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# Conceptual Design and Control Strategy of a Robotic Cell for Precision Assembly in Radar Antenna Systems

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**Abstract**

Dip-Brazing is a metal-joining process in which two or more metal items are joined together using a low-temperature melting element as filler. In telecommunication field, this process is used to fabricate radar antenna systems. The process begins with the assembly of the parts constituting the antenna and the thin filler sheet used to join the parts. The mechanical deformations of the micro-pins of the parts allow to obtain a more compact mechanical assembly, before than the antenna system is subjected to an immersion cycle used for adjoining the parts. In this work, we present the design of the robotic cell to automate the assembly procedure in the aluminum dip-brazing of antenna in MBDA missile systems. In particular, we propose a robotic cell using two stations: i) assembly, using a SCARA manipulator; ii) riveting, using a three-axis cartesian robot designed for positioning a radial riveting unit. Motion control of the robots and scheduling of the operations is presented. Experiments simulated in a virtual environment show an almost perfect tracking of the designed trajectories. The standardization of the procedure as well as the reduction of its execution time is thus achieved for the industrial scenario.


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*Keywords:* radar antennas; manufacturing automation; robotic assembly; industrial robots; motion control.

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## 1. Introduction

A precise assembly of radar antenna systems (RAS) is a crucial step towards the efficient transmission and reception of signals [1]. The challenge in this procedure is due both to the small scale of the involved mechanical components and the high precision and accuracy required by the field.
The industrial scenario behind this work is the manufacturing of RAS in MBDA[1]. Here, the current procedure to fabricate RAS involves a DIP-Brazing process to join the micro-mechanical components which will constitute the final system.
The DIP-Brazing process [2] joins two or more pieces of metal by means of flowing a filler metal between the joint interfaces at a temperature below the melting point of the base metal, but above 900°F. The filler metal, upon cooling to the solid state, forms a strong metallic bond throughout the joined area. In aluminum parts as RAS, the filler metal is 88% aluminum and 12% silicon. The parts to be brazed, after a chemical washing, are assembled together with the filler metal preplaced as near the joint as possible. The assembly is then preheated in an air furnace up to 1025°F to insure uniform temperature and after it is immersed in a molten salt bath at 1095°F for the actual joining. The last operation is a washing, used to remove the salt on the assembly.
As we can see in Fig. 1, the current procedure implemented in MBDA for aluminum DIP-Brazing of RAS involves three phases:

1. Preparation of the components and their chemical washing.
2. RAS assembly, divided in two phases:
   i. mounting
   ii. riveting
3. Cycle of heating, immersion and washing.

Since step 2 is manually performed by an expert operator, in this work we present the automatization of this phase by means of autonomous systems. We develop a robotic cell which articulates in two components, one for mounting the micro-mechanical components and one for riveting the pegs foreseen by the components design. This is a crucial step towards the achievement of a suitable assembly ready for the subsequent cycle of heating, immersion and washing.

From now on, we indicate with *Part A* and *Part B* a simplified model of the components to be joined and with *Filler Part* the thin sheet of metal that constitutes the filler. The real drawings and CAD models of RAS and components are the sole property of MBDA, thus in the following simulations we refer to simplified models.

The rest of the paper is organized as follows. In the remaining part of this section we report the related works in mounting and riveting which leveraged our design choices in the development of the robotic cell. Section 2 explains the methodology used to develop the robotic cell, whose design and control are presented in Section 3 and 4. Section 5 shows the simulations of the controlled systems constituting the robotic cell and presents the results. Section 6 concludes the paper and discusses future developments.

### *1.1. Related work and technologies*

The mounting of micro-mechanical components using robotic systems and grippers in different manufacturing scenario is a well-known subject in literature [3-8].
Currently, the most used industrial robots for assembly operations are: SCARA robots, for their selective compliance in the vertical plane [9]; six-axis robots, for their flexibility [10]; delta parallel robots (four and six-

[1] http://www.mbda-systems.com/

axis), for their rapidity [11]. In this work, we use SCARA robot for its reliability and accuracy in peg-in-hole assembly procedures [12]. This choice was also supported by a group decision making session [13].

