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Validation of an extended approach to multi-robot cell design and motion planning

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Abstract

According to both industrial practice and literature, multi-robot cell design and robot motion planning for vehicle spot welding are two sequential activities, managed by different functional units through different software tools. Due to this sequential computation, the whole process suffers from inherent inefficiency. In this work, a new methodology is proposed, that overcomes the above inefficiency through the simultaneous resolution of design and motion planning problems. Specifically, three mathematical models were introduced that (i) select and positions the resources, (ii) allocate the tasks to the resources and (iii) identify a coordinated robot motion plan. Based on the proposed methodology, we built three ad-hoc cases with the goal to highlight the relations between design, motion planning and environment complexity. These cases could be taken as reference cases so on. Moreover, results on an industrial case are presented.

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Keywords: Multi-robot cells; Design optimization; Motion planning

1. Introduction

The assembly of the vehicle metal panels and vehicle body-in-white through multi-robot spot-welding cells is generally outsourced by automotive companies to original equipment manufacturers (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 for the execution of a set of welding points and the employment of a predefined body-in-white fixturing systems and transportation device which introduces a set of geometrical constraints. In such a contest, cell design and motion planning are two relevant time-consuming critical activities. Even if the mutual-influence of the multi-robot cell design and motion planning cannot be ignored, current industrial practice is based on the division of these activities and the employment of several methodologies and software tools.

In order to support OEMs to reach these goals, the conceived research focuses on the analysis of design and motion planning problems for multi-robot body-in-white assembly cells. Specifically, this research has led to the development of a methodology able to simultaneously and automatically solve both the problems.

The paper is structured as following: Section 2 presents the state of the art; the approach is described in Section 3 highlighting the innovative aspects in comparison to previous work; Section 4 validates the approach through 3 ad-hoc cases and an industrial case; finally, conclusions and future work are given in Section 5.

2. Literary review

Although multi-robot cell design and off-line motion planning have been investigated for more than two decades, many issues are still open since (i) the complexity of the design and motion planning that represent a barrier for straightforward optimal solution, and (ii) multi-disciplinary activities and research fields are required. Specifically, the integration between the two activities has not been adequately investigated in literature so far. In [1], a 3D optimized layout for assembly

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cells is proposed, when resources, tasks and product geometry are given. A similar approach in terms of the sequential execution of the design and motion planning can be found in [2]. This paper proposed an approach for the optimization of the layout of a cell consists of two conveyor belts for part feeding, two manipulators and an assembly station. Once a possible layout is generated, robot trajectories are calculated taking into account the pre-allocated tasks. Similarly, [3] proposed a method for the selection of the most appropriate manipulator systems (combination of a robot arm and positioning table) from a set of candidate systems within the desired calculation time. Location optimization and motion coordination are integrated to derive the task completion time but robot tasks are pre-allocated. A more extended approach for the design of a cooperating robot cell can be found in [4]. Starting from an initial and rough solution, the approach leads to the definition of a final collision-free solution with optimized cycle time. However, the motion planning and collision problems are partially taken into account. A complete off-line programming toolbox for remote laser welding was proposed in [5]. The approach can provide an automated method for computing close-to-optimal robot programs. The approach has been positively tested on real industrial cases. However, the problem of robot positing is not managed.

3. Approach

The approach hereafter proposed and validated is an extension of [6,7]. The approach is based on 3 stages dealing with the motion planning for single robots, the design of the cell and the robot coordination. The simultaneous resolution of cell design and robot coordination is granted by the possibility to iteratively solve the problem till a feasible solution is found. Specifically the provided design is optimal in terms of cell investment costs and feasible in terms of robot motion plans.

The input, output and the three stages of the approach are hereafter briefly described. The differences respect to [6,7] are highlighted and are in each of the stages:

- A different trajectory generation method for stage 2 for a better exploration of the configuration space
- A new objective function for Stage 2 to better condition the identification
- A new mathematical model for the Stage 3

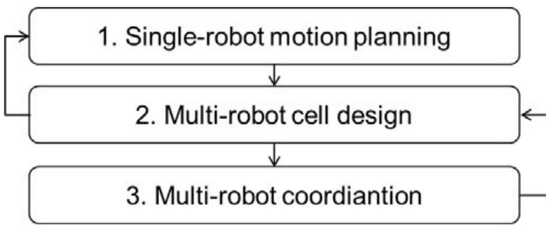

Fig. 1. The approach

3.1. Input & Output

The inputs and the outputs required of the approach have been detailed in Table 1 and Table 2.

