A COOPERATIVE ROBOTIC SYSTEM APPLIED TO THE RIVETING PROCESS

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Abstract. *This paper describes a methodology for using a cooperative robotic system for performing riveting tasks automatically within the context of a fuselage assembly process. Two high payload industrial robots manipulators are used and equipped with end-effectors for performing the tasks. The cooperative work between the controllers is performed using real time communication network architecture to exchange data and provide the necessary information to connect the controllers. The master robot carries the tool for drilling and riveting and the slave robot, the tool needed to complement the process. Software hosted in industrial computers controls the tasks of the two end-effectors and exchanges data with the robot controllers using the OPC (OLE for process control) protocol. The program commands used to perform the synchronization of path motions and the geometric coupling between the two robots is presented. Experiments were performed to investigate the cooperative robotic system effectiveness and to analyze the viability for applying this method in a local aeronautic company. These are described in detail.*

Keywords: *Cooperative robotic system, riveting, robot programming.*

1. INTRODUCTION

The automation of the aircraft manufacturing process using several industrial robots manipulators can be a solution to increase the process quality, throughput and reduce costs. The riveting process is one of the most used production processes in the aeronautical assembly lines because almost all the parts of an aircraft are assembled with riveting (Kihlman, 2001). This work describes a methodology for implementing the riveting and an experimental procedure to evaluate the cooperative robotic system in the ASAA Lab (Aircraft Structure Assembly Automation Laboratory). The robotic cell is composed by two high payload industrial robots manipulators equipped with end-effectors for executing tasks automatically. For testing the system integration and programming the robots, a part of aeronautic fuselage was used and fixed in the center of the assembly cell. The experiment for evaluating the systems was designed and the measurements were carried out with a non-contact large scale metrology system.

2. CONTROL ARCHITETURE AND COMMUNICATION SYSTEMS OF A COOPERANTING ROBOTS ASSEMBLY CELL

2.1. Components of an Industrial Cooperating Robots Assembly Cell

Cooperating robots systems for industrial applications have been recently introduced in the robotic market. For industrial applications, cooperative movements are a major challenge needed to increase flexibility (Schmitt, 2010). The assembly cell composed by cooperating robots is basically the same regarding to cell components. In an industrial assembly cell with single robot manipulator there is one control cabinet and normally one HMI (Human Machine Interface) to show the robot software interfaces for programming and configuration. The main difference of a cooperative robotic cell is the introduction of a communication network between the robots controllers (KUKA, 2007). This real time network to exchange data and signal is necessary for performing cooperative tasks. Another difference is using only one HMI for all the robots in the robotic cell. Fig. 1 shows the network connection between two cooperative robots sharing the same HMI. The software application for programming the cooperative tasks has a new group of commands available for the robot programmer for creating the tasks according with the application.

