Optimizing Collaborative Robotic Workspaces in Industry by Applying Mixed Reality

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Abstract. Collaborative robots (cobots) find increased use in industrial workspaces. The aspects of safety and ergonomics are important challenges when designing such workspaces. In this work Mixed Reality (MR) and Virtual Reality (VR) are used for the design of cobot workspaces in industrial environments. ROS (Robotic Operating System) together with Unity is used to simulate and visualize cobot applications. Simulated and real robotics are merged into one tool developed for Extended Reality (XR). To allow early planning in VR, existing industrial environments are reconstructed digitally using state-of-the-art 3-D laser scanners. VR and MR are then applied to test the developed scenarios in various environments, like variation of workspace or robot. In addition, an external tracking system allows us to monitor a human operator and to visualize ergonomics and to mitigate potential safety risks.

Keywords: Cobot · Ergonomics · Industry 4.0 · ROS · Mixed reality

1 Introduction

One target of Industry 4.0 is a high level of collaboration between human workers and industrial robots, with the aim of improving overall efficiency and productivity [24]. Modern industrial automation enjoys an increasing presence of collaborative robots (cobots), which reduce the necessity to enclose robots in safety cages and enabling new modes of man-machine interaction. In such configurations humans and machines are allowed and even encouraged to come in close contact. Thus it is of highest importance to ensure well-defined task sharing and to establish reliable safety protocols protecting the human worker from physical harm [22].

Thus, the application of cobots manifests the following main challenges:

– Safe working environment for the human co-worker,
– Design of efficient workspaces, in terms of time and costs, and
– Ergonomically optimized workplaces.

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The use of Mixed Reality (MR) and Virtual Reality (VR) can help to overcome these challenges [7]. In an overarching goal we target to optimize the efficiency of such workspaces and how they can be designed in an ergonomic way, while at the same time creating a safe environment for the workers. In this work, we focus on how MR could assist the design of collaborative workspaces by using a workflow from an experimental setup to real setups. We combine this in a laboratory setup. Thus, we did a comprehensive literature review to highlight important aspects when designing the setup of such a laboratory. Subsequently, we present the setup of the laboratory and some preliminary results.

2 State of the Art

2.1 VR, AR and MR for Robotics and Industry 4.0

In the last years, impressive work has been carried out in the application of VR/AR/MR in an Industry 4.0 context, and many suitable applications have been identified. In this paper, we focus on results related to human–robot collaboration (HRC).

A quality review on AR and VR applications for Industry 4.0 was published by [3]. In that work, the authors state that these technologies enable new ways of interaction with the workers, the shop floor, and the whole enterprise. Workers strengthen their perception of the product and its processes becoming an active part of the manufacturing decision-making as they influence the design of the manufacturing network. They highlight several key advantages: the application to production plant control and diagnostics; safety and security of production systems; improvement of planning activities including resource matching; product design and reconfiguration; provision of the required information at operational and enterprise-level; improvement of cooperation between humans and machine; teaching workers complex tasks in a safer manner to increase their productivity.

A systematic review of Augmented Reality interfaces for collaborative industrial robots carried out by [4] aimed at identifying the main strengths and weaknesses of AR with industrial robots in HRC scenarios. The results suggest that AR technology shows its effectiveness also in this particular domain. With respect to traditional approaches, AR systems are faster and more appreciated by users.

A similar literature review on using AR with HRC was done by [8]. They state that future space exploration will demand the cultivation of human-robotic systems, however, little attention has been paid to the development of human-robot teams. Current methods for autonomous plan creation are often complex and difficult to use. According to them, a system that enables humans and robotic systems to naturally and effectively collaborate is needed. Effective collaboration takes place when the participants are able to communicate in a natural and effective manner. Moreover, the common understanding between conversational participants, shared spatial referencing and situational awareness, are identified as crucial components of communication and collaboration.

