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Abstract: Dependability of robot co-workers plays an important role in increasing the effectiveness of human-robot interaction in manufacturing. Our goal is to understand the role of motion planning parameters in human-robot collaboration and to provide guidelines for the selection of the most suitable motion planner. The human factors analysis provided in this paper highlights that repeatability of the motion and predictability of the robot timing affect the quality of human-robot collaboration.

Keywords: human-aware motion planning, human factors, human-robot interaction, ergonomics.

1. INTRODUCTION

Human factors in industrial robotic applications and their consequences on the work organization have been studied in academic and industrial research for decades. Pioneering studies were proposed in the eighties (Panny, 1983; Nagamachi, 1986). In recent years, efforts were made to improve human-robot interaction in the increasingly widespread collaborative cells (Oliff et al., 2018; Bolmsjö, 2015). Many researchers addressed the implications of human factors on safety aspects in industrial scenarios (Aaltonen et al., 2018; Behrens et al., 2015; Robla-Gomez et al., 2017; Freedy et al., 2007), and their deployment (Saenz et al., 2018). A roadmap for the successful implementation of human factors in industrial human-robot collaboration is proposed in (Charalambous et al., 2015). (Hoffman, 2019) proposed metrics to evaluate fluency in human–robot collaborative scenarios, measuring the effectiveness of the human and the robot to work as a team.

A few studies pointed out the influence of motion planning on human acceptance, trust, and performance. In (Koppenborg et al., 2017), a virtual reality experimental campaign has been performed to understand how the robot movements impact the human perception. The results indicate that higher movement speed and lower predictability leads to higher risk perception, anxiety, workload, and a tendency toward lower task performance. In (Lasota and Shah, 2015), human-aware motion planners – namely motion planners that compute the path considering the knowledge of the next human task – show their effectiveness in enhancing the collaboration, reducing idle times and increasing the user's satisfaction.

These aspects are even more important in unstructured scenarios, where it is not possible to use pre-computed trajectories but the motion planner has to plan the movement on the fly. Consider for example, a collaborative scenario where the human and the robot have to pick some components from a table to assemble them and the position of the pieces is not known a priori. The robot will estimate the position of the piece just before picking it (for example, by means of a vision system) and will compute a trajectory to reach the grasping point on the fly. Similarly, the robot will compute also the trajectory to assemble the piece online. Robotic applications where online motion planning is strictly necessary are more and more widespread, especially in view of the intrinsic dynamic nature of human workers and the advances in AI reasoning that allows the robot to cope with less and less structured environments (Karpas and Magazzeni, 2020).

In these applications, the motion planning module is key. Given a start and a goal point, the motion planning problem consists in finding a collision-free trajectory that connects the two points. The problem admits an infinite number of solutions: there are usually infinite paths that connect the two points in the space and every path can be traveled with an infinite number of velocity profiles.

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Motion planning is one of the fundamental problems in robotics and a huge variety of methods have been proposed during the years. Roughly speaking, the motion planning problem can be approached through deterministic or stochastic algorithms. Under the same conditions, deterministic algorithms always find the same solution; on the contrary, stochastic planners are not repeatable. Even though stochastic planners are less predictable than deterministic ones, their effectiveness in solving the planning problem in presence of complex cells makes them the *de-facto* standard in unstructured scenarios (LaValle, 2006; Adiyatov and Varol, 2017).

To the best authors' knowledge, there is no literature providing guidelines to select and tune motion planners to cope with human factors, concerning aspects like kinematics limits and path repeatability. The motion planner should be chosen also keeping in mind questions like: "is the human more bothered by spatial variability or temporal variability of the trajectories?"; "is the human bothered by acceleration changes and/or velocity changes?","is the synchronization of the movements of human and robot important?".