Table 1. Model inputs.

Input	Range	Unit	Description
BIW		-	Body-In-White or metal sheets that have to be welded.
WP_{wp}	$1..N^{WP}$	-	Welding Points *WPs*. Position, *mm*, and orientation *deg* in the cell system of the points that have the be welded. N^{WP} denotes the number of possible *WPs* plus a fictitious point that represents the robot initial and ending configuration.
BF		-	Body-in-white Fixturing system of the BIW during the welding process.
BTD		-	BIW transportation device. It transport the BIW in and out of the cell.
RM		-	Robot Model. Type of robot employed.
RSM		-	Robot Support structure Model. System on which the robot are mounted. This system influences the position and the orientation of the robots in the cell.
RPO_{rpo}	$1..N^{RPO}$	-	Possible Robot Position and Orientation *RPOs* in the cell. N^{RPO} denotes the number of possible *RPOs*.
WGM_{wgm}	$1..N^{WGM}$	-	Welding gun models *WGMs* to be allocated to the robots. N^{WGM} denotes the number of possible *WGMs*.
RCT	R	s	Required cycle time. Imposed by the client, it represent the maximum cycle time of the cell.
NC^{RM}	N	-	Number of already aCquired *RM*.
NC^{RSM}	N	-	Number of already aCquired *RSM*.
NC^{WGM}_{wgm}	N	-	Number of already aCquired WGM_{wgm}.
$COST^{RM}$	R	€	Cost of *RM*.
$COST^{RSM}$	R	€	Cost of *RSM*.
$COST^{WGM}$	R	€	Cost of WGM_{wgm}.
WT_{wp}	R	s	Welding time for each WP_{wp}

Table 2. Model outputs.

Output	Range	Unit	Description
COST	R^+	€	Cell investment cost
TN^{RM}	N	-	Total Number of required *RM*.
TN^{RSM}	{0,1}	-	Total Number of required *RSM*.
TN^{WGM}_{wgm}	N	-	Total Number of required WGM_{wgm}.
NA^{RM}	N	-	Number of *RM* to be Acquired.
NA^{RSM}	{0,1}	-	Number of *RSM* to be Acquired.
NA^{WGM}_{wgm}	N	-	Number of required WGM_{wgm} to be Acquired.
$RGP_{wgm,rpo}$	{0,1}	-	Allocation of the welding guns to the robots – Equal to 1 if robot mounting WGM_{wgm} is in RPO_{rpo}.
$WPA_{rpo,wp}$	{0,1}	-	Equal to 1 if the welding point WP_{wp} is allocated to RPO_{rpo}.
$MP_{wgm,rpo,wp1,wp2}$	{0,1}	-	Motion plan for robot in RPO_{rpo} with WGM_{wgm} from WP_{wp1} to WP_{wp2} – Equal to 1 if robot in RPO_{rpo} processes WP_{wp2} immediately after WP_{wp1}.
$MTT_{wgm,rpo,wp1,wp2}$	R^+	s	Time necessary to robot in RPO_{rpo} mounting WGM_{wgm} to move from WP_{wp1} to WP_{wp2} and weld WP_{wp2}.
$C_{wgm,rpo,wp1,wp2}$	R^+	s	Completion time for robot in RPO_{rpo} mounting WGM_{wgm} to move from WP_{wp1} to WP_{wp2} and weld WP_{wp2} [s].
$I_{wgm,rpo,wp1,wp2}$	R^+	s	Starting time for robot in RPO_{rpo} mounting WGM_{wgm} to move from WP_{wp1} to WP_{wp2} and weld WP_{wp2}.
$D_{wgm,rpo,wp1,wp2}$	R^+	s	Temporal delay for robot in RPO_{rpo} mounting WGM_{wgm} to move from WP_{wp1} to WP_{wp2} and weld WP_{wp2}.
OCT_{rpo}	R^+	s	Obtained cycle time for robot in RPO_{rpo}.
MAXOCT	R^+	s	Obtained cell cycle time.