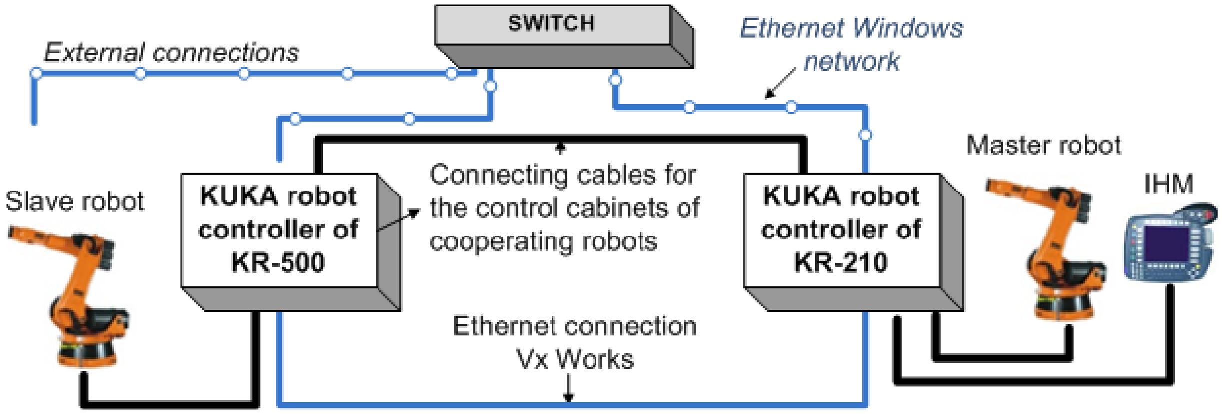


Figure 1. Network connections between industrial cooperating robots

The robots in the cooperative robotic cell need a calibration to increase the positional accuracy of the system. The procedure is carried out with measurement instruments and dedicated software to calculate the numerical optimization of the modeled system for constant conditions of process. The calibration results in a best model for a specific load weight and load grip (Schmitt, 2010). Table 1 describes a list of steps to be done in the construction of the assembly cell with cooperating industrial robots (KUKA, 2007).

Table 1. Steps of construction the assembly cell for cooperating robots

Steps	Procedures		
1	Definition of the number of robots	Planning	Construct the cell layout according with the application
2	Definition of the load of each robot	Planning	Provide the necessary information for accurate robot calibration and tools calibration
3	Definition of the master robot of the cell	Planning	Specifies the main robot of the cell and the location of the IHM connection
4	Connection of the network cables	Cell start up	Connect the robots
5	Configuration of the IP address	Cell start up	It's required for real time communication between the robots
6	Configuration of the robotic cell inside software interface of the robot	Configuration of the cell application	It's required for using the cooperating commands
7	Calibration of the robots position relative to another	Configuration of the cell application	It's a required for geometric coupling
8	Calibration of the tools	Configuration of the cell application	Preparation for the programming
9	Creation of a programm with commands Sync, Progsync and Geolink	Robot programming	Configuration of the

The communication network between the controllers of the robotic manipulators is composed by two ethernet connections and one cable for safety signals flow (see Fig. 1). The IP address (Internet protocol address) configurations of both networks were done at installation procedure. The installation procedure is also the right time for the definition of the master-slave relationship (KUKA, 2007). The master is the main robot of the cooperative robotic cell which controls the slave robots.

2.2. Forms of Cooperation and Programming Concepts

The software interface of cooperating robots provides a set of commands besides the standard commands. The robot programmer uses these set of commands to create routines of movements required by the application. A combination of commands can create the following forms of cooperation: load sharing, process-dependent procedure, combined procedure and master-slave procedure. Forms of cooperation are concepts that can be implemented in other cooperative robotic systems, only the commands used have to be specific for the manufacturer of the robot manipulator.

Before using the commands to build up the routines the programmer must carry out a calibration procedure in the final layout of the assembly cell. In this procedure, the system is able to exchange geometric information from one robot to another. Thus, each robot manipulator knows where the other one is on the working cell. This procedure is called geometric coupling of the robots (Reinhart, 2009).

The geometric coupling between robots can be activated in the movement routine in two modes: direct mode or indirect mode. In the direct geometric coupling mode, the base reference system of the slaves robots are the flange coordinate system of the master robot, and only the master performs a path of movements. In the indirect geometric coupling mode, the slaves are also geometrically coupled with the master, but the slaves perform a path of movements as well. Reinhart (2009) focuses on the form o cooperation of load sharing, what means several robots holding a heavy workpiece or moving the workpiece. Two programming commands are available to start a movement with masters and slaves robots geometrically coupled. The Geolink (KUKA, 2007) command, available in the software of the cooperative robots application is able to start and finish directly coupled movements. For implementing the movements indirectly coupled, the command Progsync (KUKA, 2007) must be used in the software routine.

A master-slave procedure is possible to be implemented with synchronization of programmed movements, without any geometric relationship between the robot's paths of movement (KUKA, 2007). For implementing the synchronization, the command Progsync can be used to create a motion start synchronization which means that independent movements have to start at the same time.