An AR software suite for enabling human-robot interaction in flexible robotic assembly lines was proposed by [12]. Even if stated as Augmented Reality, they use more a kind of Mixed Reality for this application. Their goal is to support operators in production systems employing mobile robots. These robot workers may increase an assembly system's flexibility while supporting humans, given their ability to navigate to different workstations and change tools for performing various assembly tasks. Unfortunately, their software stack is not publicly available.

The human-robot contactless collaboration with mixed reality interface presented by [10] proposed a control system based on multiple sensors for the safe collaboration of a robot with a human. New constrained and contactless human-robot coordinated motion tasks are defined to control the robot end-effector so as to maintain a desired relative position to the human head while pointing at it. Simultaneously, the robot avoids any collision with the operator and with nearby static or dynamic obstacles, based on distance computations performed in the depth space of an RGB-D sensor. The various tasks are organized with priorities and executed under hard joint bounds using the Saturation in the Null Space (SNS) algorithm. Direct human-robot communication is integrated within a mixed reality interface using a stereo camera and an augmented reality system.

An application of Augmented Reality combined with cobotics to toolmaking, allowing the user of the system to interact with the robot (or a simulation thereof) and guide it to the task at hand was proposed by [7]. The authors used an environment based on ROS and Unity, communicating using ROS Sharp. A similar system is presented by [21], using MR for planning and manipulation of robotic trajectories, combining the HoloLens and ABB proprietary simulation software.

Improvements in human-robot handover by using MR were shown by [18]. They state that MR devices, such as the Microsoft HoloLens, allow the augmentation of real environments with visualized sensor data as well as simulation of robotic parts like virtual robot heads or arms attached to a physical robot. This enables HRI experiments that were difficult or impossible to conduct before.

A concept for a mixed-reality learning environment tackling challenges identified regarding HRC is shown in [29]. Existing technologies were examined and evaluated for usage in the context of HRC training.

The impact of MR on a hand guiding task with a holographic cobot was shown by [23]. They present an interface in which some tangible feedback is provided through ultrasound-based mid-air haptics actuation. In addition, they report about a case study evaluating the impact that this haptic feedback may have on a pick-and-place task of the wrist of a holographic robot arm.

A mixed-perception approach for safe human–robot collaboration in industrial automation was proposed by [1]. They addressed safety by designing a reliable safety monitoring system for cobots. The main idea here is to significantly enhance safety using a combination of recognition of human actions using visual perception and interpretation of physical human–robot contact by tactile perception. Two different deep learning networks are used for human action recognition and contact detection, which in combination, are expected to lead to the enhancement of human safety and an increase in the level of cobot perception about human intentions.

A work on communicating and controlling robot arm motion intent through mixed-reality head-mounted displays applying the framework *ROS Reality* was published by [26]. Their interface allows users to adjust the intended goal pose of the end effector using hand gestures.

2.2 Planning Cobot Workplaces

In [16] the design of a safety framework for the coexistence of an operator with a standard industrial robot is shown. The authors devised safety measures and requirements for the coexistence and implemented them on an actual prototype cell. They use gesture commands to interact with the robotic system.

An atlas of physical human-robot interaction is available in [5]. The authors give an overview of issues to consider when tackling safe and dependable HRI and propose some benchmarks to assess safety and dependability.

An extensive review on human–robot collaboration in an industrial environment is provided in [30]. The authors give a specific focus on issues related to physical and cognitive interaction, highlighting the importance of safety and intuitive programming. They also present commercial solutions and show industrial applications where cobotics are advantageous.

The development of a collaborative human-robot manufacturing cell in the automotive context is shown by [2]. They show that collaborative robotics can greatly reduce fatigue and strain on workers, and that gesture monitoring is a viable approach for interacting with a robotic system.

An extensive survey on safety during HRI is given in [13]. The authors give a broad overview of issues and risks and extensively discuss them and highlight possible strategies to tackle them.

The term *collision event pipeline* is introduced in [9]. The authors describe a single framework for detecting, isolating, and identifying collisions, highlighting the computational needs and general advantages and disadvantages of different methods.

