ROBOTIC WELDING CELLS STRUCTURE OPTIMIZATION

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Această lucrare tratează unele aspecte privind sudarea robotizată şi are ca scop să contribuie la optimizarea structurii celulelor robotizate pentru sudare (RWC). Se are în vedere optimizarea alegerii tandemului: robot industrial – componentă perirobotică. Pentru realizarea acestui obiectiv se efectuează, prin simulare în mediu virtual, un studiu de caz privind configurarea a doua structuri de RWC pentru o aplicație impusă. Se prezintă rezultate ale analizei mişcărilor executate pentru generarea traiectoriilor cordoanelor de sudură şi modul de scriere a programelor aferente sistemului de comandă a axelor de mişcare ale robotului industrial şi componentei perirobotice. Sunt stabilite recomandări utile în etapa de optimizare a configurarii unor astfel de sisteme industriale.

This paper refers to a set of aspects regarding the robotic welding process, the main objective being to contribute to the optimization of the Robotic Welding Cells (RWC) structure. The optimization method is based on the industrial robot – part positioner tandem. In order to accomplish this objective, a case study is performed through simulation in a virtual environment. It refers to the configuration of two RWC structures for an industrial application. A complex analysis is performed and some results regarding the welding trajectories are presented. More, a new approach for the robot and part positioner program code generation is developed and detailed. Finally, some recommendations are presented for the optimization stage of such industrial systems.

Keywords: Robotic Welding Cell, Industrial Robot, Structure Optimization

1. Introduction

The development of the world's industry in the latest decades and of the equipment fabrication has led to an extensive use of the industrial robots in the welding processes. Also, the improvement of the: machine parts, mechanical transmissions, driving engines, sensorial and control systems, has made possible the achievement of robots with high precision and dynamic performances. This led to an increase number of robotic welding applications [1].

The main functions of the welding robots are: kinematics, drive, control and programming. Depending on the technological processes and parameters of the welding regimes, the industrial robots must generate various trajectories, achieving discrete or continuous positions, with determined speeds or breaks,

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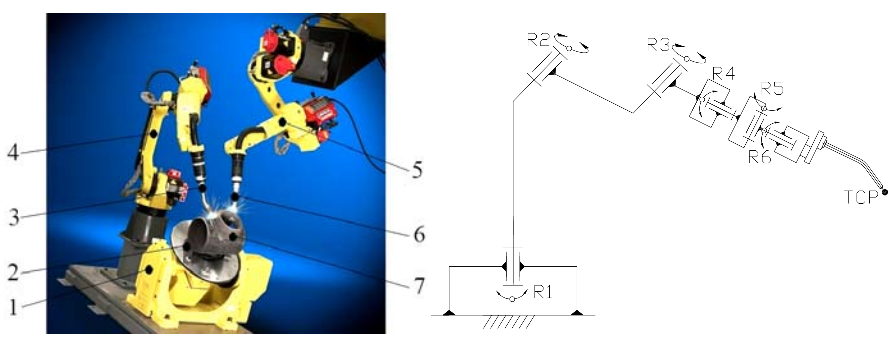
according to the information included in the work cyclograms and programs created in the system programming language [2]. In robotic electric arc welding, the kinematic capacity of six-axis robot is not often enough to achieve the optimum position and orientation of the end-effector [3]. The robot must move the welding gun along the welded joint at a certain speed and with a certain orientation, in relation with the welding cord. Also, in many cases, the parts to be welded must be positioned and oriented.

Due to these reasons, a flexible RWC must include, within its structure, one or more six-axis industrial robots, one or more part positioners with one, two or three axes, for the supplementary positioning and orientation of the welded assembly and, possibly, one or more manipulating robots, having two-three movement axes. All the components of such kinematic system must be controlled simultaneously, but, due to the complexity of the work program, the control of each element is made as a separate subprogram.

Fig. 1.a presents an example of electric arc welding – a welded valve body-type assembly (7), in a welding flexible cell, using two arm-type industrial robots (4 and 5) working in tandem. These are equipped with welding guns, using the MIG-MAG procedures (3 and 6). The welded assembly is attached using a device (2) on a part positioner component (1) which has two degrees of freedom. Also, Figure 1.b represents the kinematic structure of the robots, where all the types of movements of the couples are presented (R1 ... R6).



a. b.

Fig. 1. Robotic welding: *a*. RWC with two arm-type robots [4]; *b*. robot’s kinematics.

