COOP-CT-2004-513158

HULL INSPECTOR

Development of an Autonomous Mobile Inspection Vehicle for Detecting Structural Defects in Ship's Hulls

Horizontal Research Activities Involving SME's

Co-operative Research (CRAFT)

Publishable Final Activity Report

Period covered:	15th Nov 05 to 14th May 07	Date of preparation:	23rd Sept 07
Start date of project:	15th Nov 05	Duration:	2.5 years
Project co-ordinator:	Dr. Bruce Blakeley	Revision No:	1.0

Project co-ordinator organisation: TWI Ltd

Contents

Publishable Executive Summary

The Hull Inspector system was created as an inspection crawler that could be attached to the side of a ship, using powerful permanent magnets. The same magnets are then used to form a Magnetic Flux Leakage (MFL) array for the detection of corrosion in the hull. The crawler can also be used to inspect the ship's welds using Alternating Current Field Measurement (ACFM) and Phased-array (PA) Ultrasonics.

1 Project execution

1.1 General Project Objectives

The maritime industries, which include ship building and ship operation are vital to Europe's economy. The EU is still third behind Korea and Japan in ship building, and dominates the market for high value ships, such as cruise liners and ferries. Ship building capacity will increase when countries such as Poland join the EU. However in the supply of ship building components and services, the EU is a world leader, accounting for about 31% of the 19 billion Euro market. With regard to ship operations, the EU operates 38.5% of the world's fleet. Maritime transport is involved in 90% of its external trade and 40% of its internal trade.

In the future, ships will be designed with tough light-weight hulls. The benefits will be faster speeds and reduced fuel consumption. Among the drawbacks will be tighter tolerances and the need for stricter quality control. Hull inspector will provide confidence in new hull designs.

The scientific and technical objectives are:

- To overcome the limitations of manual and current automated inspection of ship's hulls by developing an autonomous vehicle, which will carry a range of sensors to automatically inspect Ship's hulls.
- To develop a range of electromagnetic and ultrasonic sensors for locating the position of the inspection vehicle on the hull, tracking its movement along features such as welds and detecting defects, such as corrosion and weld fatigue cracks that may be detrimental to the structural integrity of the hull.
- To develop an intelligent inspection system that is able to control inspection coverage according to the geometry of the test piece and the severity of flaws detected
- To build a prototype vehicle and sensors for inspecting steel hulls, which range from those of small harbour boats, through coastal ships to large ocean going liners, oil tankers and container ships.

- To improve the control of weld quality during hull fabrication
- To improve the maintenance of hull structural integrity during service.

The scientific and technical work programme was split into several Workpackages. The objective of each Workpackage is described below.

1.2 Workpackage Objective

WP-A System Specifications and Sample Procurement: To specify the range of applications for which the equipment will be tested in the project and the main features of the system, and to produce realistic test samples.

WP-B Development of NDT Techniques, Sensors and Systems: To develop and produce a series of NDT inspection techniques, sensors and systems to detect and locate areas of corrosion and weld defects in a ship's hull.

WP-C Sensor Integration Software and Data Fusion: To create a software program to integrate the results from the sensors in Workpackage B, D & E.

WP-D Development of Mobile Vehicle and Control Software: To produce a fully functioning mobile vehicle, capable of carrying the NDT sensors and systems to the required inspection areas, and to be able to deploy these sensors correctly.

WP-E Robot Position and Guidance System: To develop a system capable of locating the inspection vehicle's local position and orientation in terms of a global co-ordinate frame of the ship's hull. This is for the purpose of tele-operating the vehicle to an area of the hull that is to be inspected and of mapping NDT measurements to their spatial location in a weld or on a plate surface. The vehicle will also be controlled by the operator using onboard video feedback.

WP-F Integration: To integrate all the deliverables into the final Hull Inspector system.

1.3 List of Contractors

The following companies were partners in the Hull Inspector project

SME	Spree Engineering & Testing Co. Ltd	UK
	Tecnitest Ingenieros SL	Spain
	Sonatest Plc	UK
	TSC Inspection Systems Ltd	UK
	Isotest Engineering Srl	Italy
	Mikron Ltd	Greece
End-user	Atlantic Engineering Ltd	UK
	BP Shipping Ltd	UK
	Naftosol Sa	Greece
RTD	TWI Ltd	UK
	Zenon Sa	Greece

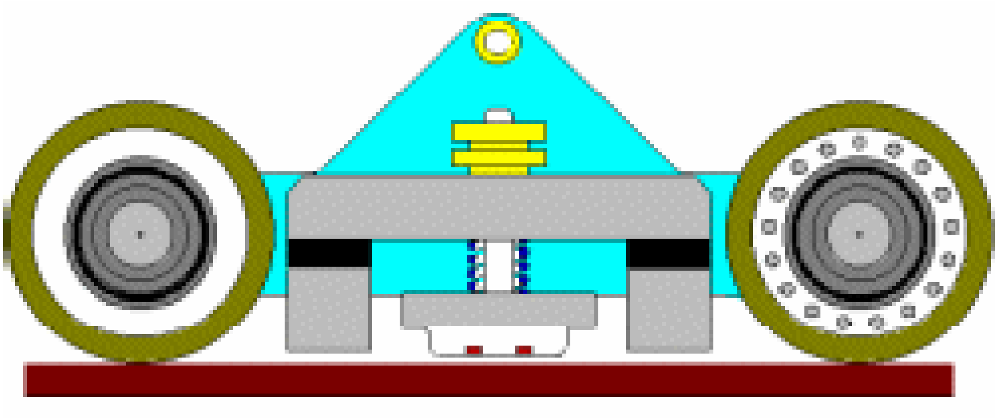
1.4 Work Performed

The objective of the Hull Inspector system was to create an inspection crawler that could be attached to the side of a ship, using powerful permanent magnets. The same magnets would then be used to form a Magnetic Flux Leakage (MFL) array for the detection of corrosion in the hull. The same crawler would be used to inspect the ship's welds using Alternating Current Field Measurement (ACFM) and Phased-array (PA) Ultrasonics. The MFL array, ACFM, Ultrasonics and robotic crawler, developed for the project, are described below.

The MFL System

A typical MFL system is shown in the diagram below:

Figure 1 Typical MFL Scanner

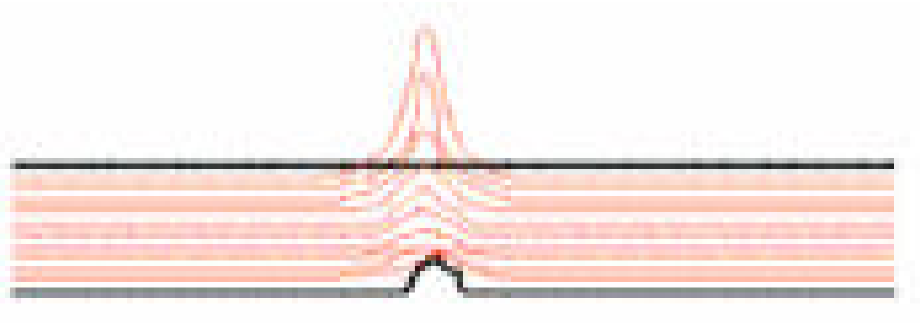


Two magnetic poles, generating 1,000Kg of magnetic attraction, are placed a few millimetres from the steel hull. This induces a near-saturated magnetic flux through the steel plates to be inspected. If there are no defects, then the flux is contained within the hull plates, as shown below.