In [19] and [20] the author highlights the ergonomic impact of cobotics and AR/VR respectively, noting that these technologies permit new ways of interaction between operator and machine. The author also emphasizes that these new tools need to be designed ergonomically, otherwise prolonged use may put an unnecessary physiological and physiological strain on the long-term user.

2.3 Coupling of ROS and Unity

Several different approaches for coupling ROS with Unity or another 3D-based software that can be utilized for AR/VR/MR can be found in the literature:

An implementation of an augmented teleoperation system based on (ROS) can be found in [14].

ROS Reality, a Virtual Reality framework using consumer-grade hardware for ROS-enabled robots is shown in [32]. It is an open-source, over-the-Internet teleoperation interface between any ROS-enabled robot and any Unity-compatible VR headset. They use ROS Bridge (a standard package provided by ROS to enable the integration of applications over Ethernet) and wrote custom Csh scripts for Unity. Since publishing the paper, no further work was carried out on this framework. It supports only subscribing and publishing joint states. Applied research based on this framework is presented in [26,27] and [31], however, the improvements seem not to be publicly available.

An operator interface for multi-robot systems and VR was developed by [25]. The main goal was the development of immersive monitoring and commanding interfaces, able to improve the operator's situational awareness without increasing its workload. To achieve this, the available technologies and resources were analyzed and multiple ROS packages and Unity assets are applied, again also ROS Bridge. Some applications were also presented, however, this framework is not available to the public.

A Mixed Reality-based simulation for mobile delivery robots was proposed by [15]. They used the *ROS Bridge* and the Unity AR foundation to realize the interface. This work is not publicly available and is very focused on mobile robots.

A more open and general framework for coupling Unity with ROS is provided by Siemens. ROS Sharp is available on Github[1], but there are no known scientific publications available. ROS Sharp allows the connection of publishers, subscribers, and services to ROS. The main limitations are, that the library must be recompiled, which is the reason why, e.g. for the HoloLens, additional adoptions are necessary. Another drawback is the fact, that they are using a JSON-based communication protocol. JSON has the benefit of being a human-readable format, but encoding and decoding it costs precious processing time and bandwidth. As a result streaming images or point clouds is mostly infeasible.

At the end of the year 2020, Unity presented their own implementation of a ROS connector. It was made available on Github[2]. The implementation is based on ROS Sharp, but there is no need for recompilation after changes. Also, the creation of various data types necessary to e.g. work with ROS messages or services is significantly easier and more comprehensive. They also rely on compressed binary coding for transferred data, allowing for image streaming in nearly real-time.

Initially VISUAL was using ROS Sharp, but we encountered significant restrictions and low user-friendliness. After Unity published its own implementation, we changed the framework. It also benefits from the advanced simulation capabilities of Unity, which allow us to simulate the robot directly in Unity, without the need for Gazebo (which is part of ROS, but again, not very user-friendly).

[1] https://github.com/siemens/ros-sharp.

[2] https://github.com/Unity-Technologies/Unity-Robotics-Hub.

3 Methodology

3.1 Laboratory Setup

In this work we propose the setup of a laboratory, called VISUAL (Virtual SimUlator for Automation Laboratory) (compare Fig. 1). The laboratory setup allows one to:

- Acquire a three-dimensional capture of an existing working environment using a survey-grade LIDAR-scanner.
- Use the three-dimensional capture of the actual working environment for a design phase in 3D-software (Unity).
- Use Virtual Reality to test the designed workplace. The use of force feedback gloves (SenseGlove) allows for a highly immersive experience in this phase.
- Simulate the cobot using the articulation joint system based on Nvidia's PhysX 4.
- Use real-time coupling of ROS (Robot Operating System) with Unity allows integrating the real controller setup early on and facilitates future portability.
- Use Mixed Reality glasses (*Microsoft HoloLens 2*) to test the designed workspaces in the real environment. A compiled application permits this also remotely without the need for physical presence in the laboratory.
- Use a motion tracking system to assess the ergonomic impact on the operator while wearing MR glasses and carrying out his tasks.
- Combining virtual with real assets allows for safe trajectory planning. The operator can test the movement of the robot in a MR setup superimposed on the real robot. When the operator is satisfied with the simulated results, the operation of the real hardware can be directly started via the MR interface.
- Use for the training of operators in VR and MR. Operators need to be trained on the system, also to get comfortable with it (which increases acceptance and security). This can be done in an early stage in VR and then in MR in the real working environment, even if the robotic hardware is not yet available.