The welding technological process is robotized taking into account the following aspects [5]:

- accessibility of the welded head in the welded joints-generating space;
- positioning of the welding head must have a precision within the range $\pm 0,5...1$ mm;
- the tolerance of the parts making up the welded assembly should be of max. $\pm 0,5...1$ mm;

- the geometric differences between the welded parts, as well as their complexity, should be between certain limits;
- the surfaces to be welded should be clean and degreased;
- the determination of the welded parts reference system, depending on which it is positioned in the fixing device.

The construction of the industrial robots integrated in the structure of a welding cell should have the following technical characteristics [6, 7]:

- the number of the degrees of freedom necessary to obtain the mobility of the welding head in order to generate the trajectory of the welded joints; usually, for the robotic welding, arm-type robots are used, with 6 degrees of freedom;
- manipulation of the welding head; usually, the payload is of: 6…20 Kg;
- the dimensions of the work space correspond to the welding application;
- the stability of the mechanical structure of the robot during the execution of the movements;
- providing the repeatability precision necessary to position the tool center point (TCP – fig. 1.b) of the welding head;
- proper speed necessary to achieve various movements, continuously adjustable within the range $0 \div 2{,}5$ m/s.
- In the RWC domain, the requirement to maximize the technical performances and to minimize the production costs has led to the need to optimize the RWC structure [7]. From the design experience, one knows that a variant of a welding cell is better than another only when it satisfies better a set of criteria. The specific activity optimization for a RWC may be the result of a better integration of the technical and logistic components, as well as of the human operator.

2. RWC Structure Configuration

The structure configuration of a RWC is determined mainly by: the shape and size of the parts to be welded, the dimensions and complexity of the trajectories of the welding cords necessary to be generated, the type and diversity of the actual and future production, the parameters of the technological process, the productivity, the flexibility and the required automation degree [5, 8]. Based on the analysis of those aspects, one can define the robot's functional performances, the feeding/evacuation devices of the welded parts, the welding equipment, the parts orientation and fixing device, the total length of the joints to be welded in a work station, the geometry and spatial position of the joints, as well as the role of the human operator.

Within the structure of a RWC, in a general approach, the following elements are necessary [7]:

- one or more robots to generate the trajectory of the welding head;
- one or more part positioners for the supplementary positioning and orientation of the assembly to be welded, chosen depending on the shape and dimensions of the parts, on the lengths, complexity and positions of the welded joints, on the simultaneous execution, or not, of the auxiliary operations;
- one or more fixing devices for the assembly to be welded;
- one or more systems for the industrial robot positioning, which should provide optimum access of the welding point in the area of the welding cords and/or to extend the robot's work space;
- the welding equipment selected as a function of the necessary welding procedure, composed of: welding source, electrode-wire advancing system, welding heads, welding head's calibration and cleaning system, cylinder and systems for the distribution of the gas making up the protective environment, equipment for the control of the welding process parameters, exhausting system, auxiliary equipment;
- the control system which connects and commands all the components of the welding cell;
- protection systems: protective panels, optical barriers for the access of the human operator.

In order to deal with the RWC structure configuration, the main objective should be fulfilled: to define the best cost/performance ratio. The optimum configuration is defined based on some optimization criteria [7, 9].

The mathematical modeling of the RWC structure optimization needs a detailed description of the process, as well as of the optimization criteria. In this regard, mathematical relations describing the interdependencies between the variables of the process are established in [9, 10].

The technological and economic requirements turn into mathematical approaches, noting with x_j, $1 \leq j \leq n$, the variables, unknown initially, which represent the levels where the n activities taken into consideration by $f(x_1, x_2, ... x_n)$, target or optimization function [7, 10] should be performed.

The optimum solution is reached through the calculation of the x_j, variables, so the function $f(x_1, x_2, ... x_n)$ should have the maximum value:

$$\max f(x_1, x_2, \ldots, x_n). \tag{1}$$

The optimization of a welding cell is a particular case of adaptability, aiming at obtaining the highest level of one or several performances. Taking into account the complexity of the mathematical model, the solving method is not always easy. In this case, one should use an algorithm for the RWC structure optimization as shown in the Figure 2 [7].

