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Development of a shared tool for collaborative robotic applications in assembly or disassembly systems

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Abstract. A methodology to develop and validate a shared tool to be used individually by humans and robots in collaborative assembly/disassembly systems is proposed. The solution allows the upgrade of a manual electric screwdriver and its integration in a collaborative application. This enables the sharing of the device with a collaborative robotic system equipped with a standard gripper, thus improving the potential for flexible collaboration without worsening the use for the operator in terms of biomechanical loads and wellbeing. Based on a relevant case-study, the methodology encompasses the definition of design criteria to properly combine ergonomic and productivity requirements and related evaluation metrics, the reverse engineering of a manual electric screwdriver, the CAD modeling and rapid prototyping of mechanical parts to realize the shared tool, the signal integration and the robot programming. To assess the performance of the shared tool from the human and robot perspective, practical tests have been performed in a collaborative assembly workstation. From the human side, metrics for measuring biomechanical loads and perceived comfort have been defined. From the robotic side, performance has been measured to assess accuracy, repeatability, and speed. Preliminary results demonstrate satisfactory performance from both the human and the robotic side.

Keywords: Human-Robot Collaboration, Assembly, Disassembly, Assistance System, Ergonomics.

1 Introduction

Nowadays, the implementation of Human-Robot Collaboration (HRC) to support operators in unsafe, physically demanding, or inefficient production processes has become essential. Furthermore, companies leading toward even more sustainable manufacturing must consider not only product assembly but also disassembly. In this context, a key process is screwing. Different commercial screwing solutions have been developed for industrial robots. These must be mounted on the manipulator, thus losing its capability to handle objects during the same process and, therefore, limiting the potential of human assistance. A Collaborative Robotic System (CRS) equipped with an automatic

screwdriver would require a tool changer to fit an additional tool (e.g., gripper), increasing cycle time and set-up costs. Thus, the objective of this work is to develop a shared tool - to be individually and effectively used by the resources of a collaborative assembly/disassembly system (i.e., the human and the robot) - starting from a manual one and without worsening the use for the operator. This requires an upgrade of the manual tool's features by considering both the human needs and the robotic performances.

2 Methodology

The methodology is based on the "action research" approach [1]. This implies the definition of a relevant case study (i.e., the process of tightening screws on a pneumatic cylinder) performed in a collaborative robotic workstation needed to drive the development and validation phases. The main steps are summarized in the following. The related experimental set-up is summarized in Fig. 1.

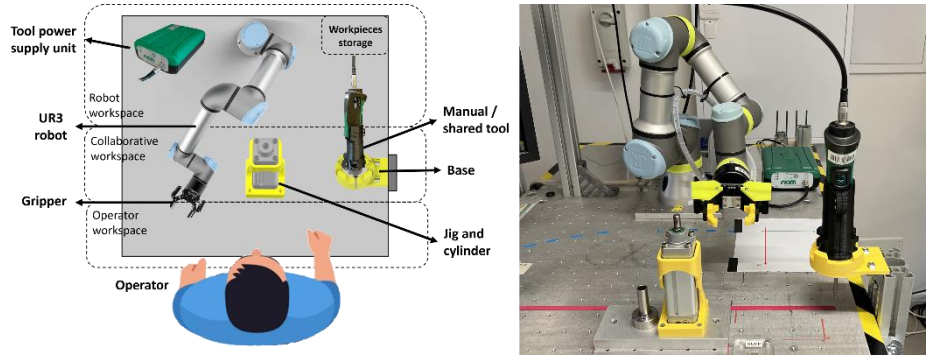

Fig. 1. Experimental set-up and related collaborative workstation. The UR3 cobot (equipped with a collaborative gripper) and the operator use the shared tool individually to conduct their fastening/unfastening activities on a pneumatic cylinder placed at the center of the workstation.

Step 1 - Definition of design criteria to properly combine ergonomic and productivity requirements and related evaluation metrics. The following design criteria have been defined for the human and the robotic system. These have been evaluated by defining specific metrics used to compare the use of the tool before (i.e., manual tool) and after the upgrade (i.e., shared tool). From the human side, it is crucial to prevent the worsening of work conditions by considering physical ergonomics and comfort. In other words, the shared tool must not introduce hazards or discomfort when compared with the purely manual one. The Rapid Upper Limb Assessment (RULA) index [2] is used to preliminary evaluate the biomechanical loads of the screwing activities (particularly focusing on the posture of the dominant upper limb). For the assessment of perceived comfort, a self-reporting Likert scale has been developed based on the "Comfort questionnaire for hand tools" (CQH) approach [3]. From the CRS side, it is necessary to

ensure satisfactory and safe performance considering handling accuracy, repeatability, and speed. Cycle time, number of errors in grabbing/releasing the tool, as well as errors in fastening/unfastening tasks have been measured.

