COOP-CT-2004-508599

FPSO-Inspect

Non-Intrusive In-service Inspection Robotic System for Condition Monitoring of Welds inside Floating Production Storage and Offloading (FPSO) Vessels

Horizontal Research Activities Involving SMEs

Co-operative Research

PUBLISHABLE FINAL ACTIVITY REPORT

Period covered: from 1 December 2004 - 31 May 2007 Date of preparation: June 2007

Start date of project: 1 December 2004 Duration: 2 years extended to 30 months

Project co-ordinator: Mr Graham R Edwards
Project co-ordinator organisation: TWI Ltd Revision 1

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group specified by the consortium (including the	
CO	Confidential, only for members of the consortium (including the Commission Services)	✓

PUBLISHABLE FINAL ACTIVITY REPORT

Full Title:	Non-Intrusive In-service Inspection Robotic System for Condition Monitoring of Welds inside Floating Production Storage and Offloading(FPSO) Vessels			
Acronym:	FPSO-Inspect			
Date of Preparation:	August 2007			
Type of Instrument:	Co-operative Research Project			
Co-ordinator:	RTD 1	TWI Ltd	TWI	UK
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	RTD 2	Miltech Hellas SA	Miltech	Greece
	RTD 3	London South Bank University	LSBU	UK
	RTD 4	Kingston Computer Consultancy Ltd	KCC	UK
Reporting Period	1 December 2004 - 31 May 2007			
Start and End Date	1 December 2004 to 30 November 2006 extended to 31 May 2007			
Document Version	0			
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EXECUTIVE SUMMARY

The original aim of this project was to build a prototype amphibious robot vehicle that can carry Non-destructive Testing (NDT) sensors from an entry port in the top of an FPSO vessel tank, to the floor or sides of the tank, where the NDT sensors can be deployed from a scanner to detect either fatigue cracks in the stiffener to tank shell fillet welds, or corrosion in the shell plates.

At the request of the end-users, the aim of the project became to build a prototype robot vehicle that simply operated in-air on the floor of the FPSO tank once it had been emptied, but left with sediment that covers the surface.
However, a swimming capability for the robot was still a key issue for the SMEs, so it was decided to build a robot that could demonstrate this capability in water, without conducting any scanning.

The FPSO-Inspect system development included new NDT techniques for deployment form a novel X-Y-Z scanner attached to the front of the autonomous robot vehicle. The robot vehicle has thrusters and buoyancy tanks for underwater swimming and wheels for moving in the sediment on the tank floor. The vehicle carries ultrasonic sensors for automatic guidance around the stiffener in a local path plan. A method of guidance along a global path from vehicle entry in the top of the FPSO tank to finding a corner between stiffener and tank wall that is the start of the local path plan was also developed.

The final demonstrations of the prototype FPSO-Inspect system were successfully completed in a diver training tank and on a mock-up of a FPSO tank floor with stiffeners. The NDT sensors and systems were shown detecting implanted fillet weld toe cracks and floor plate corrosion.

Other developments include:

- An ACFM sensor system that uses an array of sensors that could be used in many other critical inspections of fillet welded T-joints, for example in the detection of earth quake damage in the structural frames of modern high-rise buildings that are coated for fire protection.
- A creep-wave ultrasonic system for one-sided inspection of double fillet welds that uses dual-surface creep waves. This could speed up inspections of structural steel work to an extent that ultrasonics was regularly used.
- A plate-wave ultrasonic technique that has ‘intermediate’ range capabilities for use in a wide range of applications including the detection of corrosion under annular rings around storage tanks and under collars that support pipes.

The consortium members had worked well together and felt that the project had produced very worthwhile results for their businesses. They intend to work together in future collaborations.

1. INTRODUCTION

Floating Production, Storage and Offloading (FPSO) (Figure 1) and Floating Storage and Offloading (FSO) vessels are increasingly being used for production and storage of oil from offshore fields. A typical FPSO contains 20km of internal safety critical welds that require detailed offshore inspection on a 5-year cycle. These welds are prone to fatigue cracking due to the drastic increase in loading; as the majority of FPSOs in the world are converted ocean going vessels, which are now carrying heavy oil that exceeds their original design loads.

The FPSOs are currently carrying up to 1 million tonnes of oil per day. Over 2.5 billion tonnes of oil is used around the world every year and 3 million tonnes is discharged every year into the oceans as a result of oil tanker and FPSO failures. These accidents typically account for 12% of all oil pollution.

Current methods of inspection of these welds have major drawbacks as they require the FPSOs to be dry docked, emptied and cleaned with consequent disruption to production. This means that 90% of the costs of inspection are associated with the disruption of production and emptying and cleaning the FPSO. The inspections are also mainly visual and manual and therefore subjective with no hardcopy results. Operators and surveyors are exposed to hazardous conditions eg toxic gases, working through abseiling, on ropes and via scaffolding.

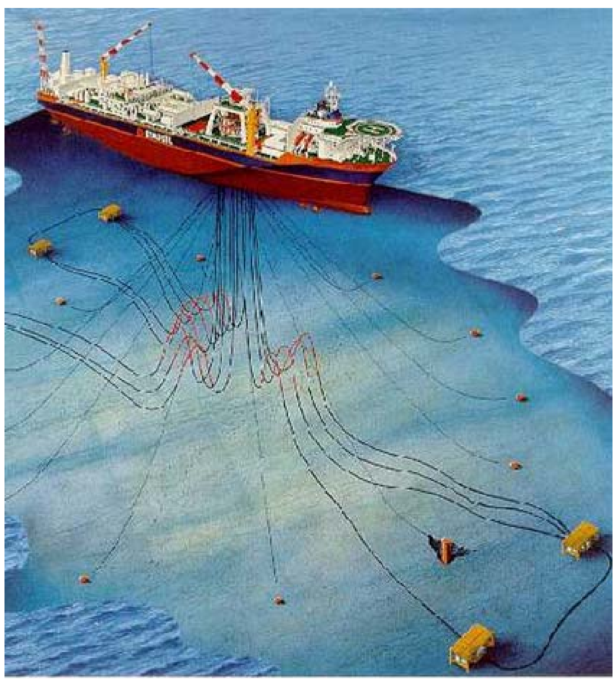

Figure 1 FPSO and associated riser

In the original proposal, the main objective was to overcome the above limitations of manual inspection by developing an amphibious autonomous robotic vehicle, which will enter the various tanks inside the FPSO (Figure 2), inspect for its structural integrity without having to empty and clean the FPSO.