A process-dependent procedure happens when the masters transfer a piece from one point to another and a slave robot executes a process at the same time (KUKA, 2007). In this case both robots have to be geometrically coupled by the indirect mode. Besides that, the Sync command (Synchronization command) can be used with the commands of movements LIN (Linear) or CIRC (Circular), providing the motion time synchronization. The motion time synchronization of two robots defines that the robots must start independent movements at the same time and finish them at the same time as well.

The Combined Procedure form of cooperation is more than one robot holding a workpiece while a third robot executes the process. In this case, the ability of transporting a workpiece together, is provided by the direct geometric coupling. Figure 2 shows the concepts of programming and their relationship with the forms of cooperation and the commands available for the programmer (KUKA, 2007).

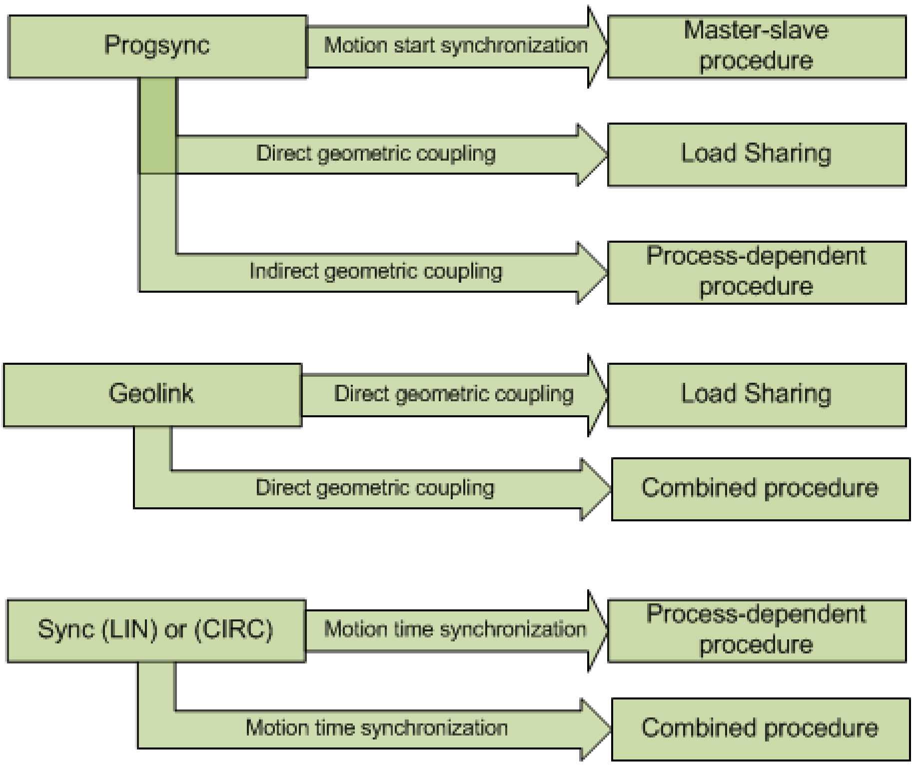


Figure 2. Concepts and commands for programming the robots

3. COOPERATIVE ASSEMBLY CELL EXPERIMENT DESIGN

To assess whether the cooperative robotic assembly cell meets the requirements of the aeronautic riveting or not, a statistical design of experiment was set up to investigate the variation of the distance between two robots geometrically coupled (Montgomery, 1997). Aeronautical assembly lines have the riveting carried out mostly by human operators (Kihlman, 2001). While one operator stays outside the fuselage barrel with the tool used for riveting, his counterpart stays inside the barrel to produce an opposite force to deform the rivet from the internal side.

3.1. Assembly Cell Layout

In the automatic assembly cell, the industrial robotic manipulators KR-210 and KR-500 manufactured by KUKA Roboter™ are used to carry the end-effectors. The robotic manipulator KR-210 is used to carry the end-effector for riveting. The robotic manipulator KR-500 is used to carry the end-effector to produce the opposite force needed to deform the rivet in the internal side of the fuselage barrel. The requirement for this process is that both end-effectors are working at the same position of the fuselage barrel and also aligned with each other. Figure 3 shows the cooperating robots assembly cell with the end-effectors and the robots.