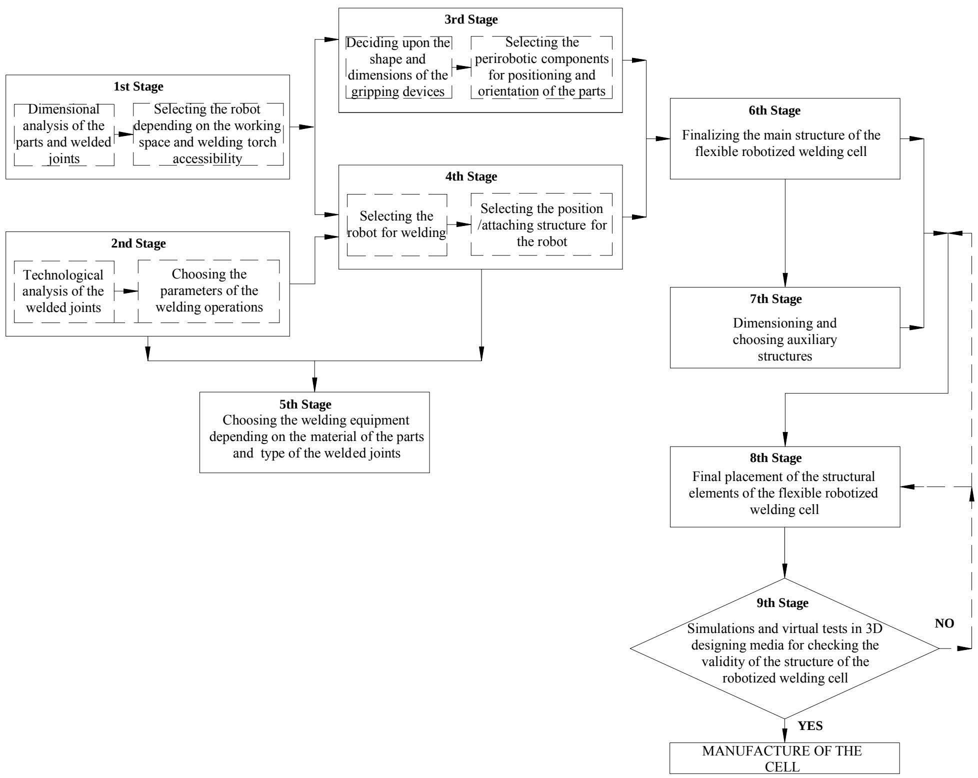


Fig. 2. RWC configuration algorithm [7].

In order to configure the RWC structure, virtual simulation programs are used [11, 12], reducing thus the total cost of setting up and integrating the robotized system into production systems, the work tasks being finalized more efficiently [13, 14].

3. Case study

3.1. Application description

The proposed application presents a case study which compares two RWC variants, distinct from the point of view of the integrated part positioner systems. The trajectories generation program is analyzed.

The welding cell structure configuration is reached using an offline virtual simulation, with the Fanuc RoboGuide program [4]. This allows the take-over of the data regarding the welded parts, the testing of generating the trajectories of the welding cords, the accessibility of the welding head and the collisions detection between the robot’s arm and the components of the welding cell. After simulation, the layout of the robotic cell is generated, as well as the time of the working cycle and the code of the program, which will be sent to the real welding cell controller [15].

The application consists in welding an assembly, gas cylinder-type, represented in Figure 3, achieved in two variants of robotic cells. It is necessary to generate three special circular welding cords (weld joint 1, 2 and 3).

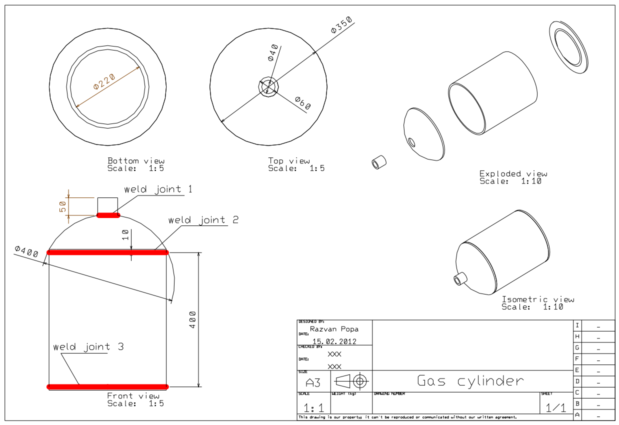


Fig. 3. Welded assembly – gas cylinder type.

