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Collaborative Robots' Perceived Safety
CROPS

Deliverable 2.2: Collaborative applications for trails

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Contents

1 Introduction

Recent changes in the production (e.g., Industry 4.0) lead to the development of new production setups. One of the most promising fields is the close collaboration between humans and robots. By using robotic skills such as power assist, inertia masking and virtual guidance combined with the human supreme sensory system within a shared control approach, it is possible to compensate weaknesses of each agent by strengths of the other. With the integration of collaborative robotics into manufacturing processes, safe human-robot interaction is possible.

Human trust in robots' autonomous decision capabilities is a known issue that significantly affects human-robot collaboration effectiveness, especially in the worker's willingness to share and allocate tasks to the robot. For this reason, the research on human perception towards robots is critical. In this document, two study cases of collaborative applications are presented. The study of human-robot collaboration included in Experiment 2 is to assess the users' perceived safety during their collaboration with a robot.

This document is divided into three sections. The first section includes a brief description of the experiment. In the second section, the experimental setup and two study cases including collaborative robot applications are presented. The last section summarises the experimental setup and robot's parameters.

2 Procedure of the experiment

All measurements that are a part of Experiment 2 will take place at the Faculty of Electrical Engineering, University of Ljubljana, in the Laboratory of Robotics. Participants will be asked to come to the faculty where they will be introduced to the aim of the study and the procedure of the experiment. Before starting, the participants will read and sign the informed consent necessary for participation in the study. The participants will then fill in demographic questions, personality questionnaire BFI-K and the short Robot Acceptance Scale.

After all the formalities participants will be asked to attend to the experimental part accordingly to the experimental protocol. Participants will go through the trail run where they will get to know the workflow and the robot. The experiment's main part will include collaboration between the participant and the collaborative robot Universal robots UR5e. Two different scenarios are designed: industrial application, assembly and electrical test of electronic device, and non-industrial application mimicking work in the pharmaceutical laboratory. Applications are designed so that during collaboration robot will alternate between tools that are considered safe and tools that are considered dangerous. Participants will also be exposed to different velocities of the robot's TCP. Motion velocities will be altered according to the experimental protocol, only motions that do not compromise the participant's safety will be included. Participants will undergo 18 different combinations of application parameters (2 different applications (industrial and not-industrial) x 3 velocities (0.25 mm/s, 0.5 mm/s, 0.75 mm/s) x 3 tools (safe, dangerous and combination of both) which leads to 18 different combinations). After each combination participants will answer a short questionnaire about their perception of safety while performing the assigned tasks.

3 Experimental setup

The main components of the experiment setup are

- collaborative robot Universal robots UR5e,
- robotic gripper Robotiq Hand-E with appropriate 3D printed fingers,
- safety laser scanner Sick NanoScan3,
- tools used in a different application with appropriate harnesses for safe gripping with robotic gripper,
- handling material used in collaborative applications.

3.1 Universal Robot UR5e

The Universal Robots UR5e is an advanced lightweight industrial collaborative robot built for medium-duty applications with payloads up to 5 kg. It has six degrees of freedom, repeatability of ±0.03 mm, and maximal TCP speed up to 1 m/s. The workspace of the UR5e robot extends up to 850 mm. Universal Robots e-Series robots are equipped with a range of built-in safety functions as well as safety I/O and digital and analogue control signals to connect to other machines and additional protective devices. For programming, a hand-held teach-pendant with touch screen is used. The robot controller is installed with PolyScope 5.8 firmware. The robot can also be controlled from an external PC connected via TCP/IP Ethernet connection. The robot with teach-pendant is presented in Figure 1.

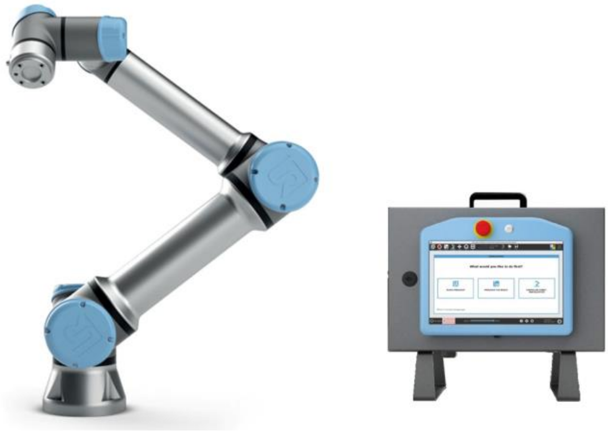

Figure 1: Collaborative robot Universal Robots UR5e with teach pendant.