Step 2 - Reverse engineering of the manual tool, CAD modeling and rapid prototyping of mechanical parts needed for the sharing. Through reverse engineering, the outer shell of the manual tool has been 3D scanned to retrieve a point-cloud of the external surface to model a mechanical flange. An interface (see Fig. 2a) has been designed to wrap the manual tool (i.e., the electric screwdriver). The goal is to allow the CRS to use it without requiring a tool changer, i.e., by using a standard collaborative gripper, also allowing manual operations without affecting the use conditions and related ergonomics. The gripper's fingers have been slightly modified to effectively engage the flange (see Fig. 2b). Furthermore, the intrinsic mechanical risks have been minimized by considering ISO TS 15066 indications [4]. A base (see Fig. 2c) used to store the shared tool has been designed to be effectively accessed by the operator and the CRS. All mechanical components were designed through CAD modeling and rapidly prototyped through a 3D printer. A dedicated jig has been developed to support the placement of the components and the robotic activities without preventing the possibility to be used for manual operations.

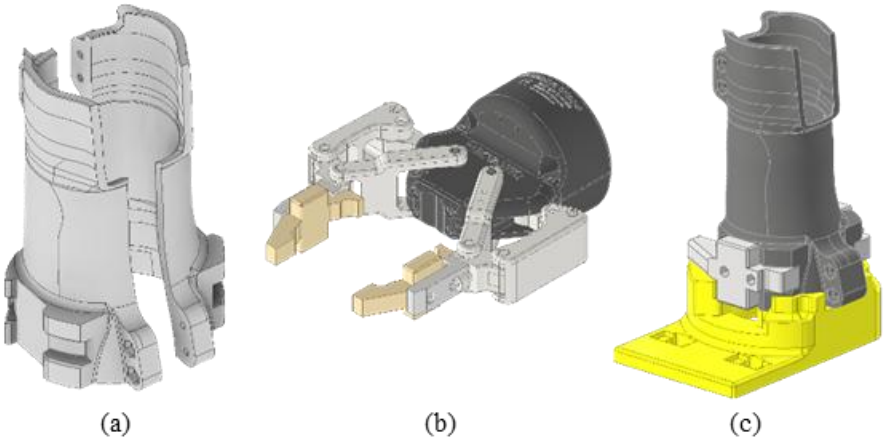

Fig. 2. Mechanical interface (a), gripper's fingers (b), basement (c).

Step 3 - Signal integration in the controller and robot programming. The signals of the shared tool were integrated with the digital I/O ports of the robot controller. Scripts were developed by using "urx" python library to let the CRS perform the required handling, as well as to control the fastening/unfastening activities of the electric screwdriver.

Step 4 - Performance validation. A testing procedure has been defined to evaluate the shared tool with respect to human physical ergonomics and wellbeing, as well as to

the CRS performance when performing automatic screwing/unscrewing activities. From the human side, metrics for measuring biomechanical loads and perceived comfort have been defined. In that regard, the manual tool and the shared one have been compared to evaluate how the changes affect the manual operations. From the CRS side, performance has been measured to assess accuracy, repeatability, and speed. In particular, the number of errors in grabbing/releasing the tool, as well as errors in fastening/unfastening tasks, and the cycle time have been measured. Details about the testing procedures and related results are provided in Section 3.

3 Results

3.1 Human performance

An analysis has been performed to compare the manual tool with the shared one to understand if the applied changes possibly affect the use-related biomechanical loads. The RULA index [2] was used to evaluate the screwing/unscrewing activities, particularly focusing on the postures of the dominant upper limb. An operator was asked to perform some representative screwing/unscrewing cycles using the manual and shared tools. Subsequently, analyses were carried out based on recorded videos. The considered critical postures are (i) the one assumed during the fastening/unfastening (i.e., "Configuration 1"), and (ii) the grabbing/releasing postures of the shared tool on the base (i.e., "Configuration 2"). For Configuration 1, the RULA scores were the following for both the tools: (i) 4 for wrist and arm, (ii) 3 for neck, trunk, and leg. For Configuration 2, the RULA scores were the following for both the tools: (i) 3 for wrist and arm, (ii) 2 for neck, trunk, and leg. Another test has been conducted to compare the manual tool with the shared one to understand if the applied changes possibly affect the perceived comfort. Participants (n=10, all right-handed) were asked to rate 17 different descriptors related to comfort by using 7-points self-reporting Likert scale. This has been developed by considering the "Comfort questionnaire for hand tools" (CQH) approach proposed in [3] (the higher the score related to each descriptor, the better the performance of that feature on the considered tool). Each participant was asked to perform three screwing/unscrewing cycles using the manual and shared tools and, subsequently, to answer a survey. The order of testing (manual vs. shared tool) was randomized to prevent possible bias in responses and comparison. In the following, results related to the comparison of the average values for comfort descriptors for the manual and shared tools are summarized in Fig. 3.