3.2. RWC Structure Determination

Considering the above aspects and following the RWC structure configuration algorithm [7], in this section two RWC variants with "stand alone"-type automation [16] and one work station are presented. The robot integrated in the cell structure is Fanuc ARC Mate 100iC, disposing of the "hollow wrist" system. The technical data of the robots are presented in Table 1 below:

Table 1

Fanuc ARC Mate 100iC Robot Specifications [4]

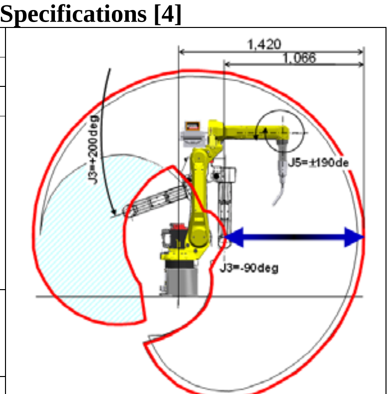
Axes		6	
Payload		10 Kg	
Reach		1.420 mm	
Motion range/speed	Axis J1	360° / 210°/s	
	Axis J2	250° / 190°/s	
	Axis J3	445° / 210°/s	
	Axis J4	380° / 400°/s	
	Axis J5	380° / 400°/s	
	Axis J6	720° / 600°/s	
Wrist Moments	Axis 4	22 Nm	
	Axis 5	22 Nm	
	Axis 6	9,8 Nm	
Mechanical weight		130 Kg	
Repeatability		+ / - 0 ,08 mm	Fig. 4. Robot's working space

Fig. 5 represents the main structure of the RWC, modeled using the Fanuc RoboGuide program, having the dimensions 6000 x 6000 mm. It is made of standard components and has the following configuration:

- Fanuc ARC Mare 100iC (6) industrial robot with: electrode-wire advancing system (10), electrode-wire drum (11) and welding gun for the MIG-MAG procedures, Abirob A360 model;
- fixed table-type part positioner system or with two degrees of freedom (7), provided with fixing and catching device (9);
- robot's over-lifting support (12) to facilitate the access of the welding head into the welding cords' generating space;
- welding source (3) with the MIG-MAG procedures, FRONIUS model, microprocessor controlled;
- gas cylinder (2) to achieve the protective environment;
- welding head's cleaning and calibration system (5);
- central processing unit-type control system (8);
- emissions exhausting and ventilation system (4);
- protection fence (1), with access door for the human operator.

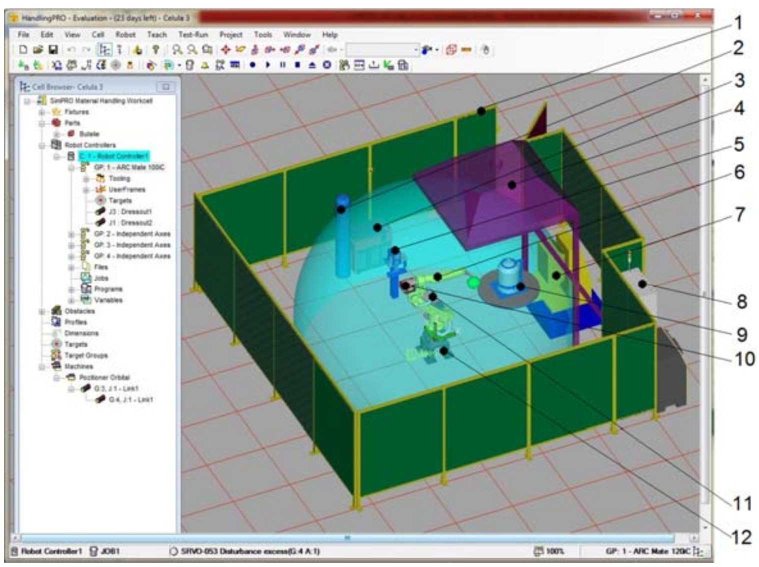


Fig. 5. RWC structure configuration for the gas cylinder welding.

3.3. Experimental study

The trajectories generation depends on a series of factors, such as: type of robotic application, restrictions existing in the work space, mechanical characteristics of the robot and of the part positioner system [5, 15]. The control of the movement axes is achieved offline, defining first the movement trajectory in conformity with the technological requirements indicated by the specialist in technology.