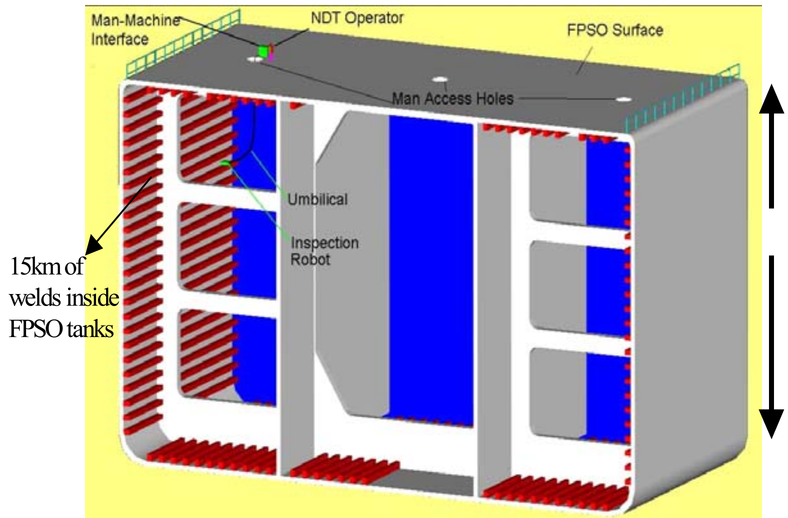

Figure 2 Mode of operation of FPSO-Inspect

At the kick-off meeting to the project, the end-users participating in the project (BP and PetroBras) declared that it was not the preferred practice in their FPSO vessels to empty the tanks and fill with water. Therefore the amphibious vehicle would have to perform in oil. This placed considerable constraints on the development of the robot within the project's resources, as it would have to be made intrinsically safe. The end-users stated that a robot vehicle that was able to carry out inspections around the stiffeners in the bottom of the tank would however be of enormous benefit.

The partners therefore amended the main objective of the project to the development of an inspection robot that could be used in-the-dry, but which demonstrated its amphibious capability in water.

2. PROJECT OBJECTIVES

- To demonstrate a robot vehicle with sensors for detecting damage from corrosion and fatigue in the floor plates and stiffeners of FPSO tanks.
- To build an X-Y-Z scanner for the sensors that is mounted on the robot vehicle.
- To develop a positioning and guidance system for the robot
- To develop sensors and sensor systems for detecting fatigue cracks in the toes of stiffener to floor fillet welds.
- To develop sensors and sensor systems for detecting corrosion on either the internal or external surfaces of the floor plate.
- To develop a man-machine interface that combines robot control with data gathering from the sensors.

3. PROJECT EXECUTION

The project brought together six small-to-medium-enterprise and two large enterprises from a supply chain providing products and services for the inspection of FPSOs.

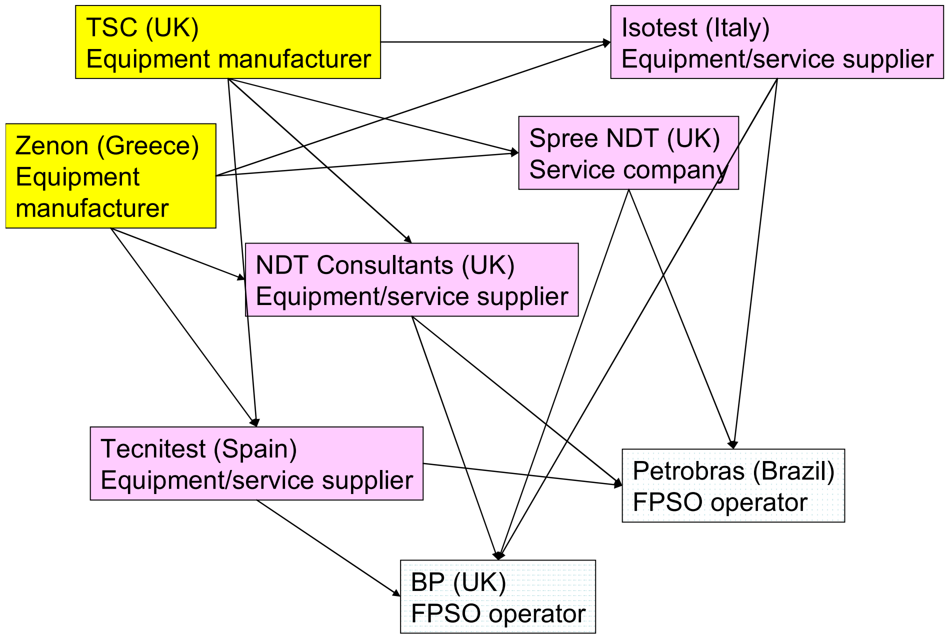

Figure 3 Partner supply chain

The consortium was supported by four research and technology organisations, namely TWI (UK), LSBU (UK), KCC (UK) and Miltech (Greece).
The project was valued at nearly €2m and ran for 30 months. The work was divided into seven work packages, each led by a different member of the consortium. The work packages broadly covered the development of NDT sensors and systems, design and build of the robot vehicle with scanner and integration followed by field trials.

