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Offline CAD-based robot programming and welding parametrization of a flexible and adaptive robotic cell using enriched CAD/CAM system for shipbuilding

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Abstract

Shipbuilding continues to be a handwork process, where many shipyard's facilities are poorly optimized, and there is not flexibility enough for more complex manufacturing techniques. In order to provide solutions, shipbuilding sector is emerging with the purpose of dinamizing its R&D environment, developing advanced tools to make easier the technological evolution of the sector. The proposed solution is a hyper-flexible welding robotic cell with 9 degrees of freedom (6 axes robot arm unit mounted on a 3 axes XYZ gantry) adapted to small batch manufacturing. The cell is programmed in a CAD (Computer Aided Design) environment allows to implement automatic welding sequences to an inexperienced programmer: 'Offline automatic system programming'.

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Keywords: shipbuilding; offline automatic system programming; hyper-flexible cell; welding; industrial robots.

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1. Introduction

The European maritime technology sector is an industry driven by innovation that includes design, construction, maintenance and reparation of vessels, which are progressively getting more complex and technology advanced in shipbuilding manufacturing. The shipbuilding, maritime equipment and ship maintenance, repair and conversion (SMRC) industry employs more than 500,000 people (civil and naval, new building, and repair yards), directly and indirectly, and the average annual turnover is around 91bn€ [1]. The European shipbuilding industry is a dynamic and competitive sector. It is important from both an economic and social perspective [2]. It is also linked to other sectors including transport, security, energy, research, and environment. There are about 150 large shipyards in Europe, of which around 40 are active in the global market for large seagoing commercial vessels [3].

However, shipbuilding continues to be a handwork process, where many shipyard's facilities are poorly optimized. The industrial robotics design is oriented to large series, results in that is economically unviable for small and medium enterprises (SME) due to small batch sizes. Robot work cells should adapt to variations in shape and size of the parts to process. There are solutions of flexible robotic cells in shipbuilding sector, [4] and [5]. However, the development is not flexible enough and the parameters cannot be modified using a CAD program.

The proposed solution is a hyper-flexible welding robotic cell, with nine axes fully coordinated. The robot is a KUKA model with 6 dof (degrees of freedom) assembled upside-down to a three axes XYZ gantry. This cell uses an off-line programming method to allow the final users to program a robot in an intuitive way, quickly, and with a high-level of abstraction from the robot language. Besides, the system is provided with a part localization system based on machine vision.

The main topic of this development is a CAD based software to program this robotic cell in an easy way, allowing welding sequence arrangements to an inexperienced programmer: 'Offline automatic system programming'. Hence, the worker is capable of configuring the welding parameters and programming the robot in an automatic way, generating the robot trajectories and sending them automatically to the robot system, without using the teach pendant.

The machine vision locates the part to be welded. This cell has two cameras embarked on the gantry to scan the work space; the software combines multiple images with overlapping fields of view, producing a high-resolution image, locates the part into the created one and calculates its pose –position and orientation–, which is sent to the robot. The software is embedded in the open source software FreeCAD, in order to make it accessible for SMEs. In this program, a complete workbench was created using Python language. The user selects in the CAD model the joints he wants to weld and adds welding parameters –e.g. voltage, current…–and location parameters– e.g. the reference system–. The welding trajectory points are extracted from the CAD, and the pose of the part to be welded is coming from machine vision system. All the data are stored in a configuration file in XML (Extensible Markup Language) format that associates CAD data with process parameters, getting an enriched CAD/CAM file.

With all the data parameterized, it is necessary to calculate the coordinates of points belonging to each joint, and generate with them a .dat file –KUKA file format that stored the path points–, that is sent to the robot. The calculation of the trajectory takes into account the coordinated movement of the nine axes. All the process instructions are sent to the robot controller from the workbench created on FreeCAD. This is carried out through a communication between the robot and the application developed, based on sending and receiving an XML structure.