Figure 2 Magnetic field confined within undamaged plate

However, if the flux encounters a thinning of the plate, usually due to corrosion, then the flux 'leaks' from the plate:

Figure 3 External field disturbance above corroded plate

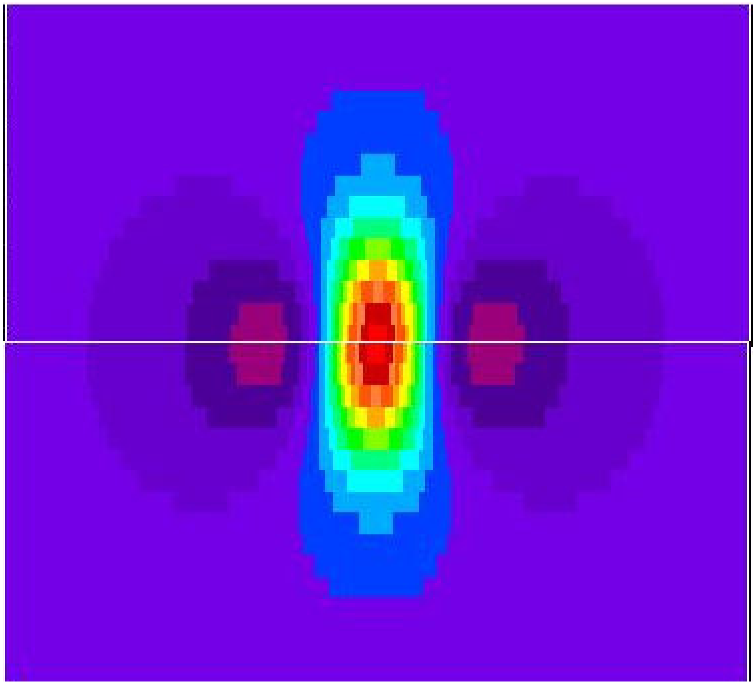


This leakage is detected by the array of sensors between the two poles of the magnets

Landmark Achievement: The Hull Inspector project has demonstrated the capability to reliably detect, analyse and map the smallest calibration defect of 20% through-wall, in 25mm thick plate, at a range of 50m from the data acquisition and control systems. This achievement represents a significant landmark in the development of the MFL technique. Previous systems were only capable of detecting such faults up to 14mm.

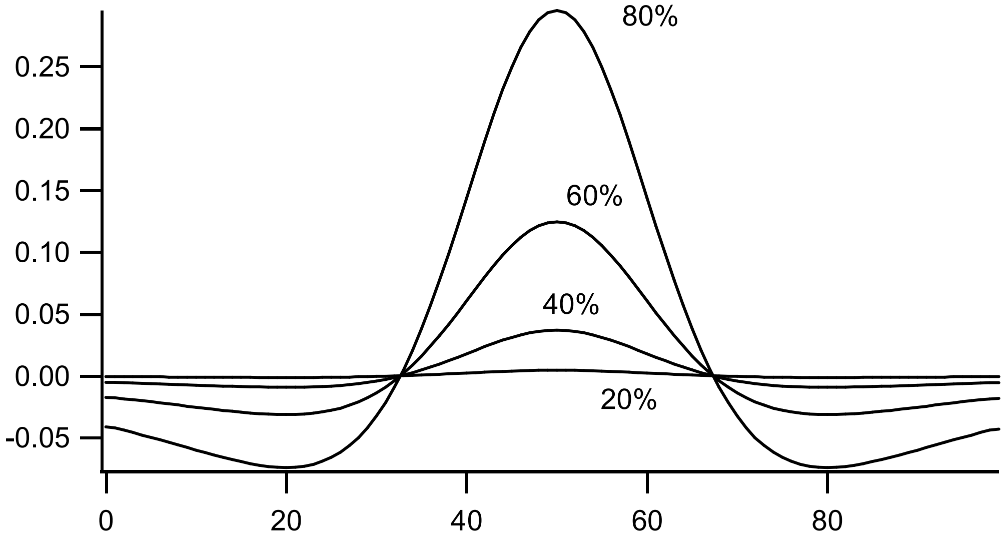
Magnetic Modelling: Basic modelling of the magnetic flux leakage intensities surrounding the calibration defects was undertaken in parallel with development of the electronic sensors and data acquisition. The typical asymmetric field distribution surrounding calibration defects, between the magnetic poles, is shown in the figure below.

Figure 4 Magnetic Field Distribution Around Calibration Defects



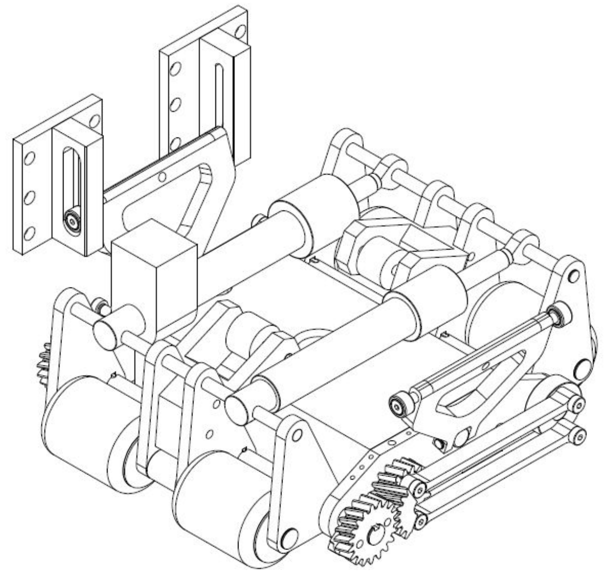
The typical field intensity of each size of calibration defect is shown below. Note the extremely low amplitude of the 20% defect relative to the 80% defect. Despite this low amplitude the HI digital data acquisition system can successfully extract the signal.

Figure 5 Relative Magnetic Field Intensity over Calibration Defects



Traditional MFL systems used a fixed stand-off between the magnetic poles and the steel plates under inspection. This meant that the amount of flux in the plate could not be varied. The Hull Inspector system used an arrangement of hydraulics and linkages to be able to control this stand-off distance, as shown below.