3.1. DEVELOPMENT OF NDT TECHNIQUES SUITABLE FOR ROBOT DEPLOYMENT

The principal aims of the NDT are firstly to detect fatigue cracks emanating from the toes of fillet welds that join stiffeners to the floor of the FPSO tank and secondly to detect corrosion in the tank floors. The sensitivity requirements set by BP and Petrobras were 150mm long for cracks and 10% loss of wall for corrosion.
From a starting point of what was desirable in terms of defect detection limits, access and geometry and what was feasible in terms of vehicle pay-loads, surface finish and other operational constraints, a specification was written that evolved during the project to take account of technical developments.
For example, the original specification included phased array ultrasonics as one of the two techniques for detecting fatigue cracks in the weld toes, Alternating Current Field Measurement (ACFM) being the other. This changed to creep wave ultrasonics as it became clear that the phased array sensor and the umbilical needed to connect it to the system instruments, placed too great a load on the vehicle and the inspection data generated was more complex than was needed.
With the development of any NDT technique it is necessary to determine which factors affect the probability of detection and the sizing accuracy. This requires extensive experimentation and a library of defect samples was built up for carrying out the investigations. Of particular importance were fillet weld test pieces into which fatigue cracks had been induced (Figure 4). A special method of creating fatigue cracks with a fatigue testing machine at selected positions along the weld toe was developed for this.
For larger scale trials at the end of the project BP made available a mock-up of a section of FPSO tank that they use for training their rope-access inspectors (Figure 5).

Figure 4 Fillet weld with fatigue cracks

Figure 5 FPSO tank mock-up

In all, five NDT techniques were investigated; phased array, creep wave and plate wave ultrasonics, pulsed eddy-current and ACFM. For each, laboratory investigations were undertaken to determine the parameters that affect the test sensitivity. Among the parameters were:

Ultrasonics:

- Ultrasound wave mode (Longitudinal, transverse, creep and plate)
- Ultrasound frequency (0.5MHz – 7MHz)
- Transducer type and dimensions. (5mm – 25mm)
- Incident angles on the probe wedge (25º - 50º)

Electro-magnetics:

- Coil design on magnetic field distribution.
- AC frequency (500KHz – 2MHz)
- Coil types (Differential, absolute)
- Pulse repetition rates.

3.1.1. Phased array ultrasonic technique

The phased array technique developed originally in this task had high sensitivity to fatigue cracks in fillet welds and was able to detect other flaws, such as lack of penetration, lack of side wall fusion and porosity. However it suffered the following problems:

- Within the sweeping transverse wave scan it was difficult to distinguish cracks signals from pronounced weld cap signals that existed in some of the fillet welds.
- The test rate was too slow.
- The sensor was too heavy.

Despite being abandoned as an operational technique, the phased array technique played an important part in laboratory investigations of creep wave and plate wave propagation.

3.1.2. Creep wave ultrasonic technique

Creep waves are propagated with shallow angle (just below the surface) longitudinal waves. They are produced as the incident beam angle from a wedge mounted ultrasound transducer approaches the ‘first critical angle’. Unlike surface waves, creep waves, or head waves as they are sometimes known, are not affected by surface roughness and are therefore used for detecting near surface flaws under the weld cap (Figure 6). Unfortunately, creep waves are very short range, because a transverse wave is continually ‘leaked’ to the far surface. Moreover the transverse wave is always present, giving rise to multiple reflections that clutter the A-scans with signals.

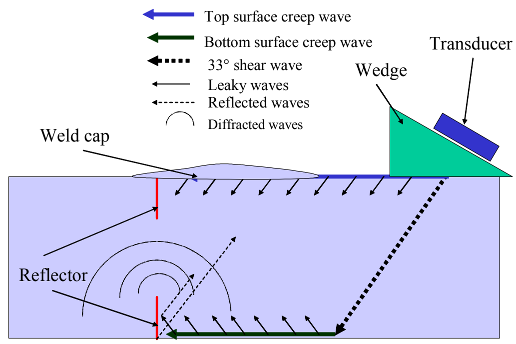

Figure 6 Creep waves

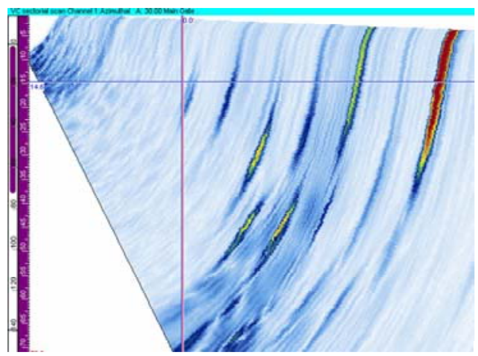

Figure 7 Phased array sector scan of plate slot

Using the phased array ultrasonics and the sector scan display created by sweeping the longitudinal wave beam through angles between 45º and 85º (Figure 7) it was possible to resolve and analyse multiple reflections from a slot in a thin plate (Figure 8). It was found for example that the signal from a slot on the opposite surface from the probe was sometimes stronger than that from the crack on the same surface, but only under certain conditions. These conditions occur when ultrasound reflections from corners and surfaces due to creep-transverse wave mode conversion reinforce one another (Figure 9). This was a significant discovery for the project. If the conditions can be met in the field, it will provide a rapid, one-sided inspection technique for double fillet welds in T-joints.

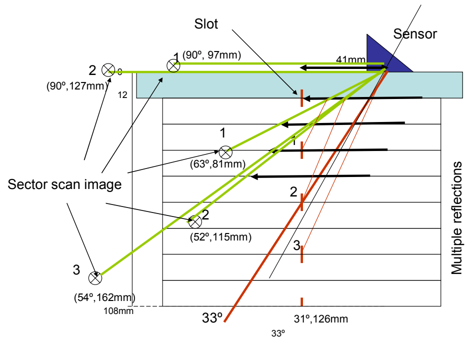

Figure 8 Reconstruction of sector scan image

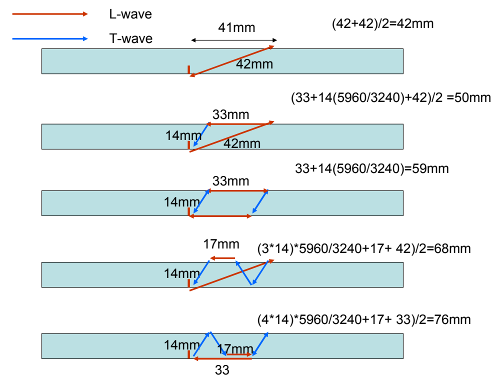

Figure 9 Analysis of signals from slot

3.1.3. Plate wave ultrasonic technique

The creep wave technique is operated at sufficiently high frequency (>2MHz) on moderately thick plates (>10mm) for the waves along the top and bottom surfaces to be independent of each other. When the frequency is dropped below 1MHz, the interference between waves travelling along the top and bottom surfaces of the plate is sufficient to propagate plate or Lamb waves (Figure 10).