This paper is a first attempt to investigate the impact of motion planning parameters on human perception, intending to help in the choice of the most suitable planner and to boost further research in human-centered motion planning. To this purpose, two experiments are carried out and evaluated by means of questionnaires and objective data (namely, variation of the human's cycle time and centroid motion due to the robot presence). Results show that motion readability strongly affects the human trust in the robot co-worker. On the contrary, differences in the velocity profile (e.g. higher or lower speed and acceleration) do not seem to bother the user as long as the robot timing is predictable. In non-cooperative tasks, it turned out that the robot cycle time influences the user behavior, as the human worker is apt to keep pace with the robot. In cooperative tasks, the human worker (especially if familiar with robots) tends to overestimate the distance from the robot, and this may pose safety hazards if the robot safety controller does not react promptly.

The paper is organized as follows: Section 2 describes the setup used in the experimental campaign. The first experiment on the execution of unsynchronized tasks in the same workspace is discussed in Section 3.1. Section 3.2 describes a scenario where the human and the robot tasks need to be synchronized. Discussion on the results and their influence on the selection and tuning of motion planning are highlighted in Section 4

2. MATERIALS AND METHODS

The hardware and software platform used for the experiments are described in Subsection 2.1. Two different experiments were designed to analyze different levels of collaboration. In the first experiment, the robot and the human execute independent tasks in the same area, while in the second experiment their tasks have casual relations and require synchronization. The experiments are described in Subsection 2.2. The evaluation procedure is given in Subsection 2.3. The tests involved 32 participants: 28 males and 4 females; age: 28.3±8.6 years; 24 were familiar with robots (>6 months of training), 8 were not.

Fig. 1. Re-manufacturing pilot plant with the collaborative robot and the human-tracking system.

2.1 Hardware and software

The human-factors campaign was carried out through the re-manufacturing pilot plant installed at CNR-STIIMA (Brusaferri et al., 2019). The experimental hardware, shown in Figure 1, is composed of:

- A collaborative robot, Universal Robots UR10 version 3.5, controlled via Robotic Operating System (ROS) (Quigley et al., 2009);
- A two-finger gripper, model Robotiq 2-Finger 85mm, controlled via ROS;
- A time-of-flight camera, model Swiss Ranger 4000, that publishes a point cloud on a ROS topic. The point-cloud generated by the camera was filtered by using the PCL (point cloud library) in order to find the centroid of the human.

2.2 Description of experiments

Experiment 1: unsynchronized tasks

The goals of the first test are: understanding the influence of path changes on human behavior in workspace sharing applications; understanding the influence of velocity and acceleration changes on human behavior in workspace sharing applications; understanding if the human synchronizes her/his pace with the robot one.

In the experiment, the user was asked to unscrew some screws from a metallic item. The used had to place

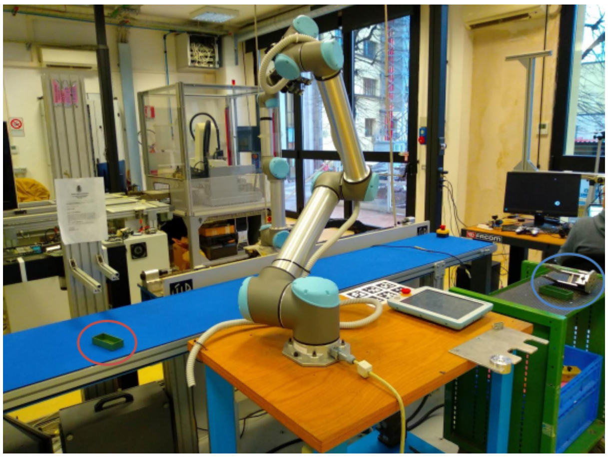

Fig. 2. Experiment 1 layout. The blue circle is the disassembly station; red circle is the screw buffer

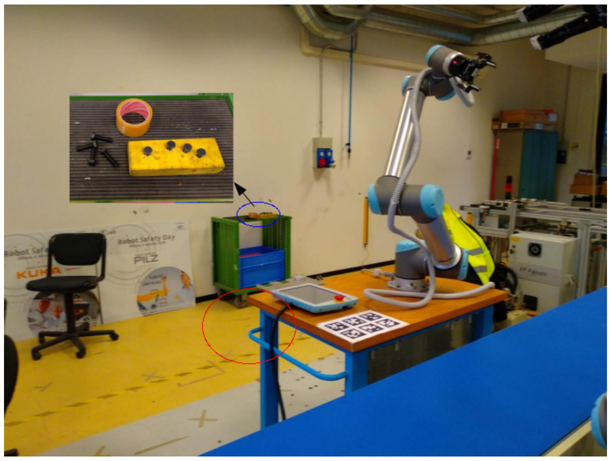

Fig. 3. Experiment 2 setup. Blue circle: worktable. Red circle: Picking area

the screw in a buffer immediately after the unscrewing operation. Figure 2 shows the working area. The path between the disassembly area and the screw buffer are inside the robot workspace but it does not intersect any robot trajectories.

