

FIELD TRIALS OF A CELL OF CLIMBING COOPERATING ROBOTS FOR FAST AND FLEXIBLE MANUFACTURING OF LARGE SCALE ENGINEERING STRUCTURES

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This paper describes the first and successful trials of a novel transportable manufacturing cell composed of cooperating climbing robots for on line quality controlled welding of large scale engineering structures such as ship hulls, large storage tanks and wind turbine towers. The cell performed welds on a 7 metre long by 2 metre wide plate configured at several inclinations including the vertical thus covering the typical range of hull angles that arise on a large ship. The cell also performed self evaluation of its work by measuring the quality of the weld metal in real time so that corrections to the weld process parameters could be performed immediately thus minimizing the time spent on welding repairs.

1. Introduction and General Principles

1.1. *The System Concept*

CROCELLS is the acronym for Climbing **R**obot manufacturing **C**ELLS. The principle of CROCELLS is deceptively simple. It is advantageous to deliver quality welding in the field on high engineering structures by means of mobile climbing robots to eliminate the need for complex scaffolding and gantries needed in existing semi automated systems and also dispense with the need for human welders in dangerous locations. However the delivery of a precision automated welding robot tool with weld utilities such as a weld wire feed device together with weld inspection and quality assurance tools, together with all the necessary propulsion and wall adhesion devices results in a very heavy payload. Such a payload on a single climbing robot platform would result in a climbing robot of very large dimensions which would limit the ability to climb over and work on curved surfaces such as arise on parts of ship hulls, wind turbine towers and. Moreover such a large robot produces almost the same initial placement problems that arise with gantry and scaffolding systems and the consequences of damage relating to the robot falling off the climbing surface are likewise multiplied. Looking at the problems of size in more detail in large ships the stiffener panels in the Hull are separated by as little as 700 mm and a single robot carrying all the necessary work tools could certainly not be made small enough to work in such channels

1.2. *The Key Innovation*

So the key innovation of CROCELLS was to distribute a payload of welding, weld quality control and weld utilities tools over a number of cooperating

climbing robots thus enabling the robots to be relatively small and be capable of dealing with high surface curvature and small stiffener channels.

1.3. *The System Components*

The CROCELLS system consists of 4 cooperating robots, (i) the welding vehicle which carries carrying a precision welding arm with three degrees of movement, two linear and on one rotational and a laser seam tracker. (ii) the weld utilities vehicle carrying the weld wire drum and feed mechanism (iii) the NDT vehicle which monitors in real time the quality of the weld melt at the instant of its creation as well as performing cold weld inspection, both by means of a state of the art ultrasonic phased array system (iv) a tug robot which when required provides auxiliary propulsion power for the welding vehicle, which bears the heaviest payload.

Each vehicle can operate between 700 mm wide stiffeners channels with the largest vehicle, the welding vehicle, being only 550 mm wide at the widest point and less than one meter long from the seam tracker to the rear umbilical link. Vehicle weights with full payloads are 110kg, 87 kg, 37 kg and 35 kg for the welding vehicle, the weld utilities vehicle, the NDT Vehicle and the Tug respectively

Each vehicle carries its own embedded local control system but there is a ground based control base station which ensures the overall cooperation of the multiple motions and overall control of work tasks on the four robot platforms task control, through a Central Software Task Manager. The Fronius weld generator is also ground based with an umbilical link to the Weld utilities robot.

1.4. *Modes of Operation*

A typical mode of operation is as follows (1) The welding vehicle is instructed to climb to a defined starting point along a line to be welded on a vertical or inclined surface. (2) The Tug vehicle resides at a higher point. Through the sensor in an umbilical link between the weld vehicle and the weld utilities vehicle the latter follows the motion of the former precisely. (3) The NDT vehicle moves to a position where the ultrasonic sensor beam impinges the starting point of the weld targeted by the welding torch. (4) Weld process parameters informed by environmental data are set in the Fronius generator (5) Through the seam tracker activation the weld vehicle starts to follow the weld line and welding takes place. (5) The weld utilities vehicle follows automatically with the weld wire advancing through the umbilical link between the two vehicles at precisely the correct speed to maintain the welding.(6) Through an infra red tracking system the NDT vehicle precisely follows the movement of the hot weld bead and captures real time ultrasonic echoes from the melt in real time.(7) If the ultrasonic weld melt echo data indicate defective welding the welding is immediately stopped and the process parameters altered in a way indicated by the ultrasonic analysis, thus minimising the amount of rewelding required. (8) The NDT vehicle carries rapid and total weld inspection after a

long weld run to detect any defects not discovered or not apparent whilst the bead is molten.