3.2 Hardware Architecture

The hardware architecture we used is shown in Fig. 2. It is built around two processing nodes. The first node (*ROS-Master*) running Ubuntu 20.04 is responsible for the high-level control of the robotic arm and the RGB-D-Sensor (*Intel RealSense D435i*). The other node (*Processing Node*), running Microsoft Windows 10, is used for processing motion tracking data. For motion tracking, a solution from Qualisys with eight tracking cameras is used. We use a time synchronization with the Linux PC running ROS. The node also interfaces with the tactile glove (*SenseGlove Developer Edition*). When using VR glasses, Unity is running on this node and streams the XR-app. The MR-Glasses (*Microsoft HoloLens 2*) are used to display the XR-app in the MR-mode. It is connected via WiFi. The robotic arm (here a *Universal Robots UR10e*) is also connected to the network. The robotic arm provides a high-level interface for ROS but has its own hardware controllers and safety control is carried out by the robot itself.

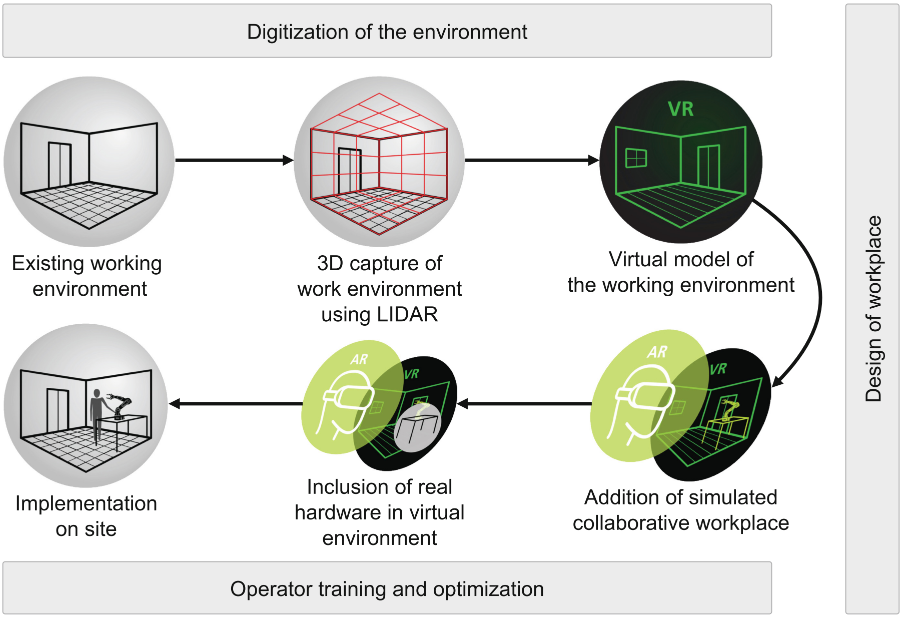

Fig. 1. Workflow in VISUAL.

3.3 Software Architecture

On the software side, we can distinguish three different software stacks (compare Fig. 3). Two of them are running on the processing nodes described in the previous section, and one on the HoloLens.

