Human-Aware Task and Motion Planning for efficient Human-Robot Collaboration

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***Abstract*— In human-robot collaboration (HRC), the variability of the human behavior complicates the deployment of robust task and motion plans, and continuous update of plans are often required to correct the task execution. We present a control-based approach to achieve robustness in the execution despite the high time variability of human and robot tasks. The proposed approach consists of two layers: task planning considers high-level operations without taking into account their motion properties; action planning optimizes the execution of high-level operations based on current human state and geometric reasoning. The result is a hierarchical structure where the lower level provides feedback on the feasibility and the upper level uses this feedback to (re)-optimize the process plan only when needed. The method is demonstrated in an industrial case study where a robot and a human worker work together to assemble a mosaic.**

I. HUMAN-AWARE TASK PLAN AND EXECUTION

In Human-Robot Collaboration (HRC), the task and motion planning problem is complex even for a task composed of a few activities [1], and the duration of the operations may vary significantly because of the interference between the human and the robot (*e.g.*, safety stops of the robot). Many works focus on the identification of a feasible solution and not the optimal one (PDDL [2], hierarchical task networks [3], [4], and constraint satisfaction problems [5]). However, these methodologies may achieve low performance in industrial application, where at least a sub-optimal feasible solution is necessary. Few works have also addressed the identification of an optimal task and motion planning via, e.g., a logic-geometric programming approach [6]. Such an approach, however, does not scale to a large number of tasks, and it cannot manage the complexity of industrial tasks. Except for [1], [7], all the approaches in literature do not deal with time-variability and constraints characterizing HRC tasks.

Within this wide field of research, the here presented work aims at presenting at the community some results related to the paper of the same authors [8]. Specifically, Fig. 1 shows an overview of the here proposed control architecture, split into to two main modules: a task planner and an action planner (which, in turn, integrates the motion planner). Task Planner addresses human-robot coordination and task sequencing and assignment, dealing with the temporal variance. Task Planner sends the goals to a human operator and it receives feedback from the HMI, as operators can accept or discard the incoming tasks, and also inform the system about the outcome of the performed task. This feedback is fundamental as the controller cannot assume the duration of human tasks but it needs to wait for feedback. The robot Action Planner computes the optimal sequence of motion plans that satisfies the operational constraint. Remarkably, the actual human position is considered as feedback when the motion plans are computed. Once the action is defined, the Action Planner sends the trajectory to be executed to the robot motion controller. The combination of these modules realizes flexible robot behaviors that can also be dynamically adapted according to the observed behaviors of a human operator, limiting negative effects on the production flow, when unforeseen events occur.

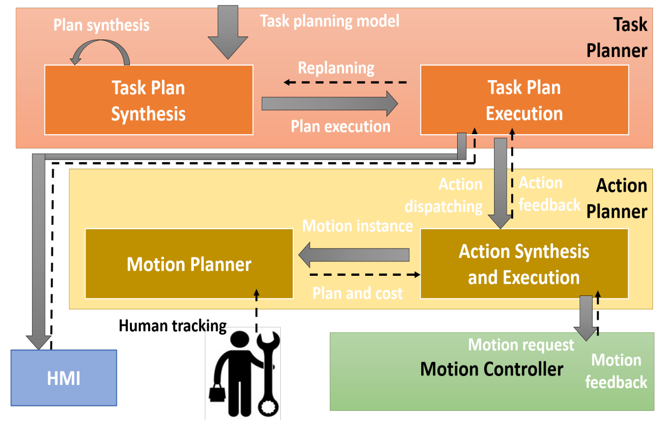

Fig. 1: Task and motion planning integration overview.

II. CASE STUDY

We analyze a case study in which an operator and a robot shall assemble a mosaic (Fig. 2), composed of 50 cubes, arranged in 5 rows and 10 columns. Each slot is identified by its column letter and its row number (*e.g.*, A1, A2, etc.). Letter 'S' is made up of orange cubes; letter 'W' is made up of white cubes; the background is made up of blue cubes. The mosaic shall be assembled according to the following constraints: i) orange cubes moved only by the robot; ii) white cubes moved only by the operator; iii) blue cubes moved by both the robot and the operator; iv) Row 3 shall begin after the end of Row 1; v) Row 4 shall begin after the end of Rows 1 and 2; vi) Row 5 shall begin after the end of Rows 1, 2, and 3.