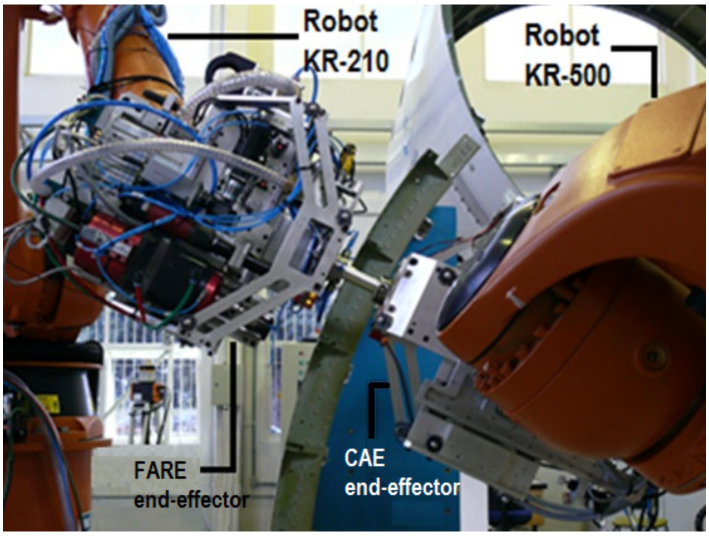


Figure 3. Cooperating robots assembly cell for riveting

In this experiment, two end-effectors developed for riveting are used. The end-effector FARE (Fuselage Assembly Robotic End-effector) was designed and built to perform the complete process of riveting including drilling and sealant placement. The end-effector CAE (Cooperative Assembly End-effector) was designed and built to work at internal side of the fuselage barrel. These end-effectors have similar mechanical structure. In the CAE, was built a cylindrical metallic structure for reaching the point riveting. There is a functional clamping module in both end-effectors for touching the fuselage part without moving the robots. This module was also designed to force the fuselage with one controlled force and to provide conditions required to perform drilling tasks.

The ethernet communication network connects the end-effector's controllers with the robot's controllers. In this network, the control software of end-effector was configured as a client OPC (OLE for process control) and the robot controller was configured as a server OPC.

3.2. The Methodology for Riveting using Two Cooperating Robots

The riveting process requires the correct alignment of both robots inside and outside the fuselage barrel. For performing this task, the method developed was saving the ideal position between the end-effectors with the clamping functional module activated and repeating the same reference position in all the points of the routine. Using a variable system, E6POS (internal variable of the Kuka system software), the reference value is stored and called at the right time during the routine. Figure 4 shows the simulation of the position for riveting in an aeronautic fuselage barrel. For repeating the reference position the slave robot KR-500 was geometrically coupled with the master robot KR-210. In the reference position, a variable in KR-500 stores the data using the flange base of the KR-210.

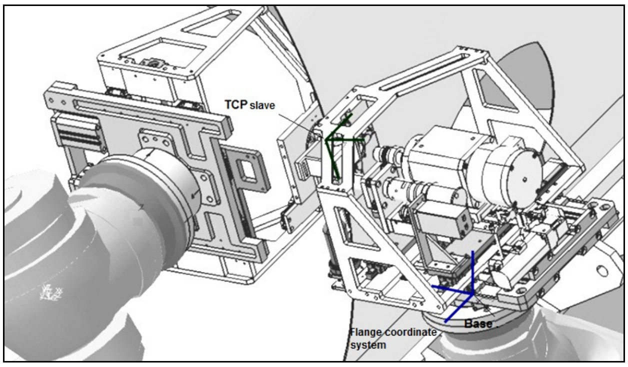


Figure 4. Simulation of the position for riveting

3.3. Experimental Setup

The reference position between the robots for performing the tasks was saved in the aligned position shown in Fig. 5 and stored in a point variable. At this experiment step, both end-effectors fixed in the robots were connected and touch each other in an alignment position. This position could be defined in another place on the assembly cell, but this location was chosen considering the position of the fixed fuselage part. The clamping functions of both end-effectors were tested to verify the alignment as well.

