Inspection of thin steel gauge welds for the shipping industry using laser guided inspection robot

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Abstract

In the shipping industry sector, structural failure is a major cause of the loss of ships, vessels and tankers resulting in loss of life and pollution of the world’s oceans, seas and coastal waters of Europe. Indeed, it has been reported in 2006, that each year over 400 ocean going ships sink, many as a result of weakened structures due to corrosion and inadequate/poor welding quality. Most of the inspection techniques used today proved to be disruptive to the manufacturing process and far from being cost effective. Additionally, as the current generation of ships are being built from thinner section steels (10mm or less) to lower the cost of build and ship operation, typical assessment methods are not as effective as for thicker sections. Therefore, there is a real need for more reliable, faster, cost effective and safer inspection techniques. A novel inspection system using a crawling robot was developed in order to deploy remote volumetric, surface and visual inspection to verify the integrity of welds during manufacture and in service shipping vessels. By the combination of ultrasonic phased array, electromagnetic ACFM and laser optical methods, this system aimed for the detection and the sizing of surface breaking and sub-surface flaws. A tracking system and a self-control robot were developed to allow the automatic inspection following the weld run. This work was carried out in the FP7 European funded project X-Scan with the collaboration of seven European companies including Lloyd’s Register EMEA, Vermon, Tecnitest, Spectrumlabs, TWI, Brunel University and Innora. Several laboratory trials with manual scanning of reference samples and scanning with the overall X-Scan system allowed the comparison of manual inspection and semi-automated inspection. The X-Scan system was then put to the test on site as to evaluate its performance in a less controlled environment as to observe whether the different sub-systems can function in such conditions and generate adequate results. This paper aims to present the background of the X-Scan inspection system, to present the results of the X-Scan project, to demonstrate the performance of this automatic inspection system.

Keywords: offshore, phased array, Ultrasonic Testing (UT), Electromagnetic Testing (ET), ACFM, PAUT, marine

1. Introduction

The X-Scan project has developed a specialized automated inspection system for ship structures that integrates optical, electromagnetic, and advanced ultrasonic NDT techniques to fully inspect welded plates and provide defect imaging and analysis quickly and more conveniently. The project focused on solving the problem of inspecting steel welds using phased array ultrasonic testing (PAUT) and alternating current field measurement (ACFM) techniques, as well as the means to inspect the welds automatically, even those that are inaccessible without scaffolding. The result is a self-controlled, laser-guided robotic system prototype that combines a laser optical system to guide the robot and provide a visual inspection, PAUT to detect and size sub-surface defects, and ACFM to detect and size surface-breaking flaws. Although the initial application is ship hulls and marine structures, the robotic system could be used to inspect many other metal structures, such as land based oil tanks and gas storage facilities, wind turbines or any large surface metallic structures.
2. Objectives and consortium

2.1 Objectives
The main objectives of the project are two:
1) to concentrate on solving the problem of inspecting thin steel welds using Phased Array Ultrasonic Testing (PAUT) and Alternating Current Field Measurement (ACFM) techniques
2) to tackle the automated inspection of inaccessible welds by means of a laser guided manipulator.

Splitting down in more targeted goals we have the following list of objectives

a) To develop PAUT technique and inspection methodology
b) To design and manufacture PAUT probes
c) To develop an ACFM technique and inspection methodology
d) To choose the appropriate ACFM probes
e) To develop the laser seam tracker technique and weld visualisation
f) To validate the ACFM and PAUT inspection methodologies
g) To compare the results with radiographic inspections and MPI
h) To design and manufacture the laser seam tracker subsystem and weld visualisation subsystem
i) To design the electronics, instrumentation and software
j) To design the mechanical components of the system
k) To manufacture and assemble the manipulator components
l) To design and manufacture the sensor holder
m) To integrate all the separate subsystems
n) To demonstrate the functionality of the system in lab and in the field

2.2 Consortium
The X-Scan consortium comprises seven collaborators from four member countries: TWI, Ltd., developer of the PAUT and ACFM NDT techniques incorporated into the X-Scan prototype; Brunel University (Middlesex, United Kingdom), developer of the robot’s laser tracking technique; Innora Robotics and Automation, Ltd. (Athens, Greece), developer of the manipulator systems; Technitest Ingenieros SL (Madrid, Spain); Vermon S A (Tours, France); Spectrumlabs (Piraeus, Greece); and Lloyd’s Register EMEA (London, United Kingdom). This project received funding from the European Union's Seventh Framework Programme for research, technological development, and demonstration under grant agreement no. 283284.