1.5. *Future Developments*

In future developments it is hoped that the analysis of the ultrasonic weld melt data can be carried out in real time so that process parameters can be altered in real time without the need to interrupt the welding process. Figure 1 shows the system without the tug robot carrying out welding and simultaneous weld melt quality inspection on a 60 degree slope. Figure 2 shows the system carrying out welding and simultaneous weld melt quality inspection on a 90 degree slope with the aid of the tug robot. Welding was carried out in both upwards climbing and downwards climbing configurations. These first trials were completely successful and to the author's knowledge this is the first published report in the world of welding carried out on vertical surfaces with a team of cooperating robots.

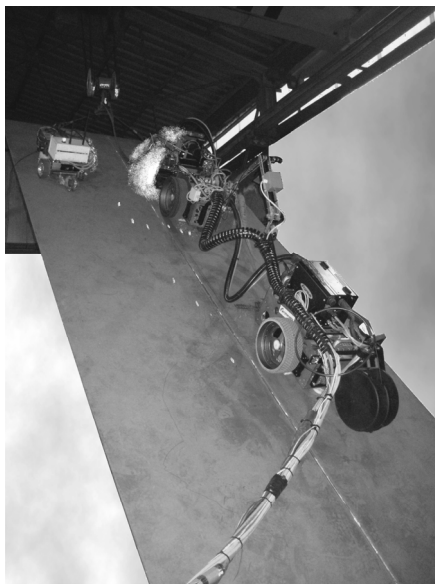


Figure 1. Welding without the tug robot on a 60 degree angle slope.

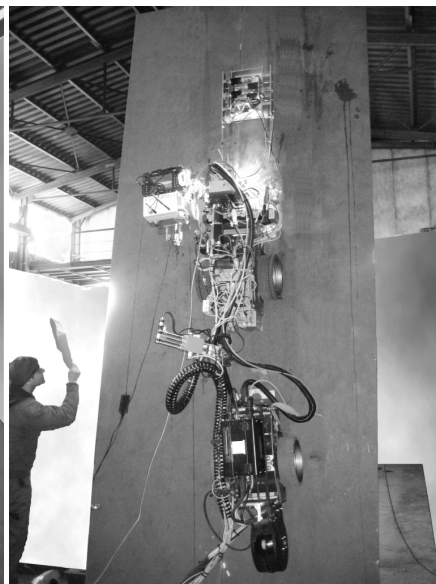


Figure 2. Welding on a 90 degree slope with the aid of the tug robot.

1.6. *Problems Experiment During First System Trial and How were Solved*

Under certain conditions on vertical, slippery surfaces the welding vehicle experienced climbing difficulties though not on inclined surfaces. The tug vehicle was then deployed to augment the propulsion system of the welding robot when carrying out welding in an upwards climbing mode. Future work on control system synchronization is needed to improve results on a climbing vertical upwards welding action. However with elegant simplicity perfect

synchronization is achieved without the need for such complications by using the tug for welding in a downwards climbing welding configuration. Here the tug is used to help the welding vehicle to the top of a line to be welded. Then the welding vehicle descends under its own control only to achieve perfect weld lines.

The tug vehicle thus provides a particularly interesting insight into the cooperating vehicle concept. The research has shown that it is extremely difficult to fit an accurate and thus robust welding arm, seam tracker and associated tools on to a single field hardened platform of such small size, within the achieved weight, propulsion problem though not an adhesion problem. Increasing the torque of the motors or contact area of the wheels adds weight and possibly enlarges the vehicle and so is not necessarily the best way forward. Further refinement of the tug approach is worthwhile and there may be schemes in which a tug provides all the propulsion power to a much lighter, free wheeling welding vehicle.

2. The Advance of CROCELLS on the State of the Art in Ship Welding

The authors believe that CROCELLS is the first system in the world (i) to perform welding on vertical structures by mobile robots in a versatile manner (ii) to provide self evaluation of its work by real timer measurement of the weld melt quality and (iii) to perform welding and inspection using a team of relatively small cooperating and climbing robots so that the welding could be performed on surfaces with substantial curvature such as arises with ship hulls, storage tanks and wind turbine towers.