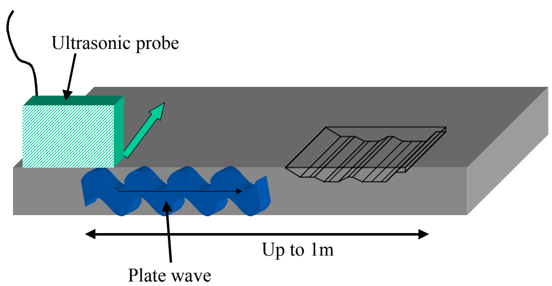

Figure 10 Plate wave technique

Figure 11 Variable angle probe for plate waves

In their simplest form, the plate waves propagate through a plate in which the surfaces are undulating in phase (asymmetric wave) or in anti-phase (symmetric wave). In practice the waves are very complex and are 'dispersive'. Calibration of the A-scan to measure distance to a signal is therefore difficult, requiring the use of pre-calculated 'dispersion curves' that plot velocity against a frequency/wall thickness ratio.

Laboratory investigation of influential parameters such as beam angle, test frequency and transducer size was conducted on a variable angle probe (Figure 11).

The important distinction of plate waves from creep waves is that they can propagate over long distances (>2m). Also, they are reflected wherever the change in wall thickness creates a change in acoustic impedance that is sufficient to reflect some of the wave energy. Plate waves will therefore reflect from weld caps (increase in wall thickness) as well as from corrosion (decrease in wall thickness) on either surface of the plate.

3.1.4. Pulsed eddy currents

In contrast to conventional eddy-current techniques, where the driver coil is excited by a simple sinusoidal waveform, in pulsed eddy current techniques, the coil is pulsed repeatedly with a square wave. Therefore the generated eddy-currents contain a range of frequencies, which, because of ‘skin-effect’, are able to penetrate to a range of depths in a conductive material. The higher frequency components are restricted to the surface, the lower frequency components to depths of perhaps several millimetres. Because of the frequency/depth relationship, a 3-dimensional picture of anomalies in a test piece can be built up by scanning the test probe over the surface.
The sensor measures the effective magnetic field, part of which is generated by the eddy-currents in the test piece and the rest by the driver coil (Figure 12).

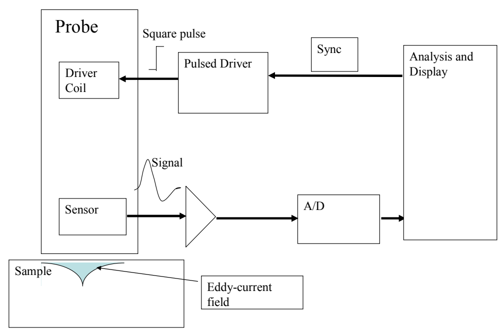

Figure 12 Pulsed eddy-current circuit

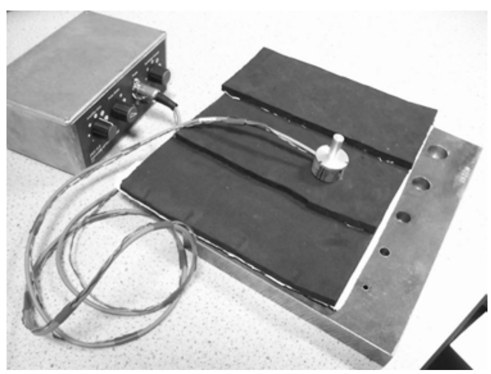

Figure 13 Pulsed eddy-current instrument

The technique can therefore be made sensitive to loss of metal caused by corrosion in the test plate. A prototype system proved successful in detecting machined holes through thick non-conductive coatings (Figure 13). However the signal amplitude was proportional to volume loss and not the depth of the corrosion. The detection of large areas of corrosion then becomes difficult. The technique was also very slow and it was abandoned in favour of the plate wave ultrasonic technique for detecting corrosion in the FPSO tank floor plate.

3.1.5. ACFM technique

The Alternating Current Field Measurement (ACFM) technique is a variant of the Alternating Current Potential Drop (ACPD) technique used in the laboratory for monitoring fatigue crack growth in mechanical tests. ACPD relies on measuring the increase in resistance of an AC on the surface as it is deflected around a growing surface breaking crack. By using an alternating magnetic field to induce the current in the test surface and magnetic field sensors to measure the strength of any deflection around a crack, ACFM is a non-contact method of detecting surface breaking cracks and measuring their depth. To obtain all the data from a surface crack, ACFM measures the Bx and Bz components of the magnetic field from the scanning sensor (Figure 14).