3.2 Gripper Robotiq Hand-E

The Robotiq Hand-E gripper (Figure 2) is designed for industrial collaborative applications. It is used as a robotic end-of-arm tool for quick picking, placing and handling a large range of parts of varying sizes and shapes. Hand-E is a parallel gripper with 50 mm stroke, 5 kg load capacity and variable gripping force from 20 N to 130 N. Fingers are powered via single non-backdriveable motor. Gripper comes pre-installed with two aluminium fingers that are changeable to make and fit their design. The Hand-E is fully compatible with most Universal Robots' robot models and integrates seamlessly with the Polyscope programming environment via URCaps plug-in. The gripping width and gripping force can be easily specified on the teach pendant of the robot and thus optimally adapted to the gripping workpiece.

Figure 2: Robotiq Hand-E gripper with generic aluminium fingers.

3.3 Finger design

Gripper Robotiq Hand-E has pre-installed aluminium fingers. To ensure a safe and firm grip, we developed and manufactured specialised fingers. Fingers were designed via positive/negative principle in combination with tools' harnesses.

3.4 Safety laser scanner SICK NanoScan3

Safety laser scanner NanoScan3 by SICK (Figure 3) delivers high-precision measurement data and is exceptionally resistant to light, dust, or dirt. The safety laser scanner operates on the principle of time-of-flight measurement. It emits light pulses in regular, very short intervals. If the light strikes an object, it is reflected. The safety laser scanner receives the reflected light and calculates the distance to the object based on the time interval between the moment of transmission and moment of receipt. The sensor has a 9 m protected field range, 275° scanning angle, and 128 freely configurable fields. The response time of the laser is ≥ 70 ms.

The sensor can be easily configured via program Safety designer; parameters such as safety fields, range of measurements, data output and other configurations can be changed. The fields can be set as protected or as warning fields.

In Experiment 2, two safety sensors SICK NanoScan3 will be used. One will be mounted parallel with the ground monitoring position of the user to the robot. If the safety fields are breached a reduced safety mode on the robot controller will be triggered. The second sensor will be mounted perpendicular to the work area and used as a light curtain. It will monitor if the user is reaching with his/her hands into the robot workspace while the robot is performing motion with high speed. In case of the breach a reduced safety mode will be triggered. Placement of both safety sensors is presented in Figure 4.

Figure 3: Safety sensor SICK NanoScan3 can be used as a safety device and/or as a LIDAR by streaming measured data via UDP connection.

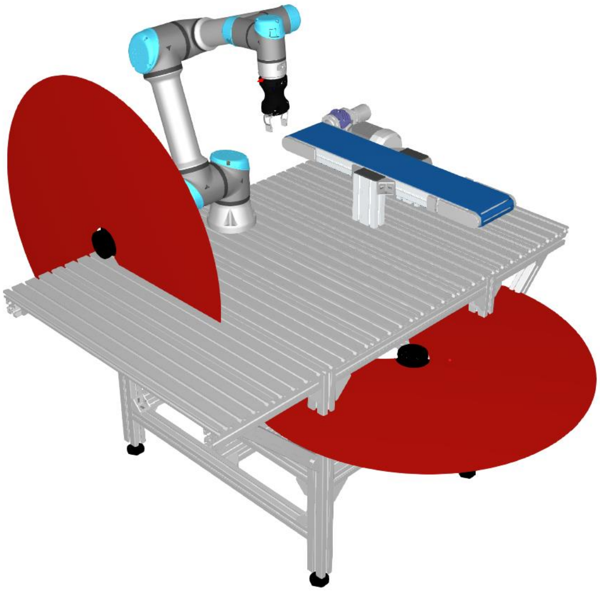

Figure 4: Placement of SICK NanoScan3 laser scanners; red areas indicate scanning planes.

