Experimental Validation of an Interface for a Human-Robot Interaction Within a Collaborative Task

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Abstract. This paper presents a prototype of a non-contact UR robot based Virtual Control (UR-VC) system for collaborative robots of the UR family, which is based on computer vision techniques and a virtual interaction interface. A control method involved specific hand movements within a field of view of a web camera, which was connected to a laptop with the running UR-VC system. We present the UR-VC system and the results of an experimental validation. To inquire if the UR-VC system is comfortable and user-friendly for an interaction with collaborative robots and to study opportunities for a further development and expansion directions of the system, we designed a test case that simulates a joint product assembly in a collaborative workspace. The constructed collaborative workspace included the UR3e robot, the laptop with the running UR-VC system and assembly parts for a collaborative task. 24 participants were involved in the experiments. First, the participants learned how to control the robot using the UR-VC system. After the training, all participants successfully controlled the robot using the proposed interface for performing the collaborative task. Participants' experience of operating the robot was analyzed via surveys, their unconstrained comments and video recordings of the experiments.

Keywords: Human-Robot Interaction · Human-Robot Collaboration · Collaborative Assembly · Virtual Control

1 Introduction

Currently, collaborative robotics has a great potential for application in industry and manufacturing [1, 2]. Automation with robots can significantly improve quality, safety, and efficiency of production processes [3]. However, full automation of processes can be difficult or impossible for various reasons [4]. Some stages of production may not be

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automated and require a human intervention [5]. Additionally, full automation may be infeasible due to a high cost and complexity of an implementation. These are particularly relevant for small and medium-sized industries. In the latter case, a production process can be arranged in such a way that production steps can be shared between a human and a robot working collaboratively in a shared workspace [6]. An example would be a process that involves a collaborative assembly or processing of a product, where the product or its parts are passed alternatively between a human and a robot.

Human-robot collaboration (HRC) implies an existence of one or more communication methods between a human and a robot. A robot control system can process verbal and non-verbal operator signals [7] and may rely on speech, gesture, and gaze recognition, tactile control, or multimodal interfaces [8]. In some cases, the most convenient method for controlling a robot involves a non-verbal communication based on operator's gestures and movements. This approach enables both simple and complex interactions between an operator and a robot and helps to integrate robots into existing workflows.

In this paper, we present a new virtual control system based on computer vision and augmented reality (AR) techniques for non-contact control of a collaborative manipulator during joint assembly tasks. An experimental validation of the system demonstrated a successful HRC during a joint assembly task.

2 Related Work

Overviews of modern collaborative robots (cobots) used in industry and service fields demonstrated a broad variety of approaches and particular applications [9, 10]. Design issues of cobot control systems' reviews focus on existing sensor-based control methodologies [11] and consider general issues in the management of cobots [12].

A special place among cobot control systems is occupied by AR-based methods, which are a promising direction in industrial robotics. Costa et.al. [13] stated that replacing a purely manual control with a collaborative scenario using AR reduces a production cycle time and improves an operator's ergonomics and identified four types of user interfaces: head-mounted displays (HMD), projector-based interfaces, hand-held displays (HHDs), and Fixed Screens. They noted that HMDs and projector-based interfaces are used much more frequently compared to HHDs and Fixed Screens in research and emphasized that a usage of HMDs for AR in collaborative robotics may be hindered by hardware aspects, such as a narrow field of view, occlusions, and weight, which may have a negative impact on an operator's sense of safety. We believe this implies an emergence of risks associated with a negative impact on a user experience (UX) while a positive UX in human-robot interaction (HRI) is essential for an efficient organization of HRC processes [14].

When developing a contactless control interface for a cobot during a joint assembly, maintaining a balance between safety, efficiency, and ergonomics in a design of collaborative assembly processes is important [15], as well as design recommendations based on international standards, research, and real-world use cases [16]. Typically, performing joint assembly and processing tasks requires a human to perform some work manually, with their hands. As a result, for a collaborative assembly and processing, contactless methods of a robot control that do not necessitate a constant presence of operator's hands on a control panel are preferred. One of these methods is controlling a robot using gestures.

A significant part of modern gesture-based control of cobots relies on methods for classifying and recognizing gestures using machine learning techniques, including such particular examples as learning semantics in experiments with a gesture-based control system in a collaborative assembly task [17], a new taxonomy for gestures classification [18], an online static and dynamic gesture recognition framework for HRI [19], a robot-human interface [20] based on MediaPipe solution [21], and others.

