

Anytime informed path re-planning and optimization for human-robot collaboration

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Abstract—In human-robot collaboration, the robot is required to properly react to the operator’s movements to avoid collisions and interference. In this abstract, we present a path re-planning strategy to change the robot path online when a human is on the robot’s way. The approach exploits a set of pre-computed paths to speed up the search for a new feasible solution and to improve the trajectory’s readability. In addition, the algorithm continuously optimizes the current path in an anytime fashion to deal with strict computing time requirements. Experimental tests demonstrate the effectiveness of the proposed framework with respect to industry best practices.

Index Terms—Path planning; Anytime motion planning; Re-planning; Human-robot collaboration; Autonomous robots.

I. MOTION PLANNING IN SHARED WORKSPACE

Human-robot collaboration (HRC) is the research area that studies the spatio-temporal overlap of humans and robots workspaces. It has gained a lot of interest in recent years thanks to the advantages which it could bring to industries. Robots have mechanical capabilities which make them fast and precise but they are not able to adapt their behavior to the current circumstances. Instead, humans are intelligent and they can plan their actions and movement depending on the environment, but they are not repeatable and tire easily. Usually, robots are enclosed into physical or virtual cages and they stop when an operator decides to enter. But these barriers do not allow for synergistic collaboration between human operators and robots. The *speed and separation monitoring*, defined in the ISO-TS15066, allows collaborative robots to operate without fencing but requires control that can stop the robot motion to prevent collisions. The most widespread and conservative application of SSM defines three areas (red, yellow, and green) with different levels of risk of collision and the robot works at full speed, at reduced speed or it stops if the operator is inside the green, the yellow or the red area, respectively. Despite real-time techniques have been implemented to optimize the speed reduction on a pre-defined path, this solution doesn’t allow for complete exploitation of the potential of the collaboration. Indeed, if the operator continuously blocks the robot’s trajectory, the robot repeatedly reduces its speed or stops to avoid collisions, resulting in a substantial throughput reduction and weak support for the operator during the task execution. In this abstract, we present a path replanning framework combined with a speed

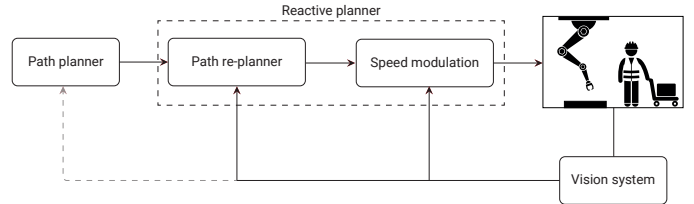


Fig. 1: Proposed planning scheme.

scaling technique to modify online the robot’s trajectory in order to drastically reduce the need for safety stops when a human and a robot work in the same workspace. Compared to existing methods, this replanning strategy exploits a set of pre-computed paths to try to connect the current robot’s path to the other available paths to avoid collisions or to improve the current robot’s trajectory. Exploiting a set of pre-computed paths enhances the search speed of the algorithm, improving the robot reactivity, and allows to obtain more readable solutions for the operator since the robot switches between paths which can be known by the operator. The results described in this abstract were originally presented in [1]; the innovative re-planning algorithm was presented in [2].

II. PROPOSED APPROACH

The proposed approach is based on the framework shown in Figure 1. The *path planner* block deals with computing the initial robot’s trajectory and the set of other paths taking into consideration the fixed obstacles and, optionally, the human position provided by the vision system at planning time. The *reactive planner* is composed by the *path replanner* and the *speed modulation* blocks and provides a reactive behavior to the human movements.

The core of the proposed method is the *path re-planning* strategy [2], which is based on three different threads:

- the *trajectory execution thread*;
- the *collision checking thread*;
- the *path re-planning thread*.