Riveting operations consist of applying a certain force in order to mechanically deform pegs using special tools [14]. In our scenario, the riveting process enhances the assembly of the RAS thanks to the mechanical deformations of pegs. Currently, apart from the classical process similar to a mechanical stroke, two riveting processes are available: (1) orbital riveting; (2) radial riveting. Riveting machines are composed by a tool and tool-holder. In the orbital riveting, the axis of the tool describes an angle with respect to the axis of the tool-holder, such that the peg to deform is located in the intersection of both axis: this intersection defines the vertex of a cone, whose lateral surface is described by the movement of the axis of the tool. The total movement results a variable oscillation without rotation. More complex is the epicycloid movement described by a radial riveting tool, which ensures a more homogeneous deformation of the pegs. Radial riveting guarantees a higher quality of the forming process, at the expense of higher costs for the tools and less time for the overall operation. Since our scenario is of added-value manufacturing, we propose to use radial riveting to form the pegs in RAS assembly.

The main contribution of the present work is to enhance the RAS assembly in MBDA by presenting a conceptual solution to design and control of a robotic assembly cell. This solution derives from different design choices discussed in the paper. We carry forward the development of the industrial case study using the methodology proposed in the next Section.

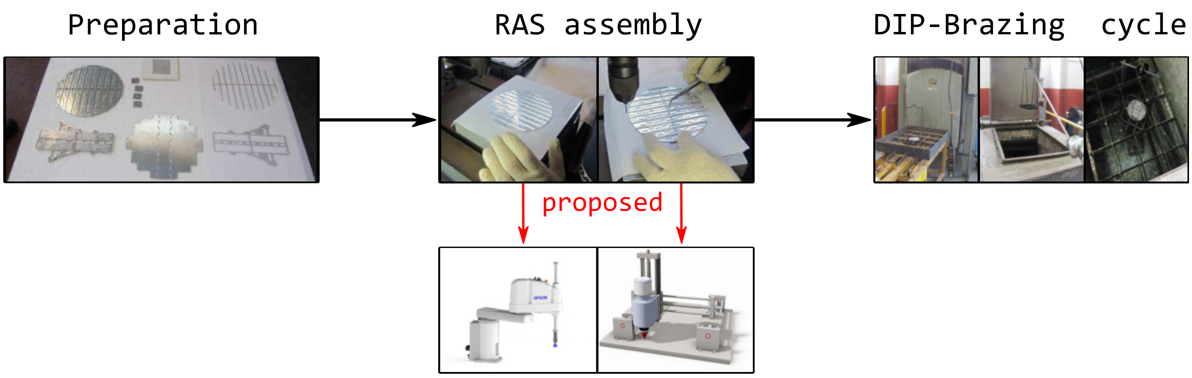



Fig. 1. Industrial scenario of the work: the manufacturing of radar antenna systems in MBDA.

## 2. Methodology

The methodology adopted in this work for developing mechatronic systems is shown in Fig. 2. In this approach, the mechanics, designed using computer-aided design (CAD) software, interfaces and interacts with the actuators and the control systems, designed using MATLAB/Simulink®. A virtual environment is used as graphic support system for the simulations. The method articulates in two steps:

- High level, which consists in: (a) designing the robotic cell, whose components can be either designed ad-hoc or chosen from those available in literature and market; (b) designing the layout of the cell; (c) scheduling of operations. The objective of this phase is the development of the trajectories for mounting and riveting processes. In this phase, we use classical CAD software (Solidworks®) for the design of components and V-REP® for designing the layout of the robotic cell.
- Low level, consisting in developing, for the robotic manipulators, closed-loop controllers and driving systems able to ensure the execution of the trajectories previously designed. In this phase, we use

MATLAB/Simulink® environment and the SimScape Multibody™ toolbox, a powerful tool for the dynamic analysis.

V-REP® is a virtual environment which offer the possibility to: (1) use MATLAB/Simulink® as client to implement controllers thanks to the *remote API* functionality; (2) import the CAD of the mechanical components and the robotic systems; (3) design the layout of the cell; (4) plan the motion for the robotic systems; (5) add sensors in the scene; (6) provide visual feedback about the overall simulation.