3. Development

3.1 Laser Guidance and Visual Inspection

3.1.1 Basic function and arrangement

In the manipulator of the X-Scan project the laser tracking system is an essential component. It provides the information (i.e. deviation value) to guide the robot along a weld seam (butt and fillet) automatically and also saves the profile geometry to be used for surface flaw inspection. The concept of the tracking system is shown in Fig. 1, which includes the laser
profile sensor, communication devices and host PC running an in-house tracking algorithm and defect detection software. The laser projector module emits an array of laser beams in a line arrangement using a low power laser diode (< 10 mW) with a wavelength of 658 nm onto the weld surface. The laser light is then scattered by the test surface and reflected back in different directions [3]. Subsequently, the profile acquisition module receives the reflected laser light on its image sensor. Using the well-known laser triangulation principle [1], [2], the two-dimensional (2D) profiles of different targets can be obtained. This information is then transmitted in real time to the host PC via the Ethernet cable for further processing by the weld’s seam tracking algorithm and inspection software.

![Figure 1: Laser guidance system concept diagram](image)

### 3.2 Phased array ultrasonics

The inspection technique specified the use of two identical transducers in order to allow scanning of the weld on both sides simultaneously Fig 2. Therefore a switch box was also specified and provided by Vermon. The transducers were manufactured by Vermon as well Fig 3. The performance of the transducers was checked at reception.

![Figure 2: Basic design of the transducers on a butt weld](image)
A trusted solution for phased array site inspection was used. Olympus IMS Omniscan MX portable phased array equipment was chosen. Olympus has more than half of the global market share of NDT phased array ultrasonic equipment and the MX units are being deployed constantly for site inspections.

Since the phased array unit was placed on the robot a solution for its remote control had to be found. The Omniscan system is a site ready equipment but also allows remote control via a dedicated software called Tomoview. To achieve this the MX unit has to be booted in a special mode and connected to a laptop via an Ethernet cable. The on board display remains blank and everything is shown on the laptop screen running the Tomoview application. Through Tomoview a user is allowed more detailed control over the phased array unit but such a control solution has two drawbacks. First of all the raw ultrasonic data are transferred to the laptop and saved there thus taking up much of the large network bandwidth. Also this data transfer does not allow the unit to achieve high pulse repetition frequencies, critical for the maximum allowable scan speed. During tests for the 10mm plate we could only achieve a speed of up to 3mm/s. secondarily not a lot of people are trained in using the Tomoview software in acquisition mode and it would make transferring the technology rather difficult.

Olympus also offers another method that can be used to remotely control the Omniscan units. The user is allowed to launch a VNC server on the unit and connect to it from any laptop of other device that has a VNC client and is on the same sub-network. VNC is a protocol that allows a computer to share its screen, keyboard and mouse inputs with a connected client much like Microsoft’s proprietary RDP protocol. The advantage of such a control strategy was that the raw data from the inspection is saved locally on the unit enabling much faster inspection speeds. Also the unit can be setup by any inspector without further training. The drawback for this method was the slow refresh times of the VNC’s screen, which made setup and calibration a relatively slow process.

### 3.3 Alternating Current Field Measurement

The equipment required for a conventional ACFM inspection is fairly simple. The AMIGO ACFM system unit developed by TSC inspection is the main unit used to drive the inspection. In conjunction to this unit, a probe and laptop are used to carry out the measurements. Details of each of those components are given below.
3.3.1 Instrument

The ACFM unit is an AMIGO instrument Fig. 4. This instrument is around 4.5kg and its overall dimensions are 206 x 292 x 127mm. This unit is designed to operate from its battery pack or from the main power. The serial communication cable is by standard 5m long but can also be extended; a 30m extension was used in X-Scan. Although, the Amigo unit is usually used with single element probes, it can also support up to 32 channels plus position encoder. Three probes driving a total of 9 elements was used in X-Scan. The use of three probes allows coverage of the whole surface of each weld; the array probes cover the toe areas and part of the adjacent parent material. The pencil probe is placed on the centreline to cover the centre but the area near to the weld toes also. For the 6mm plates, the welds are fairly thin therefore the pencil probe covers the whole surface. For 10mm and 20mm plates, all three probes are required to cover the entire weld surface.

![Image of AMIGO instrument and ACFM probe arrangement](image)

**Figure 4:** Amigo instrument and ACFM probe arrangement

A junction box was required for the project since an interface box was needed to connect all 9 elements of the three probes and the encoder input together, since the AMIGO allows only one connection.

3.3.2 Software

The software used to drive the unit is called ASSIST ACFM. It is the manufacturer’s software and is dedicated to this technique. This software enables the display of the signal of each sensor while it’s being generated. The data is encoded also which renders the location and sizing of the indications possible. This software not only drives the unit, collect the data but also enables the data analysis off-line subsequent to the completion of data collection.