4 Collaborative applications

To assess participants' perceived safety during their collaboration with the robot in the same workspace, we designed two collaborative applications: one imitating an industrial environment and the other one a non-industrial environment. Each application is designed as a three-part procedure where all parts can be performed independently of each other, enabling us to include sufficient randomisation into the experimental protocol.

4.1 Application 1: Collaborative application in the industry - assembly of small electronic device

Industrial applications are usually designed with a maximum throughput in mind. As such, the robot's motion must be as direct as possible to achieve desired cycle times. In industrial robotic application collaboration between humans and the robot is somewhat undesired as this means a smaller robot's velocity. However, in some cases, the robot needs to manipulate something undetermined and non-repetitive (e.g., electrical wires) and take the robot too much cycle time to process and manipulate the object efficiently. As a solution, human-robot collaboration can be introduced where the human takes over the problematic manipulation.

The collaborative application of assembling small electronic devices combines robot manipulation of rigid objects and human manipulation of soft compliant materials. The design of the application includes various steps that are performed by the robot or human in sequence. Robotic part involves the pick-and-place motion to place the box enclosure with the included circuit, testing the electrical connections on the circuit, and covering the box enclosure and removing the finished part. The human part includes connecting the wires to terminal blocks and connectors and applying the quality control marker to the circuit.

In Figure 5, the main components of the collaborative robotic cell are presented.

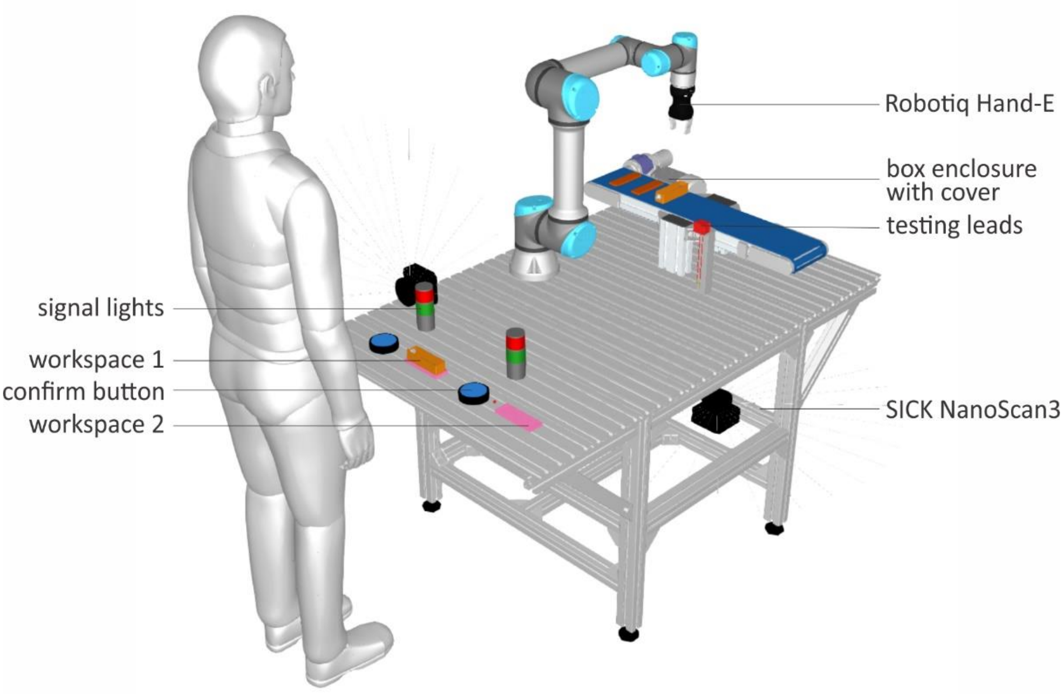

Figure 5: Industrial collaborative robotic cell.

The workflow of the application is presented in five detailed steps.

