CLIMBING ROBOT CELL FOR FAST AND FLEXIBLE MANUFACTURE OF LARGE SCALE STRUCTURES

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ABSTRACT

This paper describes the specification stages of a project which seeks to modernise and take into the future the technology of the manufacture of large fixed welded structures such as box girder bridges, storage tanks, ships and other steel fabrications which arise on construction sites, in large chemical and foodstuff plants, on offshore oil platforms etc, bringing the world of fast and flexible manufacturing to areas were construction is presently carried out by traditional use of manual labour, scaffolding and cranes and the inconvenient delivery by road of large factory prefabricated components. The Project will achieve this by creating a transportable manufacturing cell (CROCELLS) consisting of a team of cooperating climbing robot work tools whose activities are coordinated and integrated through a central intelligence. Unlike factory based cells the robot work tools must be mobile and small so that they are able to climb over long distances, to great heights and over curved surfaces and surfaces with ridges or protusions such as nodal joints providing many technical robotics problems to be solved. Small robots have payload limitations but the essence of the cooperating robot concept is that large payloads of work tools can be achieved with small robots by distributing the payload over several robots. Each robot will be dedicated to a different task to optimise overall system performance, hence there could be be a surface profiler and navigator, welder, bolt and rivet placer, hot weld quality inspector, and cold weld inspector on separate platforms. The cell will be deployed through every stage of a product life cycle, during construction where the system will perform instant weld quality diagnostics and repairs, in service inspection and repair, and final lifetime assessment.

The CROCELLS concept is described in detail and system specifications are given which arise from an analysis of the industrial problems to be solved in a first exploitation phase addressed to the business requirements of the end users in the project. Then the hardware and software Architecture optimized for these specifications is presented for a prototype system presently under construction. Presently large fabrications on construction sites suffer from long fabrication times prescribed by traditional methods. The proposed mobile manufacturing cell will greatly reduce these times with economic benefits estimated at 630 M€ per annum in save time and 1956M€ per annum equipment sales taking EU export markets into account, with data for the global market being typically a factor of 4 higher

1. Introduction

This paper provides an introduction to the CROCELLS project [1,2] the ultimate goal of which is to modernise and take into the future the technology of the manufacture of large fixed welded structures such as box-girder bridges, ships, oil and chemical storage tanks and other fabrications by the use of a team of cooperating climbing robotic work tools whose activities are coordinated and integrated through a central intelligence to provide a flexible transportable manufacturing cell (Figures 1 -2)

Factory based robot work cells in which the manufactured objects move on an assembly line and/or working robots move on gantries or rails are well established and successful. But this project proposes to bring such integrated technology to bear on very large structures welded outside the factory on construction sites that create additional problems to be solved. Here the robotic working tools must be mobile and able to climb over long distances, to great heights and over curved surfaces and surfaces with ridges or protrusions. The CROCELLS proposal is to create a **transportable and dynamically re-configurable manufacturing cell** consisting of a **team of climbing and cooperating robots** that perform specialised tasks in the production chain to automate the construction of very large structures in unstructured environments.

2. Overview of the generic system, its functions and general applications

The specialised climbing robots will perform the tasks of welding and weld NDT with robots that clean the surface, profile the weld groove and compute welding parameters, weld long seams with continuous motion, assess the quality of a hot weld pool, check cold welds with NDT methods and grind welded areas. These tasks will be performed in combination or singly as and when needed during the production and maintenance chain.