The variants of the modeled RWC, from the point of view of the industrial robot – part positioner tandem, are the following:

- 1st variant: Fanuc ARC Mate 100iC articulated arm-type robot – fixed table-type part positioner system;
- 2nd variant: Fanuc ARC Mate 100iC articulated arm-type robot – orbital-type part positioner system with 2 degrees of freedom.

For the application proposed by the 1st Variant (fig. 6) – the assembly to be welded is fixed, using a device, on a working table attached to the soil. The movements necessary to generate the trajectories of the welding cords are executed exclusively by the industrial robot. Figure 6 represents the path of the robot's characteristic point and the specification of the spatial points stored in the trajectory's programming stage.

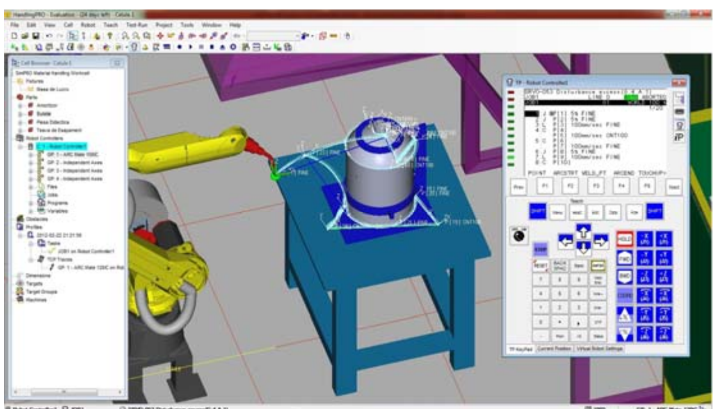


Fig. 6. Trajectory and spatial points stored by the robot within the cell, in the 1st variant.

Table 2 below presents the simplified version of the program created with the trajectory's programming function "Teach Pendant" of the Fanuc RoboGuide software, in order to generate the three cylinder's welding cords (fig. 3).

Table 2

Program for the trajectories generation on the 1st variant of the welding cell

```
/PROG  JOB1
/ATTR
OWNER         = MNEDITOR;
COMMENT             = "";
PROG_SIZE     = 2202;
CREATE        = DATE 12-02-15  TIME 13:11:14;
MODIFIED      = DATE 12-02-15  TIME 14:00:54;
FILE_NAME     = ;
VERSION       = 0;
LINE_COUNT    = 19;
```

Table 2 - continuation

```
MEMORY_SIZE  = 2494;
PROTECT            = READ_WRITE;
TCD:  STACK_SIZE    = 0,
      TASK_PRIORITY = 50,
      TIME_SLICE    = 0,
      BUSY_LAMP_OFF = 0,
      ABORT_REQUEST = 0,
      PAUSE_REQUEST = 0;
DEFAULT_GROUP = 1,1,1,1,*;
CONTROL_CODE = 00000000 00000000;
/APPL
  ARC Welding Equipment : 1,*,*,*,*;
/MN
   1:J P[1] 5% FINE    ;
   2:J P[2] 5% FINE    ;
   3:L P[3] 100mm/sec FINE
    :  Arc Start[1]    ;
   4:C P[4]
    :  P[5] 100mm/sec CNT100    ;
   5:C P[6]
    :  P[7] 100mm/sec FINE
    :  Arc Stop[1]    ;
   6:J P[8] 5% FINE    ;
   7:L P[9] 100mm/sec FINE
    :  Arc Start[1]    ;
   8:C P[10]
    :  P[11] 100mm/sec CNT100    ;
   9:C P[12]
    :  P[13] 100mm/sec CNT100
    :  Arc Stop[1]    ;
  10:  WAIT   1.00(sec) ;
  11:J P[14] 5% FINE    ;
  12:L P[15] 100mm/sec FINE    ;
    :  Arc Start[1]    ;
  13:C P[16]
    :  P[17] 100mm/sec CNT100 Wjnt
    :  Arc Stop[1]    ;
  14:L P[18] 100mm/sec CNT100 Wjnt    ;
  15:L P[19] 100mm/sec CNT100    ;
  16:L P[20] 100mm/sec FINE
    :  Arc Start[1]    ;
  17:C P[21]
    :  P[22] 100mm/sec FINE
    :  Arc Stop[1]    ;
  18:J P[23] 5% FINE    ;
  19:J P[1] 5% FINE    ;
/POS
/END
```

Remarks:

