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Multi-robot spot-welding cells: An integrated approach to cell design and motion planning

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ABSTRACT

The necessity to manage several vehicle models on the same robotized assembly cell has made the cell design and the robot off-line motion planning two fundamental activities. Industrial practice and state-of-the-art methods focus on the technical issues of each activity, but no integrated approach has been yet proposed, resulting in a lack of optimality for the final cell configuration. The paper introduces a formalization of the whole process and proposes a heuristic multi-stage method for the identification of the optimal combination of cell design choices and motion planning. The proposed architecture is depicted through a real case for welding application.

1. Introduction

Over the past 20 years, the automotive market has been characterized by the need of responding to an increasing demand of different models, generating a large diversity of market segments. In the US market, the number of vehicle models doubled from 1980 to 1999, reaching 1050 different models in 2000. At the same time, the worldwide market competition among original equipment manufacturers (OEMs) has led to production capacity saturation in order to reduce production costs [1]. As a result, the automotive industry has moved towards assembly of different vehicle models on the same assembly line through flexible and reconfigurable robotized cells [2,3].

The race towards flexible and reconfigurable robotized assembly cells has been confirmed by the increasing number of worldwide robot installations in the automotive sector that reached, in 2011, 36% of worldwide new robot installations. Specifically, the majority of these installations were devoted to spot welding applications [4] for body-in-white assembly. As depicted in [5], body-in-white assembly cells perform the complete assembly of all the components of the lower and upper body of the car and implement the joining process through multiple welding robots. Spot welding applications [4] for body-in-white assembly will be considered through the paper as a reference scenario.

In this context, the design of multi-robot cell and off-line robot motion planning has become essential. While flexibility, reconfigurability and investment cost are more related to cell design, productivity (i.e. cell cycle time) and production costs are strongly affected by robot motion planning [6–8]. Specifically, on the one hand, preliminary design of multi-robot spot-welding cells covers only the selection and the allocation of resources in term of “which”, “where”, “how many” robots and tools (i.e. welding guns) are needed. On the other hand, off-line motion planning for multi-robot cells optimizes the allocation of welding points to the robots as well as connecting trajectories. However, the mutual-influence of the multi-robot cell design and motion planning cannot be ignored: indeed, an inappropriate cell design could lead to infeasibility of the motion plan, while the motion plan can make the production rate of a cell unacceptable.

Thus, it is quite surprising that according to industrial practice, multi-robot cell design and off-line motion planning are still two time-consuming sequential activities, carried out by different specialists using several methodologies and software tools. The separation of these activities leads to several iterations and up to 14 weeks of work. Indeed, each loop causes delays and potential accumulated errors that could be avoided by integrating the cell design and off-line motion planning activities. This separation of the activities is partially justified by (i) the complexity of the two steps that represent a barrier for straightforward optimal solution, and (ii) the multi-disciplinary activities and research fields required. The separation of multi-robot cell design and off-line motion planning that characterizes the industrial practice can also be identified in the literature, where the integration between the two activities has not been adequately investigated so far. For instance, in [5] it is proposed a methodology to reduce the total design time, but the motion planning issue is not tackled. Motion planning and collision problems are partially taken into account in [9] where an approach for the design of a cell with cooperating

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robots is proposed. However, the approach uses some restrictive assumptions, which cannot be applied to real cases on hand.

The main goal and contribution of the research outlined in this paper is, therefore, to demonstrate the feasibility and advantages of integrating multi-robot spot-welding cell design and programming in real industrial contexts, while aiming at an extended formalization of the design problem. Indeed, the proposed method handles simultaneously the cell design and the motion planning problems with the following features: (*i*) time delays of the overall activity are minimized, (*ii*) the solutions are feasible and robust to accumulated errors and (*iii*) the investment cost of the design phase is minimized while granting the feasibility of the robot motion plans.

The paper is organized as follows: Section 2 highlights the industrial relevance of the topic and focuses on a real industrial case. Section 3 describes the proposed approach, while analysing the related literature and underlining the proposed architecture innovativeness step by step. Section 4 discusses the method implementation. Finally, Section 5 provides the conclusions and future work.

2. Industrial practice

The manufacturing process of body vehicles is based on three separate steps [5]: (i) manufacturing of the vehicle metal panels and their assembly; (ii) assembly of the vehicle lower-body with the vehicle upper-body; (iii) vehicle body painting. Step (ii) is generally directly managed by automotive companies, has been widely discussed in [5] where a 4-stage method is presented. Two of the four stages are performed in two separate subsequent activities: the manufacturing system design and the assembly process planning. This paper addresses specifically Step (i) which is generally outsourced by automotive companies to OEMs. OEMs need to provide the best offer in terms of price per produced unit, while coping with the requests of the clients. These requests include the required production volumes, which in turn define the cell cycle time (RCT) for the execution of a set of welding points (WPs) and the employment of a predefined body fixture (BF) which introduces a set of geometrical constraints.