Figure 6 MFL unit with Hydraulically operated stand-off



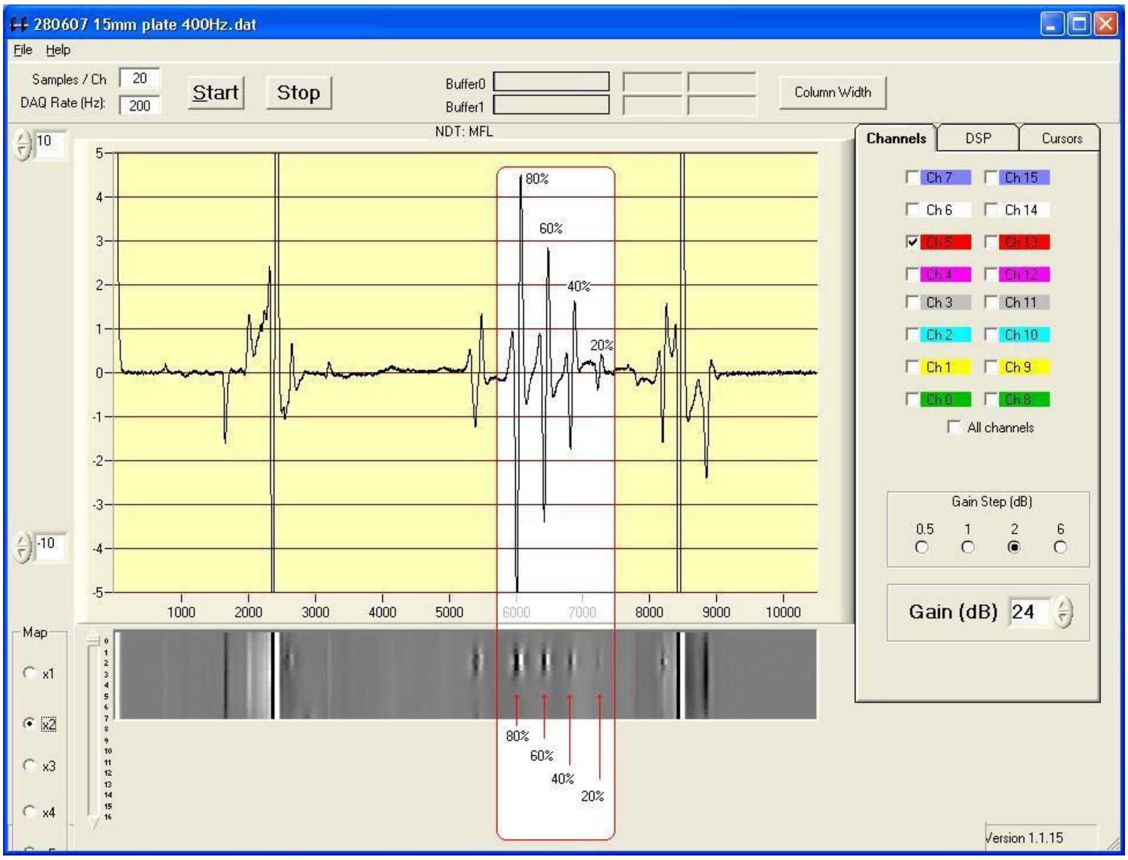
The final MFL system, mounted under the crawler, is shown below

Figure 7 The MFL and wheelprobe combination - The MFL array, mounted below the crawler

Figure 8 Close up of MFL Linkage mechanism

A typical screen shot of the MFL software is shown below. The origin of all indications is attributable to known features of the pates, e.g. bolt holes, support eyes, etc. The highlighted area shows responses from the four calibration defects, in both chart view and in map view.

Figure 9 Typical MFL Software Display (Annotated to highlight MFL Calibration Holes)



280607 15mm plate 400Hz.dat

Samples / Ch: 20

DAQ Rate (Hz): 200

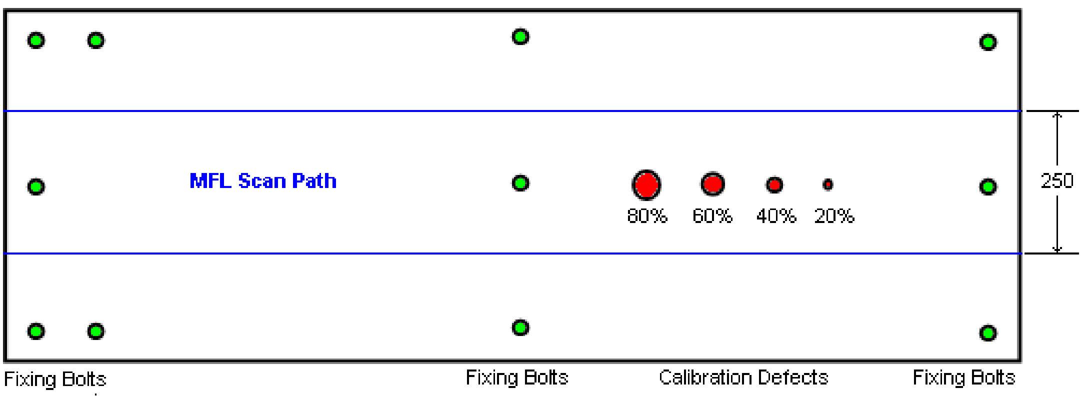
Gain Step (dB): ○ 0.5 ○ 1 ● 2 ○ 6

Gain (dB): 24

☑ Ch 5

Map: ○ x1 ● x2 ○ x3 ○ x4

Figure 10 Calibration Plate Scanned in Figure Above

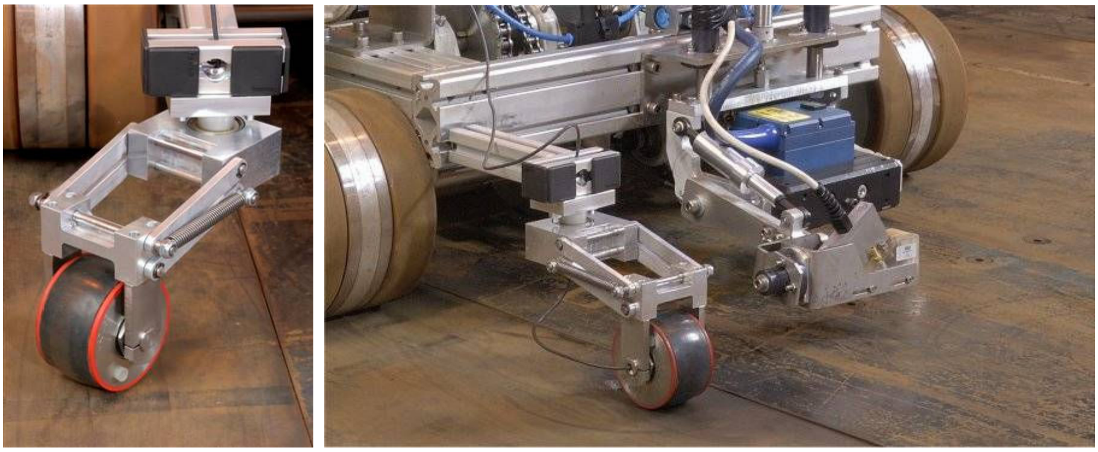


Te Hull Inspector project has created a new MFL inspection system that can successfully examine plates of 25mm thickness. Additionally, the new system has demonstrated the capability to detect corrosion defects of just 20% through-wall height.