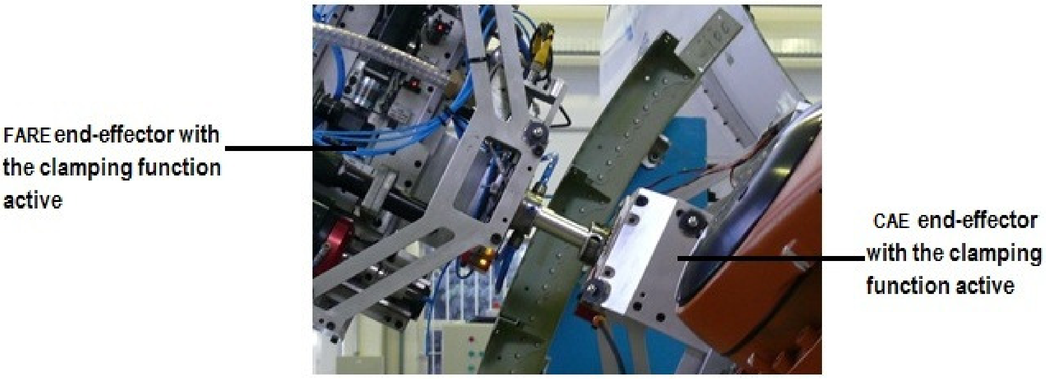


Figure 5. Calibration of the reference position

The large volume measurement instrument Laser Radar (LR) was used as a metrology system in this experiment. It is capable to scan surfaces with a laser beam without contact with the piece. With the LR equipment, it is possible to automatically measure points and reduce the time for taking measurements. It incorporates a laser technology to measure points with high accuracy (up to 0.010 mm). The instrument was used to measure the distance between the robots. Schmitt (2010) used high accuracy displacement sensor to take measurements of cooperating robots to verify the error of geometrical coupling. For reducing the time for measuring the position of these points, tooling balls were used as reference points (see Fig. 6). Four tooling balls were fixed in each end-effector and each set was used to define the reference frame of the end-effectors.

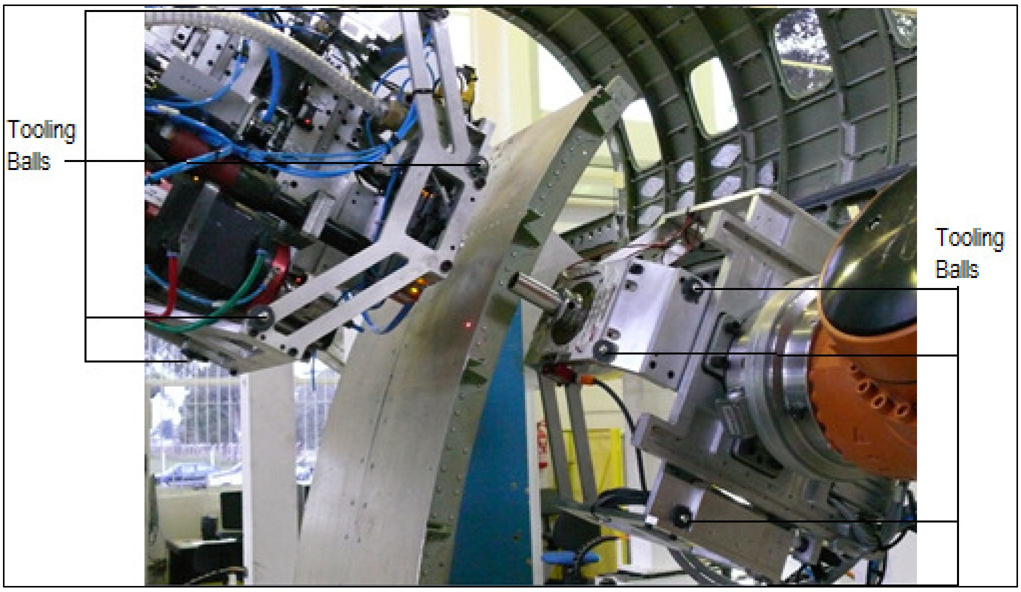


Figure 6. Tooling balls fixed in the robots end-effectors

The results of these measurements is the DBRF (Difference between Reference Frames) between the reference frame of FARE fixed in the KR-210 manipulator and the reference frame of CAE fixed in the KR-500 manipulator.