In the current industrial practice, the OEM starts solving the multi-robot cell design problem and subsequently provides a feasible robot motion plan. First, the OEM selects the robot model (RM), the robot support structure (RS), the robot positions and orientations (RPOs) on the robot support structure, and a welding gun model (WGM) for each robot in the cell. This activity is mainly based on tabular information coming from the OEM's experience and expertise. According to this expertise, configuration is based on two assumptions: (i) each robot can be equipped with a different welding gun model; (ii) the robots used in the cell are all of the same model. Second, the OEM allocates the welding points to the robots, defines a motion plan for each robot and coordinates the robots. This activity mainly requires the employment of some commercial simulation software, such as Robcad^{TM}, through which it is possible to reproduce the cell layout and to define collision-free trajectories for each robot. However, the decoupling of design and planning activities could lead to infeasible motion plans and thus require a revised cell design.

The results of these activities are hereafter presented through a real case provided by COMAU S.p.A (Fig. 1). The multi-robot cell is composed by 5 robots SMART-5 NJ4-175-2.2 (RM) mounted on a bridge support structure (RS). The bridge structure presents 6 possible positions for the robots and 3 possible orientations for each position, for a total of 18 possible RPOs. The robot in RPO1 mounts the WGM1 and welds 5 points in 25.9 s, imposing the cell cycle time. The robot in RPO2 mounts the same welding gun as in RPO1 but is responsible for 4 welding points with a cycle time of 24.74 s. The robot in RPO3 mounts the WGM2.I. Its cycle time for execution of 4 welding points is 22.98 s.

Finally, robots in RPO5 and RPO6 have a cycle time of 22.33 and 20.99 s, respectively, for the execution of 4 WPs with the WGM3. WGM1, 2 and 3 present a different spatial occupancy and costs and grant a different accessibility.

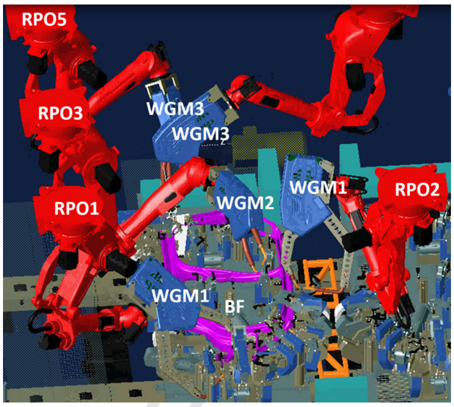

Fig. 1. Multi-robot cells for spot welding – COMAU Opengate.

3. The proposed method

The lack of integrated approaches for multi-robot cell design and off-line motion planning, both in terms of industrial practice and in available methodologies and software tools, is mainly due to the complexity of the integration that requires to address three main topics: (*i*) cell layout design; (*ii*) off-line motion planning for single-robot and multi-robot systems, and (*iii*) collision detection.

The conceived method considers and integrates these three main topics in order to simultaneously compute the design and motion planning of multi-robot spot-welding cells. The method is based on innovative architecture divided into 6 main steps (Fig. 2), that are based on both an existing method and new ad-hoc developed approaches. The method handles cases related to the common industrial practice, where product (i.e. welding points), and body fixtures, are given. At each iteration of *Step 1–Step 4*, the robot model, the robot support structure and welding guns models are selected from a database, so that each cell configuration will be based on one single support structure and one single robot model. Therefore, the domain of the cell design procedure is the set of all possible combinations of robot models, welding guns model and robot positioning and orientation on the support structures. The configuration of the cell is defined when (i) the best robot model and the best robot support structure are identified; (ii) the number of robots is calculated; (iii) the orientation and position of each robot are defined; (iv) a welding gun model is selected for each robot; (v) the motion plan of all the robots is defined.

3.1. Step 1 – Off-line motion planning for single-robot systems

Single-robot off-line motion planning aims at identifying a collision-free robot trajectory in environments with obstacles. Among single-robot motion planning approaches developed during recent years [10], probabilistic roadmaps seem to perform better in cases of complex environment with industrial robots [11]. Probabilistic roadmaps are exploited in this *Step 1* of the method (Fig. 2) to compute the off-line motion plan for a single-robot assembly cell. Specifically, for each combination of robot model, robot position/orientation in the robot support structure and welding gun model extracted from a database, the algorithm defines collision-free trajectories among all possible couples <WP1,WP2> of reachable WPs. Thus, the outcome of this step is the mapping of the global solution space.