The human was asked to perform the task twice. One without any robot movements, which is considered as the baseline, and one with the robot execute pick-and-place tasks. The order of the two experiments has been chosen randomly to avoid polarization.

When the robot was moving, it executed a pick-and-place task twelve times; three of them present differences with respect to the other ones. These variations are randomly selected among the following types:

- M-A: the operator unscrews the first piece without robot movements, and then it repeats the disassembly with the robot will change path without changes on the limits on velocity and acceleration;
- A-M: as M-A but the first disassembly is performed when the robot is moving, while the robot is stopped in the second one;
- M-B: the operator unscrews the first piece without robot movements, and then it repeats the disassembly with the robot will change on the limits on velocity and acceleration without changing the path;
- B-M: as M-B but the first disassembly is performed when the robot is moving, while the robot is stopped in the second one.

Experiment 2: synchronized tasks

The second experiment deals with a task that requires a synchronization between robot and human tasks. The goals are: understanding how the operator is influenced by changes on speed, acceleration, and execution time; understanding how the operator perceives the human-robot cooperation when he/she has to synchronize his/her activities with the robot.

The user is asked to bring to the robot a cylinder and 10 screws. The tape and the screws are located on the worktable, therefore the human has to pick one or more of them and walk to the robot, as shown in Figure 3. The robot performs a picking movement and closes the gripper finger to grasp the object, then it will place the object in the buffer. These movements can be triggered by the human position (Cases A, B, and C) or by time (Case D). The human is asked to bring the screws to the robot to place them all inside the cylinder; the user is informed that the number of screws inside the circle will be the evaluation score of his/her experiment. However, this task is introduced only to focus the user's attention on a practical task instead of the robot movement. There are four different variants of the experiments:

- A: the first five pick-and-place operations have high acceleration and low velocity; the last five have low acceleration and high velocity. The pick-and-place time is the same in all 10 operations. Each operation starts only if the human is entering the picking area.
- B: the first five pick-and-place operations have low acceleration and high velocity; the last five have high acceleration and low velocity. The pick-and-place time is the same in all 10 operations. Each operation starts only if the human is entering the picking area.
- C: the first five pick-and-place operations have high acceleration and low velocity; the last five have low acceleration and low velocity. The pick-and-place time is higher during the first five operations. Each operation starts only if the human is entering the picking area.
- D: the first five pick-and-place operations have high acceleration and low velocity; the last five have low acceleration and high velocity. The pick-and-place time is equal in all 10 operations. The last seven operations start without considering operator position.

2.3 Evaluation procedure

The human factor evaluation is based on objective and subjective measures. Subjective measures come from a questionnaire that each subject had to answer after the experiment. The questionnaires aim to understand what are the motion parameter that affect the human reaction the most. In particular, the questionnaire of Experiment 1 investigates the level of danger and interference perceived by the subject when working with the robot. The questionnaire of Experiment 2 investigates whether the subjects

Table 1. Questionnaire of Experiment 1

Q1: Did the robot perform movements that you felt dangerous?
Yes. No.
Q2: Has the robot hindered your activities?
Yes. No.
Q3: Was the robot far from you?
Yes. No.

Table 2. Questionnaire results for the first Experiment.