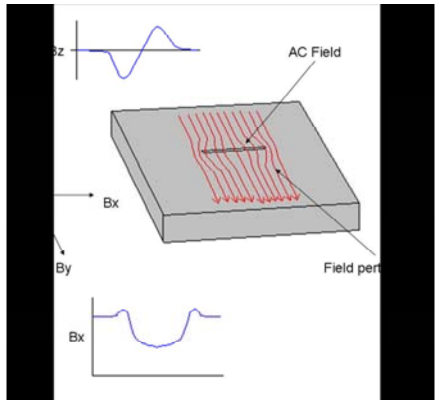

Figure 14 ACFM technique

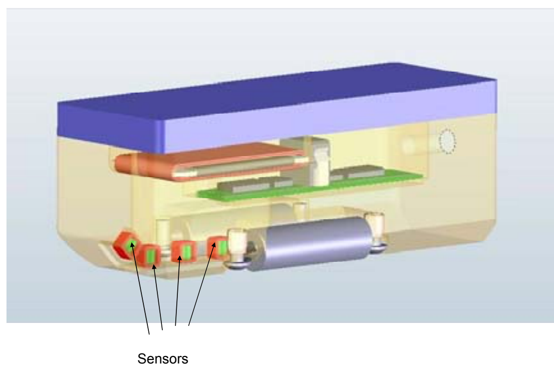

Figure 15 ACFM sensor array

The main innovation of the project was to design an array of eight sensors to detect fatigue cracks in a uniform AC field across the cap, toe and heat affected zone of the weld (Figure 15).

3.1.6. NDT system development

Each NDT system consists of a sensor, a device for generating the electro-magnetic field or ultrasound pulse and a graphical user interface (GUI) on a lap-top computer for controlling the sensor and displaying results.

For the ACFM system a holder was made for running two sensor arrays orthogonally along each side of the fillet weld (Figure 16). The GUI displayed Bx, Bz strip plots and a so-called butterfly plot for combining the two (Figure 17). Positional data for the strip plots was obtained from an optical encoder on the scanner.

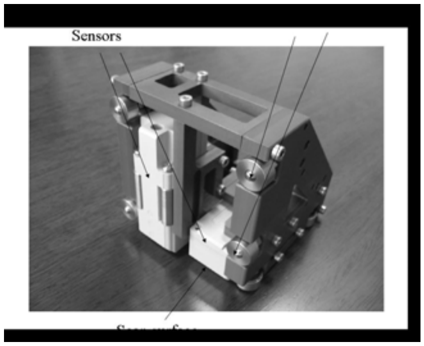

Figure 16 ACFM sensor holder

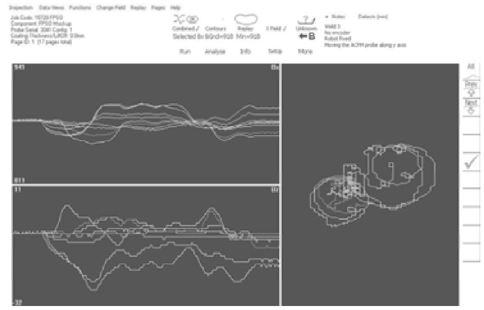

Figure 17 ACFM GUI

In the GUI for ACFM a different coloured trace for each of the 8 sensors can be viewed. The Bx is used to find the crack start and finish and the Bz the crack depth.
For the creep wave ultrasonics system, a similar holder was made to hold the sensors up against the weld toe on each side of the fillet weld (Figure 18). The GUI displayed A-scans separately and grouped side-by-side in an amplitude coded pseudo-Bscan (Figure 19) with each A-scan logged with its position relative to a datum by an encoder on the scanner.

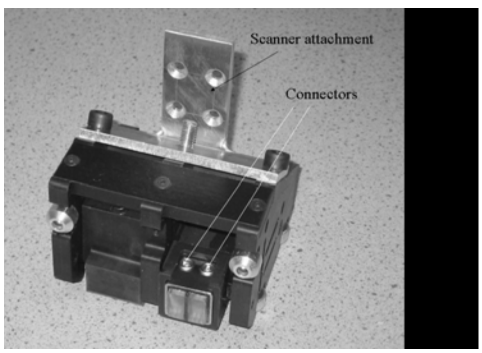

Figure 18 Creep wave sensor holder

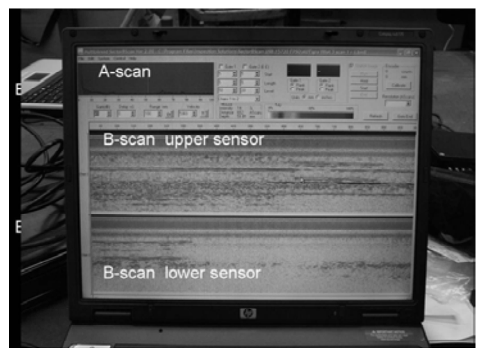

Figure 19 Creep wave GUI

For the plate wave probe a holder was not needed as it could be attached directly to the scanner for running along the floor plate. A similar GUI to that used with the creep wave probe, with the important difference that the length of the time base was several centimetres in steel.
Although a more rapid scanning technique than the creep wave ultrasonic technique, it did suffer from spurious signals caused by edge-effect. The two GUI were therefore combined to give the test operator more information on which to base his interpretation.

3.2. DESIGN AND BUILD OF ROBOT VEHICLE AND SCANNER

The original proposal was to build a swimming robot vehicle that could swim down in water to the stiffeners at bottom of the tank. BP and Petrobras made it clear at the kick-off meeting that if this was to be achieved, the vehicle would have to swim in oil and not in water as it was not their practice to fill the FPSO-tanks with water. On the other hand, they would employ an inspection robot on the tank floor when it was empty.
The consortium therefore decided to press ahead with a swimming robot that would be demonstrated in air and water with only a concept design for operating in oil. The stringent safety requirements when operating in oil would be impossible to meet within the scope of the project. The robot vehicle's inspection ability would be demonstrated only in air on a mock-up of the stiffener-to-FPSO floor plate welds.

Further, since guidance for the global path plan to bring the robot down from the entry port in the roof of the FPSO tank to the floor would not be practically necessary, a guidance system would be demonstrated in simulation only.

3.2.1. Scanner

The scanner was designed to give a 480*92*70mm work space in front of the robot vehicle (Figure 20). The scanner movement would work in conjunction with vehicle movement so that the sensor holder would start from the corner between the stiffener and tank-wall, scan one length and stop while the vehicle moved along to a new point to start the next scan (Figure 21). At the end of the stiffener the vehicle would rotate through a right angle to bring the scanner arm across the weld at the end of the stiffener. Further movements of the vehicle would take the scanner down the other side of the stiffener in a series of distinct scan lengths.