- the period of the working cycle is long: 81 sec, which leads to a low productivity of the RWC;
- to generate the welding cords 2 and 3, the RI axes are very stressed, and

the mechanical structure of the robot must reach its limit positions;

- to generate the welding cord 3, the robot would occupy a singularity position, thus being forced to change its spatial configuration; due to this reason, the generation of the welding cord 3 is not executed continuously;
- the ideal position of the welding gun, computed using the specifications of the welded joint and process parameters, is, generally, difficult to reach;
- for the welded joints trajectories generation, the robot's controller should be able to store a great number of intermediary points (23 points);
- the program contains the 23 stored spatial points P[1] ... P[23], it has a size of 3463 characters and requires a relatively long writing time;
- all the 23 spatial points on the generated trajectory are stored by the robot's controller (GP1);
- the welding equipment receives the command *:Arc Start [1]*, after the points P[1]...P[3];
- in the programming stage, the generation of the cords 1 and 2 between the procedures *:Arc Start [1] - :Arc Stop [1]*, it is necessary to store four spatial points P[4] ... P[7] and, P[10] ... P[13];
- in order to generate the cord 3, due to the robot's singularity position, two sets of instructions are necessary *:Arc Start [1] - :Arc Stop [1]*, so that the electric arc is stopped and resumed, being started again.

2nd Variant – the cylinder is fixed, using a device, on an orbital rotating part positioner system with two degrees of freedom: Roll-type movement and Pitch-type movement. The movements necessary for the welded joints generation are executed by the industrial robot in tandem with the part positioner system, thus requiring simultaneous control of the eight digitally controlled axes. Figure 7 represents the path of the robot's characteristic point and the specification of the stored points, in the stage of writing the control program.

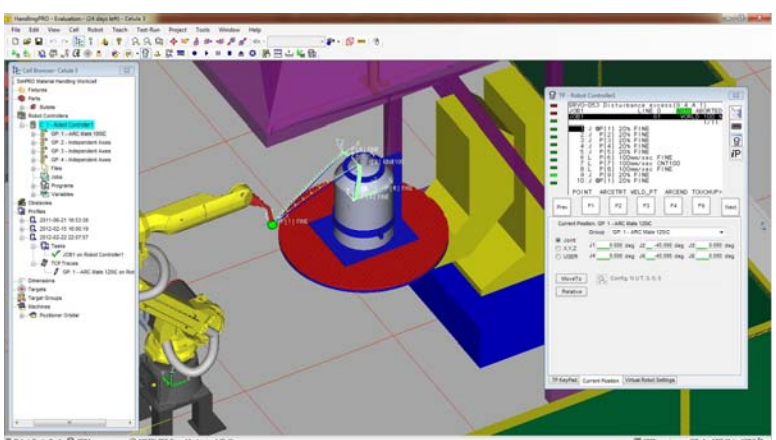


Fig. 7. Trajectory and spatial points stored by the robot within the cell of the 2nd variant.

Regarding the 2nd variant of RWC, the program created with Fanuc RoboGuide, in order to generate the three welding cords necessary to obtain the cylinder, is presented in the Table 3 below.

Table 3

Program for generating the trajectories on the 2nd variant of the welding cell

```
/PROG  JOB3
/ATTR
OWNER         = MNEDITOR;
COMMENT              = "";
PROG_SIZE     = 1154;
CREATE        = DATE 12-02-15  TIME 15:47:12;
MODIFIED      = DATE 12-02-15  TIME 15:59:36;
FILE_NAME     = ;
VERSION              = 0;
LINE_COUNT    = 10;
MEMORY_SIZE   = 1482;
PROTECT              = READ_WRITE;
TCD:  STACK_SIZE    = 0,
      TASK_PRIORITY = 50,
      TIME_SLICE    = 0,
      BUSY_LAMP_OFF = 0,
      ABORT_REQUEST = 0,
      PAUSE_REQUEST = 0;
DEFAULT_GROUP = 1,1,1,1,*;
CONTROL_CODE  = 00000000 00000000;
/APPL
  ARC Welding Equipment : 1,*,*,*,*;
/MN
   1:J P[1] 20% FINE    ;
   2:J P[2] 20% FINE
    :  Arc Start[1]    ;
   3:J P[3] 20% FINE
    :  Arc Stop[1]    ;
   4:J P[4] 20% FINE    ;
   5:J P[5] 20% FINE
    :  Arc Start[1]    ;
   6:L P[6] 100mm/sec FINE
    :  Arc Stop[1]    ;
   7:L P[7] 100mm/sec CNT100    ;
   8:L P[8] 100mm/sec FINE
    :  Arc Start[1]    ;
   9:J P[9] 20% FINE
    :  Arc Stop[1]    ;
  10:J P[1] 20% FINE    ;
/POS
/END
```