Step 1: Placing the box enclosure

In this step, the robot places the plastic box enclosure with an electrical circuit already included on the connecting station (see Figure 6). The robot grips the box directly with the installed fingers on the gripper. Since the plastic box has no sharp edges, it does not present a high risk during robot manipulation (it is considered a "safe tooling").

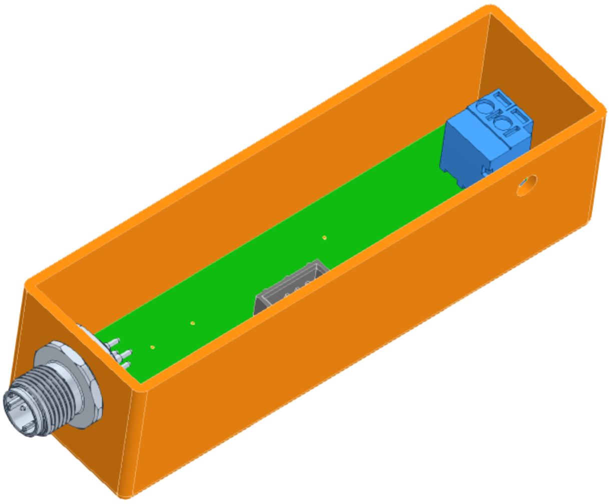

Figure 6: Box enclosure with inserted PCB. A round connector is placed on one side of the box that needs to be connected to a PCB.

Step 2: Connecting wires

In this step, the worker connects wires to spring-loaded terminal blocks and adds cable with a connector (see Figure 7). Also, the testing power cable is connected to the external connector. Worker confirms the finished task by pressing the confirm button next to the connection station.

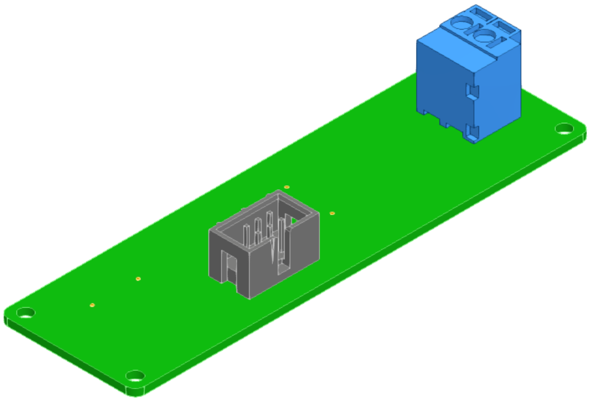

Figure 7: PCB model with two connectors: 6 pins IDC (black box) connected with a round connector on the enclosure, and spring terminal block (blue box).

Step 3: Connection testing

The robot uses testing leads to test the electrical connections on the circuit. As a tool, a pair of testing leads fitted with spring probe pins is used (see Figure 8). Because of the sharp points, this combination of gripper and testing leads can be considered more "dangerous tooling". Robot relays the test result to the user via visual information (green light for the pass and red light for fail).

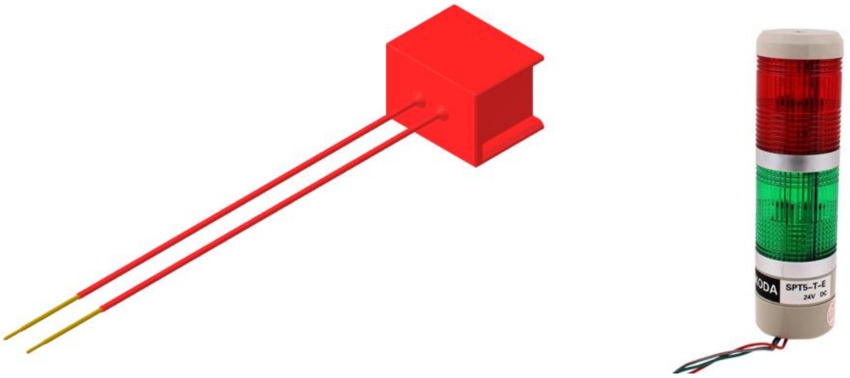

Figure 8: Testing leads with sprig probe pins; handle of the leads includes a groove for gripper finger to provide safe and firm grip (left); signal light (right).