Ultrasonic thickness Measurement

A longitudinal ultrasonic probe was mounted in a water filled ‘wheelprobe’, on a sprung caster wheel arrangement. This was able to precisely measure the thickness of the steel plate. The castor system allowed the wheelprobe to move freely over the plate. The system is shown below.

Figure 11 Probe mounting

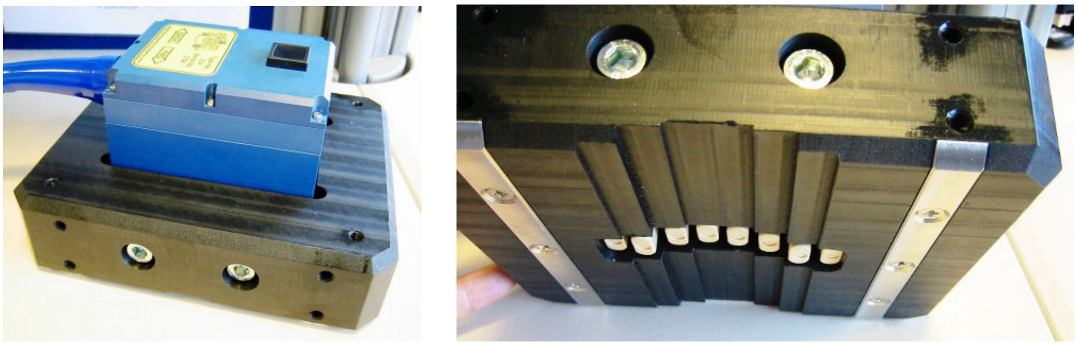


The ACFM Array

ACFM system has been used successfully in laboratories for detecting fatigue cracks in the toes of welds. The cracks can be detected through thick coatings and simulated marine growth. Current systems use a single sensor limited to one weld geometry. The objective of the project is to develop an array of these sensors moulded into a custom geometry, so that one ACFM array can be used for butt, fillet and overlap welds, without having to change sensors. The influence of one sensor on another has to be counteracted by careful coil design and the use of signal processing. These sensors will be used to detect surface breaking cracks in welds, weld toes, sharp changes in surface contour and other possible crack initiation sites.

There were two main functions of the ACFM array. The first was to detect and size surface breaking cracks in the crown of a newly fabricated weld. The second was to locate the centre of the weld; this information is used to guide the crawler along the length of the weld.

Figure 12 The ACFM probe and its protective plastic sled



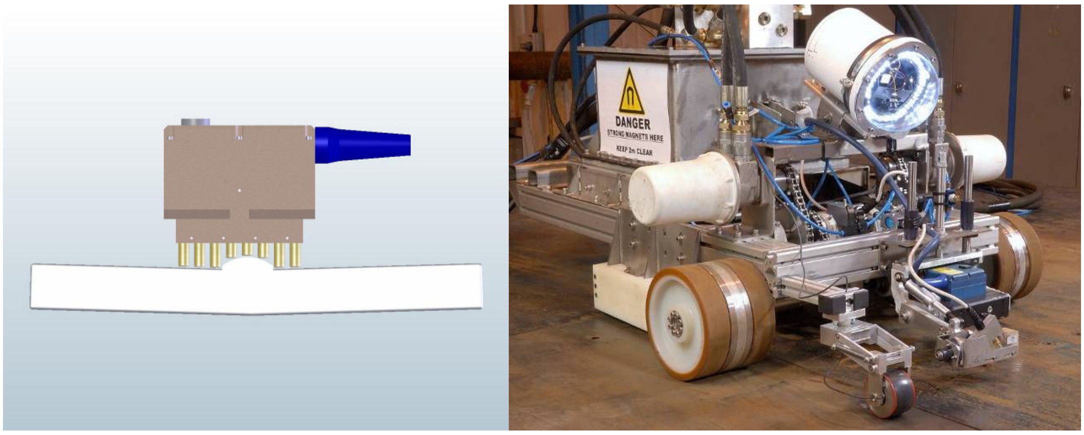
The plastic sled with chamfers enables the sensor to ride over obstructions

The maximum weld height above the plate surface was specified as 8mm for this project. Flat bottomed ACFM Array probes are capable of inspecting welds with a cap height of 4 - 5mm with good sensitivity but any greater than 5mm and the lift-off of the sensors above the weld toe leads to a reduction in sensitivity such that at 8mm lift-off only defects over 5mm deep can be detected. In order to obtain better sensitivity than this it has been necessary to design a probe that can accommodate the profile of an 8mm high weld cap whilst minimising lift-off above the weld toe where defects are likely to occur.

A probe was designed with eight sensors that can be set to any weld profile. The probe employs sprung sensors mounted in a piston that has over 10mm of travel. The profile of the sensor array can be set by compressing the row of sensors down on to a suitable profile.

The position of the pistons can then be fixed by means of a screw clamp. The probe could then be mounted in the probe mounting block and located on the crawler. The profiled probe requires a greater degree of precision in following the weld, as any deviation from the weld centre will give rise to lift-off. The figure below shows a schematic of the probe when clamped in a shape to fit the weld profile.