3.4 Robotic Manipulator

3.4.1 Manipulator description

The manipulator locomotion subsystem is implemented using two timing belts as tracks, so that the manipulator steers using differential steering (by altering speed of each belt). The belt of each side is mounted on four idlers and one driving pulley. The manipulator is driven by two 200Watt DC brushed motors accompanied with integrated high power planetary gearboxes, each one driving one side of the manipulator. In order to be able to inspect butt as well as fillet welds, the manipulator incorporates a sensor arm. The sensor arm has two actuators to ensure compliance of the sensors holder against the plates. One pneumatic
cylinder for pushing the sensors holder against the butt welded plates and one motor for pushing it perpendicularly against the wall in the case of fillet welds. For optimum compliance of the sensors holder on the inspection plates, a three axis gimbal joint has been incorporated on the sensor arm, so that the sensors holder can rotate freely and maintain reference with the surface of the plates.

To create the vertical force and as a consequence the friction that keeps the manipulator “adhered” on a steel plate, six neodymium magnets have been used to provide a 350N vertical force each (at a 6mm offset from the plate). The magnets are placed in such a way that they push the belts against the steel plate, increasing the contact area and as a result, the friction with the plate. Moreover, the belts are coated with a nitrile rubber (NBR) layer to further increase friction. Magnets are mounted on a passive sprung loaded mechanism and along with a suspension mechanism on each idler pulley, they can conform to irregularities and obstacles found on the surface of a plate (typically welds and bolt heads). In addition, with this mechanism, fine-tuned, the pulling magnetic force is distributed practically equally, for the belt’s pushing against the plate and the manipulator’s “adherence” on the plate.

3.4.2 Sensor Holder

The sensor holder has the responsibility of carrying all X-scan’s NDT related sensors and deploy them at the desired configuration for each different weld case. It was a requirement from the description of work that the same holder had to be able to serve for both fillet and butt weld configurations. Another requirement was also the ability to work under the presence of a lot of water and also to design everything considering a marinised solution. The holder was tasked with carrying:

1) The left ACFM array probe
2) The right ACFM array probe
3) The pencil ACFM probe that “rides” on the weld
4) The left PAUT sensor
5) The right PAUT sensor
6) The sensor’s encoder

Each of the devices had to independently conform to the surface of the inspected plate and overcome obstacles that were found in their path. The holder is carried by the robot thus the accurate placement of the sensors relies on the robot’s navigation and guidance. It is obvious that there needs to be a reference point, so the sensor holder assumes that the middle point of its geometry is coinciding with the weld centreline. All NDT equipment were adjusted so as to expect that the scan datum point is at the most forward point of the holder. Each of the different equipment listed above has its own requirements on how it should be held and deployed.

3.4.3 Software

Through the control software, the operator can choose from two operating modes: automatic and manual. During automatic mode, the deviation value determined by the laser tracking system is fed to the robot at a data rate of 10 values per second in order to correct the manipulator trajectory. In automatic mode, three types of scanning are available:

- Butt weld: During butt weld automatic mode the sensors are pushed constantly against the plate.
Fillet weld: During fillet weld automatic mode the sensors are pushed constantly on the two plates.

Custom: The operator can choose what is enabled during automatic mode.

The operator can choose the speed of the automatic scan from zero to 92 mm/s. The speed of each track can be set using the roller bar or the cell underneath. The tracks can be locked to have the same speed by pressing the lock button. The functionality of the sensor arm can also be controlled through the interface. In the manual mode the user takes control of the robot by the use of a standard joystick. This served as an easy and intuitive method of control, which proved popular with anyone that used it.

4. Integration and demonstration

4.1 INTEGRATION

4.1.1 Introduction

Most of the integration work was done using a large demo plate. It is a large structure that hosts the mock-up plates created during work package 1 slotted on cut-outs and is standing on the ground supported by two inverted V welded frames Fig 5. A series of integration meetings took place from the end of July up until the middle of November. In the final integration meeting the plate had been coated.

![Image](https://via.placeholder.com/150)

Figure 5: The integration plate uncoated and coated

It is quite crucial to mention that the final prototype is a quite complex system and work of integrating all independent systems and components was lengthy and hard. In the following sections we try to present how the various components are interconnected and how they were all mechanically mounted on a single device. Additionally the use of mock-up plates inserted in the larger one proved challenging for the system. The insertion inherently caused abrupt geometrical changes and also some of the plates due to their small size had a misalignment of well over 5 degrees, far above the design target of X-Scan.