The robotics stack is built on *Ubuntu 20.04* and the Robotic Operating System (ROS) *Noetic Ninjemys*. On top of it we use the *Universal Robots driver*[3],

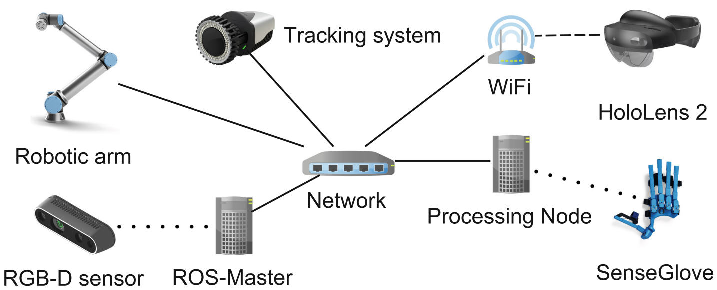

Fig. 2. Hardware architecture of VISUAL.

[3] https://github.com/UniversalRobots/Universal_Robots_ROS_Driver.

MoveIt[4] and the *ROS-TCP-Endpoint* by Unity[5]. The Universal Robot driver establishes the connection to the robotic arm interface. It allows sending trajectories and commands for the gripper. With MoveIt the planning of the trajectories is carried out. The *ROS-TCP-Endpoint* allows the connection to Unity. It is used to create an endpoint to accept ROS messages sent from a Unity scene. All types of messages and services can use this service, as the necessary code can be automatically created within C# for each functionality. The application logic of VISUAL is packaged into an application-specific module that uses the *ROS-TCP-Endpoint* and *MoveIt*.

The processing stack is built on *Microsoft Windows 10* and the *Unity Engine (2020.3f1)*. We employ the *ROS-TCP-Connector* to interface to the robotics system, and the *Microsoft Mixed Reality Toolkit* (MRTK 2.6.1) to create an XR-Application. The application-specific logic is implemented in Unity using C#. Moreover, this stack includes the *Qualisys Track Manager* (QTM) to process the motion tracking data, and the *SenseGlove SDK* to interface with the tactile glove.

The HoloLens stack is derived from the processing stack and build from the same Unity project. This allows for fast development on the main computer and rapid deployment to the HoloLens visor.

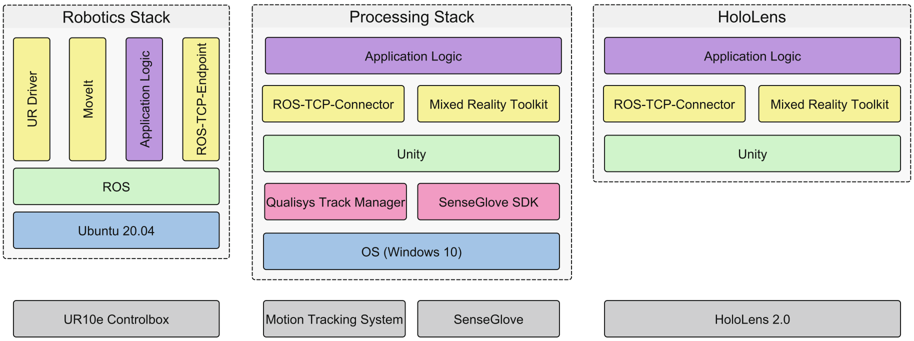

Fig. 3. Software architecture of VISUAL.

3.4 Ergonomics and Safety

For the tracking of the operator's body, we decided to use a commercially available motion tracking system. We use a system based on the *Qualisys Miqus M3* motion tracking cameras and an of-the-shelf motion capture suit. This system has various benefits, the most relevant to VISUAL being the provided integration modules for ROS and Unity. This allows us to have direct access to the operator's skeleton model in both processing systems.

[4] https://moveit.ros.org.
[5] https://github.com/Unity-Technologies/ROS-TCP-Endpoint.

Having the operator skeleton available in the robotics system allows us to implement an additional operator safety layer. Based on the work done in [6, 28], the robot can slow down, respectively stop its motion when it comes close to the operator, before even having physical contact.