The *trajectory execution thread* receives the set of paths and the current robot trajectory computed by the offline planner, it samples the trajectory at a high rate and sends the new robot state target to the robot controller. This thread communicates with the speed modulation module to scale the robot velocity. The *collision checking thread* receives the position of the mobile obstacles from the vision system and checks if paths

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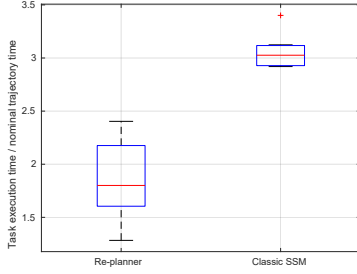


Fig. 2: Boxplot of the trajectory slowdown of each test (the lower, the better).

collide. The *path re-planning thread* receives the current path, the set of the available paths, and the current robot configuration as inputs, tries to find a new path that optimizes the current one or which avoids mobile obstacles that are obstructing it, and computes a new trajectory based on this new path. Finally, it sends this new trajectory to the *trajectory execution thread*. It uses a replanning strategy composed of two algorithms:

- *pathSwitch*: from a given node of the current path, it searches for a connecting path to each node of all the available paths; this search is conducted in a smart way taking into consideration the cost of the best solution found up to now (the cost is assumed to be equal to the path length and infinite when the path is obstructed) and exploiting the concept of *informed sampling* [3] to enhance the search speed;
- *informedOnlineReplanning*: it manages the whole replanning procedure. It adds to the set of available paths the valid portion of the current path that is behind the obstructing obstacle. Furthermore, it defines the set of nodes of the current path from which starting *pathSwitch*. When a solution is found, it updates the set of these nodes with the nodes of this solution.

The replanner algorithm ends when *pathSwitch* has been called from each of the available nodes or when the execution time exceeds the maximum time allowed. At each cycle of the *path re-planning thread*, the replanning algorithm is executed with a maximum allowed time: if the current path is obstructed, a feasible solution is required quickly, so the maximum time given to the replanner is short; otherwise, if the current path is free, a bigger amount of time can be given to obtain a better optimization of the robot's trajectory.

The *speed modulation* block is based on ISO-TS15066 and uses the speed override strategy of [4] to scale the robot's velocity. Unlike the classic SSM with three fixed areas, in this case the robot's speed is modified using a monotonic function that depends on the distance between human and robot and on their relative speed, detected by the vision system.

III. EXPERIMENTAL RESULTS

We have compared the proposed framework with the common industrial solution, the classic SSM strategy with the three fixed areas. An industrial cell consisting of a collaborative robot UR10e mounted upside down and a work table have

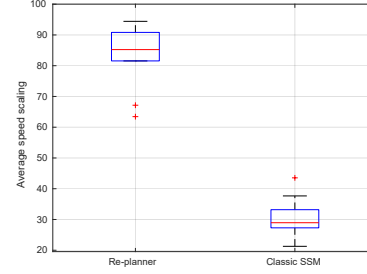


Fig. 3: Boxplot of the average speed scaling factor of each test (the higher, the better).

been used for the tests. During the experiments, the *trajectory execution thread* ran at 500 Hz, the *collision checking thread* at 30 Hz, while the cycle time of the *path replanning thread* was equal to 100 ms in case of obstruction, and 150 ms otherwise. Ten tests were executed emulating a pick and place action. At the start of the test, four paths were computed, then, when the robot started moving, an operator approached the work table for 60 s, obstructing the robot's path. Each of the ten tests was repeated twice, once using the proposed replanning framework, and once using the classic SSM. The time to execute the trajectory and the average value of the speed override were computed for each test and the results are shown in Figures 2 and 3 through boxplots. With the classic SSM, when the human approaches the work table, the robot drastically reduces its speed and stops if the path is obstructed, until the operator moves away. On the contrary, when the replanner is active, the robot reduces its speed but a free path is searched and found, so the speed reduction is milder and the robot does not need to stop. As can be seen in Figure 2, the replanner allows for faster execution of the task than the classic SSM, because each test can be performed with a higher average of the speed scaling factor (Figure 3).

IV. FUTURE WORKS

The main current limitation of the approach is the cost function used to evaluate a path, which is assumed to be equal to its length during the search of new solutions in the replanning algorithm. Future works deal with generalizing the cost function. Furthermore, the differences between the two strategies depend on the scenario, so a broader analysis should be conducted to obtain more general results.

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