Development of an Automated Mobile Robot Vehicle Inspection System for NDT of Large Steel Plates

M. Rakocevic, X. Wang, S. Chen, A. Khalid, T. Sattar and B. Bridge
School of Electrical, Electronic and Information Engineering, Centre for Automated and Robotic NDT,
South Bank University, 103 Borough Road, London SE1 OAA

Abstract: *The aim of the research project was to develop a robotic system that would perform a raster scan of large horizontal metal plates using an ultrasonic inspection technique. The project involved a number of tasks requiring in-house research in automated control and self-navigation of the robot, NDT sensor deployment and ultrasonic data acquisition and analysis. In-house software has been developed to control the scan trajectory of the vehicle and locate and plot position of the ultrasonic sensors and the presence of any defects. The system is readily transportable from one inspection site to another and a graphic display analyses and shows results of the ultrasonic inspection. The cost of the system is several times less than the large gantry X-Y scanning systems that are currently used for steel plate inspection.*

1. INTRODUCTION

The overall aim of this research project was to automate NDT data acquisition and analysis on large steel plates with an inspection technique that was implemented using a mobile robot vehicle. A prototype robot is described that performs a raster scan of horizontal metal plates of unlimited size without any external navigation aids. The only operator involvement required is the removal of the robot from one plate to another and once the robot is placed on a plate it starts and completes the required inspection autonomously, at speeds of typically 10 metres per minute.

The mobile vehicle can carry a task payload of up to 10kg. In the present application the robot carries an array of 16 ultrasonic probes and an on-board multiplexer for inspection of newly rolled steel plates from 12.5 to 200mm thick and sizes up to 25 metres in length and 4 metres width, to BS 5996. However the system is equally well suited for deploying other types of inspection equipment, e.g. magnetic flux and eddy current sensor, electromagnetic acoustic transducers, laser ultrasound probe, gamma isotope etc. Alternatively the task payload can consist of cleaning and grinding equipment, paint removal or spraying equipment etc. The system is particularly suitable for operations in hostile environments where the operator may rule out the use of external navigation aids such as optical and infra-red laser beams, airborne acoustic beams, or reflecting mirrors and the like. Indeed that was the brief given to the authors by the client. It could also be useful on large flat metal surfaces in actual service such as ship decks or storage tank floors. Currently in rolling mills, when automated inspection of large metal plates is carried out it is done by means of large fixed gantry style scanners with the steel plate being delivered to the scanner. The testing is carried out in a large immersion bath. Such systems are very expensive and inflexible. The mobile plate vehicle concept described here promises to cut inspection costs associated with equipment investment, space utilisation, inflexibility and operator involvement.

Trials on some steel plates with natural defects are described and maps of defective areas are presented. Steel plate products are sold throughout the world to a wide range of industries eg. ship building, construction etc. The plates should meet the requirements of National, European, International and customers standards when used for structural, shipbuilding, boiler, pressure vessel and other applications.

2. METHODOLOGY FOR PLATE TESTING SPECIFIED BY THE BRITISH STANDARD BS5996

British Standard [BS5996] specifies acceptance levels for internal imperfections in ferritic and austenetic steel plate, strip and wide flat material based on ultrasonic testing. The classification is on the basis of the area, length and width of individual imperfection (see Fig. 1). The maximum number of individual imperfections in a given area of plate also determines the classification. With reference to the requirements for the body test of steel plates the following acceptance levels can be achieved: B1 (100mm scan line separations), B2 (75mm), B3 (60mm) and B4 (35mm). The occurrence rate differs for each acceptance level, and for B1 is 10%, B2 - 25%, B3 - 40% and B4 - 25% of all plates inspected. A band around the cut edges of the steel plate would be 100% scanned. 100 % coverage, as defined by the British Standard, means that the maximum scan line separation shall be 75 % of the transducer diameter, which is 20mm in this case. Therefore, the scan line separation for the edge detection is 15 mm. The band scanning width could vary between 50mm to 100mm, depending on the thickness of the plate.

The presence of an internal imperfection is indicated by:

1) A 50% reduction in the signal amplitude of the back wall echo, with or without the presence of an imperfection echo.
2) The presence of an imperfection echo which equals or exceeds 50% of the amplitude of the reduced back wall echo.

According to the British Standard the following criteria needs to be satisfied:

- The material surface is scanned with ultrasonic probes in straight, parallel and equispaced scan lines normal to principal rolling direction. This is to ensure the detection of the minimum imperfection size with the limiting length and width dimensions.
- The pulse repetition frequency of each transducer in relation to the relative movement along each scan line is sufficient to ensure detection of the relevant minimum imperfection length and width dimension.

3. PRESENT METHOD OF PLATE INSPECTION

At present, most steel producers use a ‘multiple probe plate tester’. Four probes are arranged in the holder with a required spacing between them. The holder is fixed on the ‘Hoover’ type of tester shown in Fig. 2. The probes are connected via a multiplexer to an ultrasonic flaw detector. A water canister is mounted on the trolley, and water is supplied via the pipe to feed the transducers with the necessary couplant for testing.

The operator pushes the plate tester over the plate in parallel and equidistant lines carrying out a large raster scan over the entire plate as shown in Fig. 3. Also, when testing the edge band, the operator fixes the probe holder at an angle in order to achieve a required scan line separation. In this case scan line separation is smaller and therefore satisfy British Standard criteria for the 100% coverage of the edge of the plate. The probe holder is replaced when a different line spacing is required for testing.

Manual testing is dependent on the accuracy of the operator when pushing the trolley, and is very subjective. Operators can not accurately move the plate tester (and thus the probes) along equidistant parallel lines along the width of the plate because they are not externally guided. Thus it is possible that some areas can be missed during the raster scan.

4. AUTOMATED MOBILE VEHICLE INSPECTION SYSTEM FOR NDT OF LARGE STEEL PLATES

The first objective of this research was to replace the manual ultrasonic plate tester (Fig. 2.) with an automated mobile robot vehicle, which would be autonomous. The robot inspection system developed at the Centre for Automated and Robotic NDT at South Bank University has the following characteristics:

- The system is fully autonomous and does not require any operator assistance in detecting defects.
- Once placed on the edge of a steel plate the robot vehicle can automatically find the edge of the plate and align itself to it to begin a raster scan. The vehicle moves with speeds between 5-10 m/min while carrying out the raster scan.
- Once a defect is detected, the vehicle marks the position of the defect on the plate using a paint marking device. The position of the defect is also noted in X and Y co-ordinates and this is illustrated on the virtual map of the plate on the PC screen and in the printed report.

This inspection system comprises a vehicle with a payload of sixteen ultrasonic NDT sensors and a multiplexer. Ultrasonic transmitter/receiver probes of 5 MHz frequency were used with water as couplant. A mobile rack cabinet with industrial PC, motor driver rack and the auxiliary power supply is linked to the vehicle by a 30 metre long umbilical cable.

The navigation of the system is based on an odometric system (e.g. encoders). In addition to encoders the mobile vehicle has a group of eddy current sensors to monitor the plate edge so that it could align itself at the edge. This independent system reduces the errors produced by the odometric system. Software has been developed to control the scan trajectory of the vehicle, locate and plot position of the ultrasonic sensors and to detect the presence of any defects at these positions. The system is a PC based fully programmable ultrasonic flaw detector able to control the movements of the vehicle and display a defect map of the steel plate. Fig. 4 shows the scanning principle of the vehicle during inspection.