Step 4: QC Pass

If the assembly passes the connection testing, the worker applies the QC Pass sticker (Figure 9) inside the box enclosure. If not, the box is removed from the workflow and sent to manual check-up. The worker also removes the testing power cable. Again, the end of the operation is confirmed by pressing the confirm button.

Figure 9: QC Pass sticker for marking that the circuit successfully passed the quality control.

Step 5: Placing the cover

When all the previous steps are finished, the robot covers the box enclosure and puts the electronic device in the box further in the manufacturing process.

4.1.1 Different combinations of application

Due to the application's modular design, different combinations considering the type of used tools can be presented.

1. The robot uses only "safe tooling"

   Step 1 **>>** ***Step 2*** **>>** ***Step 5***

2. The robot uses only "dangerous tooling"

   Worker takes the box enclosure **>>** ***Step 2*** **>>** ***Step 3*** **>>** *Worker removes the part*

3. Robot uses a combination
   a. safe/dangerous tooling

      Step 1 **>>** ***Step 2*** **>>** ***Step 3*** **>>** ***Step 4*** **>>** *Worker removes the part*

b. dangerous/safe tooling

   Worker takes the box enclosure >> ***Step 2*** >> ***Step 3*** >> ***Step 4*** >> ***Step 5***

c. safe/dangerous/safe tooling

   Step 1 >> ***Step 2*** >> ***Step 3*** >> ***Step 4*** >> ***Step 5***

4.2 Application 2: Collaborative application outside the industry: laboratory automation

Potential areas for collaborative robotics are also outside the industrial environment. Collaborative robots can help automate processes that are time consuming, repeatable, and require a low cognitive load. In contrast to industrial applications, robot motion can be more relaxed with less emphasis on cycle time. Laboratory automation is one of the non-industrial fields with many repeatable tasks where precision and traceability are of utmost importance. The collaborative robot can be effectively used during testing for handling laboratory inventory, sample preparation, and labelling. Laboratory technicians can then fully focus on the experiment without additional distractions. With the help of the robot, experiments can be conducted faster and on a greater scale.

One of the primary methods for testing the efficacy of drugs (e.g., antibiotics) on bacteria is disk diffusion assay or Kirby Bauer method. The laboratory process for doing this test was an inspiration for us to create a collaborative application. We have used collaborative robots to manipulate petri dishes to and from laboratory technician, prepare test filter paper discs soaked with proper dilution of the reagent, and take care of the petri dish's proper labelling. Laboratory technician uses his/her skills to apply bacterial cultures to agar properly and to place correct test discs to appointed positions. Figure 10 shows a laboratory cell for testing antibiotics.