This work is partially supported by ShareWork project (H2020, European Commission – G.A. 820807). Alessandro Umbrico is also partially supported by ROXANNE project (H2020, ROSIN – G.A. 732287).

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A. Dynamic Task Planning Module Implementation

As described in [8], we define a timeline-based representation of the task planning problem for the case study. The high-level goals triggering the execution of a production process are modeled at the *production goal level*. At this level, two state variables SV_G and SV_M model the goal at the high-level tasks that should be performed to carry out the specific goal. *Synchronization rules* then link production goals to the underlying tasks and specify the *temporal relations* between these values, representing the defined constraints.

At the low-level representation, two *behavior* state variables SV_H and SV_R model the tasks that the human and the robot can perform. The *synchronization* of high-level tasks in SV_M to *low-level* tasks in SV_H and SV_R is given by a set of *rules*, that model possible allocations of low-level tasks.

Finally, the *controllability* tagging function of a state variable SV_i specifies whether a value is *controllable*, *partially-controllable* and *uncontrollable*. Partially-controllable means that the value can be started by the system but the end can only be observed. The behavior of the human is *uncontrollable*, while the robot behavior is *partially controllable*. PLATINUm [9] is used to model and synthesizes plans taking into account the duration variability and the uncontrollability of the tasks limiting the need for re-planning at execution time.

B. Action Planning Module Implementation

A pick-place is composed of several motion instances (*e.g.*, move to the cube, close gripper, etc.) We group all these instances in an *action*, which corresponds to the lowest-level task handled by the task planner. The action planner is therefore in charge of finding the best way to execute such a group of simple operations. When action from the task planner arrives, the action planning module decodes the desired color and chooses the most suitable cube from the available ones. Then, it places the cube in the slot. To select the best action, the action planner runs multiple queries of the motion planner and chooses the best given a user-defined optimality criterion. When a cube is picked, the action planner repeats the computation of the optimal path to the placing slot. The procedure is agnostic to the motion planner used.

C. Use Case Simulation

The task planner takes about 20 seconds for the synthesis of the plan of the overall collaborative process to build the mosaic. The mosaic realization requires a total number of 50 tasks. If we consider an average duration of 45 seconds for a task, the total execution time of the overall process would be 38 minutes in the worst case (all tasks assigned to the human or the robot) and 20 minutes in the best case (perfect balancing between human and operator, without physical disturbance). The plans synthesized by the task planner uniformly distribute the tasks between the human and the robot, and the resulting plans have an average *makespan* of 52 time units with 26 tasks assigned to the human and 24 tasks to the robot. Such plans show the efficacy of the task planner in synthesizing suitable and effective collaborations with reasoning time that complies with production latency.

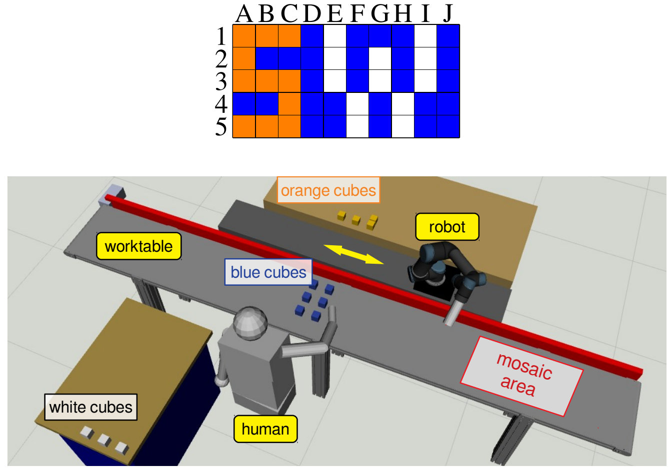

Fig. 2: 7-degree-of-freedom robot and an operator collaborate to assemble a mosaic on the worktable.

III. Conclusions and Future Works

The paper proposes a control-based approach based on two layers (task and action planning) where each layer reasons at a different level of abstraction. This hierarchical framework implements a control loop that leverages feedback to monitor the execution and dynamically (re)optimizes the process plan. Moreover, operators can accept/discard commands and give feedback about the outcome of his/her tasks. The method is applied to an industrial case study in which a robot and a human worker cooperate to assemble a mosaic. The main current limitation is related to the need of an *a-priori* raw-estimation of the sub-tasks duration. Furthermore, experiments in a real setting are necessary to assess user dependability, investigate scalability and extensibility of the approach and to compare its performance against industry best practices.

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