With this software CAD based, manually programmed paths are replaced with automatic off-line path generation. This system is adapted to small batch manufacturing with different parts designs; the system is '*easy work*' so inexperienced personnel can use it. Moreover, this adaptive cell is more productive than a conventional robotic system.

2. Robotic cell

The hyper-flexible cell consists of a 3 axes XYZ gantry and a 6-axes robot arm assembled together (Fig. 1)**Errore. L'origine riferimento non è stata trovata.**. with a working area dimensions of 5x4x1.5m. Anthropomorphic arm robot is assembled upside-down to the gantry, which works as an external positioning system, improving the range, accessibility and orientation during the process. The robot controller is provided with a seam tracker based on welding current feedback and weave function to absorb possible deviations and inaccuracies.

The 6-axes robot arm chosen was a KUKA KR16-2 model, due to the possibility of coordinating nine axes (6 axes in the robot, and 3 external ones, which one of them being controlled by two synchronized motors), economics reasons, welding features, and easy integration with KUKA robotic system

Paths welding are executed with the cartesian axes, while anthropomorphic robot will supervise and correct the deviations that could exist between theoretical and real path. The welding process is carried out and controlled by the welding equipment FRONIUS TPS 400i.. The cell is provided with a localization system based on machine vision to locate the exact position of the objects. This system has two cameras (two Genie TS 2500 with a field of view of 1,65 meters) in the external Y-axis, with the intention of obtaining images of cell workspace. The lenses are a Distagon model with a focal length of 25 mm.

Fig. 1. Hyper-flexible welding robotic cell.

The cell working area is 5x4x15m and the working table dimensions: 4x3m. The accuracy and repetitiveness is 0.1mm. The welding speed is 0.15-0.9m/min. Process characteristics provided by KUKA are Arc Welding, weaving, and Trough-The-Arc Seam Tracking features. Finally, the seam welding arrangements: Fillet arrangements, as T-Beams. Thickness range 5-12mm. Possible Butt arrangements up to 6mm.

3. Image processing

The machine vision system is used to locate the parts to be welded. For this purpose, at the beginning of the welding process, the gantry moves along the X axis while the vision system scan the work space. During the scanning, the cameras acquire eight images each one every 350 millimeters, comprising all the work space. After the scanning, the machine vision system combines the sixteen images, with overlapping fields of view, in only one using a stitching algorithm. The algorithm uses this overlapping to find similar characteristics of the elements that compose the images and use them to combine these images to produce a high-resolution image. As Fig. 2 (a) shows, this algorithm search and find the most representatives features and keypoints of each image and find correspondences between the adjacent images. The goal of this algorithm is get all the work space in only one image with very high resolution to get measures with high accuracy.

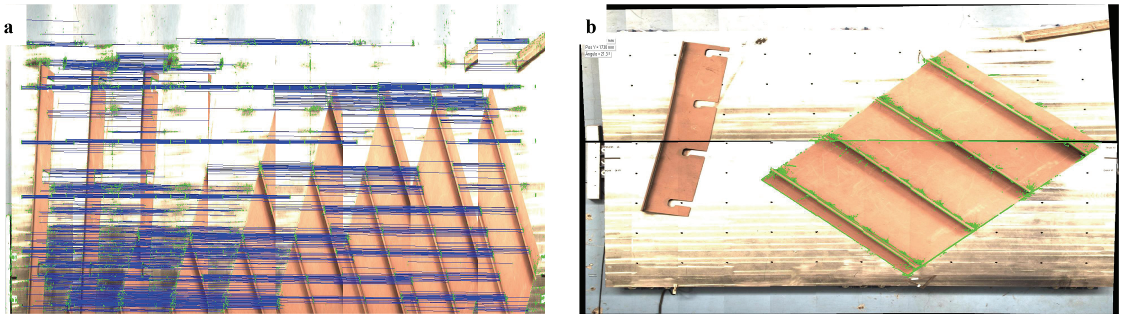

Fig. 2. (a) Stitching, join parts; (b) Matching.