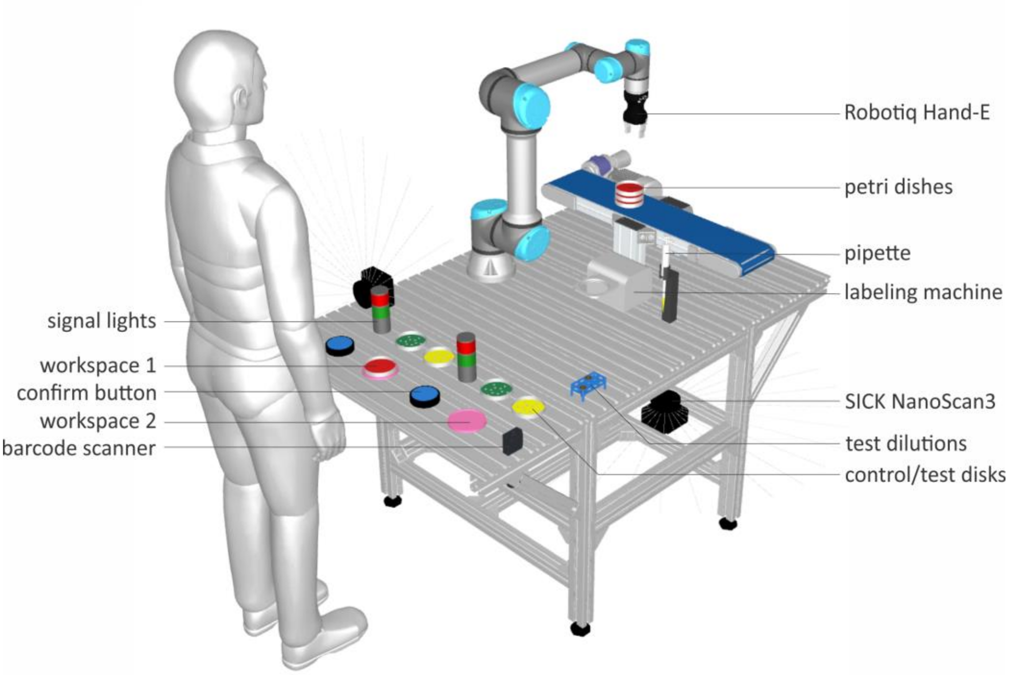

Figure 10: Design of collaborative robotic cell for laboratory automation.

The workflow of the testing method is described in five detailed steps.

Step 1: Petri dish labelling and placement

Laboratory technician scans the barcode on the bacteria suspension. Printing machine prepares the label that is applied onto the bottom of the petri dish. The robot then brings an empty petri dish with agar plate to the laboratory technician's work area.

For petri dish manipulation, specially designed fingers that enable grip based on the shape will be used (see Figure 11). Together with the petri dish, they represent "safe tooling".

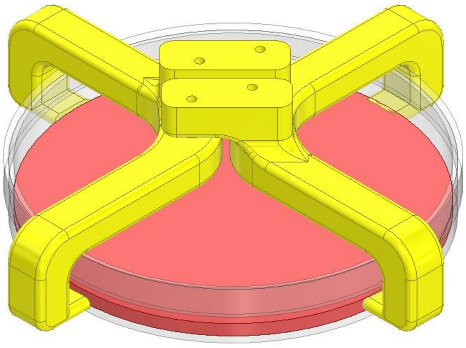

Figure 11: Specially designed fingers for a gripping petri dish.

Step 2: Lawn of bacteria preparation

After scanning the bacteria suspension, the laboratory technician streaks the bacterial culture on the plate to create a lawn of bacteria using a sterile cotton swab (Figure 12). A technician confirms the finished task by pressing the confirm button.

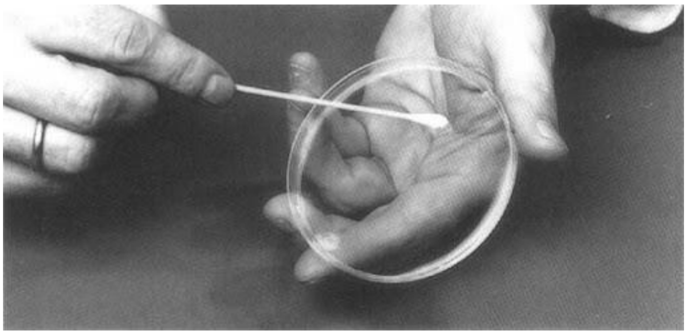

Figure 12: Petri dish swabbing.

Step 3: Reagent preparation

Based on the information from the scan, the collaborative robot starts preparing test disks. It takes an automatic pipette and soaks the filter paper disks with an antibiotic dilution of proper concentration. It also prepares control disks using only water.

The robot will be using a pipette for test disk preparation. The pipette tip is a spike and is considered "dangerous tooling" (see Figure 13).

Figure 13: Example of pipette; due to a spike tip, it is considered dangerous.

Step 4: Placing test filter paper disks

A laboratory technician takes the test filter paper disks soaked with antibiotics and places them in the correct position (e.g., one control disc and three with antibiotics) following all the sterile handling protocols.

Figure 14: Placement of test filter disks.

Step 5: Petri dish removal

The robot takes the petri dish and places it into a container that will be put into an incubator.

4.2.1 Different combinations of application

Due to the application's modular design, different combinations considering the type of used tools can be presented.