Scanning Procedure

The plate can be as long as 25m and therefore the vehicle is designed to move along the plate without twisting of the long umbilical. The two platform structure allows the vehicle to do a raster scan while turning only the inner platform and keeping the outer one fixed in the same orientation to prevent twisting of the cable. The vehicle does the edge scan at the same time as the body scan.

To begin with, the left edge of the plate is scanned using the two ultrasonic transducers at the edge of the holder. The first line is for the edge scan, then the inner platforms turns 90^0 (while the outer platform is fixed) and shifts along the plate for one width of the vehicle while scanning the upper edge. Then depending on the thickness of the edge band, the vehicle carries out another edge scan or starts the body scan. For 50mm edge band one scanning line is enough while for the 100mm band two lines are necessary. The inner platform turns back 90^0 again and scans along the width of the plate. The edge band along the length of the plate is scanned every time the vehicle comes to the edge. This way vehicle does not have to go around the plate at the end of the body inspection in order to scan the edge, as it is done in the manual testing. The design of the ultrasonic holder to satisfy British Standard requirements is described in Section 4.3. With reference to the requirements for the body test of steel plates (according to BS5996) the different acceptance levels can be achieved by changing the probe holder. A band around the edges of the steel plate would be 100% scanned.

At the start of inspection the vehicle can be placed approximately at the start position on the plate. It finds its way automatically to the exact starting position, aligns with the edge and starts the first scanning line. The whole trajectory is shown in the Fig. 5. At the end of the inspection a report is produced indicating the defect areas, and the marking system leaves paint marks on the plate where defects have been detected.

The block diagram of the inspection system is shown in Fig. 6. Four NDT control cards are mounted inside the PC. Another card in the PC is used to control the vehicle. This card also has 16 digital inputs and 4 digital outputs connected to other sensors and switches via an interface board to form a complete control system that satisfies the system requirements.

4.1. The mobile vehicle

The mobile vehicle is a special two-platform structure utilising a differential drive mode. The inner platform is connected to the outer platform via a bearing. A PC controlled lock-pin that is driven by a DC motor is designed to fix the two platforms together. The size of the vehicle is 400mm*(w)* × 670mm*(l)* × 440mm*(h)* and its weight is about 48kg. The vehicle is illustrated in Fig. 7(a) and (b). Figure 7(a) shows the vehicle without the cover.

Wheels and driving motors with encoders and gearboxes are mounted on the inner platform. There are four castor wheels to support the outer platform of the vehicle. The driving wheels drive the vehicle forward or backward when the pin locks the inner and the outer platform together. The main feature of this design is its turning mechanism. When four electromagnets mounted on the outer platform are switched on, the outer platform is attracted to the steel plate. The lock-pin is released so that the inner platform is able to rotate freely whilst the outer platform is firmly held on the plate.

Two driving wheels turn in the opposite direction to rotate the inner platform around the central axis of the vehicle. The inner platform is allowed to turn ±90° and is then fixed to the outer platform again by the pin (see Fig. 8). This ensures that the vehicle can turn ±90°, but the orientation of the whole vehicle is kept constant so that the umbilical does not twist. Thus the vehicle (given that it has ultrasonic transducers at both the front and the back) is able to cover the whole steel plate in a raster scan.

Two proximity switches monitor the position of the lock-pin. Strong permanent magnets underneath the inner platform are used to provide better friction between the wheels and the surfaces of plates in order to reduce the slippage of the vehicle. The water valve controls the water supply to provide suitable couplant for ultrasonic testing. All control signals at the input/output are connected with an I/O interface box that is linked to the remote control cabinet via a 50-way cable.

4.2. Navigation system

Mobile robot navigation is a central concern of mobile robot application. The *absolute* and *relative* positioning methods are the two basic solutions of navigation. Odometry, utilising incremental and absolute optical encoders, is a relative positioning method most widely used for mobile robots, whereas heading sensors such as gyroscopes and compasses can help to compensate for the foremost weakness of odometry [Borenstein, 1996].

The ability of the inspection vehicle to sense its environment and change its movement accordingly makes this robot different from fixed automatic systems. Besides the shaft encoder of the motor, proximity sensors are used for detecting the edge of the steel plate for self-guidance of the vehicle. The software controls the scan trajectory of the vehicle and locates and plots position of the ultrasonic sensors and the presence of any defects at these positions.

The central part of the navigation system that is used is an odometric system (e.g. encoders). Odometry uses encoders to measure wheel rotation and/or steering orientation. Its advantage is that it is totally self-contained, and it is always capable of providing the vehicle with an estimate of its position. The disadvantage is that the position error grows without bound unless an independent reference is used periodically to reduce the error. Proximate sensors are used as additional devices for detecting the edge of the plate and therefore are an independent reference for reducing the error produced by the encoder system.

The eddy current sensor is the most commonly employed industrial sensor for detection of ferrous and non-ferrous metal objects over short distance [Wojcik, 1984]. They are less affected by environmental factors (humidity, dust etc.), and have high detection rates in comparison with the capacitance sensor. The disadvantage is that there is no commercial product of this type with an analogue output.

In the navigation for the inspection vehicle the edge detector has two functions:

- *To monitor the edge of steel plate*. The vehicle will immediately stop when the edge detector finds the edge of a plate.
- *To determine the position of the vehicle relative to the edge*. The slope angle of the vehicle relative to the edge of plate can be determined by the edge detector so that the vehicle can correct its orientation error.

The first function requires an instant response when the vehicle reaches the edge of the plate. If the maximum speed of the vehicle is 150mm/sec, the sensing rate of the edge sensor should be not less 100Hz to monitor small movements of the vehicle within 1.5mm.

The edge detector consists of 8 eddy current sensors, the circuit for signal detection and an interface with the PC. A sensor consists of a coil, a carrier oscillator and associated amplifier. The output signal from the eddy current coil is a time-variable AC voltage. The presence of the edge of the steel plate may be detected simply by the change of signal amplitude when the sensor is in the air, so that a simple amplitude detector and a level comparator can be used. Although the detection results are simple on/off signals, they are not suitable for direct input into the peripheral digital channel of a PC due to the voltage level difference between sensors and the PC. A level converter hence has to be used.

An edge detector consists of a couple of eddy current sensors that are mounted in a line for measuring the inclined angle of the vehicle relative to the edge of a plate (Fig. 9). If the vehicle is not perfectly aligned with the edge of the plate, the two eddy current sensors will reach the edge with the time difference *ds*. Since the distance *w* between two sensors is constant and equal to the wheel base of the vehicle the inclined angle α can be calculated as:

$$a = \arctan\frac{ds}{w} \qquad (1)$$

The accuracy of the edge self-align algorithm depends on the practical turning accuracy of the wheels rather than the calculation accuracy of turning parameters. The vehicle is turned repeatedly until the inclined angle α is zero and the vehicle is perfectly parallel to the edge of the steel plate. After this procedure, the vehicle then carries out another line scan until it reaches the other side of the plate. The procedure of alignment is again repeated at the other edge. The arrangement of the edge sensors is given in Fig 10.

4.3. Ultrasonic NDT system

There is high diversity of testing techniques for steel plates with manufacturing defects with respect to the many different uses made of the plate in industry. The varying significance of a given plate defect, the wide range in plate thickness (from 1 mm to more than 100 mm), and the diversity of the defects according to their nature, shape, position and size all determine the testing strategy adopted [Krautkramer J, 1983].