Q1: Did the robot perform movements that you felt dangerous?

	yes	no
A-M, M-A	15%	85%
B-M, M-B	15%	85%

Q2: Has the robot hindered your activities?

	yes	no
A-M, M-A	37.5%	62.5%
B-M, M-B	18.8%	81.2%

Q3:Was the robot far from you?

	yes	no
A-M, M-A	18.2%	81.2%
B-M, M-B	6.2%	93.8%

noticed changes in the motion planning configuration and which configuration they felt more comfortable with. Objective measures only regarded Experiment 1. In particular, the required time for disassembling was measured, and the trajectory of subject's centroid was recorded. Based on these data, we were able to evaluate variations of the cycle time and of the human motion due to the different motion planning configurations as follows:

- Cycle time: the ratio between the time required to complete the experiment with and without the robot was computed; this should verify whether the human productivity is affected by the robot movement also during unsynchronized tasks.
- Human motion: the distance between the human and the robot was computed; this should verify whether the human motion is affected by the robot movement also during unsynchronized tasks.

3. RESULTS

3.1 Experiment 1 : unsynchronized tasks

The questionnaire provided to the subjects is shown in Table 1. Results are summarized in Table 2 and discussed hereafter.

Q1: Did Robot perform movements that you feel dangerous? The user declares if the robot performs dangerous movements. 19% of users answer *Yes*, it is important to remark the presence of a strong correlation between the user's experience level and the danger perception. No one with more than 6-month experience with robot considers the robot movements dangerous. Another important consideration is the absence of correlation between the experiment type (*i.e.*, variations on path or kinematic constraints) and the danger perception.

Q2: Has the robot hindered your activities? The user declares if the robot hinders the user activities. 71.8% of the answers were negative. In this case, there is a significant correlation with the experiment type. Path changing hinders the user activities more than twice the velocity/acceleration changes.

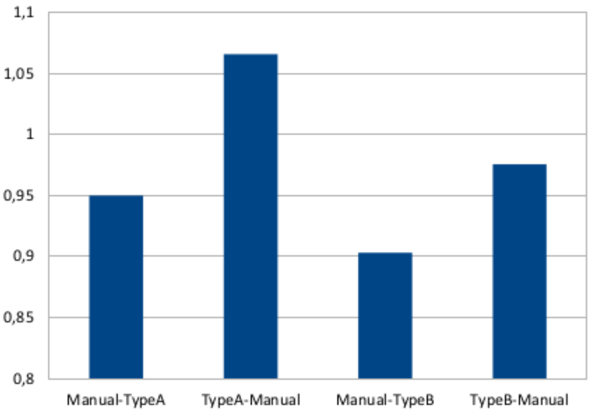

Fig. 4. Ratio between the time required to complete the experiment with and without the robot.

Q3: Was the robot far from you? The user declares if the robot was far or close in his/her opinion. As in Question Q1, the user experience is more important than the experiment type, even if in M-A and A-M experiments the robot is considered a little more closed. It is important to notice that the minimum distance during the experiments between the robot gripper and the user was around 40 cm, thus it is possible to assert that the human overestimate robot distance during tasks.

As regards objective measures, variations of the cycle time and of the human motion were analyzed. The ratio between the time required to complete the experiment with and without the robot is shown in Figure 4. As expected, the disassembly time is slower during the second disassembly due to the gained experience. However, it is worth stressing that in M-A and A-M the ratio is inversely proportional to the sequence, while in M-B and B-M the human is slower than in M-A and A-M. Considering that the robot is moving slower in experiments M-B and B-M with respect to M-A and A-M cases, it is reasonable to assert a correlation between the robot and the operator throughput also in tasks that do not require synchronization. Regarding influences on the human motion, no significant changes have been highlighted in both the experiment types. This aspect is consistent with the overestimation of the relative distance (Q3) and the absence of overlapping between human and robot paths.

Summary Experimental results highlight the path changing influences more the operator's attention with respect to speed/acceleration changes. However, human does not change significantly his/her path based on robot behavior. Conversely, Human throughput is influenced by robot throughput. Humans overestimate robot distances, especially during predictable movements. Human's path is not strongly influenced by the robot movements if the robot path does not intercept operator's trajectory.

Table 3. Questionnaire of Experiment 2

Q1:	Did the robot change speed during the test?
	Yes. No.
Q2:	If it changed speed, which case did you prefer?
	lower acceleration, higher velocity.
	higher acceleration, lower velocity.
Q3:	Did you feel like the robot was cooperating with you?
	Yes. No.