4. Robot uses only "safe tooling"

   Step 1 **>>** ***Step 2*** **>>** ***Step 5***

5. Robot uses only "dangerous tooling"

   Laboratory technician places the petri dish **>>** ***Step 2*** **>>** ***Step 3*** **>>** ***Step 4*** **>>** *Technician removes the petri dish*

6. Robot uses a combination of safe an dangerous tooling
   a. safe/dangerous tooling

      Step 1 **>>** ***Step 2*** **>>** ***Step 3*** **>>** ***Step 4*** **>>** *Technician removes the petri dish*

b. dangerous/safe tooling

Laboratory technician places the petri dish >> ***Step 2*** >> ***Step 3*** >> ***Step 4*** >> ***Step 5***

c. safe/dangerous/safe tooling

Step 1 >> ***Step 2*** >> ***Step 3*** >> ***Step 4*** >> ***Step 5***

5 Safety

Although the robot UR5e is a collaborative robot with inherent safety, we implemented two additional levels of safety.

5.1 Fail-safe gripper design

For tool handling, we used collaborative gripper Hand-E from Robotiq. When the robot is manipulating the work object, pre-installed aluminium fingers with groove are used. In this way, sufficient force and contact are provided for safe manipulation.

When the robot uses "dangerous tools" (testing leads, pipette), additional harnesses for tools are used to provide a safe and firm grip. Also, harnesses have the function of tool alignment and to provide a repeatable grip.

5.2 Safety sensors SICK NanoScan3

Two SICK NanoScan 3 are used: as an area scanner and the other as a light curtain. First, one checks the position of the participant regarding the robot. If the participant is too close to a robot, a reduced mode is triggered. The second sensor is checking the participant's position, dividing the robot workspace into two areas. The area A is where the robot can move with high TCP velocity as participants will not be entering that area. Area B includes a collaborative workspace with participants' workspace. In this area, the TCP velocity of the robot is limited to maximal 250 mm/s. If the participants enter area A, a reduced mode on the robot controller is triggered (the system is set to Most Restricted). When a safety limit is no longer breached, the robot controller changes from reduced to normal mode and continues with the program. By implementing additional speed and distance monitoring in combination with the robot's integrated safety functions, participants' safety is met under the intended conditions of the robot.

6 Robot's parameters

To adequately assess participants' responses, collaborative tasks will be performed under different conditions. Two main independent variables are tools (safe, dangerous and combination of both) and the TCP velocity (0.25 m/s, 0.5 m/s and 0.75 m/s). Use of different motion types and direction of motion as variables (as in Experiment 1) is not possible nor meaningful as the application would not be optimally performed, and participants' safety could be compromised.

6.1 Tools

Collaborative applications are designed so that two types of tools are used: "safe" and "dangerous". Descriptions are presented in Table 1. Design of the applications enables three combinations of used tools (the safe, dangerous, combination of both).

Table 1: Description of the tools used for collaborative applications.

Tool	Type	Application 1	Application 2
tool 1	safe tooling	gripper holding box enclosure with no sharp edges	gripper holding round petri dish
tool 2	dangerous tooling	gripper holding testing lead (two spikes)	gripper holding pipette with spike tip

6.2 Velocity

In the experiment, three velocities will be tested: 0.25 m/s, 0.5 m/s, and 0.75 m/s.

The velocities were defined through the experiment results for the discretisation of robot parameters (Deliverable 2.1). The study results showed that 0.78 m/s is the upper limit for people to perceive robot motion as safe.

Only the motions performed behind the safety light curtain will be adequate for velocity change. TCP velocity in the vicinity of the participants will not be changed to ensure the participant's safety.

6.3 Parameters combinations

With three tool combinations and three velocities, there are 9 different combinations of robot parameters that will be used for each application. Combinations are presented in Table 2.

Table 2: Parameter combinations for one test application

Combination	Tool	Velocity [m/s]
1	safe tooling	0.25
2		0.50
3		0.75
4	dangerous tooling	0.25
5		0.50
6		0.75
7	safe and dangerous tooling	0.25
8		0.50
9		0.75

Because we have two applications with 9 different combinations, the participants will be subjected to 18 different test conditions presented in randomised order.

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