The next step is executing a shape-based matching algorithm (SBM). This algorithm does the important part of the machine vision system, locating the part to be welded and calculating its pose – position and orientation –, regarding the robot cell. The matching algorithm uses a pattern file to get the shape of the element to be welded and, with this shape, try to look for and find the element in the work space. Once it is located, the SBM algorithm gets the part pose. Them a translatione from pixels to millimeters with a previous cameras work calibration is carried out, obtaining the real piece position in an XY frame as Fig. 2 (b) illustrates. That calibration consists in measure in pixels and pattern calibration with a known size and get the relation between pixels and millimeters. Once the position is known, next step is translating the coordinates of the found element to robot coordinates. The SBM calculate the distance between origin of the robot and the calculated pose and send it to the robot in XY and angle, thus, the robot can reach the right position to start the welding. Even with a small separation between the union of the images acquired by the two cameras, the matching algorithm is able to locate the part and get the pose referenced to the origin of robot coordinates.

4. CAD-Based robot programming

4.1. Shipbuilding workbench on FreeCAD

There are different CAD 3D non-specific programs on the market such as CATIA and SolidWorks. Nowadays, the design enterprises oriented to naval design have their own design solution, e.g. FORAN system developed by SENER [6] or RinasWeld that generates robot welding programs based on a 3D CAD model [7]. However, these systems are proprietary and closed solutions and have an elevate cost for SMEs. Furthermore, none of these solutions are completely automatic. It was necessary to find a CAD program, that could append new functions, plugins, graphical tools, etc… in an easy way. The proposed solution was to use FreeCAD [8], a free and open CAD 3D program that can be modified using scripts programmed in Python language to create personalized workbench.

The main reason of using FreeCAD is its capability of being modified in an unlimited way with different parameterizations, allowing to SMEs access of such a technology. Some advantages are the price, control over the software and many overseers of code. With this objective, a *Shipbuilding* workbench was created focused on add welding parameters and trajectory parameters such as position or orientation. FreeCAD is divided in two modules: App and Gui. App module allows to add new functions to the program and Gui is used to develop a HMI (Human Machine Interface). The QtDesigner program was used to create a new customized workbench.

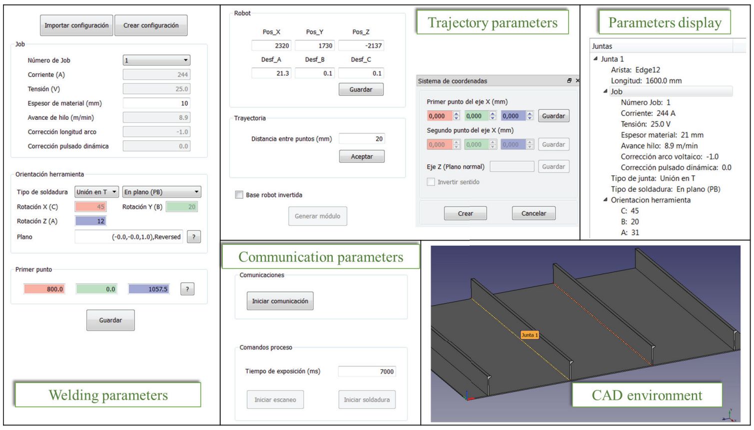

Fig. 3. Tabs and widgets created for the workbench.

Shipbuilding workbench is composed by different tabs and widgets to parameterize the behavior of the cell, add settings, configuration… in order to manage the multiple components of the hyper-flexible cell –robot, gantry, cameras and welding equipment–, and to generate the necessary files to program them. In the Fig. 3 it is shown the tabs of the workbench interface that the user will handle.

The user imports the CAD file of the part to be welded. Then, he selects the sequence of the joints to be welded and adds different welding parameters for each joint. In addition, it is necessary to place a reference system in the part CAD model, which will be the reference frame for all trajectory points. Now, it is possible to generate the file with the robot path and transform the coordinates to the real position. After these steps, the system will perform the rest ones automatically. Fig. 4 shows the system flow chart, emphasizing the steps that imply user intervention.