Using measurements of the tooling balls position and the Spatial Analyzer™ software, the frames of reference are created (see Fig. 7).

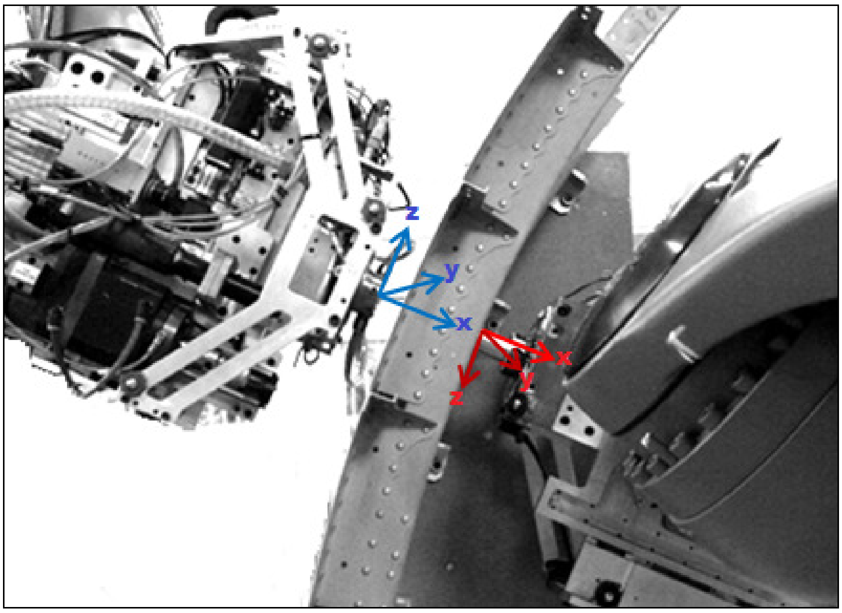


Figure 7. Frames of reference in the end-effectors

The frames measured with the Laser Radar are not the same as those calibrated in the robotic system. They have been chosen to decrease the setup time of the experiment. The calibration of tool center point (TCP) of both robots was done with a movement based method available in the robot interface. The tools calibrated in the robotic system are close to the position of the reference frames, and for the experiment goal, this difference is not relevant. After taking the needed measurements, the data were processed by the Spatial Analyzer™ application software. In this software environment, the values of the point's position are processed in turn to a coordinate system. The last step for obtaining the response variable is to calculate the difference of the two coordinate systems. In the beginning of the experiment, the very first measurement was set as the reference point of the experiment. The result of the DBRFN is a frame with the following values: XN: 96.294[mm], YN: 0.160[mm], ZN: 5.429[mm], AN: -0.844[°], BN: -3.010[°], CN: -176.094[°].

Considering the need of data replication to improve the quality of the collected data and to prepare the statistical analysis (Montgomery, 1997), the routine of movement was elaborated with five points of end-effectors aligned position, and all the routine was repeated three times, according to Tab. 2.

Table 2. Number of measurements of the experiment

Variation of distance between the robots					
	Points				
Replicates	**P1**	**P2**	**P3**	**P4**	**P5**
1	DBRF1	DBRF2	DBRF3	DBRF4	DBRF5
2	DBRF6	DBRF7	DBRF8	DBRF9	DBRF10
3	DBRF11	DBRF12	DBRF13	DBRF14	DBRF15

The movement path, of the coupled robots, is the path to perform the tasks of applying a clamping force with both end-effectors in the fuselage part. For this experiment, the clamping tasks were deactivated and the robots just stopped in the programmed points for the positional measurement instrument in order to enable the reading of the four reference tooling balls positions. In the positions P1 to P4, the robots were geometrically coupled using the direct geometric coupling mode. In the position P5, the slave robot deviates of an obstacle and moves back to avoid a collision with internal part of the fuselage. Because of this part of movement path, a decoupling command was programmed and a command of indirect coupling was executed before the slave robot returned to the position stored in the robot controller. Figure 8 shows the robots coupled in two points of the routine, in P1 and P5.