Remarks:

- shorter working cycle: 64 sec;
- in the program writing step, in order to generate the trajectories, it is necessary to store a reduced number of spatial points, specifically 9 (P[1]

... P[9]), the size of the source program for the controller being smaller: 2080 characters;
- for each spatial point stored, in the program necessary to generate the trajectories, the movements of the industrial robot (GP1) and those of the part positioner system are separately programmed for each axis: GP2 – Roll axes and GP3 – Pitch axes;
- the command *:Arc Start [1]*, is transmitted to the welding equipment, after the storing step of the points P[1] and P[2];
- to program the welding cords generation, between the procedures *:Arc Start [1] - :Arc Stop [1],* it is necessary to store one spatial point P[3], P[6] and, respectively, P[9] for each welded joint;
- the set of instructions *:Arc Start [1] - :Arc Stop [1]* must be introduced in the working program three times, once for each welding cord;
- to generate three welding cords, the robot places the effector's characteristic point in a fixed point and the rotation movement necessary to make the circular joint is executed by the part positioner system;
- to generate the cylinder's welding cord 1, only one rotation movement is used to additionally place and orient the part positioner system, specifically the Roll movement, and, in order to generate the welding cords 2 and, respectively 3, beside the robot movements, both rotation movements of the part positioner system are used (Roll-type and Pitch-type rotations), the part being oriented at 90^0 to the horizontal plan;
- the ideal position of the welding gun is reached easily (horizontal welding for the cords 2 and 3), which confers a better quality of the welding cords, also disappearing the danger of the melted material flowing.

3.4. Results

Subsequent to the analysis of the two RWC variants, differently configured for the achievement of the welded gas cylinder-type assembly, the following conclusions can be drawn:
- the productivity of the welding cell is higher if the generated trajectories for the welded joints are executed through a combination of the robot movements with those of the part positioner system, thus a 26.5 % time reduction, afferent to the working cycle, is obtained;
- in order to program the necessary movements for the welded joints (trajectories generation), made by combining the movements of the robot with those of the part positioner system, the controller should store a reduced number of intermediary spatial points; the path of the characteristic point is shorter compared to the situation when the movements are executed by the robot only; the size of the resulted

program is reduced and it requires a shorter writing time;

- if the movements necessary to generate the trajectories are executed by the robot only, it is unable to continuously generate the welded joints, which leads to additional steps of starting and stopping the electric arc; more, supplementary instructions are included in the main program *:Arc Start [1] - :Arc Stop [1]*;
- regarding the welding cell variants, where the movements for the trajectories generation are executed by the industrial robot and by the part positioner system, one should note that each axis will be programmed separately (individually);
- the quality of the resulted welded joints is better when the positioning of the welding head (in space) is performed by combined movements of the industrial robot in tandem with the movements of the part positioner system because it is possible to properly orient the welding head.

Another conclusion of the presented analysis is that the performances are directly proportional to the cost of a robotic cell.

4. Conclusions

The optimum configuration of a RWC structure and the optimization of the movements of the industrial robot and part positioner system are achieved through the optimization of the welding working cycle and of some process parameters which have a strong influence on the welded assembly.

The movements of a six-axis industrial robot are not always enough to achieve the optimum positioning and orientation of the welding gun in the welding cord generating space. Depending on the complexity of the welding cords, it is necessary to integrate, within the structure of the welding cell, a part positioner system with one, two or three degrees of freedom, necessary for the supplementary positioning and orientation of the welded assembly.

Combining the movements of the industrial robot and of the part positioner system, high quality welded joints and higher cell productivity are obtained, decreasing the times of the working cycle. Also, it is necessary to store, within the structure of the program code, a reduced number of intermediary spatial points, placed along the path of the robot's characteristic point, the resulting program having a reduced writing time and reduced size.

When we try to achieve the optimum structure of a RWC, from the point of view of performances and cost, we will find out that the performances are directly proportional with the cost of a robotic cell. The optimum structure of the welding cell means to find the optimum cost – performances ratio.

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