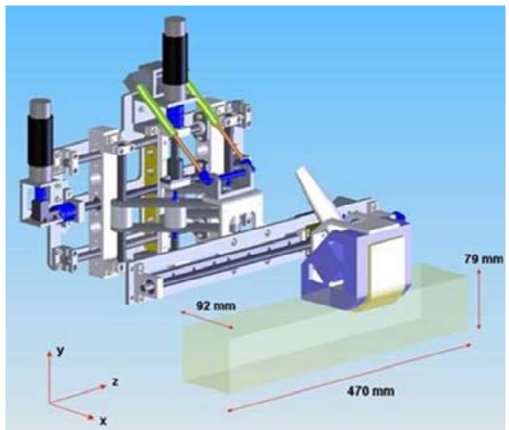

Figure 20 Scanner design

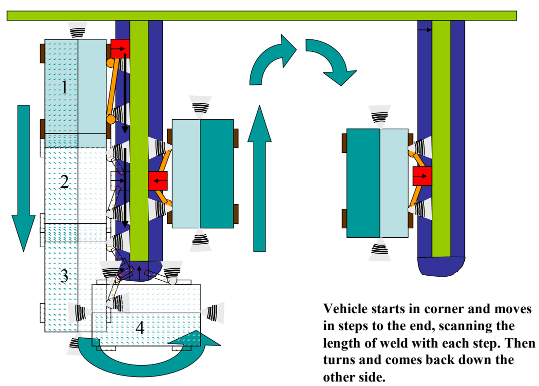

Figure 21 Local scan path

3.2.2. Robot vehicle

The robot vehicle was designed to swim with a payload of the scanner and sensor to the floor of the FPSO tank where its wheels would allow complete manoeuvrability inside the spaces between the stiffeners (Figure 22).
A critical feature of the robot vehicle was the method of controlling its buoyancy while swimming. Two methods were investigated, constant volume and constant mass (Figure 23).

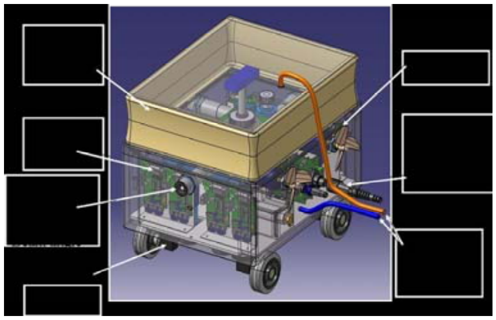

Figure 22 Initial robot vehicle design

Figure 23 Buoyancy control

Despite advantages when used in oil (the liquid does not have to be sucked in or blown out), the constant mass type was less stable and the more commonly used constant volume type buoyancy control was incorporated with the robot vehicle.
Among the other features on the vehicle were four independently powered and steerable wheels for ground traction, two thrusters for swimming and ultrasonic proximity sensors set around the vehicle for aligning it with the stiffener during scanning.

3.2.3. Global path planning

In order to simulate the global path a specific design of FPSO tank was selected for the simulation exercise (Figure 24). To guide FPSO-Inspect, a scanning ultrasound sonar would create a sweeping 120º beam under the vehicle that would create an image which the operator would read to identify objects close to the vehicle (Figure 25).

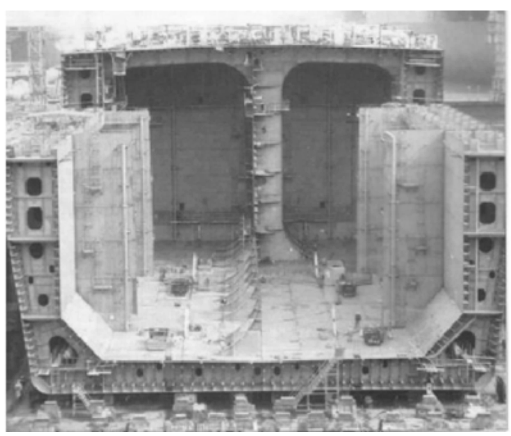

Figure 24 FPSO tank used in simulation

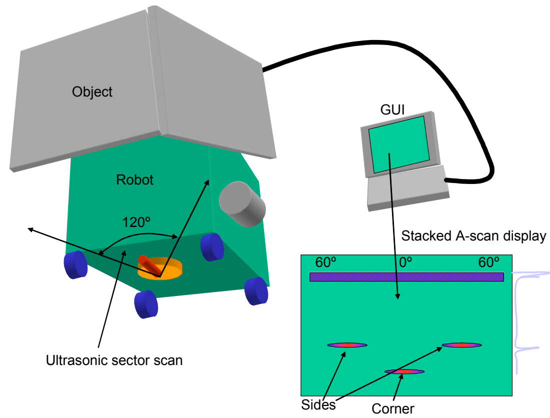

Figure 25 Ultrasonic sonar

The global path plan would take FPSO-Inspect from the entry port in the roof of the tank, follow the ladder down to the floor (Figure 26), then use the tank side to take the robot vehicle to a corner with a bulkhead, where the vehicle could turn though a right angle to cross the tank, following the bulkhead to the other side where the stiffeners to be inspected were lined up (Figure 27).