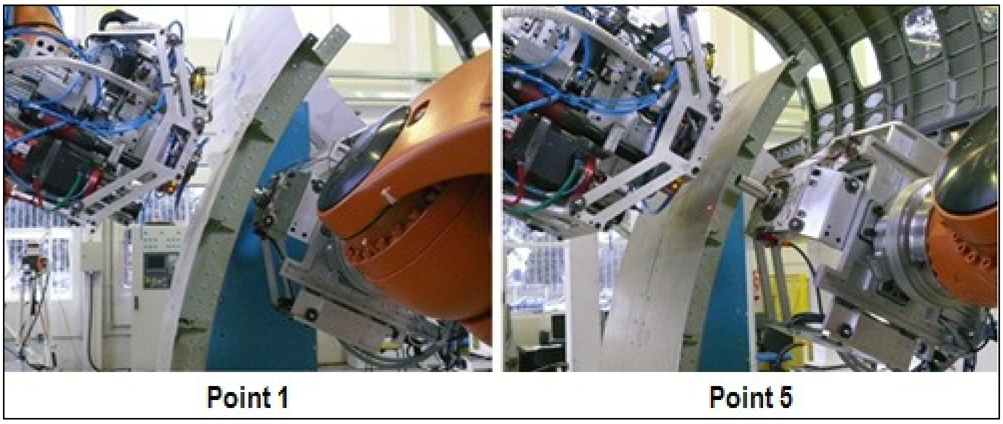


Figure 8. Programmed routine of the cooperating robots

3.4. Experimental Data

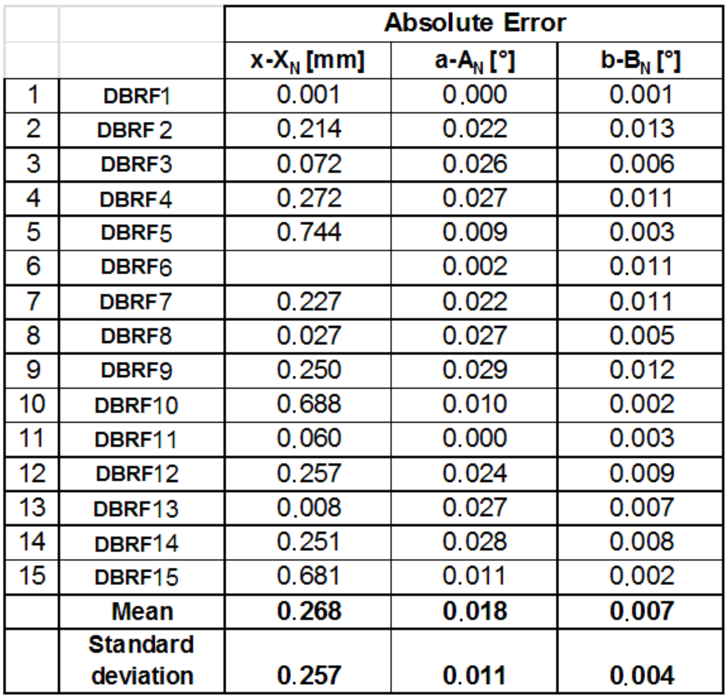
The data results of the experiment were fifteen values of DBRF, each one with the positional components (x, y, z, a, b, c). In the analyzes of the riveting process, the important components are *x*, *a* and *b*, because they represent the relative position that cannot have a big relative displacement. For each measured data, it is possible to analyze the variation of the values comparing them with the nominal values. The data collected in the experiment was divided into three sets of the components and using the equations (1), (2) and (3) the absolute error of each value measured was calculated as listed in Tab. 3.

