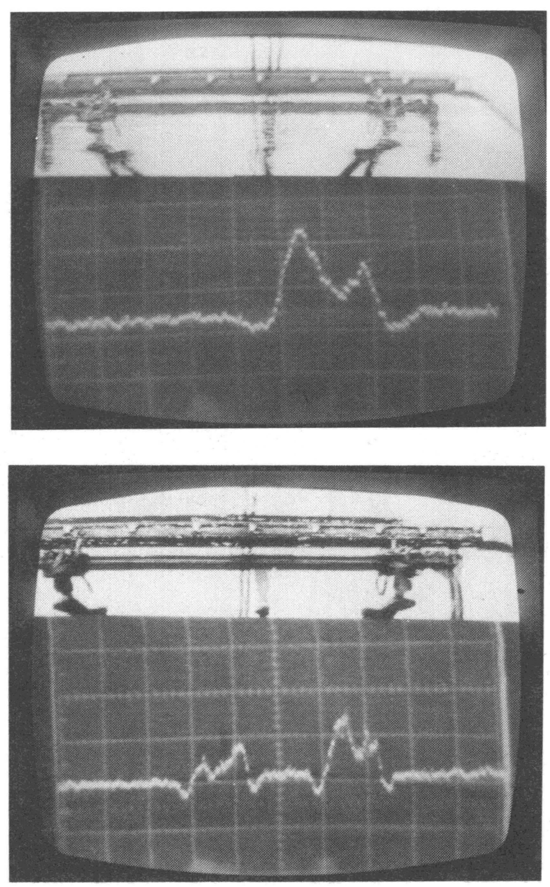

Fig. 9.

With components that were available at our Institute a simple prototype inspection system has been constructed. The instrument contained a.o. the following parts:

- a large one radius doublet as front optics (Ø = 300 mm)
- a fairchild linear CCd camera (1728 elements)
- a 5 mW HeNe laser (λ = 633 nm)
- a narrow bandfilter (λ = 633 nm, FWHM = 10 nm) for background suppression

With cilindrical lenses the He-Ne laser light was imaged in the right way on the contact wires.

The prototype instrument was installed in the inspection waggon of the Netherlands railways company and up to a travelling speed of 90 km/hr over a limited FOV in cross direction reflected signals of the overhead wired were detected. Figure 8 gives a picture of the prototype instrument. In figure 9 measured signals are presented.

From the best detected signals (in the center of the FOV of the prototype system with good focussing) the thickness of the contact wire could be determined with good accuracy. Besides, the reflection pattern also indicated a wear profiling, which results in a variation of reflection in cross direction.

These measurements have been carried out by day and night at different background illumination conditions.

In spite of the limited FOV and only with the display of the analog CCD-signal on an oscilloscope valuable measurements were made with this system and in fact the feasibility of the measuring principle was demonstrated.