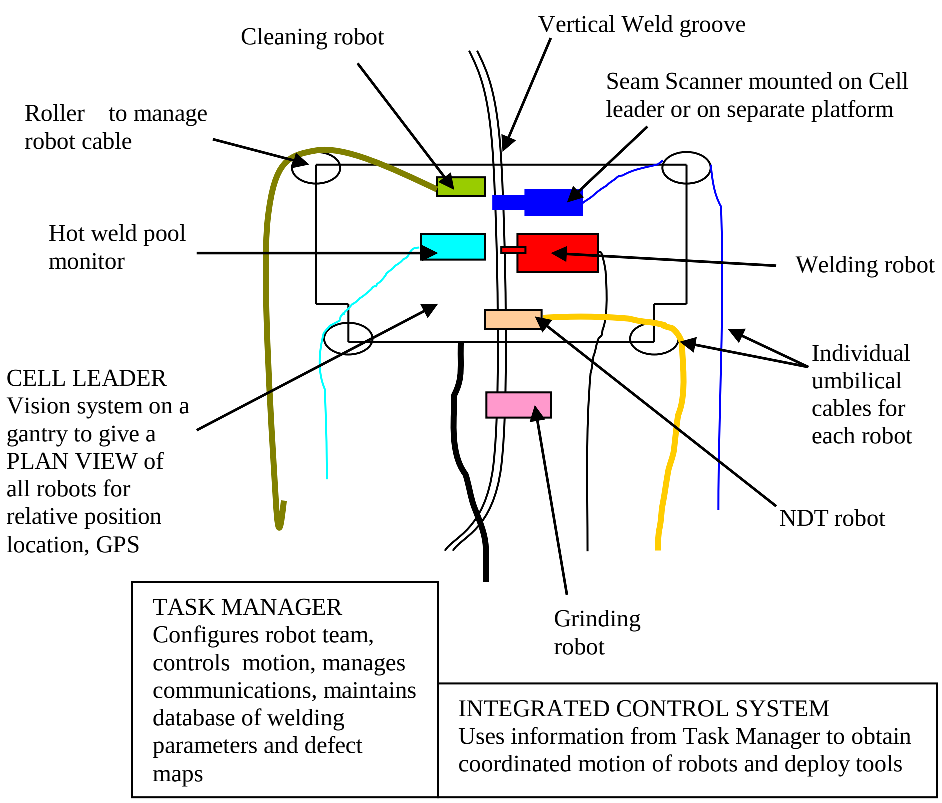

Figure 1: Schematic of the proposed climbing robot cell for automated manufacture of very large vertical and horizontal structures with climbing robots developed by LSBU for NDT and CYBERNETIX for cleaning.

Each climbing robot will be dedicated to a different task or set of tasks to optimise overall system performance. For example one obvious process of optimisation from vehicle task sharing is that the work tool payload capacity and hence the size of each vehicle can then be minimised, thus allowing them to climb on more highly curved surfaces, expanding the versatility of manufacturing applications.

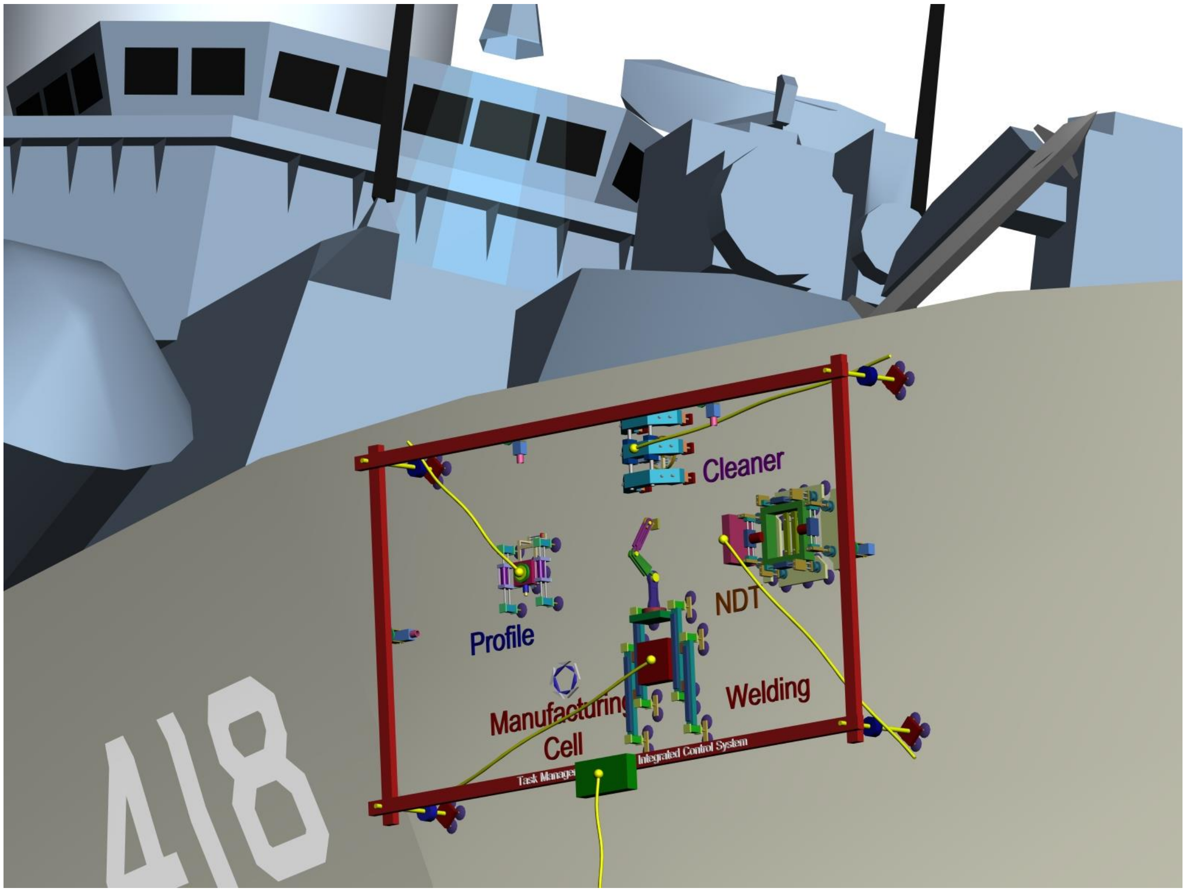

Figure 2. CAD Conceptual drawing of a manufacturing cell base on of a team of cooperating working robots climbing on a high vertical surface such as hull of a large ship