The system for ultrasonic NDT used on this project consists of ultrasonic and data acquisition expansion boards and a 16 channel multiplexer. Data acquisition boards supplied by Ultrasonic Sciences Ltd. include a general-purpose Master System Controller, 100 MHz Analogue to Digital converter and the 100 MHz peak amplitude and time interval measurement card (ATP4). The ATP4 card is configured with two gate peak detection (GPD) sets for reading the amplitude in two gates. One gate is set for detecting the back wall echo of the signal and the second one for detecting an imperfection echo. The amplitude of the signal in the second gate should exceed 50% of the backwall echo, to be considered as a defect under BS5996. Following a trigger and the delay counter counting down to zero, 100 MHz A/D converter will fill the 1024 bytes with sampled data at the rate determined by the conversion frequency selected. This array of data is mapped into memory, which is a flash eight-bit device with a maximum conversion rate of 100 million samples per second.

Software has been written for data acquisition and a user interface in a Windows environment. As the vehicle is moving on the plate a screen map of defects is built on the PC using the signal amplitudes from two hardware gates on the amplitude measurement card. Default settings for the ultrasonic gates are set but can be changed in the dialogue box.

Transducers that are used for inspection are twin crystal 5 MHz Sonatest ultrasonic contact transducers with 20mm diameter elements. Maintaining the constant probe orientation and coupling proved to be a major problem associated with this automated testing system. Uniform coupling at all points of a given specimen is very important for quick and reliable evaluation of the reading. In manual inspection this can be checked by means of monitoring a backwall echo. In automatic testing, the absence of constant observation of the screen image and of the sense-orientated manual guidance of the probe is a shortcoming. It is possible to use the backwall echo for checking the coupling, although this has the disadvantage that it is not only bad coupling but also a flaw that can reduce signal amplitude. Control software for this system is programmed in the way that stops the vehicle and double checks the area if the defect alarm occurs. This way the bad coupling problem is removed.

Direct contact between the transducer and the steel plate is not preferred for reasons of wear and insufficient constancy of the degree of coupling. Direct contact makes wear of the transducer unavoidable because the probe, during scanning, cannot simply be placed on and taken off again. It must be shifted because any change in the flaw echo while shifting the probe provides valuable information of the flaw to the examiner. Information such as the disappearance and reappearance of echoes and their change with depth can be observed. Particularly when used on rough surfaces of steel covered by very hard and sharp edge scale, the probe can become severely eroded. Spacing layers consisting of liquids or plastics cut down the wear but increase the amount of interfering echoes. Ultrasonic probes used here have 16mm thick Perspex buffer layers and therefore the surface echo and its multiple echoes become separated from the transmitting pulse. [ASNDT, 1991]

Three different transducer holder prototypes were designed. An adjustable transducer holder had been built as the first prototype. It was made of aluminium, with a steel plate underneath, to increase weight and therefore maintain better contact with the surface. It allowed adjustment of transducer plates for different line separation. Ultrasonic probes were fixed to the small aluminium plates that could be screwed to the holder. Edge plates that hold two transducers remain in the same position on both sides, and the other plates could be unscrewed and moved along the holder, giving the necessary line separation of 35, 60, 75 or 100 mm. In this first prototype, aluminium plates were spring loaded in order to maintain best contact with the surface. In this case there was no water gap, but the probes were scraping the surface which affected the movement of the vehicle, and it was necessary to change the design. The other problem of this design was wear and insufficient constancy of the degree of coupling. The second holder prototype remained similar, and only the aluminium plates carrying the probes were fixed instead of spring loaded. Even though it performed better then the first prototype still the orientation of the probe could not remain perfectly stable because of the way it was fixed to the plate.

In the third transducer holder design for this inspection requirement, the probes are permanently fixed in the holder. Hence, it is necessary to have a separate holder for each line separation, but it is very easy to replace them when needed. The holder is made of MoS_2 Filled Cast Nylon. This is a low friction self-lubricating material with high mechanical strength, high melting point and good abrasive resistance. It provides stable orientation of all probes, and no need for any adjustment before the testing. The holder makes contact with the surface under test, but provides a couple of mm gap between the probes and the steel plate. Canals are machined into the bottom side of it to provide the water stream for each probe. Water is discharged from a pipe and a valve controls its flow (see Fig. 11). A couplant retrieval system could be added to the system to minimise the loss of couplant.

Correct and maintained orientation of the transducer in the automated NDT inspection system is essential for correct and accurate measurements of signal amplitude or time of flight. Experiments were done to show the effect of alterations in the probe orientation angle to the signal amplitude. The results suggested that single crystal probes should be used for plates with thickness greater than 50mm and twin crystal probes should be used for plate thickness less then 50mm. The reason for this is that in the single crystal probe the angle of incidence equals zero and therefore it is parallel with the bottom of the probe. The double crystal probes have a fixed angle and slight misalignment on thick plates creates loss of received signal.

5. TESTING AND RESULTS

The system that has been described in detail in the previous section is easily transportable and able to find internal imperfections in the plate and to produce a map of defective areas. Testing was conducted in one of the major steel production factories in UK.

Ultrasonic probes are connected to a 16 channel multiplexer that acquires data from each probe. The scan generally starts from the bottom-left corner of the plate. The vehicle can be placed anywhere on the plate because it is designed to locate its starting position before it begins the scan. The scanning trajectory has been described at the beginning of

Section 4. When the scan is finished the vehicle stops at the end point and returns to its starting position. Fig. 12 shows the vehicle without cover to display the NDT sensors and driving mechanism.

The first plate to be tested was 50mm thick, and had an internal imperfection, that can be seen as a yellow trace on the screen in Fig. 13(a). Fig 13(b) shows the defect magnified. Second plate was 20mm thick, 9.5m long and 3m wide and did not have any imperfections as shown in Fig. 14. Vehicle was programmed to repeat the scan if a defect was found to make sure that a loss of couplant did not occur.

A report was produced at the end of each scan, which displayed the position of the defect on a plate (see Fig. 13). To complement this report a paint marking system has been developed to mark the defective areas on the plate. The difficulty was determining the adequate paint that would be able to mark the plate through the layer of water, and not to be smeared when the vehicle went over it. The marking system has been installed on the left hand side of the vehicle. Since the scanning procedure makes the vehicle move in the direction from left to right, the vehicle would not go over the painted area and smear the mark. Also, a correction fluid was used, since it proved to be the best fluid to mark the steel plate through the few millimetres water layer. The control system activates a solenoid that pushes a correction pen that makes a white mark on the plate. The vehicle is programmed to go back and scan the same area again when a defect is detected. When confirmed, the paint marking system is activated, plate marked, and also the defect is placed on the PC screen display. To re-itterate, the following action is taken when a defect is found:

1. The vehicle rescans the area to confirm the presence of a defect.
2. The position is physically marked by the paint marking system.
3. The position is marked on a display on a PC screen, and recorded in the formal report.

6. CONCLUSION

A robotic system has been developed for the inspection of internal imperfections in flat steel plates, producing a map of defective areas. It is a vehicle employing magnetic adhesion to the steel plate for stability, with a self-navigating system that carries 16 ultrasonic transducers. The control software is implemented in the Windows environment. The user-friendly interface provides real-time NDT display and virtual vehicle status simulation as well as control menus and buttons for control of the vehicle.