Table 4. Questionnaire results for the second experiment.

Q1: Did the robot change speed during the test?

	yes	no
Type A	25%	75%
Type B	21.8%	78.2%
Type C	81.2%	18.8%
Type D	28.1%	71.9%

Q2: If it changed velocity, which did you prefer?

	lower acc., higher speed	higher acc., lower speed
Type A	100%	0%
Type B	100%	0%
Type C	85%	15%
Type D	100%	0%

Q3: Did you feel like the robot was cooperating with you?

	yes	no
Type A	100%	0%
Type B	100%	0%
Type C	43.7%	56.3%
Type D	100%	0%

3.2 Experiment 2 - synchronized tasks

The questionnaire provided to the subjects is shown in Table 3. Results are summarized in Table 4 and discussed hereafter.

Q1: Did the robot change speed during the test? The question allows understanding if the user perceives the speed/acceleration changes during the experiments. In experiments A, B, and D, 75% of the users did not recognize speed/acceleration changes. In these experiments, the execution time is constant while limits on acceleration and velocity are changed. In experiment C, all the users perceive the speed change.

Q2: If it changed velocity, which case did you prefer? In experiment C, all the users identify that the robot velocity was slow down during the experiment. In experiments A, B, and D, the users were able to detect the speed/acceleration changes preferred the low-acceleration/high-velocity trajectories.

Q3: Did you feel like the robot was cooperating with you? This question allows understanding if the operator thinks to cooperate with the robot even if he/she is not dictating the pace. In experiments A, B, and C the robot starts the pick-and-place movement only if the operator is in the picking area. Thus, the operator can decide his/her velocity during the movements from/to the working table. Almost all the users (91%) consider the robot to be cooperating. In experiment D, the last 7 pick-and-place movements respect a fixed time schedule therefore the operator has to accommodate his/her velocity to the robot velocity. The majority of the user (75%) consider the robot to be non-cooperating.

Summary Considering operator feelings, trajectory time is more important than speed and accelerations. Different motion profiles with the same total time are difficult to recognize when the operator focuses his/her attention on the task. Humans consider the robot more collaborative when they can decide the cooperation activity timing.

4. DISCUSSION

Experiments show that it is very important to compute motion paths that are predictable by the workers, moreover also the execution time should be predictable as much as possible. This aspect is very important in the selection of the motion planner. As a matter of fact, non-optimal stochastic motion planners, like RRT (LaValle, 1998; Kuffner and La Valle, 2000), are very effective in finding a solution in a limited amount of time, but they are characterized by a large variability of the solution path. (Jaillet et al., 2010; Devaurs et al., 2013) proposed an improvements on the basic RRT algorithm using transition-based sampling. The algorithm improves the solution quality with respect to basic RRT implementation, leading to more repeatable paths and execution times.

Optimal motion planners should provide a unique solution to the planning problem as shown in (Luo and Hauser, 2014) using a simple benchmark, but they still own a certain level of variability due to limited computational time dictated by the application. To overcome this limitation, informed sampling techniques have been proposed to speed-up the solver (Gammell et al., 2014; Choudhury et al., 2016).

Considering the experimental results, optimal motion planners with limited computational time should be preferred in human-robot interaction, due their ability to compute repeatable and predictable solutions. If computational time does not fulfill the application requirements, improved RRT algorithms able to improve solution quality has to be preferred.

When focused on his/her activities, the user seems to be unable to distinguish different velocity profiles (namely, different limits of velocity and acceleration) if the total cycle time is the same. From the human point of view, it is important to execute the movement in a predictable amount of time allowing the human to synchronize its activity. The choice of the velocity profile is therefore less crucial in terms of motion dependability, as long as the cycle time is predictable by the user.

It is also worth stressing that the robot throughput resulted to influence the human behavior also without any need for synchronization of the task.

In cooperative tasks, operators prefer to decide the task timing and, when focused on his/her activities, the operator overestimates the distance of the robot. These considerations imply that the motion planner has to take care of maintaining the appropriate distance to avoid the need for a significant slowdown of the robot velocity during the path.

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