So for example there could be on separate platforms, a vision system and GPS to locate global position and relative position of robots, a surface cleaner, a weld seam profiler, a welding arm and gun, a hot weld quality inspection system, a cold weld NDT inspector and finally a surface grinder (the task performers) A **Central Task Manager and Planner** that possesses the manufacturing intelligence and database will coordinate the construction process and facilitate robot/operator communications and robot motion. The Task Manager has to accept data and process from numerous task and platform position sensors, make decisions on this basis and then issue and continuously update instructions to the multiple task performers and the several platform motion systems, all in real time. It will, therefore, be a next generation expert and intelligent system, necessarily based on innovative, faster control algorithms, based on a mathematical model of the dynamical behaviour of the multiple mechanical components of the system

Using the same Central Task Manager the manufacturing cell can be flexibly extended, so that more specialised robots can be simultaneously deployed over large areas to provide increasingly fast manufacturing or networks of cells operating in different areas could also be under the control of the same Task Manager. At the same time the range of tasks could be extended with dedication of robot vehicles to perform drilling, bolting, riveting or a whole suite of surface preparation operations such as cleaning, removal of graffiti and damaged coatings, grinding and polishing, painting and protective coating application.

The development of such a construction cell seeks to bring the world of fast and flexible manufacturing to the fabrication of large steel structures such as arise in ship building, on construction sites, in large chemical and foodstuff plants, offshore platforms, and oil/gas/chemical storage tanks where presently manufacture is presently very traditional, carried out almost entirely by means of manual labour assisted by scaffolding and cranes and the inconvenient delivery by road of large prefabricated components and constrained by long construction times.

The cell will be deployed through every stage of the product life cycle, during construction where the system will perform welding, instant weld quality diagnostics and repairs, in-service inspection and repair, and final lifetime assessment. Presently large fabrications on construction sites suffer from long construction times and welding interruptions prescribed by traditional manual methods. The proposed cooperating robot cell will bring the advantages of automation and greatly reduce these times with **economic benefits estimated** at **632M€** in time saved per annum (based on time reductions in welding and inspection as reductions in factory fabrications and associated transport costs) and **1956M€** in equipment sales per annum taking European export markets into account as a whole with data for the global market being typically a factor of 4 higher [1].

Through the above combination of features the project addresses the special joint call in FP6 on IST and NMP3 (from which it was funded) under the headings of (ii) innovative mechatronics and advance control and networks for dynamic reconfiguration of complex assembly, production and manufacturing production and manufacturing processes (ii) multidisciplinary and dynamic work environments facilitating multi stakeholder involvement and life cycle management of production and manufacturing systems, products and services (iii)Improved management of product lifecycle and (iv) Innovative approaches to customisation fulfilment and maintenance via miniature and wireless devices. In accordance with a STREP programme [1] the innovations in this proposal have a worldwide significance in production of large-scale structures outside the factory.

3. The key technical and scientific innovations and advancements over current state of the art

There is **no precedent** for the CROCELLS project as just described. It is not simply a transfer of existing robotic manufacture from the factory floor to the field with robot climbing and mobility functions added on. In factory manufacture the structured environment mean that the robots are relatively easily programmed by learning the prescribed trajectories. In contrast, in large scale constructions in the field no two environments are exactly the same the same. For example on the sub-millimetre scale of the precision of factory manufacture the hull of a ship is an extremely rough surface and randomly so. Also in factory manufacture many robots might seem to be cooperating but in fact there are performing tasks in unison or with fixed time delays whereas CROCELLS will involve continuously variable time intervals between sets of tasks. These two factors present **unprecedented challenges for the Central Task Manager** and its interaction with the multiple system sensors for navigation, vision and performance of work tasks.

As for climbing robots technologies an overall perspective on current state of the art with respect to service applications such as cleaning, painting and inspection is available in the Proceedings of the CLAWAR 2005 conference [3]. A broad perspective on world leading surface changing and curved surface climbing robots for inspection tasks in complex safety critical and hazardous environments such as ships, nuclear plant and aircraft can be found in some recent papers of Bridge et al [4-6]. However none of these involve welding. Pioneering projects for the welding of ships by mobile robots such as the EU projects ROWER 1 & 2 [7] and DOCKWELDER and DOCKLASER [8] concern only ground based robots with or without the use of rails. These are large systems completely impractical as a basis for developing portable climbing welding systems. Apart from robotic gantry welding there exist a few semi automatic systems for the welding of ships high above the ground for example the projects by the US Cybo Robot and Japanese Kobelco companies but these are not based on mobile robot principles and requiring a lot of manual support in moving a welding jig from one location to another.