The edge detection sub-system plays an important role in the inspection system. The eddy current sensor is employed for the plate edge detector due to its small size, high detection rate and insensitivity to environmental conditions. It has been proved that the two-sensor structure to detect an edge of plates is optimal for the configuration and accuracy of the control system. The results of the system testing have shown that the system meets the design requirements to perform NDT on steel plates. However, some problems with the stability of the ultrasonic signal and the scanning mechanism occurred when the robot was first tested on the very uneven plate. The modification of the two-platform mechanism and the ultrasonic probe holder were done, improving the performance of the system. The latest field trial showed improved results.

The system described here is a prototype and may require some further improvements in robustness in both purpose built and off the shelf components before it could be used for plate inspection on a continuous basis.

7. REFERENCES

American Society For Nondestructive Testing, (1991). *Nondestructive Testing Handbook, Volume 7 - Ultrasonic Testing*, Second Edition,

Borenstein J., Everett H.R. and Feng L. (1996). *"Where am I?" Sensors and Methods for Mobile Robot Positioning,* University of Michigan.

British Standard 5996, *Specification for Acceptance Levels for Internal Imperfections in Steel Plate, Strip and Wide Flats, Based on Ultrasonic Testing*.

Krautkramer J. and Krautkramer H (1983). *Ultrasonic Testing of Materials*, New York: Springer-Verlag,

Wojcik S (1984). *Noncontact Presence Sensors for Industrial Environments*, Sensors, pp. 48-54.

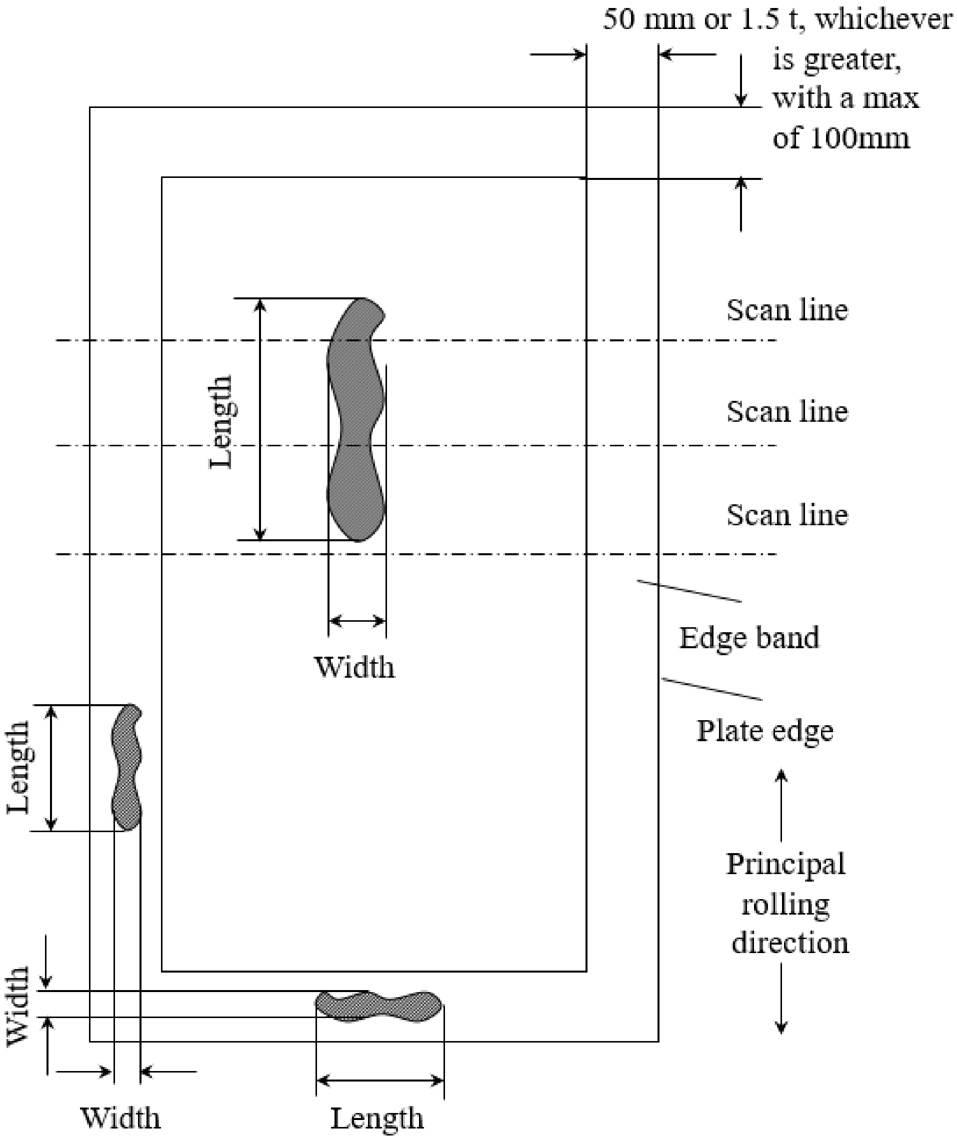

Fig. 1. Specifications for the plate inspection given by the British Standard BS5996