The files automatically generated are two ones: an XML file format with the process parameters, and a dat file in KUKA format that store the path points. XML file has a specific structure and is used to save all geometric and welding data necessary; while dat file has a KUKA language specific structure and it is loaded automatically in robot RAM through '*Directory Loader*' KUKA technology package.

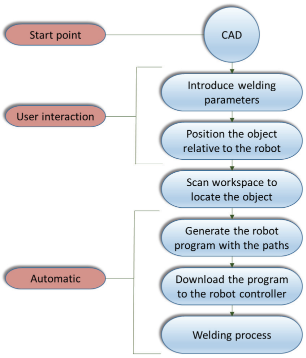

Fig. 4. System flow chart.

4.2. XML Setting file

When the user creates a setting files, an XML-based file is created and geometric data of the object and process parameters are saved. For each joint, the geometric necessary data to calculate the robot path and the orientation of the welding tool are stored in this file and the user, through the interface, introduces the welding parameters –e.g.

voltage, current, gap, …–, parameters that are also stored in this file. Therefore, this file associates CAD data with process parameters, getting an enriched CAD/CAM file [9].

4.3. Intuitive robot programming based on CAD

Robot programming using a teach pendant is a tedious and time-consuming task that requires technical expertise. Furthermore, as a result of the size of shipbuilding parts, this method requires that the operator defines all poses –position and orientation– of all points of the part to weld.

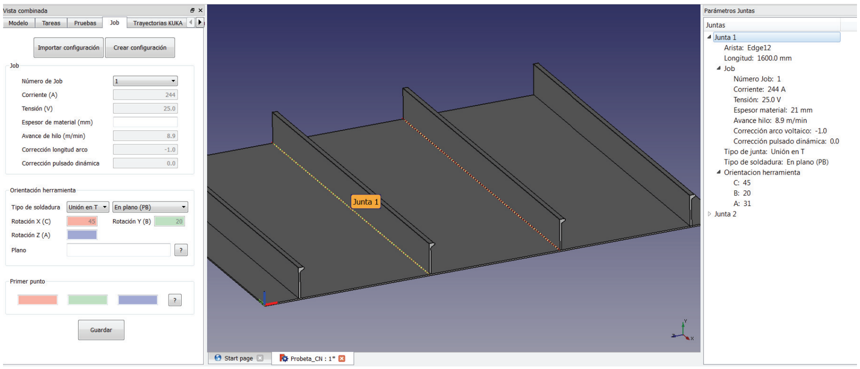

Fig. 5. Workbench designed on FreeCAD.

The solution proposed is to develop methodologies that help the final users to program a robot in an intuitive way with high-level of abstraction from the robot language. Fig. 5 shows a CAD-based programming system as a starting point to develop a Flexible and Adaptive Robotic Cell for small batch manufacturing. In this system, the operator generates the robot routine simply selecting the robot paths of the weld on the CAD environment. Next, the CAD file is processed in order to generate the trajectory–including tool orientations– where welding must be applied. The software developed to extract these routines automatically is integrated on the workbench shown in Fig. 5.

There are two types of joints: butt joint and tee joint, with different software processing in order to extract the robot paths because depending on the type of joint there is a specific orientation of welding tool according to UNE-EN ISO 6947 [10] and UNE-CEN/TR 14633 [11]. Furthermore, to define the robot pose it is necessary not only to obtain information about the X, Y, Z coordinates and orientation, but also to define the position of three external axes. Finally, robot trajectories created from CAD environment should be readapted to current location of the object, based on the information obtained from the cameras.