3.2. Step 2 – Multi-robot cell design

Step 2 of the presented method (Fig. 2) proposes an extended formalization and a general and innovative solution for the multi-robot design problem for spot-welding cells. Although the cell layout has an essential impact on factory performance (time-optimality, task-flexibility and required floor-space), comprehensive studies on the design of multi-robot cells for spot welding cannot be found in the literature. Indeed, available papers focused

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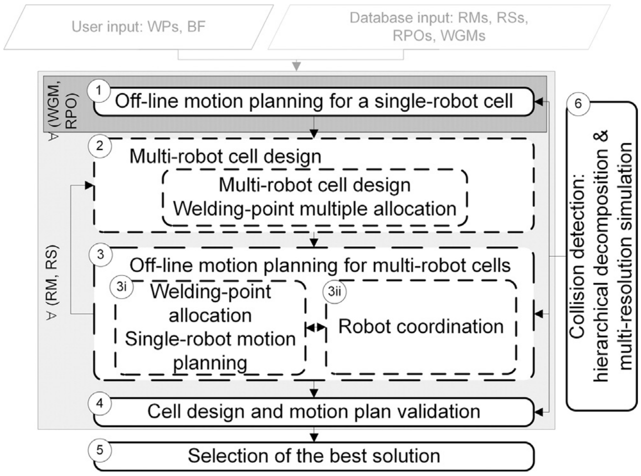

Fig. 2. The approach – Dashed line for innovative steps.

on specific aspects of the problem. For instance, the approach proposed in [12] copes with the selection of the gun model and the definition of the position of the robot; in [9] design alternatives for two-robot cells are derived, given the product specifications and an initial cell design. Opposingly, the innovation of *Step 2* here consists of the generalization of the problem and in its resolution.

Step 2 (Fig. 2) spans the whole set of trajectory solutions elaborated in *Step 1* and identifies a sub-set, such that the total investment cost is minimized. The result is a complete cell design and a first attempt of allocating the welding points WPs to the robots. Thus, in comparison to existing methodologies, trajectory planning is integrated into the design phase with the advantages described in Section 1.

3.3. Step 3 – Off-line motion planning for multi-robot systems

In the literature, multi-robot motion planning is based either on centralized or on decoupled techniques [10]. Decoupled motion planning approaches define the motion of each robot while ignoring the existence of other robots; then resulting paths are combined. These approaches cope with small-dimensional search spaces but are usually incomplete, since a solution is not guaranteed. On the contrary, centralized motion planning approaches treat multiple robots operating in the same workspace as a single multi-arm robot, thus resulting in higher dimensional search spaces.

Step 3 of the method presented here takes into account the global solution mapping of *Step 1* and the cell layout proposed in *Step 2*. It is based on two different steps (*Step 3i* and *Step 3ii*) and can be defined as a new decoupled approach. First, the results of *Step 2* are refined in terms of allocation of WPs to the robots and a motion plan is identified for each robot on the basis of the collision-free trajectories of *Step 1* (*Step 3i*). Second, execution of the trajectories is shifted over time to avoid collisions among robots while granting the cell cycle time (*Step 3ii*). Trajectories are shifted over time modifying their starting time, thus introducing robot idle time. In case of detection of an infeasibility of the motion plan, *Step 2, 3i* and *3ii* can be iteratively re-run to obtain a solution.

3.4. Step 4/5 – Validation and selection of the best solution

Step 4 validates the proposed cell design and motion planning through a multi-resolution simulation, presented in *Step 6*. Since numerous solutions differing in input data (robot model, welding gun models, robot support structure) can be provided by *Step 4*, *Step 5* selects the best solution in terms of productivity (spot per minute) and costs (initial investments).

3.5. Step 6 – Multi-resolution simulation

Trajectories generated by motion planning techniques aim to move the robot from initial configuration to goal configuration, avoiding static or dynamic obstacles in the environment. Three different approaches can be found in literature for collision detection [13]: feature tracking, swept volume and hierarchical decomposition. Feature-tracking methods perform geometric computations on object features to determine if pairs of features are disjoint. They cope with objects made of few convex components and do not handle them as rigid multi bodies. Swept-volume methods aim at calculating the volume swept by the objects and then checking for collision, yet they generally require high computational effort. Hierarchical decomposition methods pre-compute a hierarchy of bounding volumes for each object (robot link, obstacle), allowing multi-resolution simulation [14].