The project will require step improvements in state of the art for (i) robot miniaturisation to cope with curved surfaces, (ii) **Wireless technology**: robots will communicate with each other and with the Central Task Manager for control, data acquisition and coordination purposes as much as possible via wireless technology to minimise umbilical cables and their associated management problems and permit minimisation of platform payload requirements and therefore minimisation of platform sizes allowing deployment on highly curved surfaces. (iii) **Advanced distributed and networked control**: The Central Task Manager has to handle communications between the robots and an operator console, enable calibration of the global location of the cell and the relative position of individual robots in the cell, issue command instructions to perform integrated control of the motion of the robotic tools, maintain a database for welding parameters, and the information obtained from weld profile scanners and NDT data acquisition. To achieve that outcome The Task Manager is involved in numerous control loops involving position coordinate sensors for several platforms, the weld profile scanner, weld head position sensor, weld quality sensor, global position system and so on. Coordinated response changes in the loops must be fast enough to achieve the target outcome of faster defect-free single pass welding, with immediately implemented repairs to occasional production flaws. So new and faster control algorithms, which improve on present state of the art Task Function methods will be essential. The algorithms will be based on mathematical models of the dynamical behaviour (inertial motions and vibrational modes) of the mutiple interconnected system mechanical components of CROCELLS to realise the maximum speed of smooth welding over long lengths. The algorithms will be based on mathematical models of the dynamical behaviour (inertial motions and vibrational modes) of the multiple interconnected system mechanical components to realise the maximum speed of smooth welding.

4. A prototype three-vehicle cell for the initial exploitation phase and its targeted applications

It is not possible to design for the full scope of the CROCELLS concept within the 3 year 2.37 MEuro project budget. The overall conclusion of the conceptual and planning stages of the project was to validate the cooperating climbing robot concept by producing a three-vehicle cell (Figures 5-7) that could perform integrated welding and inspection tasks on ships, storage tanks and wind turbine towers on surfaces of radius of curvature exceeding 1.5m. Welding fabrication operations in such areas constituted the core business of the end users as well as constituting a large global market. However the Central Task Manager software module would be of open design so that by simulation one could demonstrate the operation of a cell with an arbitrary number of vehicles or of cells operating in different areas of a large structure, all under the control of one Central Task Manager. Likewise one could simulate the coordination of other work tasks such as surface preparation (cleaning etc) bolting and riveting under Central Task Manager control.

The working payload will be approximately evenly distributed over three vehicles so that vehicle sizes are minimised which maximises their flexibility in coping with curved surfaces. The key parts of payloads are the welding manipulator, the wire feed spool and the weld inspection system respectively with the Central Task Manager off-board. In addition the welding robot and inspection robot will have their own seam tracking systems. The vehicles will be wheeled so that their motions form an integral part of the weld and inspection sensor scanners. This avoids the virtually impossible problems of controlling stepped vehicle sufficiently well to produce smooth weld passes or alternatively avoids the use of heavy multi-axis welding and inspection arms with large enough working envelope to obtain the requisite lengths of smooth (i.e. defect –free) weld passes or defect inspection scans. Two field trials which will allow the CROCELLS system to be tested to its design limit with respect to the smallest diameter surface that it can operate on.

Ship construction and repairs. The CROCELLS 3-vehicle prototype as specified below would be applicable to the welding of (i) all areas of the outside of a hull under construction or repair except in the relatively small areas of high curvature (which could be done manually at a proportionally low additional cost) (ii) The interiors of large cargo holds were the stiffener separation is not less than 700mm (Figure3).

CROCELLS would be applicable to all <u>unit assemblages</u> a unit being a 3 dimensional structure consisting of welded steel panels which subdivide into the following types (i) Side shell units of a ship hull, consisting of shell plates, longitudinal stiffeners and frames (ii)Bottom units shell plating, forming the keel, consisting of shell plates, bulkheads, tank tops, longitudinal girders and stiffeners (iii)Deck and bulkhead units, forming the deck and hold compartments and consisting of stiffened panels (iv) Superstructure, comprising the upper deck, superstructure sides and internal bulkheads. It would be applicable to all phases of ship construction: the assembly of collections of units into blocks or megablocks (a section of vessel large enough for outfitting) and the assembly of blocks or megablocks to form a ship

CROCELLS would be applicable in all cases to welding of multiple plates before the application of unit stiffeners. In general it would not be applicable to the welding of unit stiffeners as usually their separations, typically down to 300mm are too small for CROCELLS platform sizes specified in D2.1 to fit between. If the system had been specified to deal with such stiffeners the performance on large area coverage of panel welds would be prejudiced. Also given that the CROCELLS system would have to be lifted across adjacent system on assembly units, it could not achieve the speed of manual welding. Existing semi automatic ship welding systems cannot be used on unit stiffeners for the same reasons of impractical access. The one exception is the important case (ii). The robot vehicle sizes are to be specified so that they can weld stiffeners in large cargo holds as these are enormous structures (Figure 4) were potential savings over manual welding during both assembly and repair are very high.