Figure 13 Probe with sensors clamped to fit the weld profile



The Phased-array System

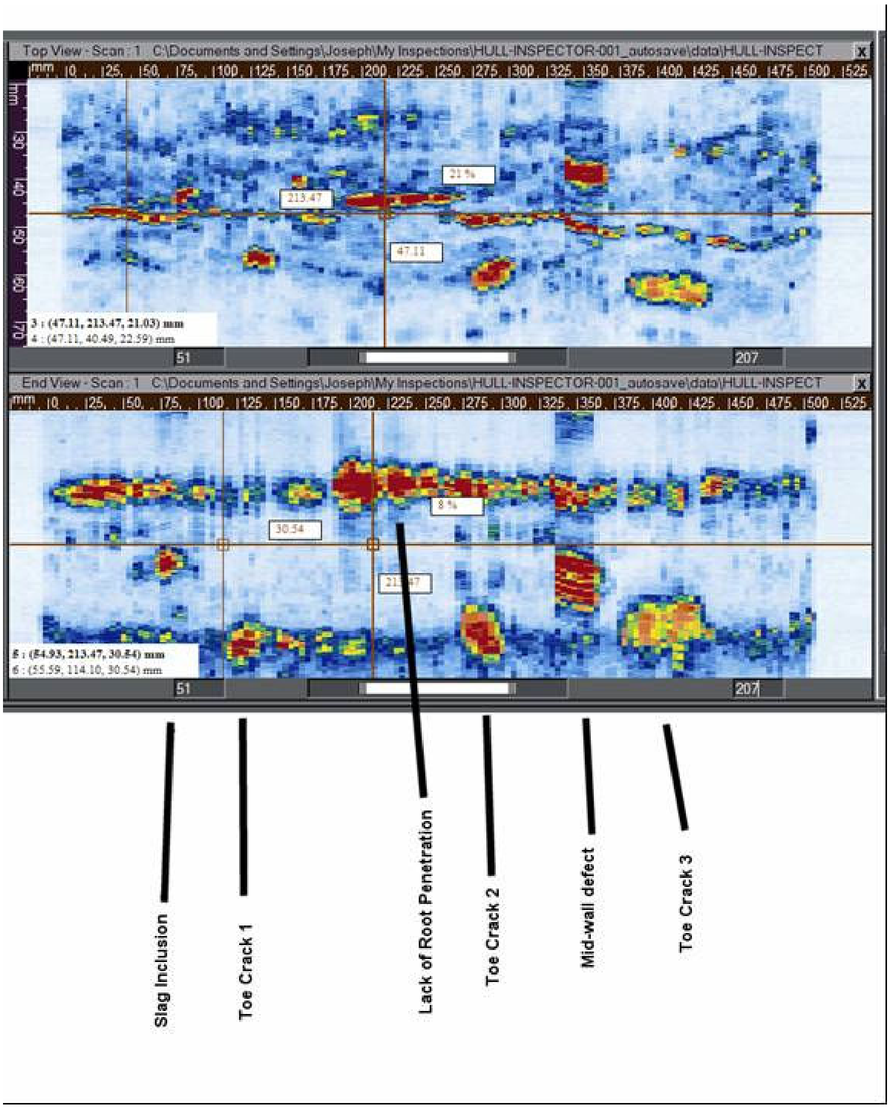
The phased array sensor is a recent innovation in NDT, although it has been used in clinical medicine, where human tissue is a much more accommodating medium for ultrasound, for many years. The minute individual UT piezoelectric transducers in the array can be fired individually by a precise Multiplexer, the ultrasound waves combining, according to Huygens principle to form an electronically steerable beam, which can be focused to any depth required. These sensors are used to detect volumetric weld defects to a high degree of precision in only one linear scan of the weld, with a considerable reduction in time over raster scans with conventional UT probes. It is particularly suited to complex welds and for measuring the depth and orientation of fatigue cracks. The cost of array technology rises exponentially with the size of the array and therefore to make the technique feasible economically the optimum array design must be found that produces adequate coverage of the welds in ship hulls.

A semi-analytical mathematical model of the phased array beams was included as an integral part of the system software. This model will be used to support sensor design, e.g. avoidance of unwanted side-lobes in the beam, checking inspection coverage and generating of training data for pattern recognition algorithms used in data fusion. As introduced above it is intended to use these probes mounted into a wheel probe so that they can c-scan over the outside surface of the hull in the splash zone where the surface is relatively rough and ultrasonic coupling will vary from immersed to semi dry. A photograph of the probe is shown below

Figure 14 The Phased-array probe

The phased-array system was validated on a steel plate weld with a variety of defects. The results are shown below.

Figure 15 The Phased-array ultrasonic results



Probe holder

A probe holder was designed to mount the two phased-array probes and the ACFM array to the front of the crawler. Each probe was protected by a plastic sled, with large chamfers, which enabled the probe to ride over any obstacles, such as weld spatter of excessive crowns. The ACFM and two phased-array probes were then mounted in the aluminium frame. Each of the three probe holders are individually gimballed to allow the probes free range of movement to ensure constant coupling. The probe pan itself was then fully gimballed so that it could move independently of the crawler.

Figure 16 The probe holder for phased-array and ACFM

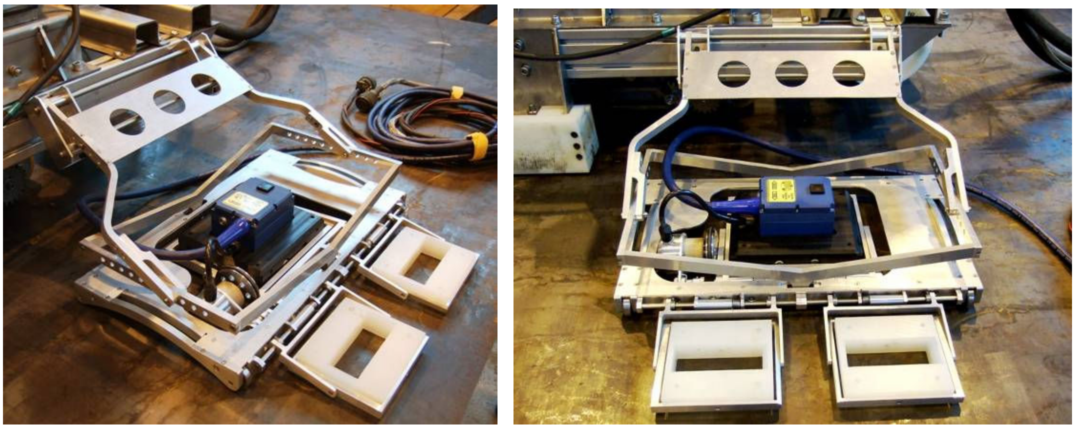
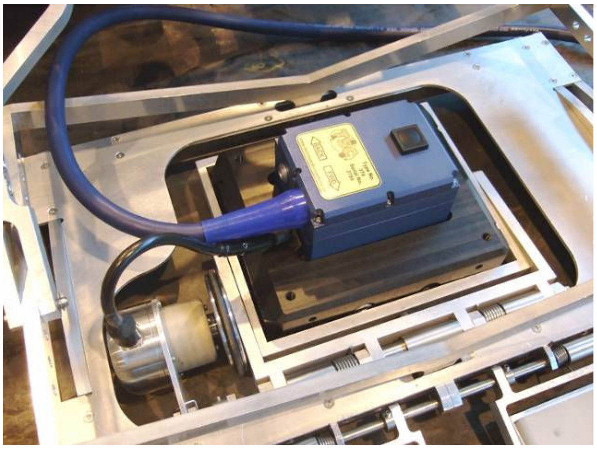


Figure 17 Close up of ACFM probe holder and encoder



The Robotic Crawler

A crawler was developed which used the powerful magnets of the MFL system to attach itself to the steel hull of the ship. Hydraulic motors were used to drive port and starboard wheels to drive and steer the crawler. CAD models of the crawler are shown below.