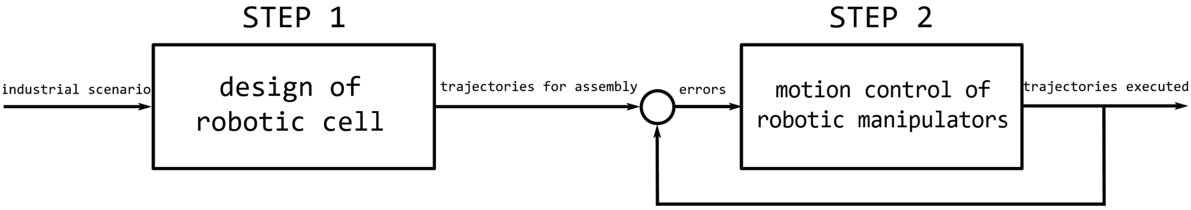



Fig. 2. The design methodology used in this work, based on an integrated CAD-MATLAB/Simulink® approach.

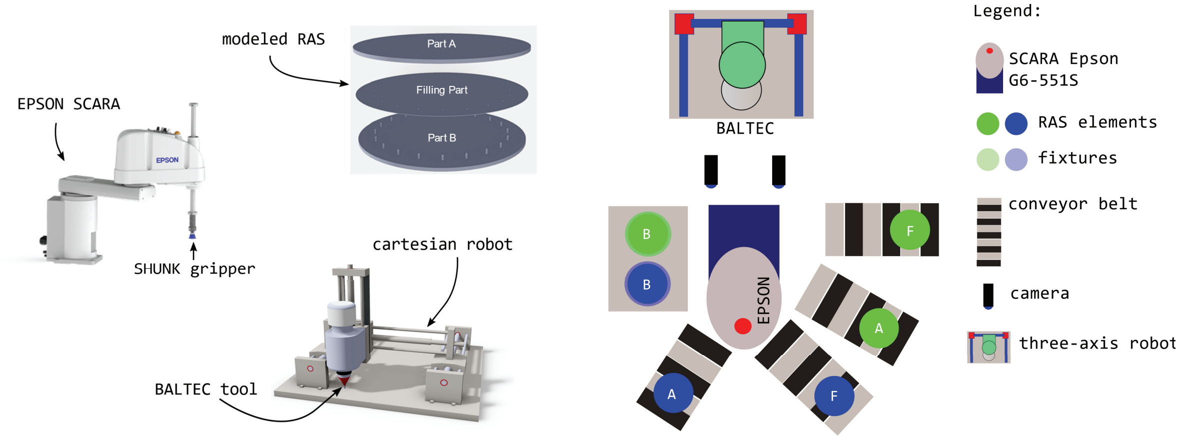
## 3. Robotic Cell Design

The robotic cell is composed by two stations, one for mounting and one for riveting the RAS. The mounting station articulates in one EPSON G6-551S SCARA[1], a four-DoF robot composed by three revolute joints and one prismatic joint, equipped with four SGMAS Yaskawa AC servo drives[2] and one SHUNK GSW-M 20[3] magnetic gripper system. Riveting station articulates in one three-axis gantry robot designed ad-hoc and one BALTEC RNE 081[4] radial riveting unit. One CMOS Mako U-503B[5] machine vision camera is placed in the cell. Robotic cell components are depicted in Fig. 3a, while Fig. 3b shows its layout.

The design of the cell is flexible, in the sense that it can accommodate whatever typology of RAS. Each RAS is modeled with two components, one presenting holes (*Part A*) and one presenting pegs (*Part B*). These parts need to be joined using the filler sheet metal (*Filling Part*). Part B is in a fixed position, mounted on its fixture system: the SCARA robot, in two five-seconds tasks, mounts on it first the Filler Part, then the Part A. These parts are transported by different conveyor belts. The layout shown in Fig. 3b accommodates the mounting of two different RAS, as illustrated by the different colors. A camera detects which RAS needs to be mounted based on the corresponding Part A and Filler A which arrive at that moment. The overall process is supervised by a human operator: when a RAS is mounted, she/is moves it under the riveting unit, which provides to the corresponding forming process.