Fig 2. Manual plate tester used for testing plates at present

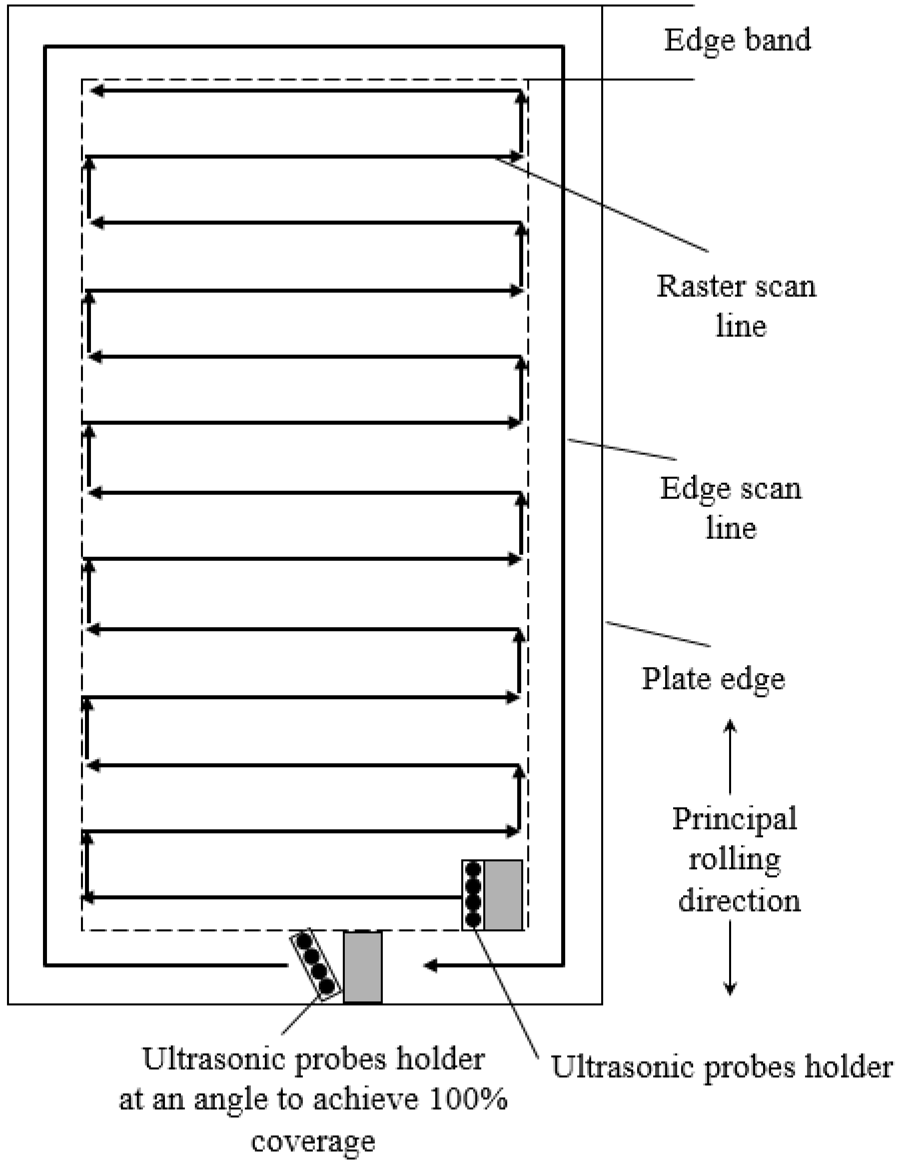

Fig 3. Scanning trajectory of the operator during manual inspection

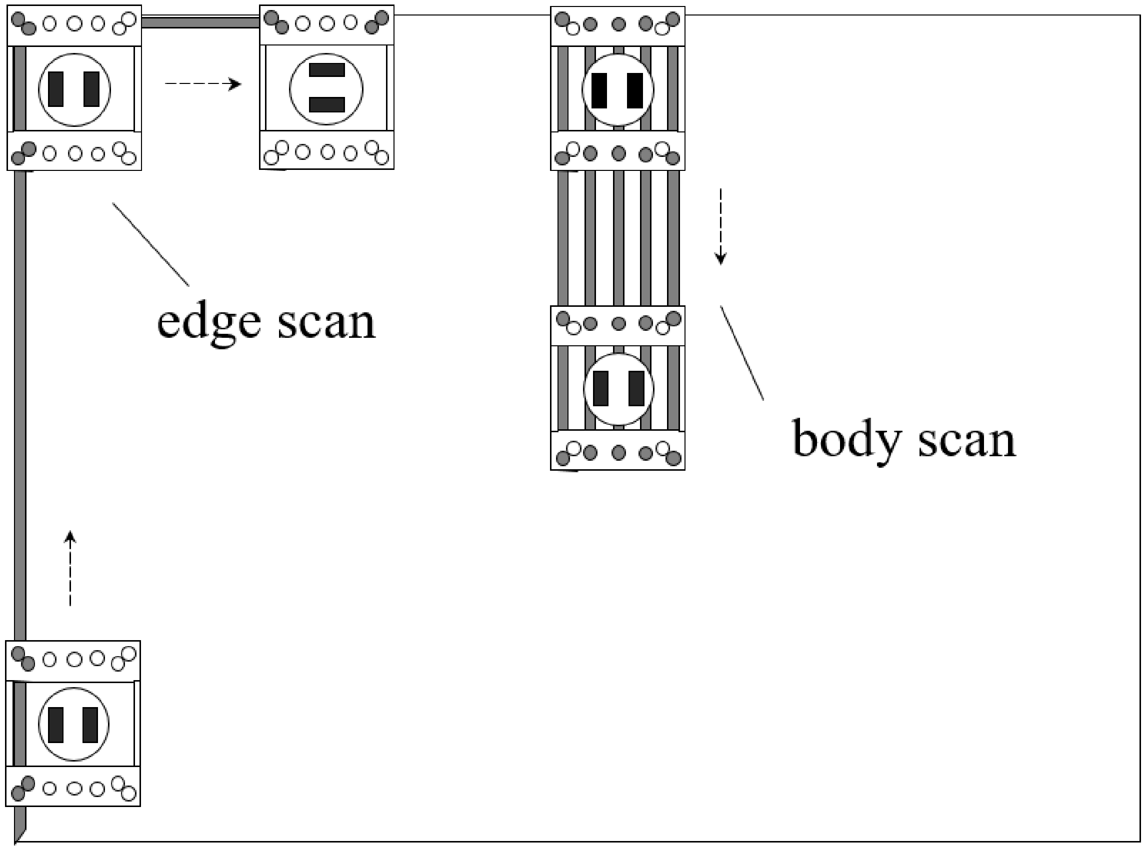

Fig. 4. Scanning principle for the self navigated vehicle

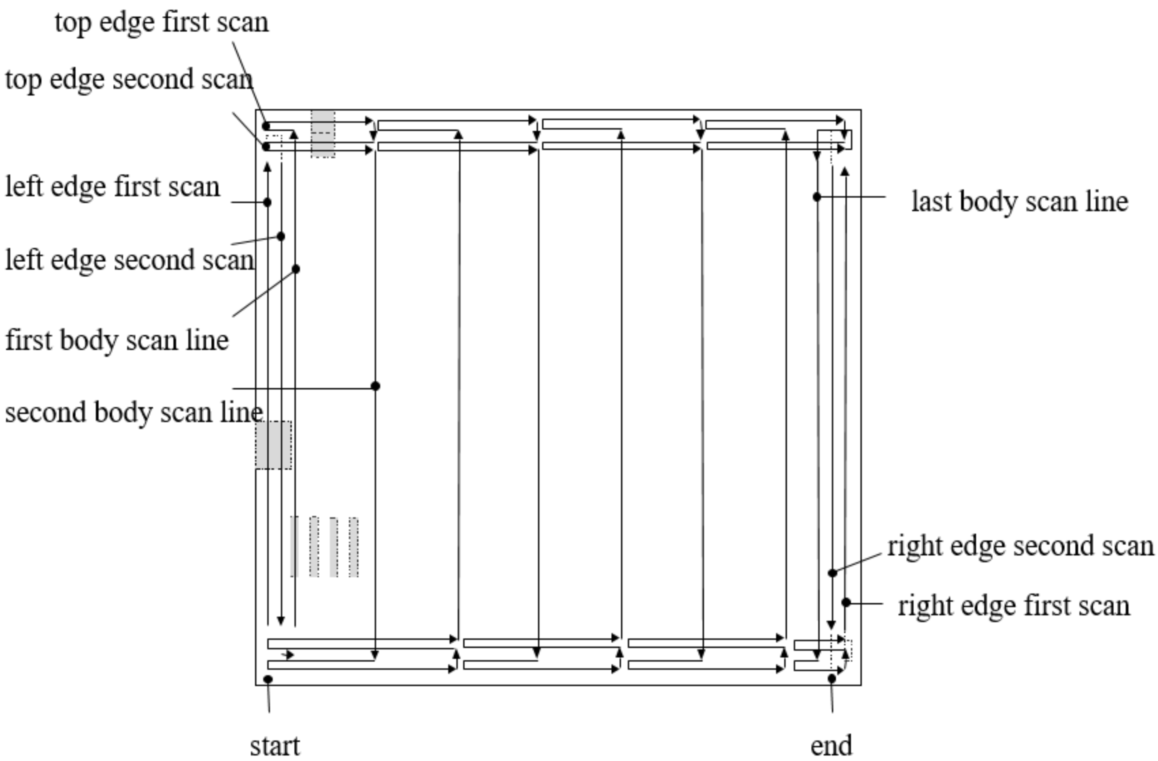

Fig. 5. Scanning trajectory

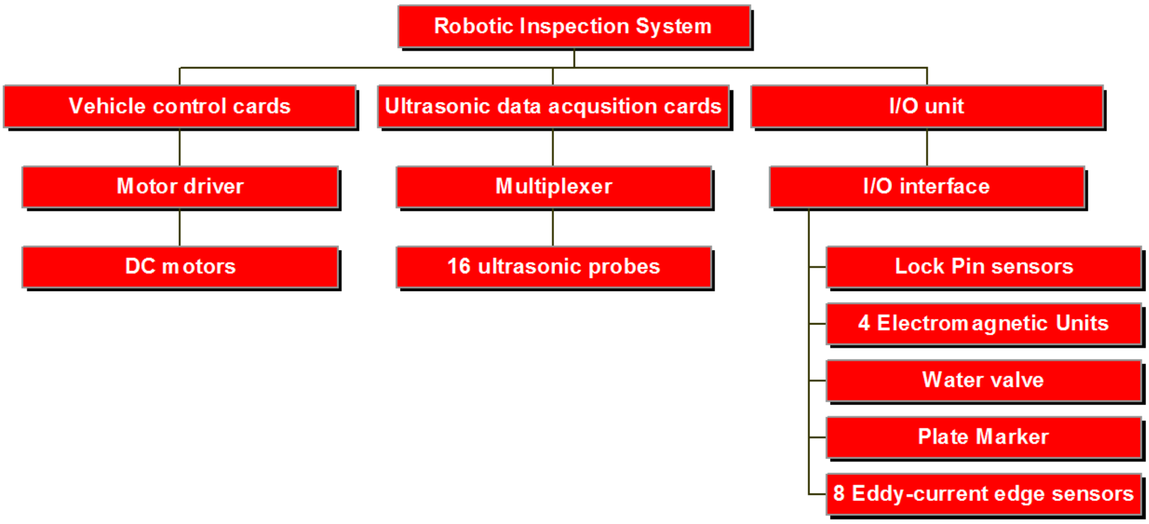

Fig. 6. Principle diagram of the inspection system.