In our previous work [22], we conducted a series of pilot experiments on gesture-based control of UR5e robot in a collaborative assembly task. The experiments revealed the general user satisfaction with the contactless control method using gestures, however, they identified a number of disadvantages of this approach. The first issue was a necessity to select a universal gesture system for the robot control. Even though all users successfully employed the gestures we had proposed for the control, some users noted that particular gestures were not quite familiar to them. In light of this, we encountered a challenge of fine-tuning a command set according to users' preferences. Simultaneously, expanding the gesture vocabulary requires additional research, which may not necessarily guarantee a development of a universal set of gestures that accommodates all users' preferences. The first disadvantage was a necessity to employ all fingers, which can affect a biomechanical load on a user's hand, their comfort level, and focus. As a number of commands increases, a user must not only operate different hand joints but also memorize all the commands.

Considering the abovementioned literature analysis and our own experimental experience, in order to develop a new interface for a virtual robot control system we abandoned the gesture-based approach in favor of a mixed method that involves AR elements and a single gesture of closing a thumb and a forefinger.

3 Materials and Methods

This section overviews our virtual control interface concept, a robot control system architecture, and a workcell configuration. Additionally, we describe a collaborative task that was used for the system testing.

Using our previous research as a starting point [22], we aimed to develop a new computer vision-based method for interaction and control of a cobot. The new approach was designed to be adaptable to a wide range of users and scalable to future needs, including new functionalities and features integration. It was important to develop an application, which does not generate haptic feedback but provides a feedback to a user via audio (application sounds) and visual signals (interface appearance changes).

The use of a contactless control of a cobot through a virtual interface during collaborative assembly tasks was supported by a number of arguments. Firstly, the contactless control reduces a biomechanical load on an operator; for example, when an operator controls a cobot using a teach pendant, the operator needs to hold it in a hand, which causes an arm muscles fatigue. Secondly, if the operator's hands are dirty, the contactless control prevents a further contamination of work area surfaces (the teach pendant, objects within the cobot workspace); thus, the contactless control allows operator's working environment to stay clean and tidy for a long time. Thirdly, to control the cobot with the teach pendant the operator needs to devote some time learning and practicing pendant's capabilities. Therefore, a user-friendly and intuitive application that uses computer vision and simple interaction commands (which may also include all functions of the teach pendant) will optimize time and efforts of the operator.

3.1 UR Robots – Virtual Control Application

UR robots – Virtual Control (UR-VC) application was programmed in Python3 and uses Pygame and Playsound libraries at the frontend. The Pygame was used to draw and animate interface elements. The Playsound was used to play predefined sounds when an operator selects a button or presses a button. The backend of UR-VC application employed CVZone, MediaPipe, OpenCV, and NumPy libraries for hand detection and data processing.

The UR-VC application User Interface (Figs. 1 and 2) contains the following elements:

1. A current robot program state (takes values "Playing", "Paused" or "Stopped").
2. A last command of a user (which button was clicked).
3. UR robot responses to user's commands (UR log).
4. "E-STOP" (Emergency Stop) button – a user can stop the robot immediately, which ends an execution of a current robot program.
5. "Power On" button turns on the robot.
6. "Play" button launches a robot program.
7. "Pause" button pauses a robot program.
8. A main cursor is located at a fingertip of a user's index finger in the interface of UR-VC. The main cursor allows a user to select any button.
9. A clicking cursor is located at a fingertip of a user's thumb in the interface. The user can click any button using this cursor and together with the main cursor.
10. A progress bar for clicking is designed to indicate a remaining time, which a user should keep his/her pointing fingers together in order to produce a button click. The bar was designed to exclude accidental and unintentional clicks.
11. "Next detail" button is responsible for sending the robot a command to proceed in order to assembly the next product (a fidget spinner). The button appears after clicking "Power On" button, waiting the robot to turn on and loading its program.

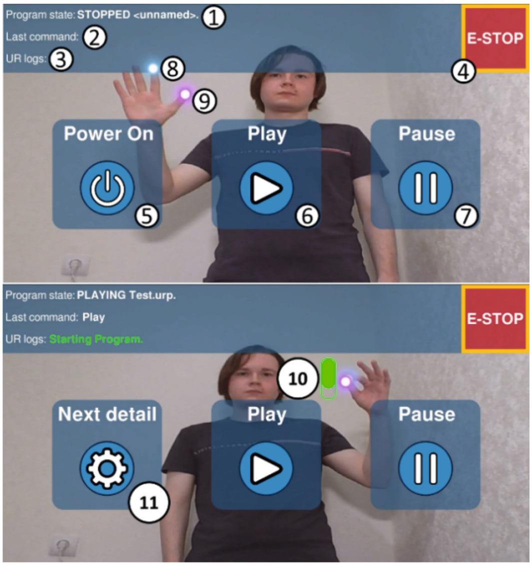

Fig. 1. UR-VC application User Interface.