4.1.2 Topology and connections diagram

The X-Scan prototype comprises of several systems connected together in a complex final whole. The systems have to share electrical power, data and compressed air and the interconnections of the various subsystems is shown in the images below.
Most of the data traffic was routed through a common Ethernet TCP/IP sub-network. All devices were set with a static IP, but with the use of a router one could easily change the addresses to dynamic. The ACFM system uses a proprietary link and had to communicate its data through an independent multi core cable. The robot is provided with 220V AC power through its umbilical. This high voltage is not directly used by any of the equipment on board and is immediately transformed and rectified by a series of power supplies. Noise sensitive devices such as the Omniscan unit and the encoder splitter are battery powered. The sensor arm is using pneumatic power to press the holder downwards, a pressure regulator and flow controller help adjust the magnitude of the force. The sensor holder uses pneumatic power to move the ACFM array probes close to the weld toe. Each probe has a separate regulator as the friction force of each probe with each side of the plate is different and they need independent control. There is also a hydraulic system used for PAUT irrigation that pumps water from a reservoir to the probes.

Figure 6: Graphic representation of the data communication between the different subsystems of X-Scan.

4.2 Demonstration

Trials were organised in the premise of Chalkis shipyards and the prototype was put in action. Two days were spent in a dry dock deploying the system. The empty dry dock could easily fit
a car and the shipyard’s personnel allowed us to bring a car very close to the trial location. This fact eased logistics very much and all equipment was carried in the car. A rope was secured from the robot to the superstructure of the dry dock, although from all the previous tests we knew that the magnetic force of the robot’s caterpillars was more than adequate. A safety exclusion zone was used once the robot moved at a height above 1.90 meters from the dry dock’s surface. The zone was set at 1/3 of the maximum height, which is the suggested rule of thumb. The shipyard’s personnel also provided with a 220V power supply and cabling. Following these arrangements the robot was placed on the vertical wall of the dry dock and testing commenced. Tests were performed for over 3 hours, some issues were encountered and mitigated, but most importantly the crews from all RTDs became more accustomed to using the prototype in the field. A selected image of the demo is shown in Fig 7.

![Figure 7: Demonstration on a dry dock in Chalkis Shipyards.](image)

5. Results and Conclusions

5.1 Lab Results

Results of the weld inspection tests in the laboratory with the PAUT and ACFM probes conclude that the new inspection technique can provide results comparable to radiography and MPI. This proves that the combination of the two methods have the potential to substitute the currently mainstream ones.
5.2 Integration Results

Overall the results of the PAUT technique on the test plate were good but deteriorated as the thickness was lowered. The 20mm plates had results comparable to manual scans, but the thinner plates whose sectorial scans are imaging a tight portion of the weld were sometimes susceptible to sensor offset placement errors. These led to partial coverage of the weld area and in some cases, hitting defects with unfavourable angles resulting in lower amplitude reflections. Coated samples were more difficult to inspect as more dBs had to be added to achieve equal penetration and the noise level was higher. Selected defects are presented in the following figures.
Overall the results of the ACFM technique on the test plate were very good and even comparable with manual scans in the laboratory. This is applied to all but the 20mm fillet weld where size of the weld cap and the shape of the probe tips did not allow for good full coverage of the weld. Also it was observed that the “left” array probe always had weaker response that the right one. This was alleviated by applying a different sensitivity setting for the probes. The transverse crack was recognised in all samples, which is crucial as it cannot be detected by PAUT. Coated results did not differ with uncoated. A selected defect is shown in Fig 12.
The laser subsystem also has the ability to create depth maps of the weld seam. These can be used to detect surface defects as the notch shown in Fig 13. The visualizer program shows the surface plot in 2 separate images (top and bottom) indicating the intensity level of the optical signal which corresponds to the weld and plates regions. The current 2D profile of the weld is also shown (top right), the depth of the defect can also be deducted from it.

5.3 Conclusions

The integration and validation successfully completed the task of creating an automated manipulator able to reach difficult to access places and simultaneously deploy three
inspections techniques. The systems exhibited good data gathering and provided adequate results, although not as good as manual scanning. However, the small modifications needed are known and already planned. But more importantly much more tests have to be conducted to verify from inspection results in the field, before being able to totally substitute radiography. Minor redesigns to improve the positional accuracy and changes to the scan settings have already been done.

6. Future Activities

At the current stage funding is sought to perform additional testing to prove the technology, but upcoming plans for the X-Scan project also call for creating a more compact, and lightweight robot design, with highly integrated electronics and meeting higher ingress protection ratings (above IP56). The addition of an optional PAUT probe with the capability to create a map of the entire hull surface measuring and illustrating variations in material thickness caused by corrosion is also considered.

References