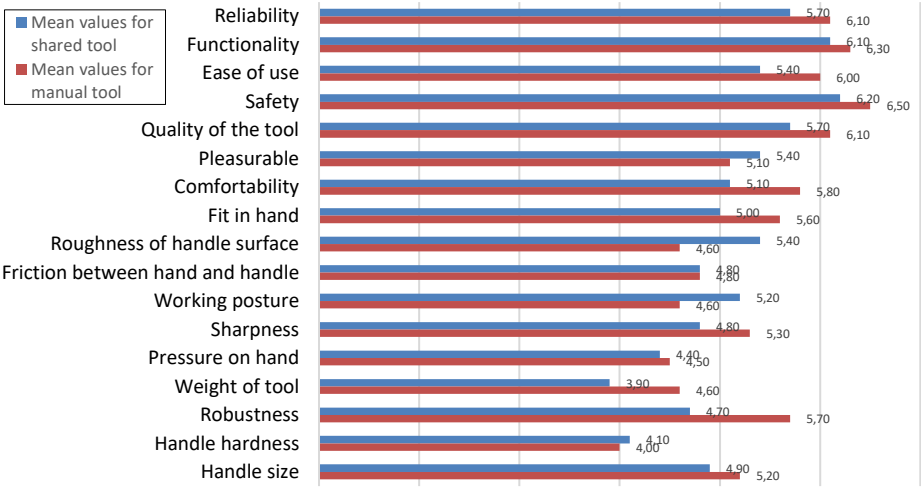

Fig. 3. Comparison of the average values for comfort descriptors for the manual and shared tools.

3.2 Collaborative robotic system performance

A test of the performance of the CRS when performing automatic activities using the shared tool has been performed. The following metrics have been used: (i) variation in cycle time with respect to manual process, (ii) errors in grabbing/releasing the tool, (iii) errors in fastening/unfastening tasks. To assess the variation in cycle time, the average value of three representative manual cycles has been recorded (mean value: 21.3 s). This cycle encompasses grabbing the shared tool, performing eight fastening activities (divided into two crossed path sequences), and then releasing it on the base. To assess the errors in grabbing/releasing the tool, 60 catches/releases have been performed. To assess the errors in fastening/unfastening tasks, 56 screwing/unscrewing activities have been exploited. In the following, results related to the performance of the CRS when performing automatic screwing/unscrewing activities are summarized Table 1.

Table 1. Performance of the CRS when performing automatic screwing/unscrewing activities.

Performance	Value
Variation in cycle time with respect to manual process	+12.2 s (21.2 s vs. 33.5 s.)
Errors in grabbing/releasing	0
Errors in fastening/unfastening tasks	2

4 Discussion

From the human perspective, according to the RULA index, the postures of the hands, wrists, and forearms are comparable for both the tools (i.e., manual vs. shared), showing no deterioration in terms of biomechanical loads. Considering the comfort descriptors, the comparison between the two tools highlights slightly lower performance for the

shared one in aspects such as “weight of the tool” (-15%), “comfortability” (-12%), “fit in hand” (-11%), and a moderate improvement in terms of “roughness of handle” (+13%) and “working posture” (+13%). User’s open feedback revealed conflicting opinions about the suitability of the shared tool thickness and the sharpness perceived, mainly depending on the size of the hand. Overall, the perceived comfort of the two tools can be considered comparable since the mean value of all the descriptors differs by about 4.6% in favor of the manual tool. From the CRS perspective, results revealed 97.6% success rate in screwing/unscrewing activities, 100% success rate in grabbing/releasing operations, and an increase of the cycle time of 57% respect to the manual one. According to [5], the CRS cycle time is acceptable. In addition, in assembly/disassembly operations, the performances of operators usually decrease in time due to stress and fatigue, also possibly leading to errors, while the performance of a CRS can be considered constant over the long period. Indeed, it is expected that after several working cycles, the performance of the CRS and the operator are comparable.

5 Conclusion

Results demonstrate satisfactory performance from both the human and the robotic side. Further improvements will optimize the design and investigate human tracking to recognize the intention of using the shared tool when collaborating with the robot. The aim is to adapt the robotic behavior according to human actions. This will be used to further study cognitive workload and related variables when human and robots must interact and share resources in assembly settings.

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