The trajectories for the assembly procedures have been designed in the V-REP simulation environment, in terms of positions and orientations for the end-effector of both robotics manipulator, respectively the gripper and the riveting unit. Starting from the points in the cartesian space, a Bèzier curve has been constructed: this interpolates the initial and final points of the trajectory, while the other points are considered as a via points.

[1] http://robots.epson.com/
[2] https://www.yaskawa.com/
[3] https://hu.schunk.com/
[4] http://baltec.com/
[5] https://www.alliedvision.com/




(a) (b)

Fig. 3. The robotic cell: (a) components; (b) layout.

## 4. Robotic Cell Control

In this section, we describe the motion control of both manipulators, the SCARA and the cartesian robot. Since the velocities in this scenario are relatively small, a good compromise between simplicity and effectiveness is represented by the independent joint control (IJC) scheme [15], a multivariable decentralized control technique.

This scheme is naturally effective for the cartesian robot where the three-axis are decoupled by construction. The validation of this scheme for trajectory tracking in industrial scenario for the SCARA manipulator can be found in [16]. We propose to use a double loop controller, one internal PI for velocities and one external P for position. This structure is mathematically equivalent to PID controller, but it allows to put a saturation for both velocity and position for the real motors, an advantage for implementation on real hardware. In Fig. 4 we can appreciate all the components of the controlled mechanical system: the reference trajectory $r$ obtained from the previous section, the inverse kinematics algorithm to map the reference trajectory $r$ given in the cartesian space to the desired positions $q_d$ in the joint space, the P+PI controller, the mathematical model of the actuators and the mechanical system. We use the closed loop inverse kinematics (CLIK) algorithm [17] for mapping the trajectories from the operative space to the joint space. This inverse kinematics block is present only for the SCARA manipulator, since the axis of the cartesian robot are already decoupled. Each servomotor has been modeled using the equations of motion described in [14] and illustrated in the dash-dotted box of the figure. The input for each joint of the mechanical system is a torque $\tau$; the outputs are the position $q$ and velocity $\dot{q}$ of the joint itself.

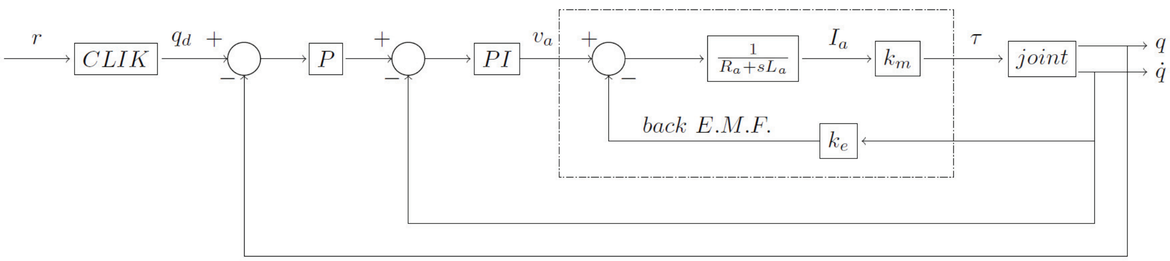



Fig. 4. The proposed system for controlling the motion of each joint of the manipulators in the robotic cell.

## 5. Simulations and Results

The robotic manipulators were controlled in MATLAB/Simulink, while the dynamical analysis was performed using SimScape Multibody™, a toolbox used to simulate the motion of rigid multibody systems. The SimScape solver constructs a system of differential algebraic equations (DAE) of motion where the bodies are modeled as rigid elements and the joints as algebraic constraints.

We first performed an inverse dynamic analysis for the non-controlled system. This analysis was conducted to set the forces (or the torques) required to produce the motion specified by the joint trajectories. The mass and inertial parameters of the rigid bodies have been estimated through the CAD models. The inverse dynamics of the three-dimensional cartesian robot was used to size the parameters of the actuators, since the desired joint trajectories are given by the RAS. Different is the case of the SCARA robot, for which we used the inverse dynamics to verify if the actuators of this manipulator are actually able to reproduce the planned trajectories. We sized the electric drives of the cartesian robot based on the maximum force required to move the vertical axis, which results the most stressed. For the SCARA manipulator, we consider the five seconds' trajectory to move Part A on Part B (blue RAS in Fig. 3b). The maximum torques required for all the trajectory are always lower than the rated torques of the actuators which drive the EPSON G6-551S. Thus, this manipulator is suitable for the assembly procedure. The actuators' parameters used in the simulations are listed in Tables 1 and 2.