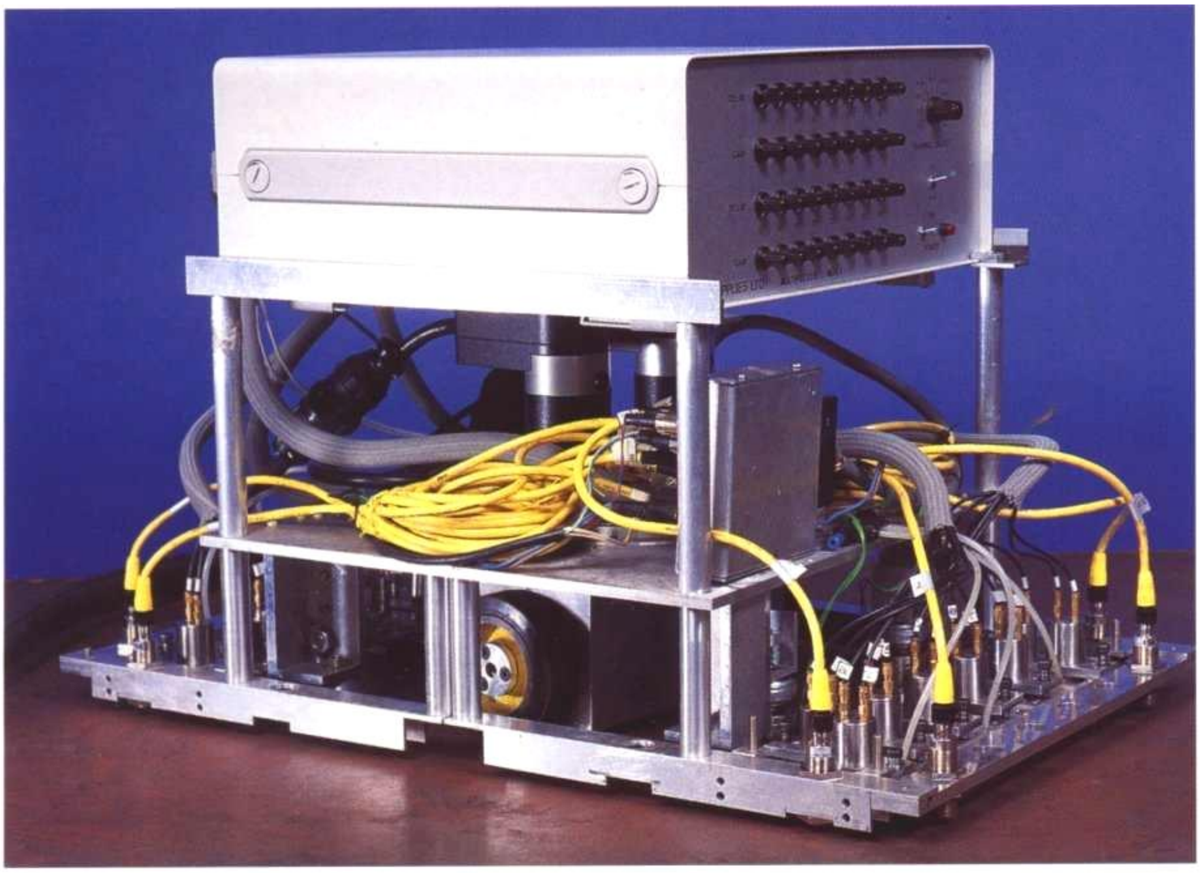

Fig. 7(a). The mobile vehicle composition

Fig. 7(b). The inspection system in the laboratory

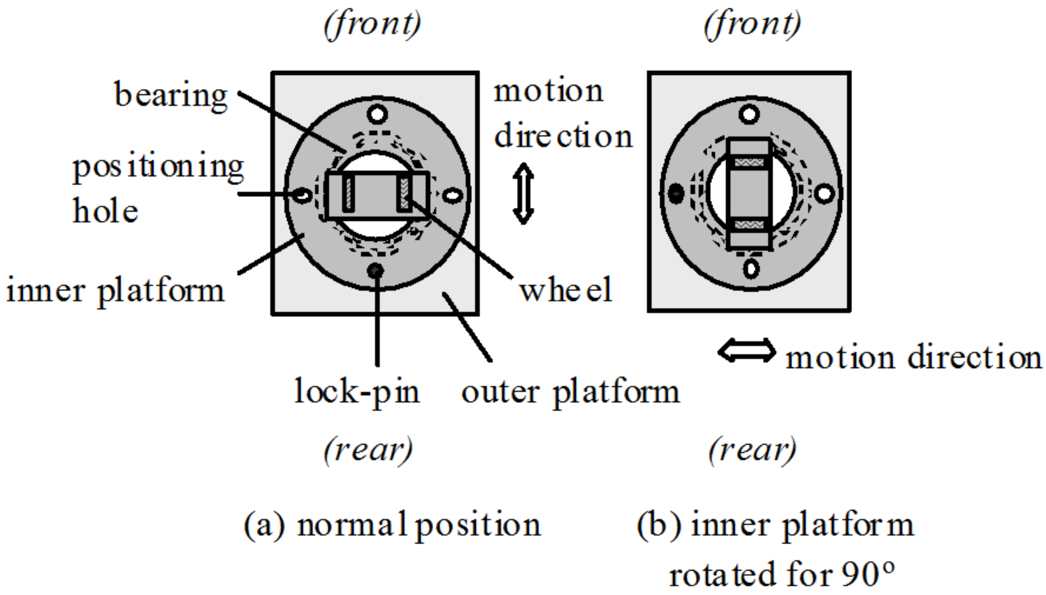

Fig. 8. The principle of turning mechanism

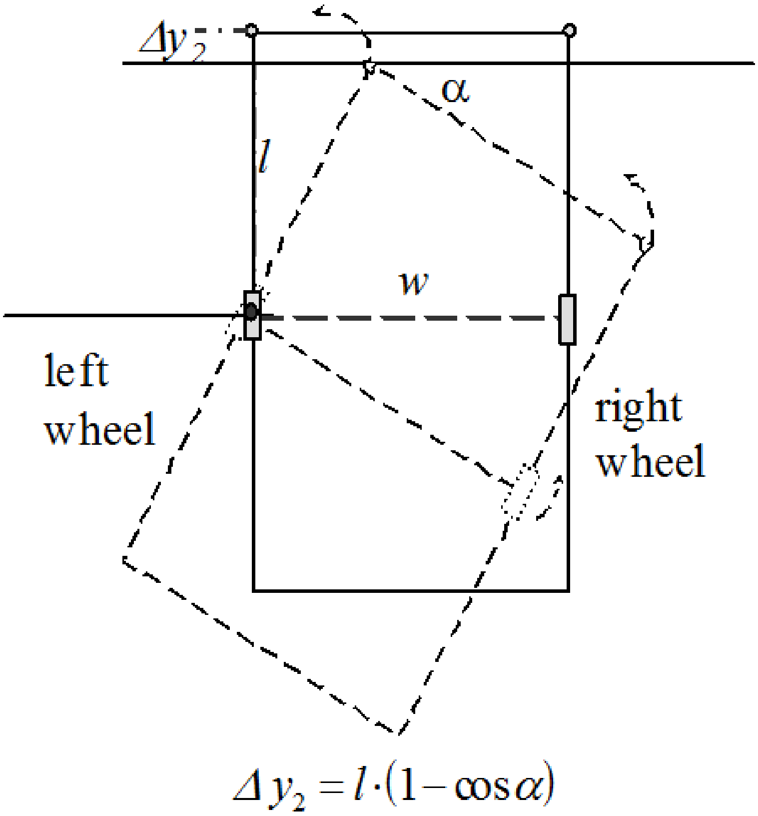