Step 6 of the proposed approach exploits hierarchical decomposition and multi-resolution simulation for the evaluation of collisions among robots and obstacles and for the visualization of robots movements. Collision detection is based on the existing "RAPID" library [15] that, relying on OBB hierarchy, grants a fast identification of collision. On the basis of the hierarchical decomposition operated by this library, a multi-resolution simulation has been developed according to the principles detailed in [16]. First, all objects are visualized with the same rough level of details (uniform representation) that consists of the bounding box of each object. Second, as far as the robot moves along a path and a collision is found, the level of all objects in the simulation environment is automatically increased.

4. Method implementation

The probabilistic roadmap employed in *Step 1* is obtained from a robot joint space sampling through Halton points [11]. The connection of such points is computed according to the nearest-n technique [11], where the criterion is the trajectory time. Trajectories are calculated through the Open Realistic Library – the robot motion planner module of COMAU controllers [16], in order to reproduce real robot movements (Fig. 3). Once the roadmap is created, all the couples of reachable WPs are connected to the roadmap. The search for collision-free trajectory between the selected WPs is performed through Dijkstra's algorithm [11].

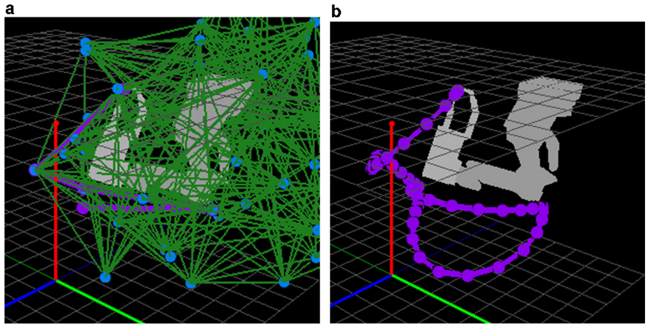

Fig. 3. Generation of a path between the starting position of robot in RPO6 and WP21 through probabilistic roadmap.

Then, *Step 2* spans the whole set of trajectory solutions elaborated in *Step 1* and identifies a sub-set such that the total investment cost is minimized. *Step 2* consists of a mixed integer programming model partially discussed in [17], and represents an innovative formalization of the problem in terms of parameters, variables, objective functions and constraints. The selected objective function Eq. (1) presents the following terms:

- the cost of the acquired resources, i.e. the cost of the robots (COSTRM [€]), of the welding guns ($COSTWGM_{WGM}$ [€]) and of the robot support structures (COSTRS [€]).
- the number of acquired resources, i.e. number of acquired robots (RM), of welding guns for each model (NWG_{WGM}) and of robot support structures (NRS), that is equal to the number of required resources minus the number of already available resources (this last aspect is important in the case of cell reconfiguration).

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- a penalty cost (PC [€]) whenever the solution exceeds the requested cycle time (ECT [s]).
- a term introduced to minimize the possible overlaps between the working areas of adjacent robots ($\mathrm{SIA}_{\mathrm{RPO1,RPO2}}$), so that the possibility of collisions among robots is reduced. This term is multiplied by a low value coefficient (L) to avoid influencing the final value of the objective function. Therefore between solutions with similar costs, the one with less overlapping is selected.

$$\min\left\{\begin{array}{c}\mathrm{NRM}\cdot\mathrm{COSTRM}+\sum_{\mathrm{WGM}}(\mathrm{NWGM}_{\mathrm{WGM}}\cdot\mathrm{COSTWGM}_{\mathrm{WGM}})+\\ \mathrm{NRS}\cdot\mathrm{COSTRS}+\mathrm{PC}\cdot\mathrm{ECT}+\underbrace{L\cdot\sum_{\mathrm{RPO1,RPO2}}\mathrm{SIA}_{\mathrm{RPO1,RPO2}}}_{E}\end{array}\right\} \tag{1}$$

The model is based on 29 constraints formulated to cope with the issues of the multi-robot design approach. 12 constraints related to the resources impose that: the total number of selected guns is equal to the total number of robots; the number of selected robots copes with the maximum number of available robot positions; the number of total selected resources is the sum of acquired and reused resources. 13 constraints grant the coherence among variables related to the robot motion plan: tentative allocation of each welding point to at least one robot; allocation of welding points only to feasible robots and welding guns; sequencing of welding point on the basis of predefined collision-free trajectories. Finally, 4 constraints are used to constrain the cell cycle time. Resource-related constraints are partially derived from resource-related constraints generally employed in the design of flexible manufacturing systems [18]. However, new constraints have been generated in order to specifically cope with the resources characterizing multi-robot spot-welding cells. Moreover, motion plan constraints allow the definition of a first-attempt motion plan strictly connected to the optimized cell design. The motion plan is therefore not given a priori as in existing approaches [6].