On the other hand, having a precise skeleton model of the operator allows to simultaneously also perform a basic assessment of operator ergonomics. Especially joint angles and overall posture can be evaluated in real-time and allow for a user-centric design of the overall workplace (compare [11]) (Fig. 4).

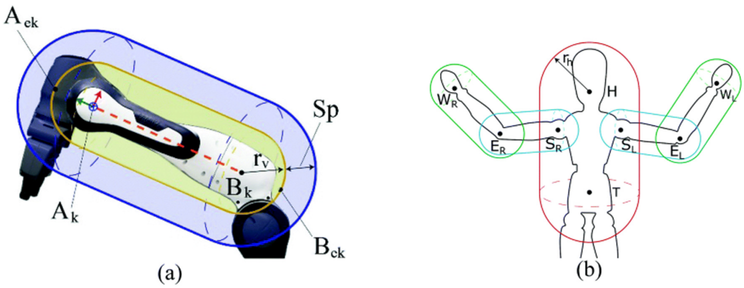

Fig. 4. Use of Sphere-Swept-Lines as dynamic safety zones (a) on robotic arm and (b) for human skeleton as described in [28].

4 Results and Discussion

In the following section, we want to demonstrate the principal workflow of the proposed methodology and the results that can be achieved. We want to highlight the main challenges in each step and the future potential of the methodology.

4.1 3D-capture of the Current Working Environment

In the first step, the existing working environment is scanned using LIDAR scanners. Modern laser scanners, as used in our environment, reach accuracies in the sub-millimeter range and have a working range of more than 50 m. By using stationary and mobile laser scanners, even complex industrial environments with machines (compare Fig. 5, where a laser cutter was scanned) can be digitized accurately. This high accuracy facilitates also the design of difficult scenarios where precise path planning of the robotic arm is necessary. 3D point clouds can look very impressive as first (like Fig. 5), but they have some significant drawbacks when used VR or MR. As they represent only a set of points, a surface - that can be rendered - must be attached to each point. This surface can be a circular or square area. To achieve a high level of immersion in VR, the size of this surfaces must be scaled depending on the distance to the viewer. Also, they do not represent closed surfaces, which creates artifacts when using shadows. Thus, the preferred solution is to first create a mesh out of the point cloud. For creating these meshes several commercial and open-source tools are available. They usually have in common, that the model needs to be split into sub-models to achieve good results when using automatic algorithms. Manual adaption of the meshes is time-intensive and in many real-work applications not target-oriented. We suggest to use horizontal sub-dividing of the model when applying this method to larger scenes.

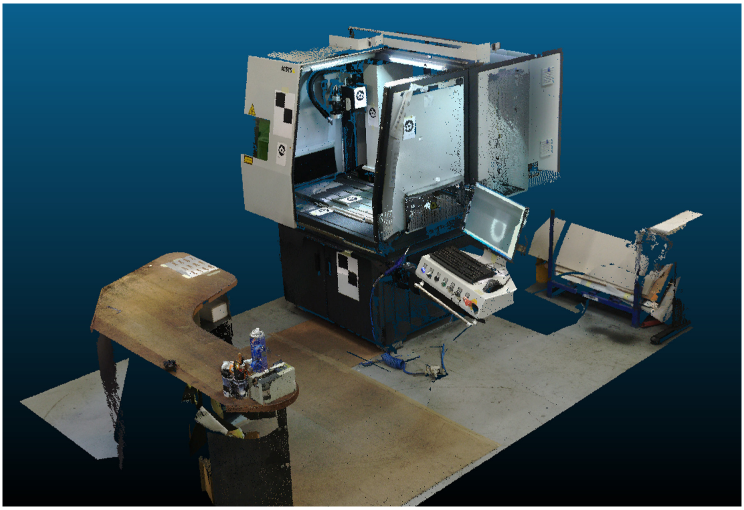

Fig. 5. Example of point cloud of working environment.