Figure 18 Overall CAD Model. Top view

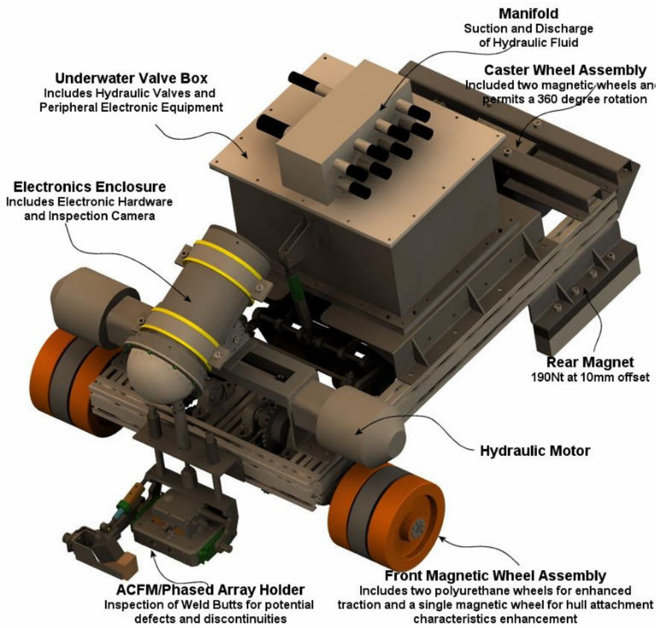
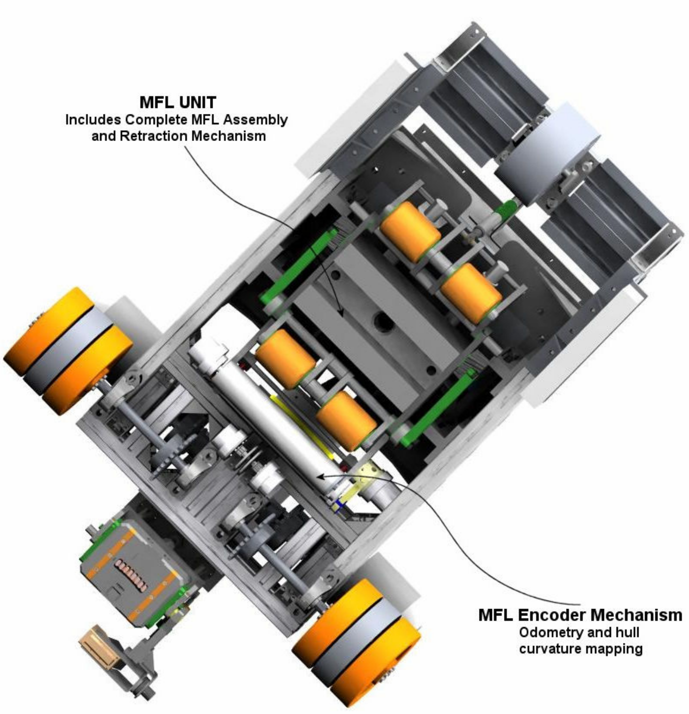
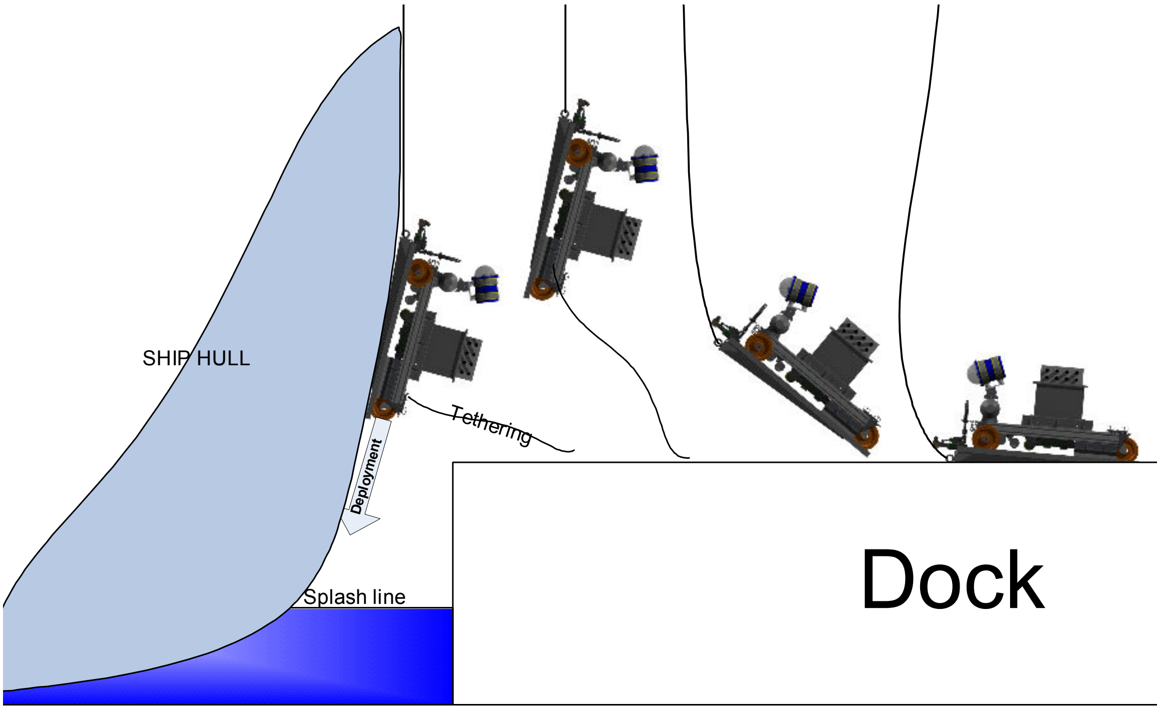


Figure 19 Overall CAD Model. Bottom view



The magnetic attraction of the crawler exceeded 1,500Kg, and the weight of the crawler was approximately 200Kg. Deployment on to the side of the ship had to be carefully designed. A ramp system was developed for this task. The ramp consisted of a steel platform at a 5degree angle, so as the crawler was driven on, the magnets were pulled away from the steel hull. A crane would then be used to move the ramp and crawler from the hull to the dock. Mounting the crawler on to the ship was the reverse of this process, as shown below.

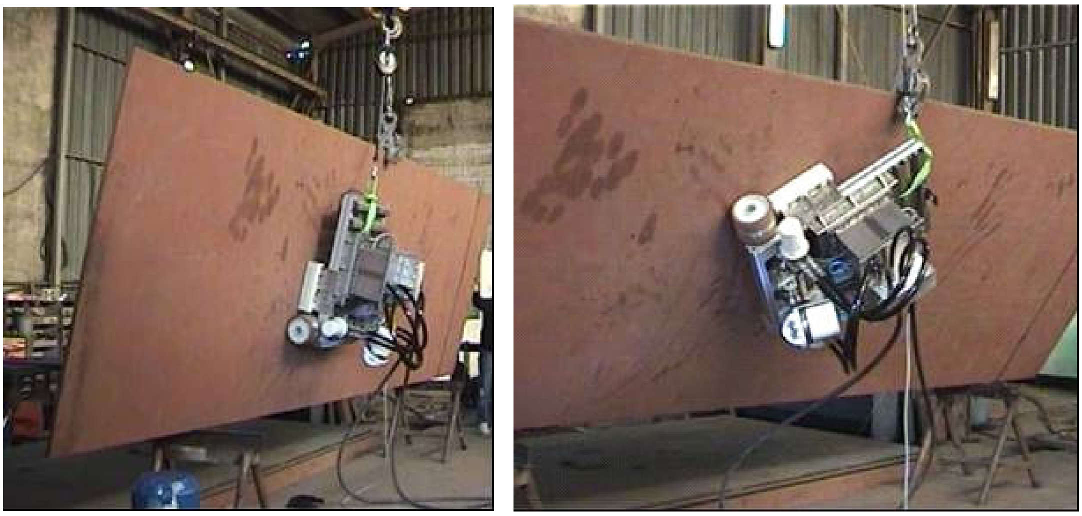
Figure 20 Robotic deployment method



The photographs below show the results of the test at the Naftosol ship yard. The crawler was tested on the steel plates at a variety of angles.