Step 3i revises through a mixed integer programming the first-attempt motion plan defined in *Step 2* by satisfying the one-to-one allocation (each WP to one robot). The objective function Eq. (2) minimizing the cycle time takes into account the welding time of each WP ($\mathrm{WT}_{\mathrm{WP}}$ [s]) and the robot motion time ($\mathrm{MT}_{\mathrm{WGM,RPO,WP1,WP2}}$ [s]) both according to the selected motion plans ($\mathrm{MP}_{\mathrm{WGM,RPO,WP1,WP2}}$) and the resource availability (welding gun model availability $\alpha\mathrm{WGM}_{\mathrm{WGM}}$ [%] and robot availability $\alpha\mathrm{RM}$ [%]). Constraints grant the correctness of the motion plan and the satisfaction of the max cycle time condition.

$$\min\left\{\max_{\mathrm{RPO}}\left\{\begin{array}{c}\alpha\mathrm{RM}^{-1}\cdot\sum_{\mathrm{WGM,WP1,WP2}}(\mathrm{MT}_{\mathrm{WGM,RPO,WP1,WP2}}\cdot\\ \mathrm{MP}_{\mathrm{WGM,RPO,WP1,WP2}})+\sum_{\mathrm{WGM,WP1,WP2}}\\ (\mathrm{MP}_{\mathrm{WGM,RPO,WP1,WP2}}\cdot\mathrm{WT}_{\mathrm{WP1}}\cdot\alpha\mathrm{WGM}^{-1}_{\mathrm{WGM}})\end{array}\right\}\right\} \tag{2}$$

The motion plans resulting from Eq. (2) do not guarantee collision avoidance among robots and a further step is necessary: the mixed integer programming of *Step 3ii* schedules the execution of the welding points so that robots cannot be in the same place at the same time. Thus, the algorithm shifts the starting time ($\mathrm{I}_{\mathrm{RPO,WP1,WP2}}$) and the completion time ($\mathrm{C}_{\mathrm{RPO,WP1,WP2}}$) for each single-robot motion plan. The model differs from existing models [19] since it copes with articulated robots independently from the shape of the links. The variables through which the final output is formalized aim at defining a feasible motion plan ($\mathrm{SS}_{\mathrm{S1,S2}}$, $\mathrm{SF}_{\mathrm{S1,S2}}$) for which the trajectory starting time and the completion time are set, and the cycle time of each robot ($\mathrm{OCT}_{\mathrm{RPO}}$) and the cell cycle time (MAXOCT) are minimized. On the basis of this last variable, the objective function is described in Eq. (3).

$$\min\left\{\mathrm{MAXOCT}+L\cdot\left\{\begin{array}{c}\sum_{\mathrm{RPO,WP1,WP2}}(I_{RPO,WP1,WP2}\cdot C_{RPO,WP1,WP2})+\\ \sum_{S1,S2}(SF_{S1,S2}\cdot SS_{S1,S2})+\sum_{\mathrm{RPO}}\mathrm{OCT}_{\mathrm{RPO}}\end{array}\right\}\right\} \tag{3}$$

In *Step 1*, the generation of one probabilistic roadmap with 400 points on a 2.66 GHz processor desktop requires around 2.5 h. Global optimal solutions are found in few seconds for the mixed integer programming models in *Step 2* and *3* through dynamic search algorithm. The tolerance of these solutions from the optimal global solution is 0.01%. The solution eventually provided by the whole approach will be optimal from the design point of view, and feasible from the motion plan point of view.

5. Conclusion and future work

In this paper, a new approach for the simultaneous design of multi-robot cells for spot welding and the generation of related robot motion plans is presented. The approach represents a radical change in the traditional way of solving these problems providing: (a) reduction of design time and cell installation time; (b) homogeneity of the provided solutions thanks to the high formalization granted by the approach; (c) high independence from operator's skill and knowledge; (d) better ability to explain operated choices to the final client. Future work will consider also energy consumption in the definition of the optimal cell design and motion planning in order to minimize the overall life cycle costs and to respond to the issues of sustainable manufacturing.

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