$$Ex = \sqrt{(x - X_N)^2} \tag{1}$$

$$Ea = \sqrt{(a - A_N)^2} \tag{2}$$

$$Eb = \sqrt{(b - B_N)^2} \tag{3}$$

Table 3. The absolute error of the experiment



		Absolute Error		
		x-X_N [mm]	a-A_N [°]	b-B_N [°]
1	DBRF1	0.001	0.000	0.001
2	DBRF 2	0.214	0.022	0.013
3	DBRF3	0.072	0.026	0.006
4	DBRF4	0.272	0.027	0.011
5	DBRF5	0.744	0.009	0.003
6	DBRF6		0.002	0.011
7	DBRF7	0.227	0.022	0.011
8	DBRF8	0.027	0.027	0.005
9	DBRF9	0.250	0.029	0.012
10	DBRF10	0.688	0.010	0.002
11	DBRF11	0.060	0.000	0.003
12	DBRF12	0.257	0.024	0.009
13	DBRF13	0.008	0.027	0.007
14	DBRF14	0.251	0.028	0.008
15	DBRF15	0.681	0.011	0.002
	Mean	**0.268**	**0.018**	**0.007**
	Standard deviation	**0.257**	**0.011**	**0.004**

The absolute errors are also presented in graphs. Figure 9 shows the graphical results of the error for the translation in *x* and angle of *a*, *b*. Observing the plotted data, it is possible to notice that the variation is smaller than one millimeter and smaller than one degree, respectively.

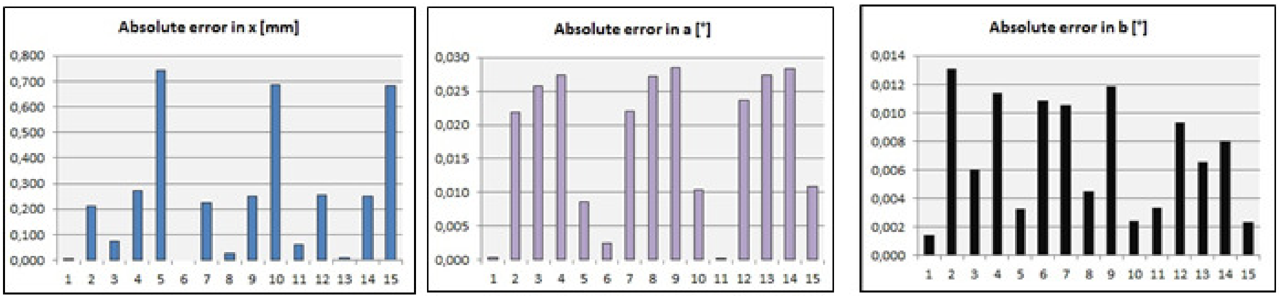


Figure 9. Graphical analysis of the data

Using the standard deviation of DBRF and the mean of DBRF of the components *x*, *a*, *b*, its possible to conclude that distance and angle variation of the geometrically coupled movements of the robots is very small. The replicates 5, 10 and 15 are related with the point P5, where a command of geometric decoupling was executed before the robots reach P5. That could be the reason for a bigger variation in the component *x* of the DBRF results at point P5.

4. CONCLUSIONS

The cooperating robots assembly cell is suitable for complex assembly tasks and for carrying heavy workpieces in an automatic assembly cell. It provides a flexible solution but it is also necessary advanced level of knowledge in robot programming to implement the applications.

The experimental results suggest that the automatic system with two cooperating robots is suitable for riveting process. The development of new experiments with the next steps of inserting fasteners process is necessary to assure the capability of the process to fulfill all the requirements of the aircraft assembly process. A new approach of the data collected in the experiment can be carried out for detecting if the geometric decoupling affects the relative position between coupled robots. The experiment developed can be repeated for another fixture of a fuselage part and in another local of the assembly cell, according with the real application in an industrial cell.

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5. RESPONSIBILITY NOTICE