Existing in situ automated and /or robotic welding systems for ship hulls involve either (i) welding arms moving on huge fixed Cartesian gantries or Cartesian gantries suspended over the side of a ship deck [1-3] (ii) welding arms moved around moved around by cranes [4] (iii) welding arms moving on railed robots or legged robots on the ground [5] or (iv) robots using stiffener panels as rails [6]. Only systems in category (i) are in the standard usage whilst systems in category (i) to (iv) are prototypes in various stages of development. In all of these cases the versatility of the welding performance is clearly limited compared with the CROCELLS concept. For wind turbine towers and storage tanks existing practice is less advanced and involves welding with human operators aided by scaffolding.

The conceptual stages of CROCELLS through different stages of research have been recorded in a number of previous publications [7-9].

3. System Architecture

Modules and architectures of tasks and their interfaces with the central task manager and cooperation with the welding and utility robot is shown in Figure 3. It shows that if there is potential defect identification by the NDT system an immediate signal will be sent to the CTM and a command will instruct the welding robot to correct the weld in the specified area.

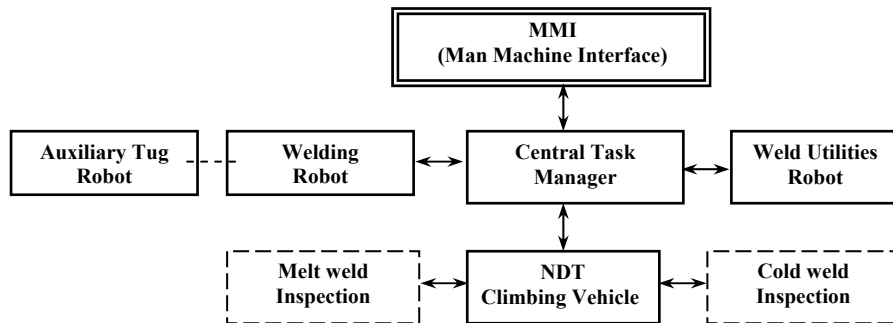


Figure 3. CROCELLS system module and architecture of tasks.

4. The Central Task Manager

The Crocells System Central Task Manager (CTM) has been designed and implemented using the *C++* programming language. The choice was made with regard to portability and low resource employment as the system's real time control and monitoring are crucial in terms of safety and efficiency. Modules and algorithms have been integrated to compose a user friendly control panel for the system. In addition the CTM is able to control and acquire defect detection information from the NDT vehicle using a client-server architecture. The CTM acts as a server and listens for connections and messages from the NDT control application. The NDT control application has been enhanced to work as a client providing the interface for robot control through the CTM. The application communicated with the CTM via a local TCP socket and with the robot itself via a wireless TCP communication.

5. NDT Robot

For surface adhesion, the NDT robot used an array of neodymium magnets (50mm x 50mm x 25mm) which generate a maximum normal adhesion force of 2600N at a typical operational air gap of 20 mm, the gap being chosen to allow climbing on surfaces with a roughness or other forms of protusion up to 20 mm in height. The weight of the NDT robot including payload is 35kg. The maximum antisliding force generated with a coefficient of friction of typically 0.6 is thus 1560N giving a safety factor against vehicle slippage of 4.5. The anti overturning moment generated by the magnetic field is about 3. Two DC motors drive two wheels individually for the movement. Each motor is 250W and maximum speed is 30rpm (after gear reduction). With the 120mm diameter wheel, the maximum moving speed of the robot is 11m/min.. The two Omniwheels for supporting the structure in the front and back are bi-directional, so that the robot can easily change directions. Each Omni wheel has 100kg payload capability.

In case of power failure, a motor brake is used on each motor shaft, so that the robot does not slide down. The robot profile is low, so the overturning moment is not a big issue. The NDT robot climbing on the 90 degree vertical surface is shown in Figure 4.