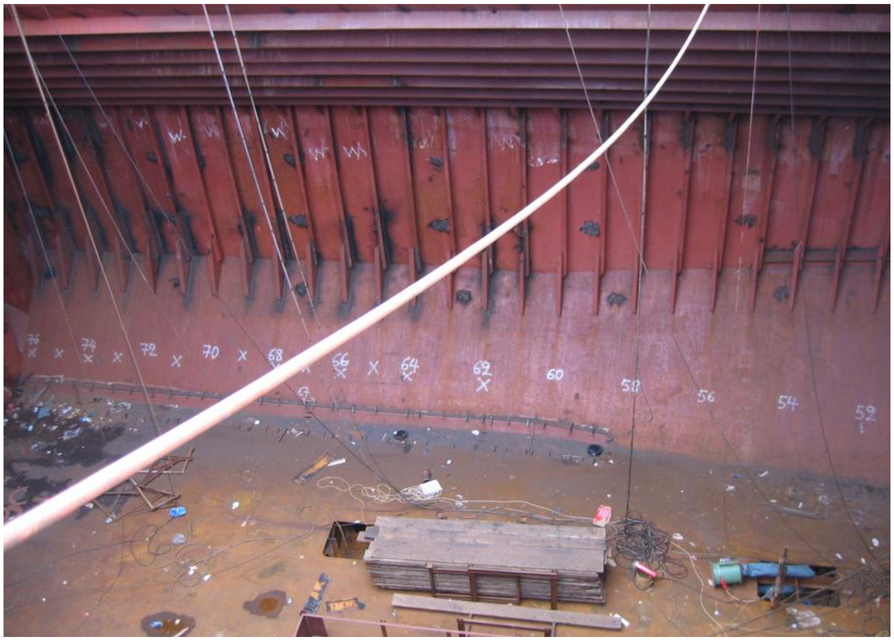

Figure 3. A typical large container hold on a ship. The 3 –vehicle CROCELLS prototype is designed to be able to operate between the vertical stiffeners whose separation is 700mm.

Storage Tank construction and repairs the shell (sides) and roof are target applications for CROCELLS.

Wind turbine tower construction. Sections 2.5 meter long and diameters up to 3m are factory welded together into 10-15 meter sections to be transported to the erection site and welded together to form 44-60 m high Towers. The relatively small lengths of welding needed for section assembly minimises the advantages of replacing manual welding. However CROCELLS provides an option in the long term of doing all section welding on site thus allowing cheaper and easier transport using smaller vehicles.

One area of immediate potential is the access door at the bottom of the tower, which is an area of highest stress because it bears the full weight of the tower, turbine and blades permanently. To cope with this stress, presently 16 manual weld passes round the door perimeter, which is a double curved environment are used, a total of 150metres. This represents as much welding work in one place as the entire tower. Robotic welding is thus an attraction and thus a potential application area for CROCELLS, although the ground based OCTOWELDER, reconfigured to move automatically on rails encircling a tower, might well be a more immediate alternative.

5. <u>Requirements of the 3-vehicle CROCELLS system to address the above target applications</u>

The overall architecture of the proposed 3-vehicle CROCELLS prototype is shown in Figures 4-6. There is space here only to discuss the key specifications.

(a) Vehicle sizes and weights. Each vehicle must be less than about **1m long** to cope with curved surfaces of radius down to 1.5m and **width less than 700mm** including any side overhang of welding torch, so allowing welding inside large container holds having 700mm. Vehicle weights including work tool payload but excluding umbilical weight is required to be less than 70kg to allow transport by two human operatives. The height will be restricted to 500mm to minimise vehicle overturning moments because it these moments rather than the antisliding or gravity forces that restrict the payload capacity except for very low vehicles.

(b) Welding. The low height requirement and payload considerations precludes the use of a anthropomorphic style of arm like the ground based DOCKWELDER [8] or even LSBU's ultra-light (22Kg) 7 axis capable of manipulating a 5kg welding torch [5]. A low lying Cartesian style welding arm combined with the ability of the vehicles to move in any direction and inparticular to follow a weld seam will be combined to produce sufficient degrees of freedom for long continuous pass welding.