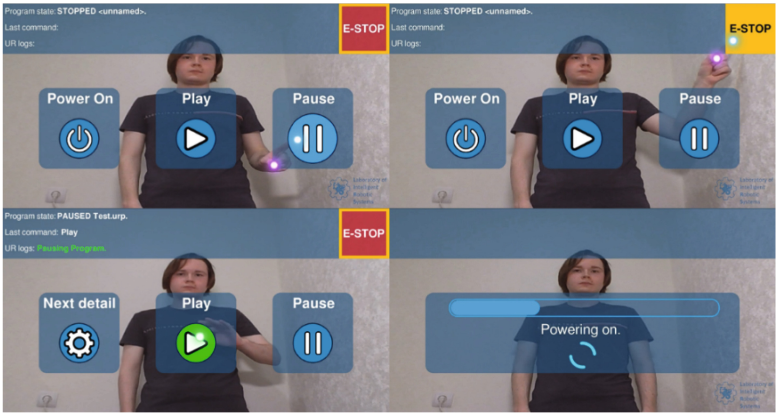

Fig. 2. Using UR-VC application showcase.

3.2 Workcell Description

A designed workcell included a robot table and a small additional table where necessary for experiments items were set up. The robot table allows placing objects on its top and fixing them with screws. The workcell included the following items (Fig. 3):

1. The UR3e manipulator; this collaborative robot has a small size, which improved participants' safety and left more free space within the workcell.
2. The starting location of the robot (marked with a A4 paper sheet with "Start" label); this was a location where the robot moved after launching a loaded program.

3. A waiting location of the robot for a command from the operator (marked with a A4 paper sheet with "Waiting for the "Next detail" command" label); this was a location where the robot moved after assembling one product and waited a user to click "Next detail" button in UR-VC application.
4. A felt-tip pen in the robot's gripper was used for drawing squares by the robot during the training stage for the participants.
5. Assembly parts, fidget spinner frames, were used for assembling the product (the fidget spinner) during the main stage.
6. A plastic mold for the fidget spinner frame for the collaborative assembly was a location where the robot placed a fidget spinner frame to assembly one product.
7. Assembly parts, 3D printed plastic bearings in a pallet, were used for assembling the product during the main stage.
8. A sheet of paper was attached to a robot's desktop for drawing squares on it during the training stage for the participants.
9. Felt-tip pens for participants for the training stage; the participants used these felt-tip pens for drawing on the paper inside the squares (that were drawn by the robot) during training stage.
10. A laptop with the UR-VC application running on it.
11. An experiment instruction listed steps for the participants to complete all stages of experiment.

In addition, the workcell contained a siting chair, which participants could use at their will.

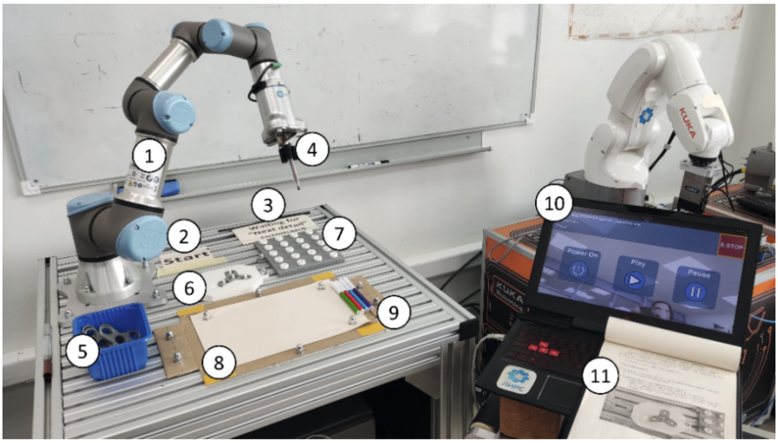

Fig. 3. The experimental workcell.

3.3 Collaborative Task

Collaborative assembly task is to assemble the product, the fidget spinner, using the UR3e robot. An operator takes the fidget spinner frame and puts it in the plastic mold for the robot. Next, operator waits for the robot to insert four plastic bearings into the fidget spinner frame (Fig. 4). In Fig. 5, the assembly parts and the finished product are presented.