Fig. 9. The determination of the slope angle by the edge detector

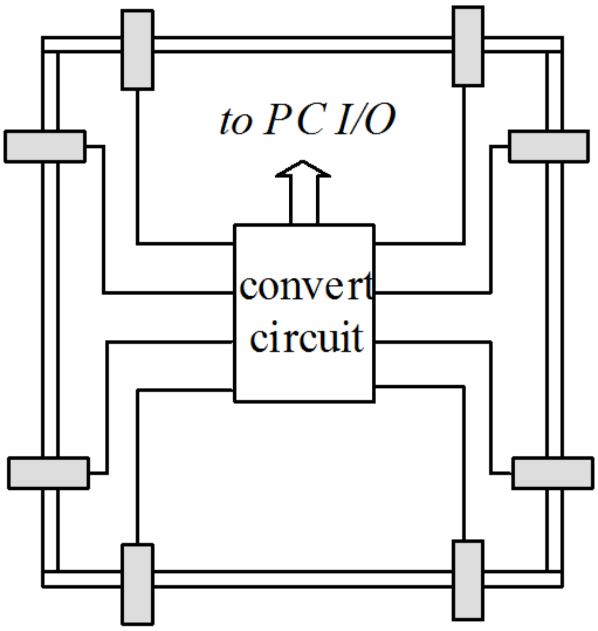

Fig. 10. The edge sensors arrangement

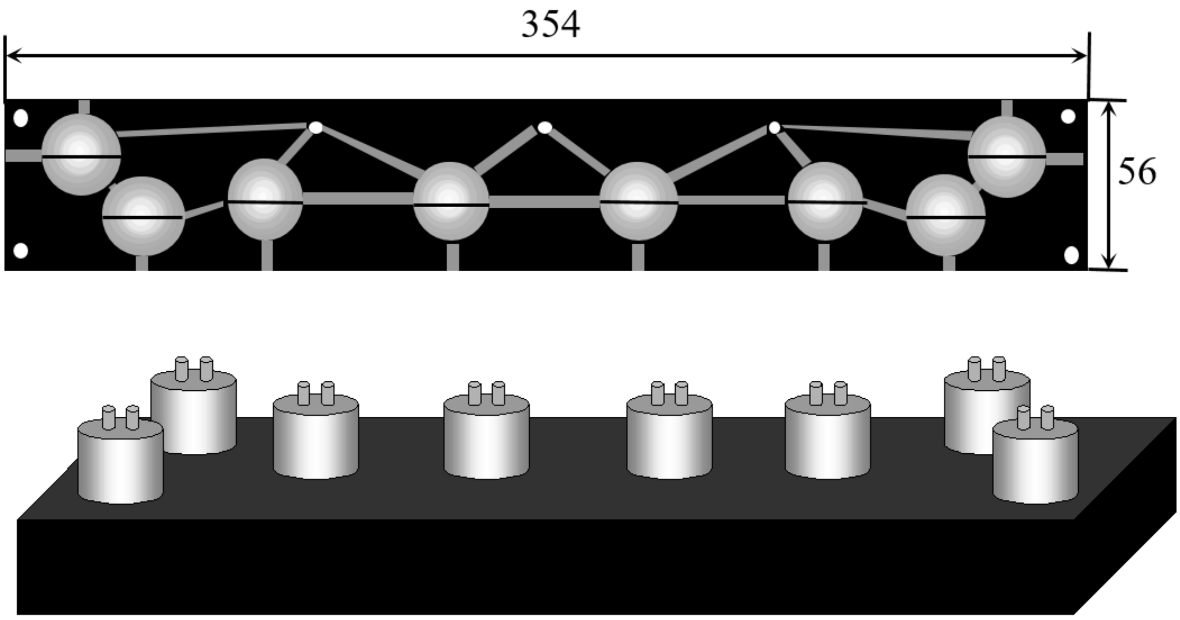

Fig. 11. Ultrasonic probe holder

Fig. 12. Inspection vehicle in the field test

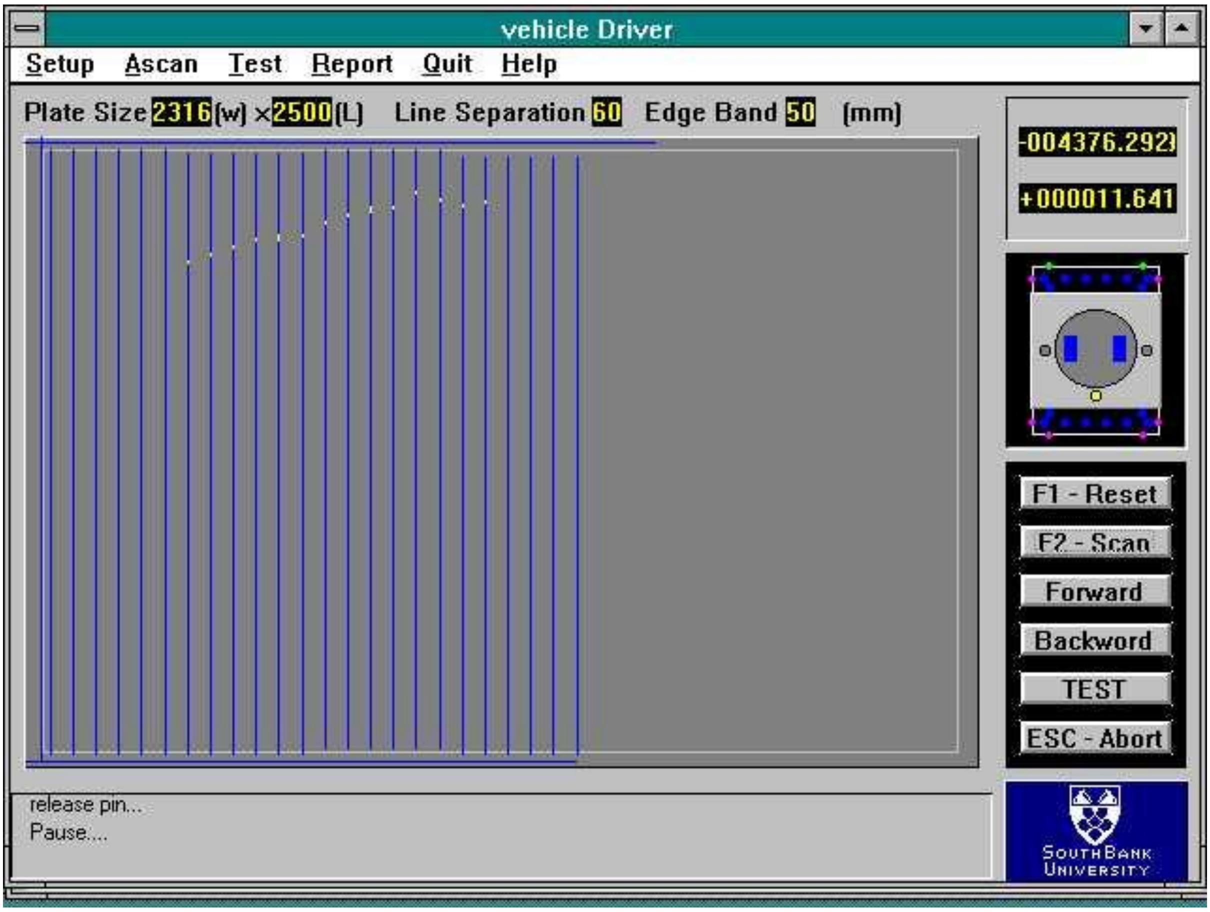