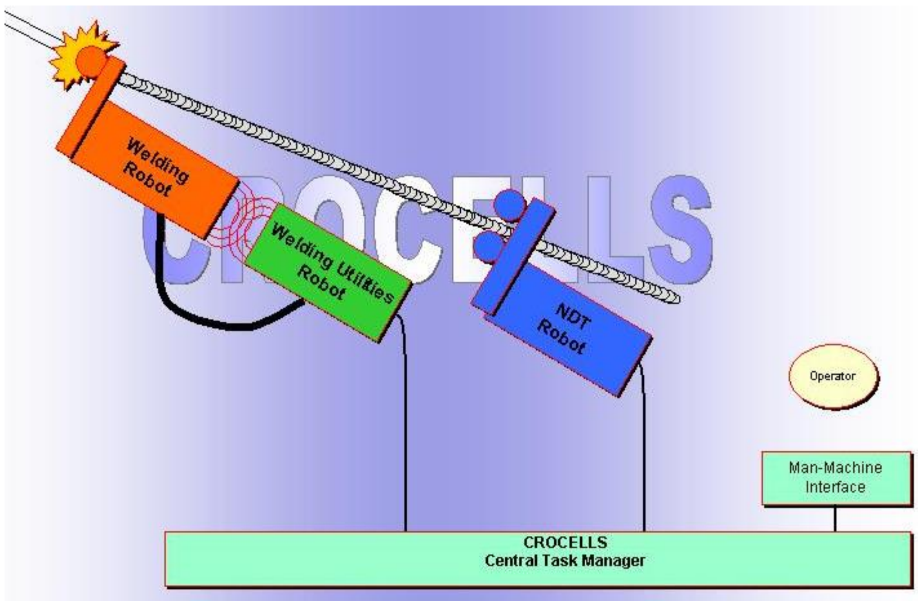

Figure 4: Three robot CROCELLS scenario

Plate thicknesses in the various application areas range from 4-38mm are to be welded with speed to exceed 27m per pass per hour, this being the achievement of the human welder and existing semi automated systems on storage tanks and wind turbines (on ships they achieve 15m per pass per hour) Continuous passes are to exceed 1.5 m, this being the present manual achievement on storage tanks and wind turbines. The welding gap requirement is 1-3mm and the Joint types are symmetric and antisymmetric V and X and Double sided Y. MIG/MAG welding technique will be used as it covers all application areas whilst allowing longer continuous passes (and so fewer defects) and uninterrupted working especially advantageous high above ground, through the use of welding wire instead of electrodes.

(c) Vehicle payloads capacity (working and navigational tools)

The lead vehicle carries the welding torch (5kg) and manipulator arm (20kg), weld seam tracker (5kg), multiple navigational cameras and sensor, and the weld quality monitoring sensor, the total payload being 35kg. The second vehicle carries the pushing device (weld wire spool) (20kg) and navigational sensor, the total payload being 25kg. The third vehicle carries the NDT sensors (5kg), an independent seam tracker (5kg) and multiple navigational sensors (5)kg, the total payload being 15kg. The estimated welding robot payload requirement exceeds the design payload capacity of the existing OCTOPUS vehicle. However taking a very rough rule that climbing robots can carry up to their own weight in payload these payloads permit the total weight of each vehicle to fall within the 70kg limit required by the end users. This ignores the umbilical whose contribution to the payload may need to be minimised (see **(e)**). The 'ballpark' calculation in the next paragraph considers quantitatively the feasibility of a vehicle within the dimensional and weight specifications of the end users being able to carry the required payloads.

A large rare earth magnet plate of area A separated about 10 mm from a ferrous surface will deliver an attractive force of about $62A$kNm-^{2} so that the antisliding force acting on the wheels is $62x10^3AF$kNm-^{3}, where F is the coefficient of friction between the wheels and climbing surface. Practically it is difficult to make A greater than 50% of the cross sectional area of a vehicle. For a vehicle 1m long and 0.7 wide this would make A = 0.35 m-^{2}. Taking F typically as about 0.6 between rubber wheels and a dry metal surface the antisliding force would be 13 x10^3 N, sufficient to support a vehicle with payload weighing 1327kg on a vertical surface providing distance from the centre of gravity of the vehicle and the surface was negligible. In general, of course, this is not the case and overturning moments typically have a greater effect than sliding forces by a factor of up to 10 for a high vehicle. As the vehicle height will be low we might safely assume a factor of 5. So 260kg is a more realistic estimate of the vehicle plus payload weight that could be supported. With a 70kg vehicle (with on board payload) weight (with on board payload) the safety factor would thus be a factor of 3.7. But this would be eroded by slippery surfaces (i.e. a lower value of *F*) or if an umbilical weight had to be supported, as this could be up to 30 kg at a height of 30m. Given the weld vehicle on board payload proposal of 35 kg, the weld vehicle itself must have a weight within 35kg whilst being able to withstand the magnetic forces quantified above. Broadly this sounds feasible.

