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Motion planning and scheduling for human and industrial-robot collaboration

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ABSTRACT

Step-changes in safety technologies have opened robotic cells to human workers in real industrial scenarios. However, the lack of methodologies for a productive and effective motion planning and scheduling of human–robot cooperative (HRC) tasks is still limiting the spread of HRC systems. Standard methods fail due to the high-variability of the robot execution time, caused by the necessity to continuously modify the robot motion to grant human safety. In this context, the paper introduces an innovative integrated motion planning and scheduling methodology that (i) provides a set of robot trajectories for each task as well as an interval on the robot execution time for each trajectory and (ii) optimizes, at relevant time steps, a task plan, minimizing the cycle time through trajectory selection, task sequence and task allocation. The application of the approach to an industrial case is presented and discussed.

1. Introduction

Global mass customization and products servitization push robotized assembly and manufacturing systems to evolve in the direction of customer-oriented and personalized production, while trying to guarantee the advantages of mass production systems in terms of both productivity and costs [1]. These systems are actually based, on the one hand, on high flexible and reconfigurable machines [2] and, on the other hand, on having humans in the loop [3]. Specifically, in line with the concept of factory 4.0 [4], the presence of human operators in flexible and reconfigurable environments is considered essential (i) for the accomplishment of all those operations that require excessive investments to be automatized and (ii) for the manual and “intellectual” dexterity that characterizes humans when compared to machinery. However, even if human-in-the-loop could boost system flexibility and performance, it increases the complexity underlying planning and scheduling (P&S) activities [5].

This complexity further increases in human–robot collaborative (HRC) assembly systems (Fig. 1) for two reasons. First, problem complexity is dramatically high even for a small number of tasks. Indeed, a generic HRC task can be accomplished through many robot trajectories (nominally, an infinite number of trajectories with the same start and end position exists) and each trajectory could be executed concurrently to different human tasks. Second, robot execution time may be different from the expected one, since robot speed may be reduced until robot stop to avoid collision with the human, granting his/her safety [6]. Although the time interval of a HRC task can be estimated using statistical models [7], task P&S result to be coupled with robot motion planning, and complex to be solved using available task planners and schedulers [8]. Furthermore, available A.I. techniques are not currently able to cope with temporal and spatial constraints as well as the goal of achieving HRC taking into account temporal uncertainty [5].

This paper aims at presenting an innovative methodology leveraging a temporally flexible A.I. planning approach for addressing robot motion planning, task planning and scheduling in an integrated way. The approach represents a novelty since, for the first time, a task planner and scheduler is able to manage human unpredictably and robot temporal uncertainty, exploiting the integration with a robot motion planning approach. The robot motion planner provides the trajectories as well as an estimation of the expected robot execution time during HRC tasks. The system deployed to control the working cell is then capable of dramatically

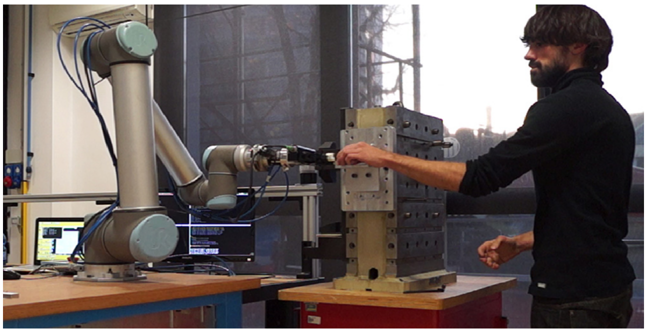

Fig. 1. Human–robot collaboration in assembly.

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increasing flexibility in HRC assembly systems as demonstrated by its application in an industrial HRC case study. The paper is structured as follows: Section 2 describes the state of art and the contributions of the paper; Section 3 presents the pursued approach; Section 4 presents a test case and the results; Section 5 gives conclusions.

2. Related work and contribution

Literature shows how robot motion planning and task P&S, analyzed singularly, are computationally complex, making difficult their integration in an unified approach, without relying on limiting hypothesis and applicability contexts [9,10].

A hierarchical approach to address task and motion planning problems is proposed by Refs. [11,12] where a task plan is constructed at an abstract, high and discrete level and recursively re-evaluated in details just before the execution, taking into account robot motion planning. In Ref. [13], symbolic planners are merged with geometric planners to check the geometric feasibility of the actions proposed by symbolic plans. In Ref. [14], motion planning of collision-free trajectories and task reasoning over discrete valued actions are combined. Moreover, Refs. [12–14] do not provide temporal planning features and, thus, they result as not fully suitable to address temporal variability of human/robot coordinated tasks. The limitations of these approaches in terms of unfeasibility of the plan have been faced in Refs. [15,16]. Dantam et al. [17] discussed a probabilistically complete method to extend constraint-based task planning, incrementally and dynamically incorporating motion feasibility at the task level.

The HRC methodologies presented above are not able to manage the coupling of motion planning and dynamic task P&S under time uncertainty. This paper aims at addressing this issue by integrating the methodology in Ref. [7] with the improvement of a flexible temporal planning framework [18] based on timelines [19].