4.4. Robot routines automatically generating

Manually programmed paths are replaced by automatic generation off-line using the CAD environment developed, sending the path points and the robot routines to the controller. The 9 axes of the system are taking into account by the trajectory calculation. Paths welding are executed with the cartesian axes, while robot supervises and correct the deviations between theoretical and real path; therefore, to limit the possibilities, there are three robot configuration to weld (Fig. 6)–shrunken, intermediate, stretched–. Thus, only the position of external axes in the inverse kinematic is taken into account. To reach a specific position and orientation in cartesian space with a tool mounted in a 6 axes robot unit, there are up to 8 possible solutions given by inverse kinematics algebra. In the case of 9 axes robot system the solutions will be infinite. Therefore, we implement the strategy of fixing the 6 robot axes, to calculate the 3 XYZ cartesian axes values of the gantry. In order to fix the 6 robot axes, we decided that the robot 1 axis should be perpendicular to the welding seam. The axes 2 and 3 should correspond to one of three possible combinations. Axes 5 to 6 are calculated from tool orientation, and axes 1, 2 and 3 position.

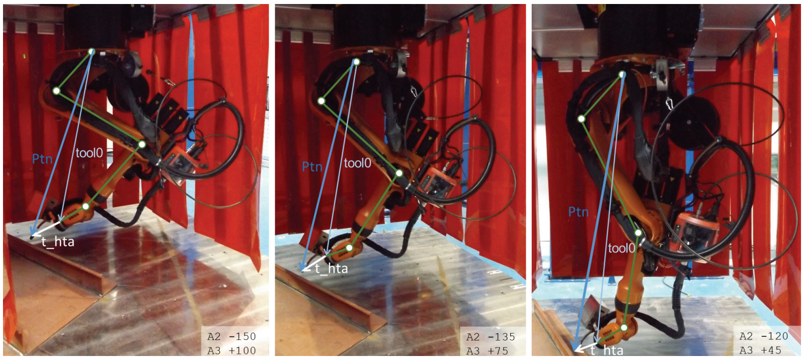

Fig. 6. Robot configurations.

One of the objectives is to calculate the coordinates of the point to be welded and the orientation of the torch relative to coordinate frame $BASE (See Fig. 1), that is done automatically in the CAD. Then, the calculation of the configuration of the robot axes cannot be done through reverse kinematics because initially the position of the robot base is not known. For this reason, it is necessary calculate the first axis of the robot through the normal vector of the joint (in case of T-fillet, the first axes are perpendicular to the joint) and fix the second and third axes. With the orientation of the torch, axes 4, 5 and 6 are calculated. Thus, the configuration of axes of the robot is known and, therefore, the relationship between the base of the robot ($ROBROOT) and the point to be welded. Finally, the coordinates of external axes are calculated from the calculation of homogeneous matrices. As the position of the point relative to coordinate frame $WORLD is known, the relationship between $WORLD and $ROBROOT is calculated. This relationship is the position (x,y,z) of the external axes to reach the point.

The rotation of the robot base (A1) is the first step to calculate the external axes position, and can be calculated using the angle between the normal vector of the joint and the X-axis of the system frame. Thus, the angle *A1* is defined and it's possible calculate the *tool0* vector. Setting the configuration of the second and third axes of the robot, from its dimensions (*d1* to *d6*) and the *A1* angle calculated, the *Ptn* vector can be calculated through linear algebra. Once *Ptn* vector is known and through the welding tool reference system, the *tool0* vector is calculated; getting, thus, the configuration of the fourth, fifth and sixth axis. Therefore, the coordinates of the robot can be calculated through forward kinematic. The external axes coordinates are calculated also, since the robot and CAD coordinates are known.

The coordinates of the points to weld are relative to the CAD-coordinate system previously created in the CAD environment and it must be the same axes system of the localization machine vision system. Thus, the transformation of this system to the world coordinate system is carried out. The user does not need to have any programming knowledge since the program designed makes all the transformations, thanks to the environment and software programmed. Once the file is generated with the transformed coordinates, the final step is the loading of the file to the robot controller through the *DirectoryLoader* KUKA technology package that can load modules from a definable directory of the robot controller using a command sent from the FreeCAD environment.