Figure 21 Vertical crawler trials

Figure 22   Vertical crawler trials on overhang



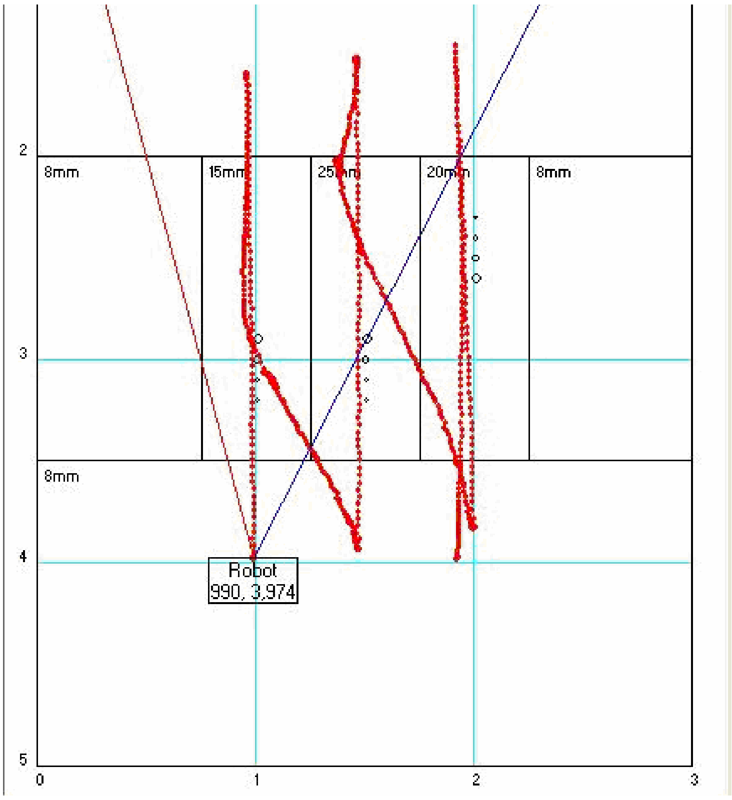
Local Positioning System

The position of the crawler on the demonstration piece was plotted by the use of two draw string encounters. One end of the wires were tethered to known reference points.

Figure 23   Local positioning system

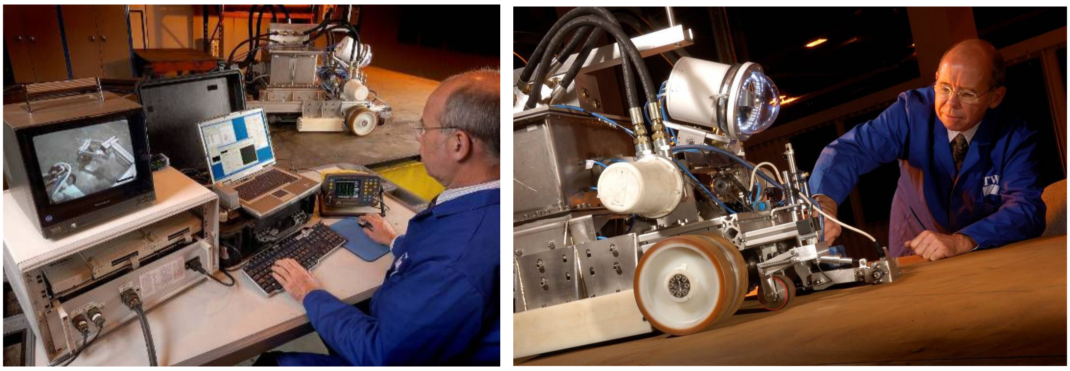
Triangulation was used to determine the position of the crawler and sensors within 20mm.

Figure 24 Local positioning system software



The completed system was demonstrated at the TWI laboratories in Wales, as shown below.

Figure 25 Final Trials at TWI



1.5 Project Achievements Against State-of-the-art

Limitations of current inspection methods for inspection of ship's hulls during fabrication are:

- The NDT is applied manually. The PANI trials carried out to assess the effectiveness of manual inspections have shown that operators detect only 50% of defects during manual inspections.
- Test operators have to be highly skilled. There is a shortage of skilled test operators.
- Ultrasonic inspections, which are the only way of providing 100% coverage of welds are slow, necessarily restricting coverage to about 10% of weld length.
- There is no 'hard copy' of test results. Only film radiography provides "hard copy" results but cannot be easily used because of health and safety considerations.
- Test operators, like welders must have safe access at the weld, requiring secure scaffolding. Inspection cannot be conducted at the same time as welding, therefore scaffolding must be kept in place for a longer period than might otherwise be necessary.

Limitations of current inspection methods for inspection of ships' hulls in-service, in addition to those given above are:

- The ship has to be put into a dry dock before carrying out inspections.
- Large areas have to be manually inspected quickly, leading to interpretation errors caused by tiredness.
- Corrosion has to be mapped using so-called ultrasonic C-scanning. This is a very slow process, when using current ultrasonic techniques.

There have been many achievements of the Hull Inspector System. Some notable successes include the following:

Magnetic Flux Leakage System for Thick Sections

Magnetic Flux Leakage (MFL) consists of an array of electromagnetic sensors located between two powerful magnets. The magnets create a saturated magnetic flux in the hull of the ship. As the sensor array passes over any thinning of the hull - due to corrosion - the flux 'leaks' out of the steel plate and is detected by the array of electromagnetic sensors. This is used in industry to quickly screen and locate areas of corrosion in steel plate.

This system has been substantially improved upon by the Hull Inspector partners in the following ways:

- Previously commercially available system only capable of inspecting steel plates up to 14mm in thickness. Hull Inspector system has proven capable of detecting loss of material up to 25mm.
- Previous systems only capable of operating at one fixed speed, Hull Inspector system capable of operating at variable speed
- Traditional MFL units have a set stand-off distance between the magnetic poles and the steel plate under inspection. The Hull Inspector system uses a complex system of linkages and hydraulics to alter this stand-off distance. This allows the system to vary the amount of magnetic flux in the steel plate.
- Overall system reduced in size and marinised for use underwater. This was achieved by replacing the analogue electronics enclosure with a DSP software package.