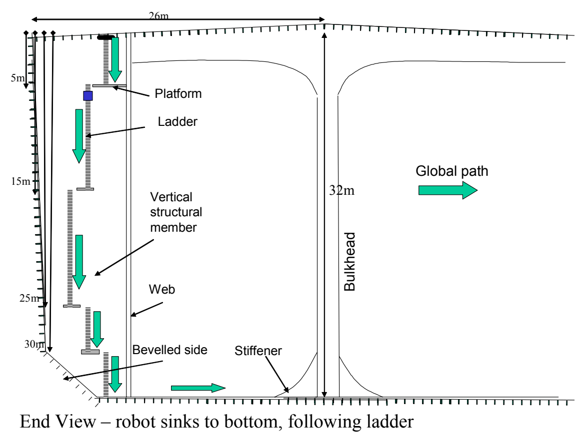

Figure 26 Diagram of global path descent to floor

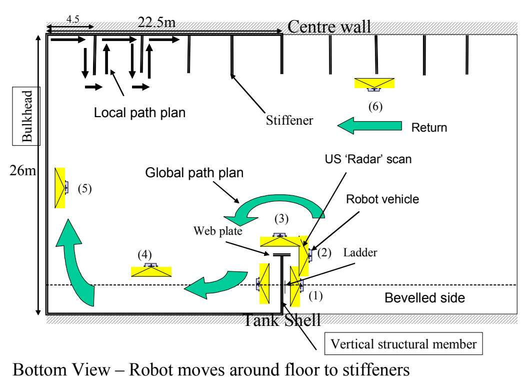

Figure 27 Diagram of global path around floor to stiffeners

Exercises were undertaken using the ultrasound sonar in an immersion tank to simulate various objects along the route (Figure 28) to (Figure 31).

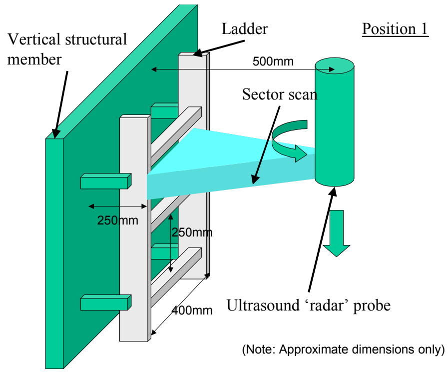

Figure 28 Object at position 1 in planned path

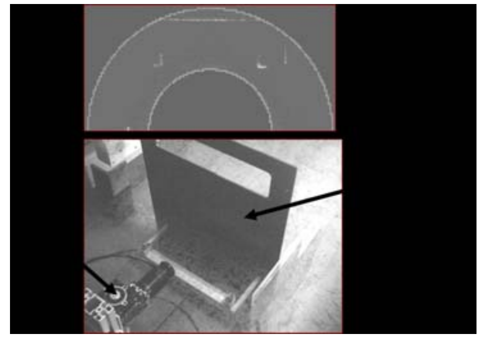

Figure 29 Object simulation and U/S sonar image

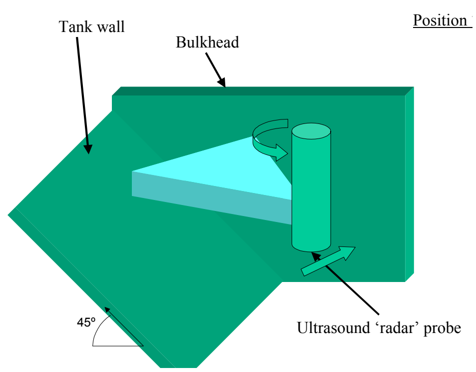

Figure 30 Object at position 7 in planned path

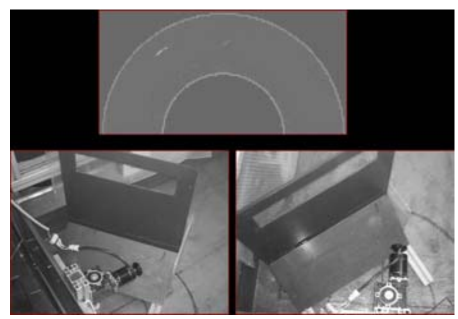

Figure 31 Object simulation and U/S sonar image

3.3. INTEGRATION AND TRIALS.

3.3.1. Man-machine interface

The man-machine interface integrated controls for the vehicle, scanner and the three NDT sensor systems. The graphical user interface for control of the scanner and robot is shown in (Figure 32), for combined creep wave ultrasonics and ACFM in (Figure 33).

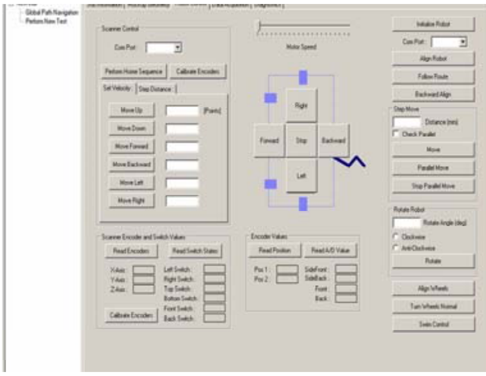

Figure 32 Control GUI

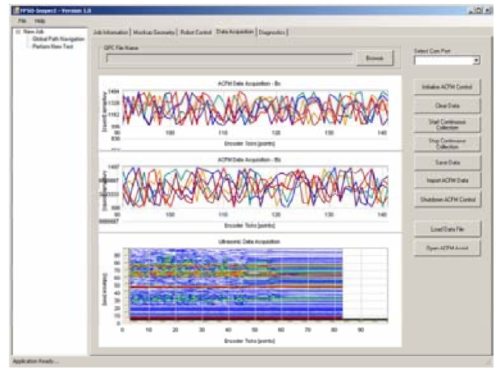

Figure 33 Combined ACFM - Creep wave US display

3.3.2. Underwater trials

The robot vehicle underwent successful underwater trials in a 6m deep tank used to train divers. Manoeuvres included swimming around on the surface (Figure 34) and being wheeled around on the floor of the tank (Figure 35).