4.5. Communication XML-Based

There is a reciprocal communication between the computer and controller based on an XML structure using a KUKA technology package, transmitting the data via TCP/IP protocol. The Ethernet connections are configured using the configuration XML file where process variables are defined. The configuration is read in when initializing a connection and an XML-based structure is used to transmit data. First, an XML file is created in the robot with the variables needed, file that is duplicated in Python program using several classes. The communication between PC and controller is based on a server-client program that use sockets. Server is created on PC through Python language, while client is created on controller through KRL (KUKA Robot Language). Server sends an XML structure with parameters, variables and commands and as response, the robot acts according to the value of these variables.

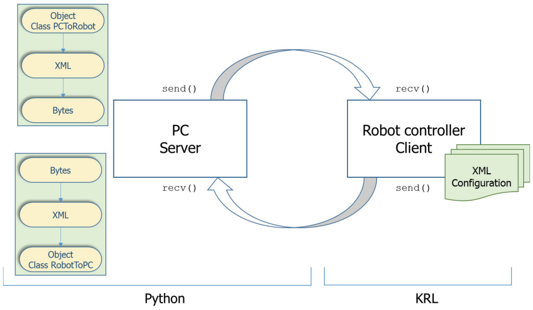

Fig. 7. Communication XML-Based.

The steps to follow are shown in Fig. 7. The data is sent to the robot through an object created from a *PCToRobot* class, this object is converted to an XML structure, as defined in the robot XML configuration file, and this XML is converted to bytes and send it to the robot controller. When the PC receives data from the robot, first the bytes received are deserialized, it is converted to an XML structure and the *RobotToPC* object is generated.

5. Welding performance

The performance and behavior of the robotic cell was tested welding several joints of a specific shipbuilding part (Fig. 8). At this point, the part to be weld is located with a ± 3 mm of precision. The inaccuracies were adjusted using the wire tip as a sensor to detect initial and final point of each seam. Deviations of trajectories were corrected using seam tracker and weave function. The use of these different technologies allow the minimal interaction between operator and robot. The use of robotized welding instead of a manual one minimizes the deformations produced, according to the feedback provided by local shipyards, reducing reworking tasks. Moreover, robotized welding is quality and time-processing enhanced.

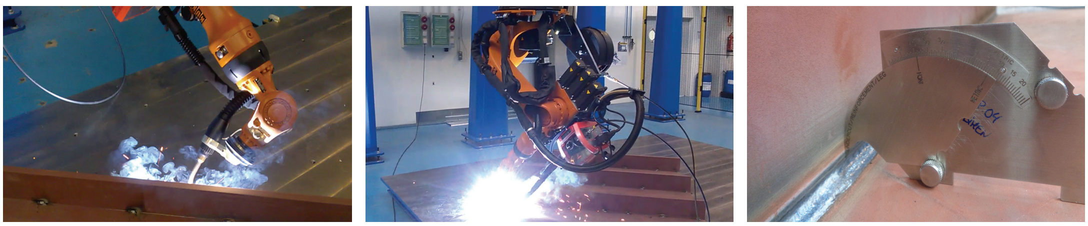

Fig. 8. Welding process.

6. Conclusion

A hyper-flexible cell that enables the automation of welding operations through a CAD open source program has been described allowing to implement welding sequences to an inexperienced programmer. The vision system locates the part and the user parametrizes the joints that have to be welded. Then, the robot program and trajectory is automatically generated. The full production can be automated using the hyper-flexible cell, free of manual operations. The system is expected to increase the sector competitiveness and the technology level of the shipbuilding manufacturing, decrease the handwork process and the time of the process and improve the quality of the final product, decreasing the reworking tasks. The developed hyper-flexible welding robotic cell is expected to make a significant contribution to the necessary efforts to upgrade the production infrastructure in shipyards and to integrate new forms of production able to benefit from evolving automation technologies. Besides, this work improves cost efficiency, performance, robustness and flexibility to reach a more adaptive and competitive shipbuilding.

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