The gains of the P+PI controllers have been tuned using the control system tuning available in Simulink. The system was numerically solved using a second-order Runge-Kutta time integration (by means of the *ode*23 function) with variable-step size. Figure 5 and 6 show the errors between the desired trajectories $q_d$ and the actual trajectories $q$ for the cartesian robot and SCARA manipulator. The results show almost zero errors for the overall simulated trajectories, thus a perfected trajectory tracking for the manipulators is achieved. Figure 5 illustrates the position errors for the three-axis of the cartesian robot while it executes the first four pegs riveting, as we can see from the vertical lines: the errors are exactly zero when the riveting unit approaches to the pegs. Figure 6 shows that the position errors go rapidly to zero for the SCARA manipulator.

Once that the control parameters of both systems have been tuned, V-REP environment has been used for simulating all the assembly of the RAS. A snapshot of the simulation is shown in Fig. 7. The result is that the simulated robotic assembly of a RAS with 20 pins takes 160 seconds in average, while the manual procedure lasts 15-20 minutes, and results operator dependent.

Table 1. Electric drive parameters of the brushless DC motors of the three-axis cartesian robot. $R_a$ = armature resistance [Ω]; $L_a$ = armature inductance [H]; $k_m$ = torque constant [Nm/A]; $k_e$ = voltage constant [rad/sV].

| Actuator | $R_a$ | $L_a$ | $k_m$ | $k_e$ |
|---|---|---|---|---|
| x, y, z | 1 | 0.005 | 1.3 | 1.3 |

Table 2. Electric drive parameters for the actuators of the SCARA manipulator. $R_a$ = armature resistance [Ω]; $L_a$ = armature inductance [H]; $k_m$ = torque constant [Nm/A]; $k_e$ = voltage constant [rad/sV].

| Actuator | $R_a$ | $L_a$ | $k_m$ | $k_e$ |
|---|---|---|---|---|
| $J_1, J_2$ | 0.99 | 0.0015 | 0.527 | 0.527 |
| $J_3$ | 0.5 | 0.0008 | 0.375 | 0.375 |
| $J_4$ | 0.3 | 0.005 | 0.375 | 0.375 |

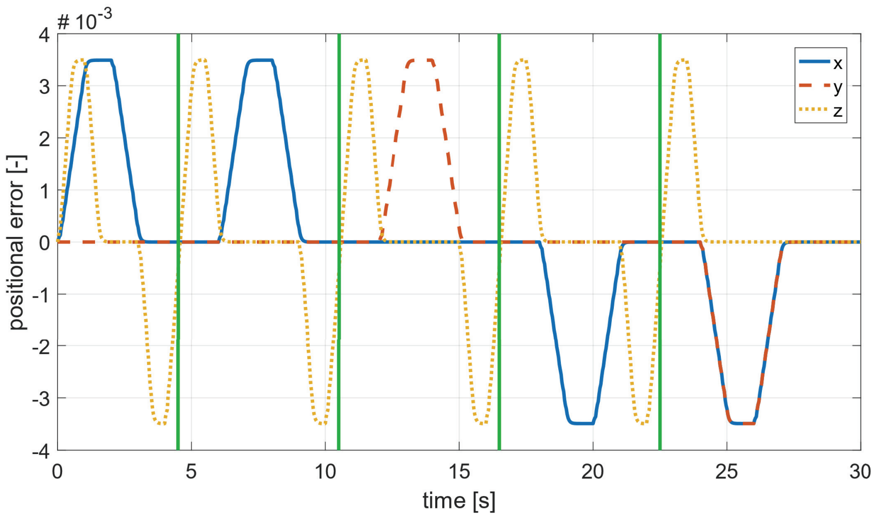



Fig. 5. Position errors along the three directions in the simulation of the first four pegs riveting for the cartesian robot. The vertical green lines correspond to the temporal instant of riveting. External controller: P = 1800. Internal controller: P = 100; I = 1.