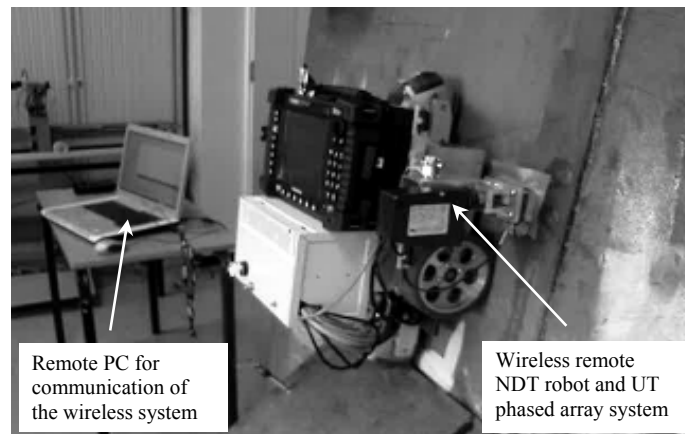


Figure 4. NDT climbing robot on vertical surface performing weld inspection.

6. Welding Arm Robot

Weld vehicle has been designed to carry the weld arm robot and the welding torch to perform weld on the vertical surface. Due to the heavy payload of the weld arm to be carried, one extra wheel has been added to eliminate the swinging effect and keep the vehicle as steady as possible. Array of magnets have been used to increase attraction force. With the 10mm air gap vertical maximum payload is 30kg and the nominal speed is 0.2m/s. The picture of the weld vehicle and the weld arm robot is shown in Figure 5.

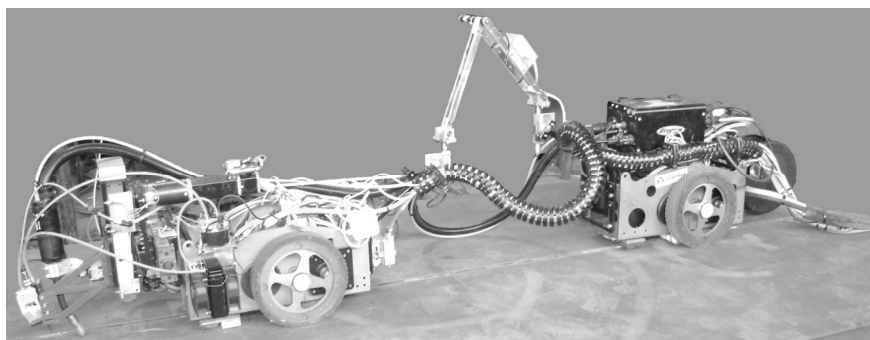


Figure 5: Showing details of the welding vehicle, its umbilical link to the weld utilities vehicle and the umbilical services cable on a flat plate. The welding vehicle carries a Cartesian welding arm, a variable angle welding torch and the laser seam tracking camera. The weld utilities vehicle carries the weld wire drum and wire feeder which guides the welding wire through the umbilical link to the welding vehicle (courtesy of BIC, CYX and Zenon: see acknowledgements)

7. Weld Utilities Vehicle

Weld utilities vehicle has been developed with the same principle of the welding vehicle to carry extra payload for the welding tools and cables. Two welding vehicles were linked by a mechanical link arm through which the cooperation in the movement of the two vehicles is ensured. The mechanical link arm was used to adjust the direction of movement of the two robots and guaranteeing synchronised motion as shown in Figure 5.

8. The Tug Robot

The climbing tug robot has no on board payload in order to maximise its pulling force on external objects. It is controlled by a tele-operated system through an umbilical service cable of 8 m length. The size of the robot is 500 mm by 450 mm and a height of 150 mm, mainly made in aluminium. The centre of mass of the robot above the bottom of the chassis is exceptionally low (3cm) and correspondingly the overturning moments are very low. This greatly increases the force available for pulling.

The main optimization criterion for this robot was to design it as light as possible with as much pulling force power it can provide, so as not to interfere with the trajectory of the welding robot.

The robot moves at a constant speed to follow the welding process, the target welding speed for ship hulls and storage tanks are about 10-15 m per pass per hour. The robot weight is 25 kg and it can provide nearly 50 kg of extra pulling force in a vertical position.

The tug vehicle is a high power wheeled design robot with capability to overtake any weld obstacle and provide the option to make angular transitions between surfaces of 120 to 180°. It is built in one section with the advantage of getting high pulling force in a low speed, good manoeuvrability in flat and curve surfaces, Figure 6.