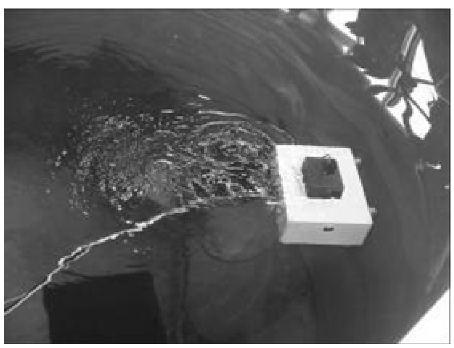

Figure 34 Vehicle swimming on surface

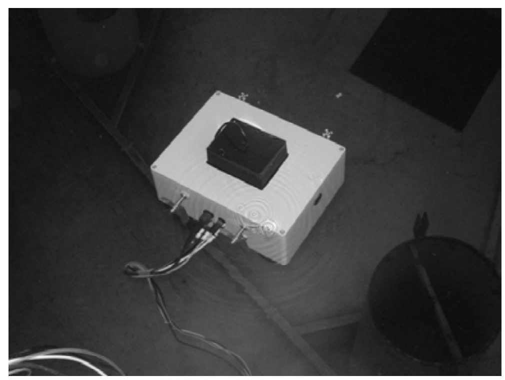

Figure 35 Vehicle moving around on the floor

3.3.3. Trials with NDT systems on a mock-up.

The mock-up was designed to represent stiffeners on the floor of a FPSO tank and contained notches to simulate weld toe cracks and machined flats to simulate plate corrosion (Figure 36). The mock-up was set up on trestles in the engineering hall of TWI's laboratories (Figure 37), where it was used to demonstrate FPSO-Inspects performance.

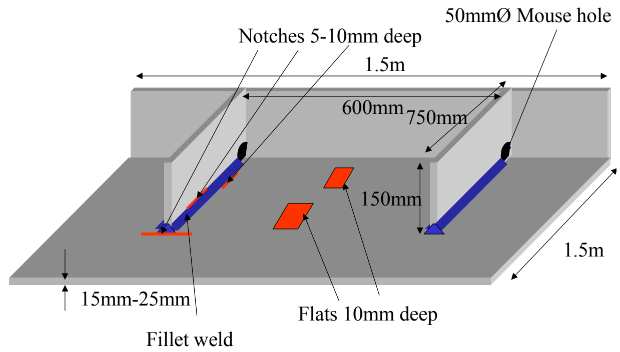

Figure 36 Mock-up design

Figure 37 Mock-up set for performance demonstration

A video was made of the vehicle successfully following the local path plan without operator guidance except for positioning at the stiffener ends for the transverse scan. Scans with the ACFM and creep wave sensors at the location of the notches in the weld groove (Figure 38) successfully picked up the two indications with both techniques (Figure 39).

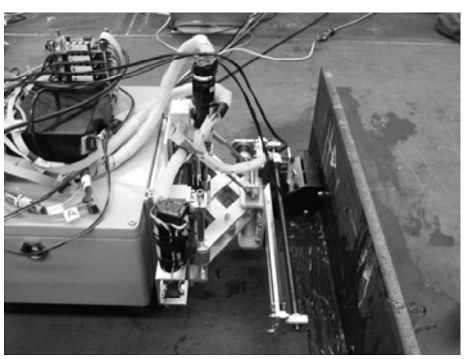

Figure 38 Scanner at position of notches

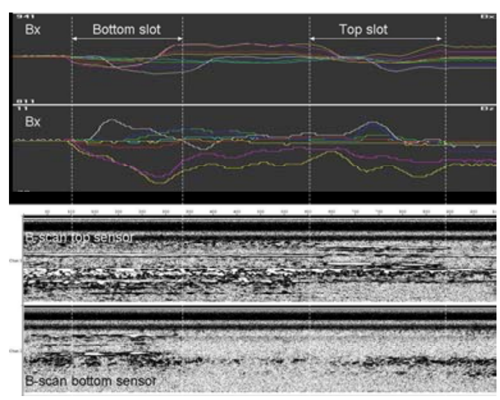

Figure 39 Combined ACFM Creep wave display

4. DISSEMINATION AND USE

Result description	FPSO-Inspect system
Possible market applications	Inspection of FPSO tank floors for corrosion and stiffener to FPSO tank floor welds for fatigue cracks
Stage of development	Prototype
Collaboration sought	Financial support for commercialisation
Collaboration details	Investment institution, venture capital
Intellectual property rights granted	Consortium agreement among SME participants.
Contact details	graham.edwards@twi.co.uk

Result description	Amphibious robot vehicle
Possible market applications	Inspection of nuclear waste containers in containment pools.
Stage of development	Prototype
Collaboration sought	Financial support for commercialisation
Collaboration details	Investment institution, venture capital
Intellectual property rights granted	Consortium agreement among SME participants.
Contact details	sattartp@lsbu.ac.uk

Result description	3-dimensional scanning frame
Possible market applications	Automated NDT for QC of welded frames in fabrication shops (eg welded I-beams for bridges)
Stage of development	Prototype
Collaboration sought	Financial support for commercialisation
Collaboration details	Investment institution, venture capital
Intellectual property rights granted	Consortium agreement among SME participants.
Contact details	ypmarkop@zenon.gr

Result description	ACFM array sensor
Possible market applications	In-service inspection of welds in structural steel work (Bridges, buildings)
Stage of development	Industrial product
Collaboration sought	No
Collaboration details	No
Intellectual property rights granted	Consortium agreement among SME participants.
Contact details	martin@tscinspectionsystems.com

Result description	Dual surface creep-wave ultrasonic technique
Possible market applications	In-service inspection of welds in structural steel work (Bridges, buildings)
Stage of development	Knowledge of probe design
Collaboration sought	No
Collaboration details	No
Intellectual property rights granted	No
Contact details	rajesh@apex-research.co.uk

Result description	Plate wave ultrasonic technique
Possible market applications	Detection of corrosion in plates at intermediate range (up to 10m) under cover plates, collars and other items covering the surface.
Stage of development	Knowledge of probe design
Collaboration sought	No
Collaboration details	No
Intellectual property rights granted	No
Contact details	dflorez@tecnitest.com

Result description	Man-machine interface for combining ACFM and ultrasonic data.
Possible market applications	In-service inspection of welds in structural steel work (Bridges, buildings)
Stage of development	Demonstrator
Collaboration sought	No
Collaboration details	No
Intellectual property rights granted	Consortium agreement among SME participants
Contact details	bjorn@kccltd.com