Indeed, Pellegrinelli et al. [7] presented a probabilistic model of human tasks that is integrated with robot motion planning. The method describes each robot task by a set of trajectories with different probability of collision risks, and the execution time of each trajectory is described by an interval confidence time. Such methodology displays a double benefit: the human is modeled as a statistically controllable dynamic obstacle; human tasks and robot tasks (i.e., the trajectories) are characterized by a confidence interval on execution time. A further benefit of this methodology is that the provided probabilistic model copes with the assumptions at the basis of flexible timeline based approaches [18], that is an A.I. methodology extremely powerful when the decision variables of the problem display partially known time variability.

Based on these considerations and on an extension/integration of Refs. [7,18,20], this paper introduces a novel methodology able to cope with both temporal and spatial constraints as well as with the achievement of human–robot cooperation taking into account temporal uncertainty. Specifically, the main novelties presented consist in the (i) extension of Ref. [7], able to provide an estimation of the robot execution time in HRC tasks, for the generation of map of the human–robot tasks that are unlikely to be executed simultaneously; (ii) extension of the system proposed in Ref. [20] implementing the flexible temporal planning framework presented in Ref. [18] for addressing temporal uncertainty of human–robot collaborative tasks during both task plan generation and execution; (iii) definition of a novel framework for the integration of the motion planning and task planning methodologies.

3. The proposed methodology

A framework (Fig. 2), implements the proposed methodology by means of three main modules: a *Motion Planner*, relying on off-line analysis of the volume occupied by the human during the execution of a task, i.e. human occupancy volume (*HOV*), and generating robot trajectories entering at different levels the *HOV* as in Ref. [7]; a *Flexible temporal Task Planner* and a *Plan Executive* that, pursuing the timeline-based planning approach, provide a unified solution to planning and execution with uncertainty.

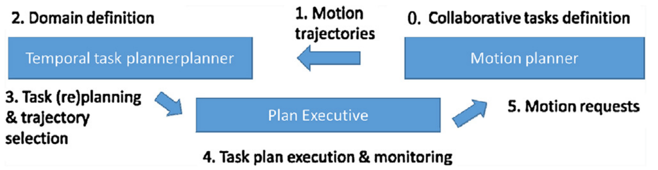

Fig. 2. The methodology blocks.

The proposed methodology is composed by a sequence of steps. The first step (Step 0) consists in the analysis of the considered industrial process to identify the relevant tasks, the resources that can perform the tasks (human, robot or both), and the relations among the tasks (e.g., precedence or synchronization constraints). Each human task is off-line studied through the use of a Kinect in order to identify the *HOV* and the execution time. For all the possible robot tasks, a set of robot trajectories [7] is defined by the Motion Planner (Step 1). The identified tasks coupled with the information of the duration of trajectories execution are encoded in a temporal planning model (Step 2) as alternatives for implementing a robot task. Namely, the information of the temporal duration of trajectories execution generated by the Motion Planner is exploited to characterize the temporal uncertainty of duration for tasks in the task planning model. Then, the Flexible Temporal Task Planner generates a suitable task plan (Step 3) for coordinating over time the robot and the human activities and selecting the most suitable trajectory for robot motion actions according to the actual collaborative context. The Plan Executive executes and monitors the task plan execution (Step 4) dealing with the uncertainty introduced by the variability in the duration of human tasks possibly also requiring to replan in case of unexpected behaviors. For each robot motion task, the execution of the selected trajectory is requested to the Motion Planner (Step 5) that is also responsible to realize the trajectory avoiding collisions with the human (Step 6). Hereafter, robot motion and task P&S are analyzed in terms of extensions of Refs. [7,18] and of changes for their integration.

3.1. Robot motion planner

Robot motion planner has to (i) identify 3 collision-free trajectories for each human–robot task (with different risk level); (ii) provide an estimation of the robot execution time when the human is cooperating with the robot; (iii) generate a map of the human tasks and robot tasks that are unlikely to be executed simultaneously. Goals (i) and (ii) are fully covered by Ref. [7] and, thus, are hereafter not addressed. Goal (iii) represents an extension that allows the reduction of the problem complexity underlying task P&S problems. Specifically, the approach in Ref. [7] has been modified and extended to extract also information relevant for task P&S.

First, given a couple of human–robot tasks, i.e. a robot task and a human task to be simultaneously executed, the Motion Planner has to identify a set of trajectories considering *HOV* as an obstacle. When the *HOV* is large, the robot may fail in the definition of the entire set of trajectories. This information is shared with the Task Planner that will not allow any simultaneity between the two tasks.

Second, the set of trajectories generated by Ref. [7] stands on the hypothesis of having possible interferences between the human and the robot. In this work, the Motion Planner tries first to generate a robot trajectory without considering the human (empty *HOV* considered). Then, possible collisions between the trajectory and the *HOV* are checked. In case of no collision, the planner can state that robot and human do not share the working space and the robot trajectory should not present any time variability. In this case, Task Planner simultaneously schedules the tasks.

3.2. Flexible temporal Task Planner and Plan Executive

According to Ref. [18], a timeline-based planning model is composed by *multi-valued state variables*, representing the set of features to be controlled over time and specifying causal and temporal constraints characterizing their allowed temporal behaviors. A state variable describes the set of values $v \in V$ the related feature may