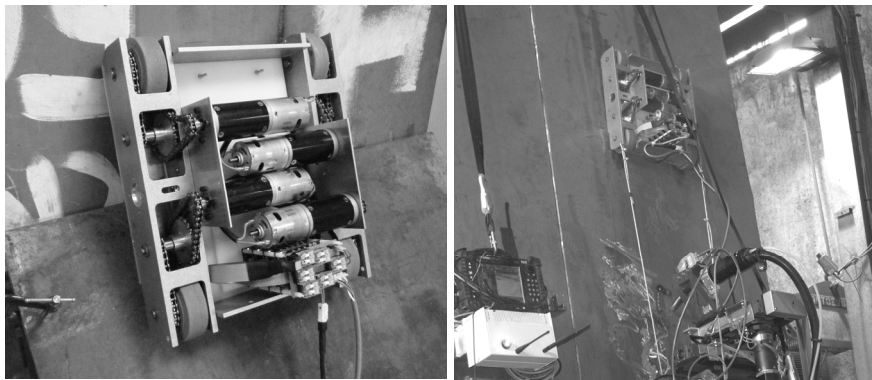


Figure 6. Left: Tug robot transferring two vertical surface of 135°, Right: Tug robot pulling the welding robot on vertical operation.

9. Field Trials

The final trials were conducted in three phases. First, the system was tested on a horizontal mock-up in order to monitor the performance of all subsystems. All necessary modifications and adjustments were carried out so that the system performance reaches the maximum. Next, the system was tested on the inclined mock-up in order to timely identify any problems directly associated with the slope of the plane. The first test on the mock-up under slope was made on the 60 degrees as shown in Figure 1. In this angle the welding vehicle was able to climb without support of the Tug robot. The final test was made with the mock-up set to 90 degrees as shown in Figure 2. In this angle tug robot was needed to pull the welding vehicle for climbing.

9.1. *The Welding Results*

The weld has been carried out during the final trial by the welding arm robot as shown Figure 8 and 9. Due to meta camera problem in the welding torch sometime weld was not in the straight line.



Figure 8. Shows inspection being carried out when the welding torch putting melting weld pool in the weld line on the vertical surface.



Figure 9. Shows the cold weld after completing the welding process. Due to meta camera problem in the welding robot arm some weld was not in the straight line.

9.2. *The NDT Weld Melt and Cold Data*

The NDT melt weld data obtained in concurrent with the welding process is shown in Figure 8. Figure 10 shows the inspection result of the melt weld and Figure 11 shows the inspection of the cold weld and indicates an image of the defect.

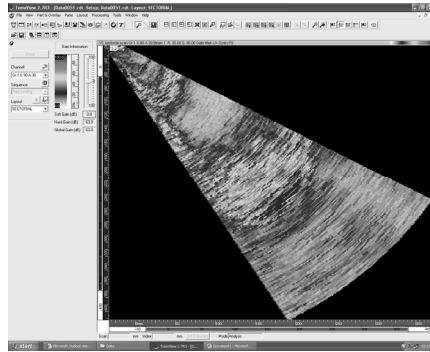


Figure 10. A typical inspection result from the molten weld pool.

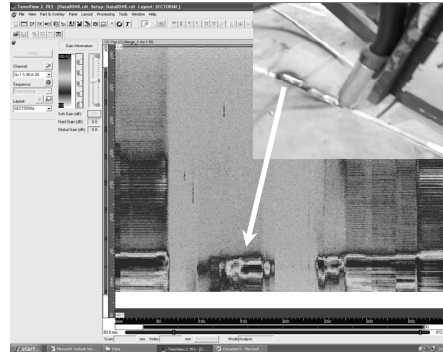


Figure 11. A typical inspection result from a cold weld line.

The NDT robot followed the welding robot by using an array of temperature sensor which focused at the hot point of the melt weld. The cooperation between the NDT robot and the welding robot had been established via a Central Task Manager. When a defect was detected above 30% of the threshold, NDT system raised an alarm signal and recorded the position of the defect. This position of defect then sends to the CTM so that the welding robot can take an appropriate action. This test has been done successfully in the laboratory, in the real field need to be explored further.

10. Conclusion

The CROCELLS system successfully tested on the vertical surface and co-operated each other during the welding operation. Due to heavy payload of the weld robot arm the welding vehicle was unable to climb over 60 degree angle on the vertical surface. This problem is being solved by introducing the tug robot which movement synchronized with the welding robot. It was able to pull 50kg without slippages. The NDT robot followed the welding robot continuously during the welding operation and gathered NDT data from the molten weld pool.

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