Fig. 13(a). Results from the third probe holder prototype on the 50mm thick plate

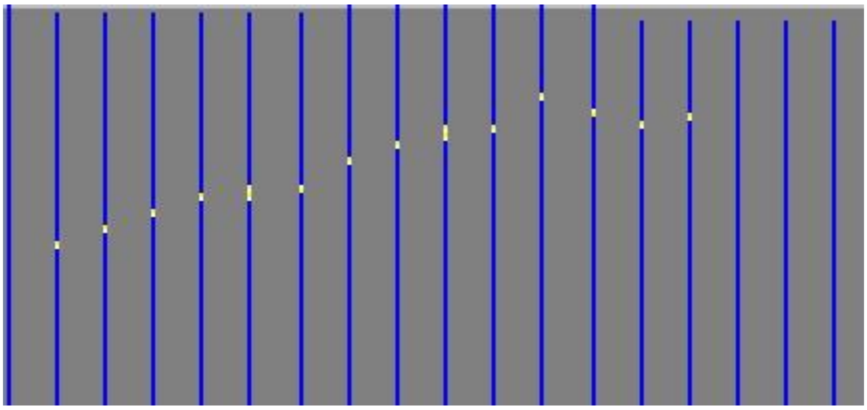

Fig. 13(b). Defect area magnified

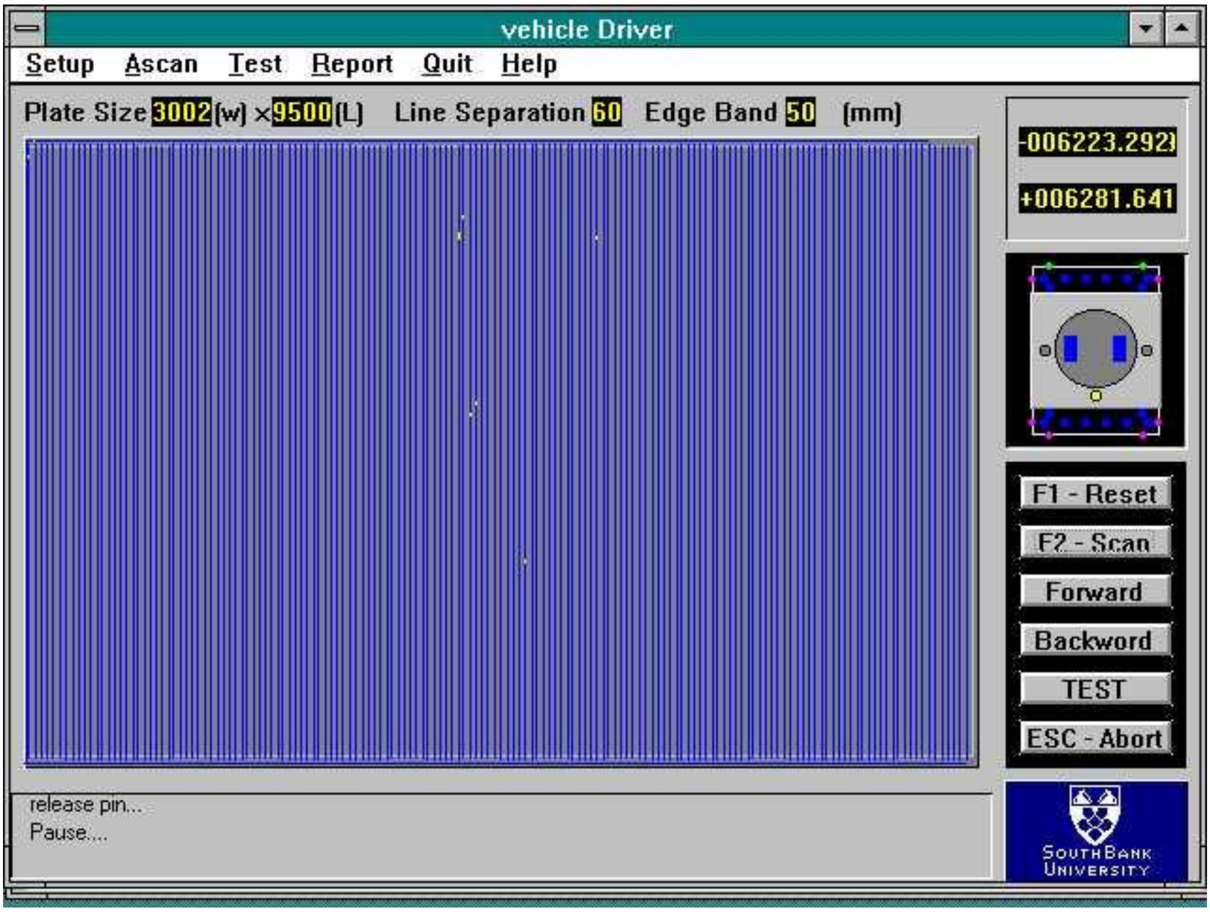

Fig. 14. Results from the third probe holder prototype on the 20mm thick plate