Gimballed Phased-array and ACFM holder

A major limiting factor in the construction of ships is the requirement to use manual ultrasonic probes to inspect the hull welds. These pose several problems for the inspectors. The first is access, as the welds are often several metres above the ground and must be accessed via ropes, scaffolding or cherry-pickers. The concept of using the magnetically attached crawler to gain access to these welds will be discussed below. This section deals specifically with the concept of using a combination of advanced UT, in the form of twin phased-array probes, and the surface inspection using Alternating Field Current Measurement (ACFM). ACFM is used to inspect the surface of the weld for surface breaking cracks which act as potentially fatal stress raisers. The combination of the volumetric inspection using PA and the surface inspection method using ACFM has been combined to form a powerful technique for the validation of hull welds. Neither of these techniques is new, but the combination of the two, held within a four-way fully gimballed probe-holder with a magnetically attached crawler is.

The gimballed holder consists of three holders combined, two for twin phased-array probes arranged on each side of the weld and a variable geometry ACFM array spanning the width of the weld. The variable geometry ACFM probe will be discussed in the next section as a separate exploitable product. The gimballed holder unites the three advanced inspection tools together in a manner that ensures the three probes always remain correctly coupled to the inspection plate without deviation from the centre of the weld crown.

ACFM variable geometry array

Alternating Current Field Measure (ACFM) consists of an array of electromagnetic sensors positioned across a weld. A fluctuating magnetic flux is played across the surface of the weld, produced by coils in the sensor heads. As the flux encounters surface breaking cracks, small magnetic poles are formed which are detected by secondary coils in the sensor array.

TSC have been developing this technology for many years, and have made great strides in further advancing their product in the Hull Inspector project. Their previous arrays consisted of fixed unmovable sensors based in a rigid plastic block. As part of this project they have added a series a small pistons, each containing a sensor head. This gives them the ability to ‘mould’ the array across the crown of a weld, so that the sensor stand-off between the coils and the weld material is consistent. The addition of a plastic ‘sled’ with large chamfered corners has further increased the robustness of the probe by effectively adding a ‘bumper’ around the probe which allows the array to slide over any defects that may otherwise harm the probe array. When this is coupled with the gimballed probe holder described above, it allows the array to be attached to an automated magnetically attached crawler without potential risk of damage. The conformable array allows the sensor heads to move closer to the weld crown, increasing surface inspection sensitivity.

The Completed Hull Inspector System

The completed system combines all of the above mentioned exploitable techniques with a magnetically attached crawler. The system is aimed at any industry that has a requirement to inspect welds - using ACFM, PA and the sensor holder - to industries concerned with corrosion of steel plates - using the auto-calibrating MFL system.

Every five years a ship must be dry-docked so that its hull plates can be inspected for corrosion. These inspections are particularly expensive, as not only do the dry-docks carry a heavy fee for their use, but the ship may be out of commission for over ten days. The plan is to conduct partial inspections each time the ship arrives in port to load/unload. The precise area of the hull inspected will be logged, so that by the time the next five-year inspection comes around, the operator can conclusively prove that the ship has been adequately inspected.

By increasing the range of thicknesses that the system can inspect, the system has moved significantly closer to the stage where it can be validated by the classification societies.

1.6 Impact on the Shipping Industry

A typical large crude carrying vessel or civil liner has:

- 120 km of safety critical welds that require detailed inspection on a 5 year cycle (ships are made from box sections, where each section is welded onto another to construct a ship/tanker). The vessel needs to be “dry docked” to inspect these welds. These welds are prone to fatigue cracking due to the drastic dynamic loading during service by their cargo of humans, crude oil, other goods and also storms at sea.
- 600,000 m2 of steel that requires detailed inspection for corrosion monitoring.

Currently, the above inspections are largely carried out manually at “dry dock” periods by operators working in hazardous conditions. Current methods of inspection of these welds for cracks and other large areas for corrosion have major drawbacks as follows:

- Require the vessel, ship or tanker to be dry docked, emptied and cleaned with a consequent 2 week disruption. Each day at dry dock currently costs 50,000 Euros to the ship/vessel/tanker operator.
- The inspections are mainly visual and manual and therefore subjective with no hardcopy results. They are also prone to operator fatigue.
- Operators and surveyors are exposed to hazardous conditions e.g. toxic gases, working through absailling on ropes and via scaffolding, etc. During an inspection of a large ship/tanker an operator climbs on average 10,000 meters. New EC regulations regarding operator safety [Directive 94/57 on common rules and standards for ship inspection and survey organisations. Directive 94/57/EC], will make it increasingly difficult for manual inspections on ships/tankers to be allowed. Also note that Shipyard work has an injury-accident rate more than twice that of construction and general industry.

Inspections are also required at the manufacturing stage. Ships are generally fabricated using ‘dock and block’ techniques in which each section of the hull is welded under the controlled conditions of the ‘shop floor’ before being moved into the dockyard for attachment to the hull with one module closure weld. Only 10% of the weld length is subjected to non-destructive testing (NDT). The test is conducted manually, is slow and only provides a limited amount of data, namely about whether the weld is acceptable or not to the design specification. Inspection is also carried out at height and requires platforms for test operators. The 10% coverage is therefore not representative, is gathered under time restrictions and cannot be cross-checked before the scaffolding is removed.

The impact of the Hull Inspector project is the creation of a magnetically attached crawler, capable of inspecting hull welds during fabrication, using Phased-array and ACFM, and for corrosion of hull plates using Magnetic Flux leakage (MFL).

2 Dissemination and use

2.1 Magnetic Flux Leakage System for Thick Sections

A Magnetic Flux Leakage (MFL) System has been further developed by TWI to increase its range from 15 to 25mm of steel wall thickness. A novel auto-calibration technique is used to allow the system to automatically re-calibrate itself as it passes from one steel thickness to another, without the need for operator intervention

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2.2 Gimballed Phased-array and ACFM holder

TWI has developed a probe holder to mount a ruggedised variable geometry ACFM array and twin phased-array probes for the automated inspection of welds, such as found in the shipping and oil and gas industries an 8 DoF gimble system ensures that all the probes remain correctly coupled at all times, while a unique sled system ensures that any weld spatter, excessive crown or other obstacle will not damage the probes or impeded their progress.

Interested parties should contact:

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2.3 ACFM variable geometry array

TSC have developed a variable geometry array ACFM probe, for the inspection of welds with excessive crowns. Welds with excessive crowns are difficult to inspect with any electromagnetic array, as the standoff distance between the inspected material and each of the sensors varies across the width of the weld. The sensors above the centre of the weld are close to the surface, while the sensors at the toe of the welds can be several millimetres away, reducing the sensitivity at this crucial line of the weld. By allowing the array to have a variable geometry, the operator can 'set' or 'mould' the array to the weld.

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2.4 The Hull Inspector System

The Hull Inspector Consortium have developed a magnetically attached inspection crawler for the inspection of ships, using a variety of advanced NDT sensors, including phased-array, ACFM and MFL systems. They are looking to further commercialise this systems for the inspection of ships while at dock, without the need to dry-dock the vessels.

Interested parties should contact:
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