The proposed in this paper collaborative assembly task is much simpler than the original task from our previous work [22]. For example, screws tightening by the UR5e robot in the original task made the experiment process rather long and difficult. Therefore, this time we intentionally simplified the original task to allow a participant concentrating on a developed UR-VC system evaluation rather than on the task complexity.

Fig. 4. The process of assembling the fidget spinner with the UR3e robot.

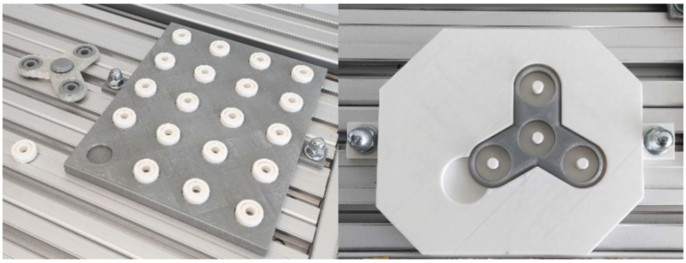

Fig. 5. Assembly parts and the finished product.

4 Experiment Description

This section describes the experimental setup aimed at testing the developed interface. The experiments had two stages: a training stage to teach the participants operating the system and the main experimental stage that was performed in order to evaluate the proposed system.

4.1 Training Stage

In total, the experiments involved 24 participants (Fig. 6): four laboratory members and 20 not professional robot operators. The participants were divided into two groups, which differed by dates of experiments. In the first stage (a learning stage) of the experiment, the participants learned to control the robot via the UR-VC application. The learning stage consisted of two parts: theoretical and practical.

Fig. 6. All participants of the experiments.

In the theoretical part, the participants watched a prerecorded video, which taught basics of working with the UR-VC application. In the practical part the participants had to apply the obtained theoretical knowledge (of the theoretical part) in order to develop basic practical skills of working with the robot via the UR-VC application and get acquainted with a concept of a collaborative assembly by completing two tasks.

These two tasks required a sequential execution of steps (clicking the UR-VC buttons in a specific order and explaining outcomes of the clicks), which were described in the instruction. The first task allowed the participants to interact with the UR-VC application for the first time and to understand a correspondence of the robot's movement and the user commands. The second task was a simple collaborative task, in which the robot drew squares one by one with the felt-tip pen at a command of a participant, and the operator drew a number inside the square. A fragment of the participant training experiment is presented in Fig. 7.

Fig. 7. A participant of the experiment during the training stage.

4.2 Main Stage

A main stage or a collaborative assembly task stage was built around a comparison of a manual and a collaborative assembly of products by the participants. At a beginning, the participants need to assemble five products manually. Then they needed to assemble five fidget spinners with the UR3e robot using the UR-VC application. A participant took the fidget spinner frame and put it in the plastic mold for the robot. After that, the participant clicked "Next detail" button in the UR-VC application and waited for the robot to insert four plastic bearings into the fidget spinner frame. When the robot was done, the participant took out the finished product and put it in a special box. All these steps were listed in the instruction.

Additionally, during the collaborative assembly, the participants had to completely stop the robot program execution and move the last four bearings in a certain way so that the robot could immediately begin assembling the last fidget spinner after the program was launched. A fragment of the main part of the experiment is presented in Fig. 8.

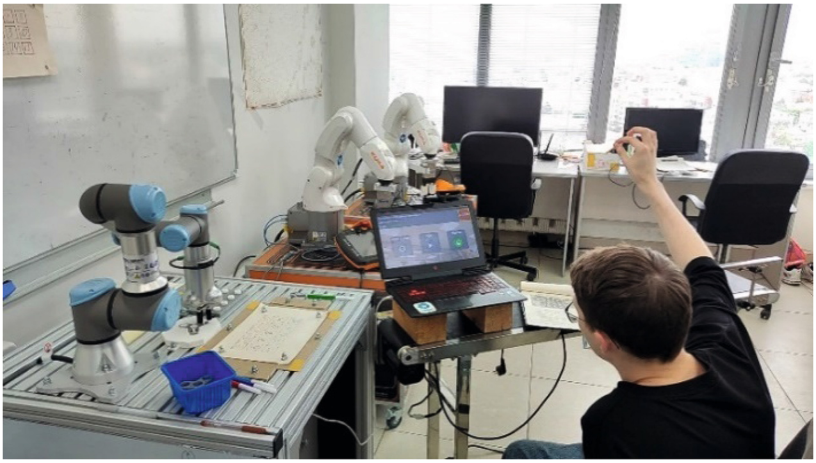

Fig. 8. A participant of the experiment during the testing stage.