4.2 Coupling of ROS and Unity Robot Simulation

In our case study, we use the package *MoveIt* to carry out the trajectory planning of the arm. For the controller itself (a kind of task manager), we programmed a ROS service *pickandplace*. The ROS service can then be called from Unity in a C# script. When a button is touched in the virtual/mixed environment, this script is invoked and the associated task is executed. So far, the (exact) coordinates are given directly by Unity to ROS to simplify the process. For a real-world application, the Intel *RealSense* is applied to detect the shape of the object to be gripped and to determine the best gripping position.

The simulation of robots in ROS is usually carried out by applying a tool called *Gazebo*. However, additional modeling is needed to work with this tool and it is far away from being as user-friendly as Unity. Thus, we apply Unity and the new articulation joint system. The results obtained by that simulation are very fast and accurate. Compared to *Gazebo* (which we used for previous projects) Unity is much more user-friendly and results can be obtained faster. Applying the URDF-importer a model can be imported into the editor very quickly and joints are already pre-configured. Modeling surfaces with real physics is only possible in Unity and delivers very good results. As Unity can also simulate lighting via raytracing, this opens up interesting possibilities for using it together with machine learning algorithms. The only drawback so far (that also *Gazebo* shows) is the missing support of parallel manipulators like those are often used for grippers.

4.3 Designing in Virtual Reality

Unity allows us to combine previously scanned assets from the real workplace with virtual ones (compare Fig. 6, a virtual table and robotic arm were added). In this phase, it is very simple to add objects based on CAD models, test the results using VR glasses and then move them or swap them out based on what the operator experiences in VR. This allows for rapid iteration of workplace design without costly (in terms of time and money) investments into hardware. Furthermore, the ability to include captured assets enables experimenting with rearrangement of existing environments, without disrupting production.

Fig. 6. Designing of working environment in VR.

4.4 Testing with Mixed Reality in Real Working Environment

In a further step, the proposed laboratory permits to bring the virtual assets into the real world using an MR visor (compare Fig. 7). In this phase, the previously designed workspace can be tested in a real working environment. This allows for optimizing the placement of components and on-site training of operators. It is also possible to place e.g. a virtual robot onto an existing, real work table, to further test and refine the workplace design. As distributed working is getting more and more important, this setup allows also to send a potential costumer only the access to the MR app, and he can test the developed setup in it's real environment while instructed by a person in a remote place.

One of the main remaining challenges in this field is to work with large holograms. Usually in industrial use-cases with cobots the holograms get quite huge (in the range of $2\,\mathrm{m}^2$). Due to the restricted field-of-view it can be difficult to work with this holograms.

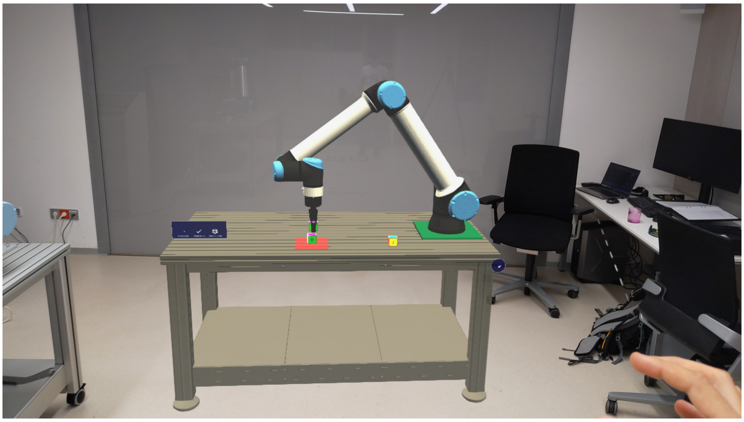

Fig. 7. Testing in MR. Virtual assets placed in real environment.

An other aspect enabled by the proposed setup is the overlay of virtual and real setup (compare Fig. 8). This allows an operator to test certain operations with the virtual robot. He is only executing them on the real hardware when he is satisfied with the results of the simulation. Especially when manipulating fragile and/or costly workpieces this could help avoiding damage to workpieces and workplace. Trajectory planning can be more efficient in terms of time required and accuracy.