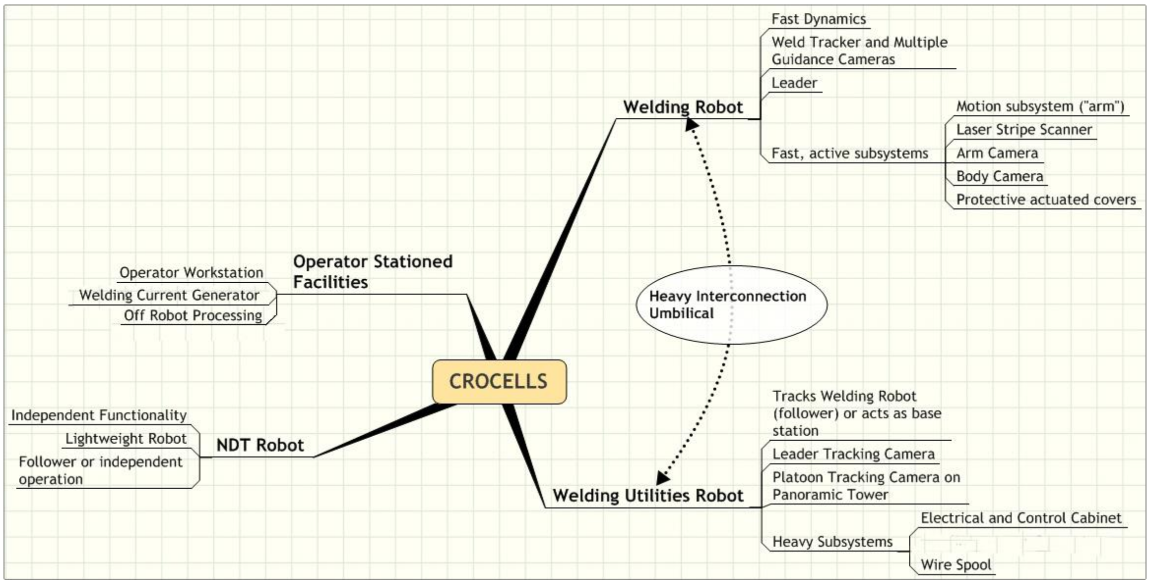

Figure 5: MindMap on the CROCELLS Architecture in the three vehicle scenario

(d) Navigational strategies. The weld vehicles and the inspection vehicle need independent means of precise weld tracking as they tasks that they perform will be frequently independent in time. For example cold weld inspection during weld manufacture as well as during life cycle inspection and repair will be required under existing standards. These requirements will remain even of a system for hot solidified weld inspection is developed in the project. The utilities vehicle does not need independent seam tracking but does need a navigational strategy to follow the weld vehicle and keep sufficiently close for effective weld wire feeding. Each vehicle will have its own coordinate system to which its working tools are referenced. Vehicle position determination will be by a combination of techniques selected from (odometry, acoustic localisation with accelerometers, on- board compliant balls –a ‘robot computer mouse’, theodolith coupled with GPS)

(e) Climbing heights. A maximum climbing height/depth of 30 m was decided upon, given that the weld current generator should be sited no further than 25m from the pushing device, and the problems of umbilical weight, which could be 0.5-1kgm^{-1}. This will cover all applications under consideration. Ships can be 50m high but the top half can be serviced by CROCELLS simply by placing the ground station on deck and the system could then climb 30m down. The umbilical constitutes an off board payload which could present problems. Support by a crane or cherry picker etc would not reduce the attractions of the CROCELLS as these items are usually readily available in the CROCELLS operational environment. However a better option would be to use umbilical support hooks, electromagnetically attached to the working surface. For example they could be lowered from the deck of a ship.

(f) **Surface obstacles:** Vehicles will be designed to surmount obstacles (such as ridges on ship hulls) up to 20mm (the existing OCTOPUS vehicle is able to do this) Higher obstacles, for example the stiffeners in Figure 1 below) or nozzles etc will be circumnavigated.

(g) **Non-contact NDT sensing:** In order to fulfil the strategy of fast or even real time repairs to welds during their manufacture, non contact sensors must be considered to permit weld melt quality monitoring as well as inspection of hot solidified weld. Miniature EMATs (Electromagnetic acoustic transducers) and miniature pulsed eddy current sensors will be considered. The same sensors would be applicable to life cycle inspection of very rough, corroded or paint covered surfaces, or surfaces with protective coatings. For weld pool monitoring optical sensing is also to be considered for guaranteed inspection to existing standards. With a wheeled NDT vehicle (the best option to fit in with the overall operational concept for CROCELLS applications as presently defined) a fixed phased array probe seems the best option at present. A wheeled vehicle can provide large scale one and two dimensional probe scanning whilst the array can provide an omni-direction all beam scan over successive small volumes during the scan. A wheeled vehicle tracking a weld would allow a single mechanically fixed array to provide total weld coverage. The novelty of **hot weld pool monitoring** is to (i) identify satisfactory/ unsatisfactory melt properties i.e. properties that will not lead/lead to defects on solidification (ii) use a sensor to detect unsatisfactory properties and use this data to adjust the process conditions in real time back to the values which produce a perfect melt. International standards specify the maximum length of weld defect d_{min} that is acceptable so that if $d_{min}/t_m < w_s$, where t_m is the time taken to make a melt condition measurement and make consequent adjustment to the process parameters and w_s is the welding speed it will be possible to weld without producing cold weld defects thus greatly reducing overall welding costs which include cold weld inspection time.