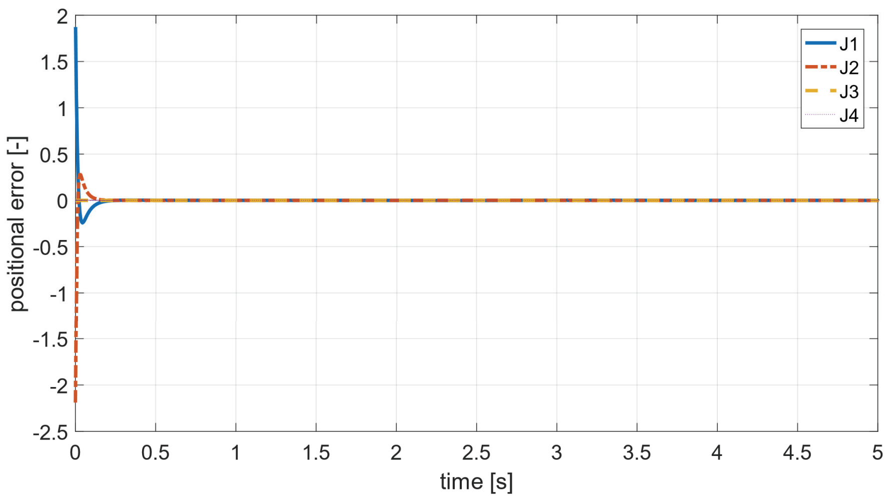



Fig. 6. Position errors for the joints of the SCARA manipulator. External controller: P = 2000. Internal controller: P = 200; I = 10.

## 6. Conclusions

A methodology to simulate controlled mechatronic systems is presented for the conceptual design of a robotic cell. The procedure involves an integrated approach wherein the mechanical design interacts with the control system design. The method was used in a real industrial scenario, the automation of the radar antenna systems' assembly in MBDA missile systems. We design the layout of a robotic cell for the assembly procedure and we control the motion of the involved manipulators using a decentralized approach. The results show a perfect tracking of the reference assembly trajectories and a significant reduction of the time used for the assembly procedure. Future works of this applied research will deal with the force control of the riveting unit during the deformation of the pegs.

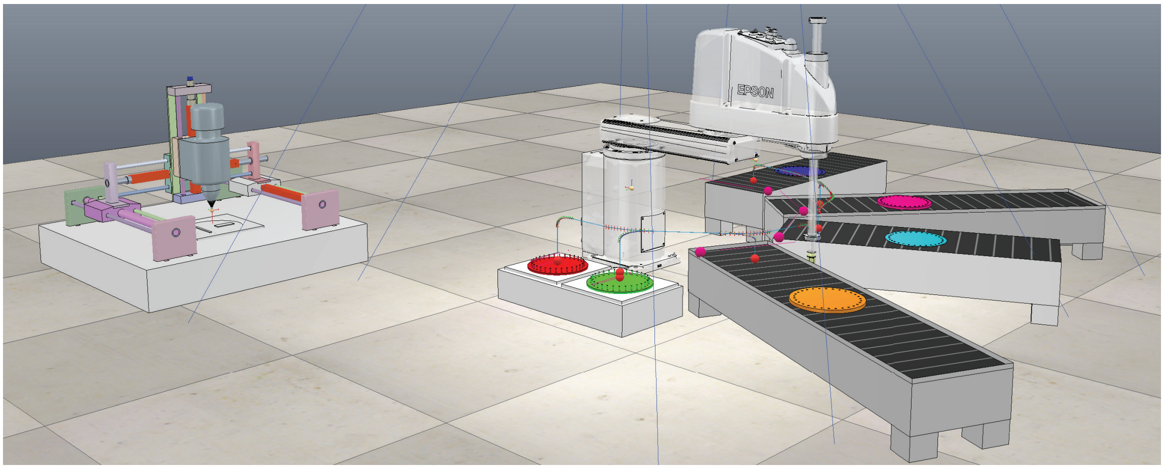



Fig. 7. Snapshot of the simulated robotic cell.

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