An optional phase foreseen in the laboratory covers testing ergonomically and safety aspects. The operator is asked to wear a motion capture suit, permitting precise capture of his body movements. On one side, this permits assessment of ergonomics according to RULA [17] which assigns scores based on joint angles, on the other side, precise assessment of possible (near-) collisions is made possible (compare Fig. 9).

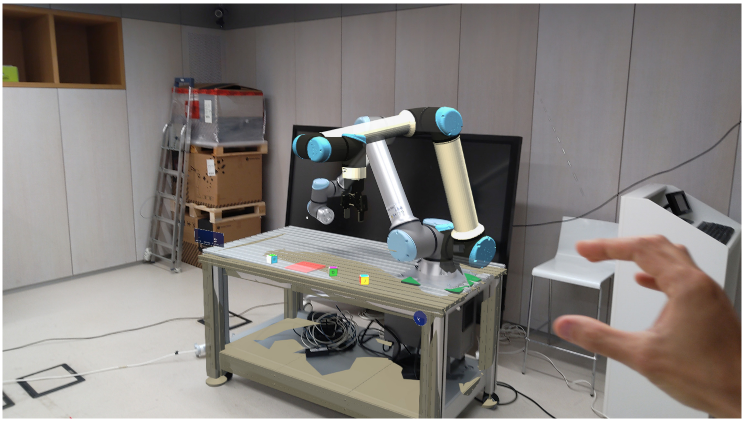

Fig. 8. Virtual and real robot in MR.

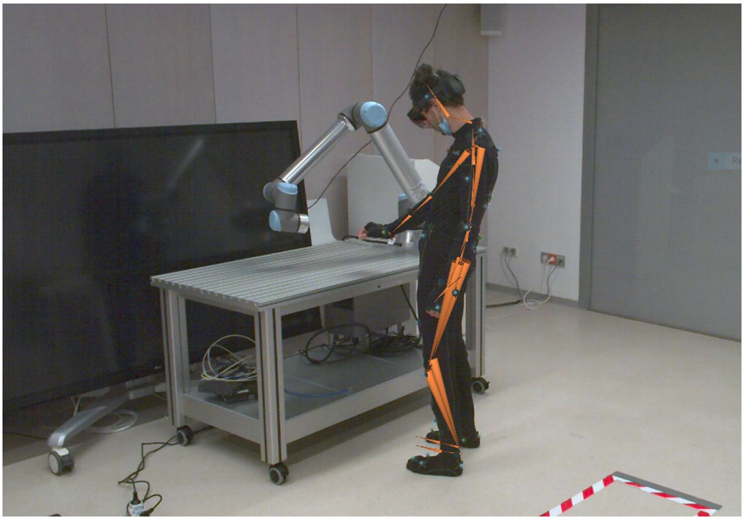

Fig. 9. Evaluation of ergonomically and safety aspects.

5 Conclusion and Outlook

In this paper we have described a laboratory setup, using state-of-the-art technology, for designing, planning and evaluating of collaborative robotic workspaces in MR. It allows for various degrees of virtualization, covering the whole spectrum, from purely virtual to purely real assets. The individual components used are industry proven, and each of them has an active user base, hopefully ensuring longevity and long-term compatibility.

Using ROS allows us to work with a widely applied framework for robotics. This enables a quick transition from design to application phase. Unity makes it possible to simulate the robots with highly-accurate physical solvers.

As an outlook we plan to extend this setup further, allowing e.g. for direct designing and modification of the workplace in VR/MR by being able to add objects directly from a library of virtual assets. Intelligent pre-placement of assets is also an interesting possible extension, as it would permit faster initial designs. Using advances in real-time tracing will also allow to develop control and vision algorithms based on machine learning in the same environment. The integration of force-feedback will be improved to enable a more realistic immersion, both, in VR and MR. This is essential to enable the setup for training purposes.

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