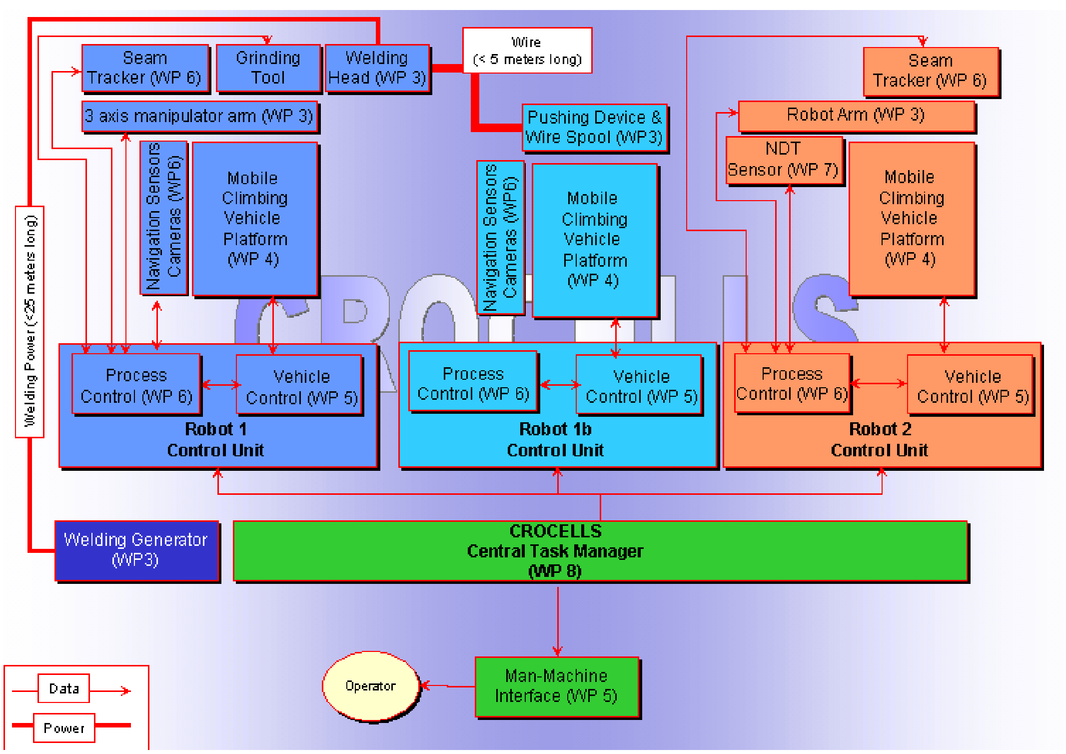

Figure6: Global Architecture for a three vehicle CROCELLS scenario

(h) **Process control:** two cascaded close loop closely coupled control systems will (i) maintain the welding wire at optimal height above the seam and (ii) maintain the weld head above the seam at all times and tracking the seam at constant speed.

(i) **Vehicle Control Systems:** There is a motion controller for each vehicle with coordination of each controller by the Central Task Manager. **High level control** of each vehicle is off - board to minimise payloads, together with the Central Task Manager module and MMI. These make up the 'ground station'. On-board microcontroller units on each vehicle will interconnected by the 12C bus for maximum modularity, flexibility, expandability and ease of debugging. The final chosen detailed control architecture and layout of electrical interfaces requires some work under each work package 3-7. A microcomputer (12C bus master) will control all on board microcontrollers, routing 12C data over the Ethernet or equivalent bus to high level control and image processing tasks.

(j) **Central Task Manager:** this software module coordinates all the vehicle motion and process controllers, decomposing the welding and inspection tasks into a set of discrete tasks and maintaining the flow of control amongst these tasks. Whilst the CTM will be able to automatically change the process parameters or reissue a weld instruction on the basis of NDT/weld melt quality data maps, at all times the man- machine interface **(MMI)** observer will be able to manually override these instructions through the MMI**.** The software component of the MMI will consist of a graphical use interface **(GUI)** with a multi screen camera view, which allows an operator to configure, deploy and supervise a welding operation. The MMI will automatically generate a welding quality report (defect maps, weld melt composition etc. As already mentioned three-vehicle system has in part been chosen to illustrate the CROCELLS concept in the field trials and within the available project time and budget. However to facilitate progress toward the long term potential as defined in the original proposal, the **CTM software must be of open design** and thus up to the task of coping with additional vehicles performing other functions such as grinding, riveting, cleaning etc or coping with a network of CROCELLS systems. Overall supervision of jobs.

6. Conclusion

The specifications and Architecture of a novel flexible manufacturing cell for initial applications to ship, storage tank and wind turbine towers has been summarised and they form a basis sufficient to all system design and prototyping to begin.

7. Acknowledgements

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