4.3. Laboratory measurements

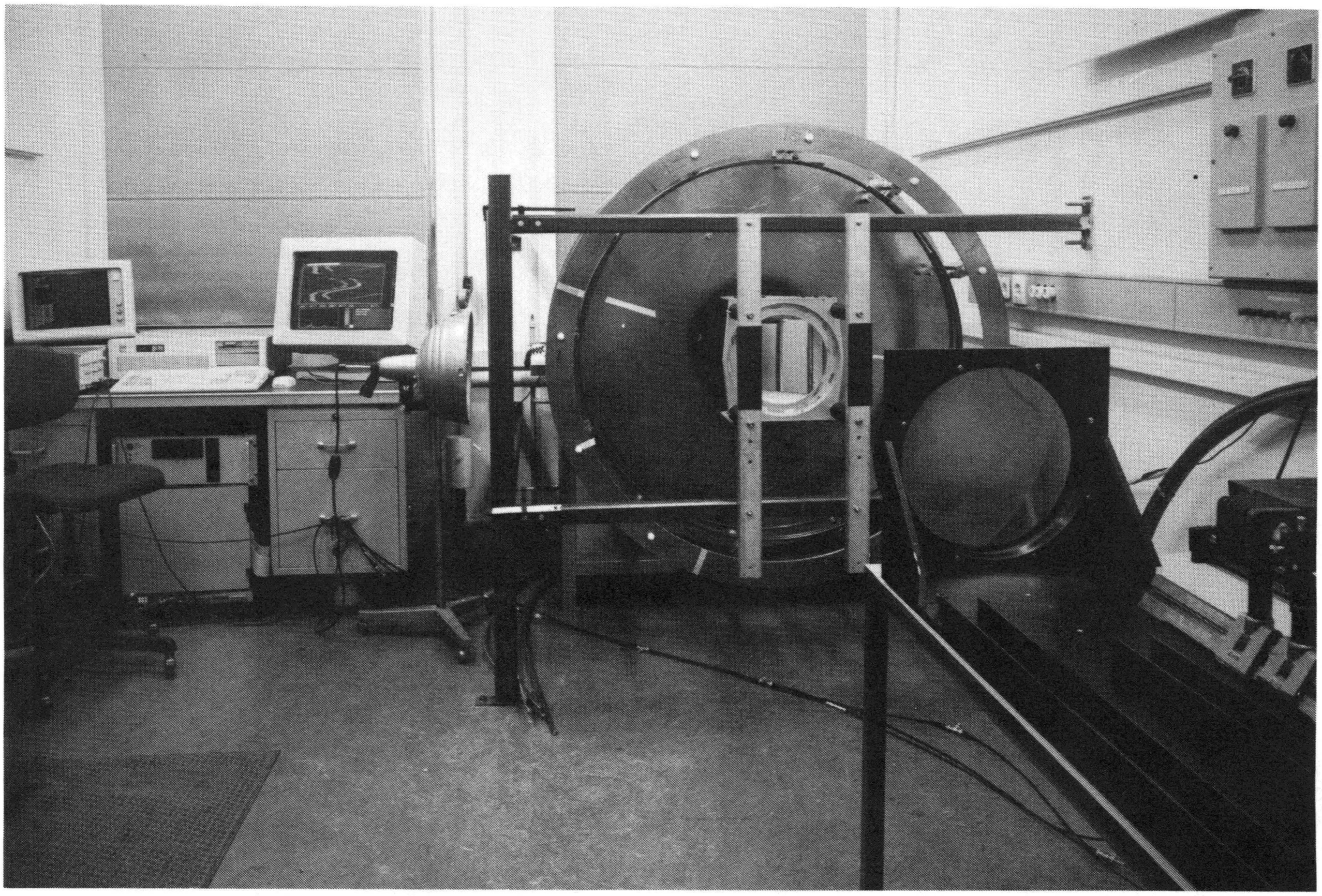

Fig. 10.

At an early stage of the development of ATON a laboratory arrangement has been made to study under realistic circumstances the contact wire reflection signals.

The purpose was to find out at one hand the accuracy of determining the wire thickness out of the reflection signal and to provide at the otherhand for the signal processing a realistic set of accurate measurements.

The arrangement is pictured in fig. 10.

Several overhead wires are mounted inside a drum, that can rotate and simulate a travel speed up to 45 km/hr. Via a 45° mirror, the reflected surface of the wires is inspected with the prototype arrangement. The signals from the CCD camera were handled by a data acquisition signal processing workstation. The reflection signals were studied with respect to threshold level detection at the left and the right slope of the signal, peak level detection and integrated threshold level detection. The outcome of these measurements has determined to a large extent the signal processing structure and the definition of the detection algorithms.

5. CONCLUDING REMARKS

A new type of system for inspection of railway contact wires is described. In this system advanced techniques are applied for detection and processing of the large amount of signals, while at the same time a dedicated optical system for illumination and imaging is designed. In the previous description the optical aspects are emphasized, although the electronical part of the sensor development (both software and hardware) requires as much effort.

With the system it will be possible to inspect, at a travelling speed of 90 km/hr a maximum of 4 overhead wires on wear and appearance of craters every cm in travelling direction.

At this moment the system is being manufactured and it will become operational in about 1 year.

It is expected, that with the system the condition of the contact wires of the total railway traject in the Netherlands can be measured in about 3 weeks.