4.3 Evaluation

After the experiment, the participants were asked to take a survey that consisted of seven questions (Table 1). Additionally, the experiments were recorded and we could postprocess the videos in order to evaluate all informal comments of the participants.

Table 1. The survey questions.

Number	Question
Q1	Was it easier for you to assembly the products with the robot assistance than without the robot?
Q2	How accurately did the robot execute your commands?
Q3	How quickly did the robot respond to your commands?
Q4	How comfortable were you while working with the robot?
Q5	How good did the robot perform its task?
Q6	What disadvantages in the robot and the UR-VC app operation could you note (if any)?
Q7	What changes, improvements, innovations would you like to propose for the UR-VC application?

We used a 5-point Likert-type scale for questions Q1-Q5 and a free form for questions Q6 and Q7. During the participants' behavior observation, we evaluated the following factors: time spent for training (average ~16 min), time spent for performing the main collaborative task (average ~13 min), comments made during interactions with the robot and the users' reactions to unexpected situations.

5 Results

All participants successfully coped with the task of controlling the robot using the UR-VC application. Figure 9 presents the results of the survey with questions Q1–Q5. The x-axis (horizontal axis) represents the questions' number, while the y-axis (vertical axis) shows the number of participants who selected a specific answer option.

In general, the participants noted a positive experience of using the application and did not notice any significant disadvantages. However, some participants pointed out that the robot could work faster. One participant complained that it was not very convenient to turn around and click the buttons in the UR-VC after each operation with the robot. Another participant reported that sometimes it was inconvenient to control the UR-VC with a single hand.

The participants made valuable suggestions on the UR-VC application potential improvements, including adding a support for controlling the robot with both hands, adding a controlling hand selection, adding voice commands for emergency stop, enabling tracking of operator's performance of their part of the work in a collaborative assembly, and selecting a robot's operating speed mode.

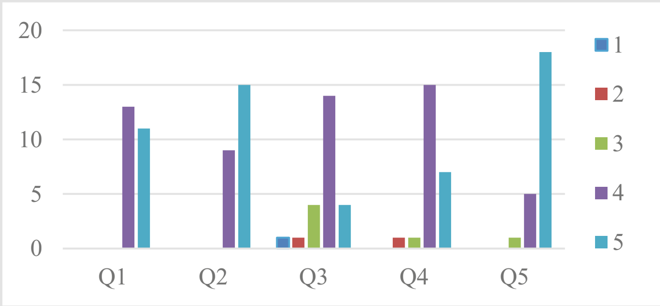

Fig. 9. The survey results. Avg.: Q1 – 4.5, Q2 – 4.6, Q3 – 3.8, Q4 – 4.2, Q5 – 4.7.

6 Discussion

To evaluate the experimental results, we conducted an analysis of the surveys and compared them with our previous research outcome where a pure gesture-based interface was employed [22]. The analysis demonstrated that the UR-VC application turned out to be more convenient, generic, intuitive, user-friendly, re-usable in collaborative assembly tasks and scalable then the previous gesture-based control system.

While observing the participants' behavior, we noted a number of interesting features. Even though some participants forgot or followed some steps in the instructions incorrectly, which caused unexpected situations (i.e., a participant forgot to put the fidget spinner frame in the plastic mold for the robot) during the assembly task, the participants still coped with it with a minimum of hints due to a fact that they quickly learned the basics of controlling the cobot using the UR-VC. To evaluate the participants' behavior in an unexpected situation, they were arbitrarily asked to suspend the robot's operation in the course of a task. Even though a proper button for suspending was not specified to them explicitly, all participants made a correct choice within the UR-VC interface.

No difference was observed in evaluations provided by participants with and without experience in robotic manipulators. Emphasized by the participants deficiencies mainly concerned the system response time and ergonomic requirements for the operator's workplace, e.g., suggesting different screen or emergency stop button locations with regard to the operator's position. These comments highlighted additional ergonomic requirements, which should be considered in HRC interfaces' development.

Overall, both the qualitative and quantitative assessments from users of the UR-VC application were significantly higher than the assessments obtained by the pure gesture-based interface [22].

7 Conclusion

In this study, we presented the results of experimental validation of a virtual interface for contactless control of the UR cobot within a joint assembly task. The results of experiments with 24 participants with and without robotic manipulation background indicated that people can effectively and rapidly learn a novel type of interaction with a robot in collaborative assembly tasks.

The new method of non-contact control of the UR robot turned out to be significantly more convenient for the users than a pure gesture-based interface [22]. The experiments emphasized the requirements for fine-tuning of ergonomics related parameters of virtual control applications for cobots, which is a part of our further research.

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