International Journal of Manufacturing Research

ISSN online: 1750-0605 - ISSN print: 1750-0591
https://www.inderscience.com/ijmr

Virtual reality platform for design and evaluation of human-robot collaboration in assembly manufacturing

Patrik Gustavsson, Anna Syberfeldt, Magnus Holm

DOI: 10.1504/IJMR.2023.10041856

Article History:

Received:	09 June 2020
Accepted:	10 February 2021
Published online:	06 March 2023

Virtual reality platform for design and evaluation of human-robot collaboration in assembly manufacturing

Patrik Gustavsson*, Anna Syberfeldt and Magnus Holm

Production and Automation Engineering,
University of Skövde,
Högskolevägen 1 – 541 40, Skövde, Sweden
Email: patrik.gustavsson@his.se
*Corresponding author

Abstract: This paper presents 'virtual collaborative robot', a virtual reality platform for designing and evaluating collaboration between operators and industrial robots. Within the platform, human-robot collaboration scenarios can be created and a user can interact with a robot without the safety risks that might arise with physical industrial robots. In an initial evaluation of the platform a scenario was implemented combining speech recognition, haptic control, and augmented reality to assemble a car model. The results from this evaluation indicate that the suggested platform can be used to successfully test new applications with the standard equipment of virtual reality headsets.

[Submitted 9 June 2020; Accepted 10 February 2021]

Keywords: human-robot collaboration; HRC; human-robot interaction; HRI; virtual reality; augmented reality; speech recognition.

Reference to this paper should be made as follows: Gustavsson, P., Syberfeldt, A. and Holm, M. (2023) 'Virtual reality platform for design and evaluation of human-robot collaboration in assembly manufacturing', *Int. J. Manufacturing Research*, Vol. 18, No. 1, pp.28–49.

Biographical notes: Patrik Gustavsson holds a PhD in Informatics and received his BSc and MSc in Automation Engineering from the University of Skövde in Sweden. He is currently working as an Associate Senior Lecturer at the University of Skövde focused on robotics. His research interests include production and automation technology, simulation, multi-objective optimisation, multi-modal communication, and human-robot collaboration.

Anna Syberfeldt is a Professor at the University of Skövde, Sweden. She holds a PhD in Computer Science from De Montfort University, UK and a Master's degree in Computer Science from the University of Skövde, Sweden. She is pursuing research within simulation-based optimisation, evolutionary algorithms, meta-heuristics, and advanced information technology with applications in manufacturing and logistics.

Magnus Holm holds a PhD in Manufacturing Engineering from De Montfort University in England and a Master's degree in Automation Engineering from the University of Skövde, Sweden. He worked on automation and programming at Siemens Building Technologies and other engineering companies before pursuing an academic career in 2004. His primarily research interest is in shop-floor decision support systems.

1 Introduction

Human-robot collaboration (HRC) is currently a hot topic both from an academic and industrial point of view. A lot of potential is seen in combining the advantages of humans, such as flexibility and adaptability, with the advantages of robots, such as strength and exactness, in order to increase efficiency and reduce costs in manufacturing assembling (Michalos et al., 2014). To be safe to work with, collaborative robots are lightweight and have force limitations on all joints (ISO, 2016). Usually, collaborative robots comes with a lower cost and a simple programming interface, which makes them popular to use not only by large manufacturing companies but also by SMEs (Mandel, 2019; Sharma, 2018). Another advantage of collaborative robots that have made them popular within the industry is that they require less space on the shopfloor as no safety fences are needed. Several successful applications of collaborative robots have been reported in the scientific literature during the last years, and many manufacturing industries are interested in investing in HRC solutions as a way to incrementally automate the production and increase flexibility (Saenz et al., 2018). HRC is together with concepts such as cyber-physical production systems (CPPS) and industrial internet of things (IIoT) seen as key enablers for realising the smart factories of the future (Garcia et al. 2020; Gualtieri et al., 2020).

In the existing industrial implementations of HRC there are, however, often a limited interaction between the human and the robot and a minimal contact between the two of them due to conformation to safety regulations. The current safety standards for HRC are rigorous and pose lots of restrictions on the implementation, which in practice often becomes a hinder in the industrial adoption of collaborative robots and restricts to utilise their full potential (Michalos et al., 2015; Saenz et al., 2018). Safety regulations also make it challenging to explore new, efficient support technologies for HRC as a new technology that is not yet fully mature or production-ready inevitably involves a risk. Of special importance is to be able to test support technologies that can realise a natural and seamless integration between the human and the robot, including for example voice commands, augmented reality (AR) visualisation or connected body sensors. Such solutions are critical for enabling successful HRC but are currently hard to explore in a safe way in adherence to safety standards.

In order to enable an increased use of HRC in the manufacturing industry, this study set out to investigate how new HRC applications and support technologies can be designed and evaluated in a safe and efficient way. The idea in the study is to use virtual reality (VR) (Etzi et al., 2019; Metzner et al., 2018), which allows a user to step into a virtual environment by using a head-mounted display (HMD) to interact with the surroundings without the risk of getting hurt by external forces. By using VR, the HRC cell can be constructed and tested in an early design phase, be used in virtual commissioning processes, and be used as a training tool for operators. Some previous attempts have been undertaken in using VR for HRC development, see for example Dahl et al. (2017), Matsas and Vosniakos, (2017), Etzi et al. (2019) and Malik et al. (2020) and these previous studies show promising results that have motives to look further into the potential of VR in this study. Recent also studies specifically pinpointing that more research into VR-based HRC solutions are needed, see for example Malik et al. (2020).

In the paper, we present a platform designed be used to test interaction in HRC using VR, called ViCoR. Compared to the previously mentioned attempts to use VR for HRC, this platform adds an additional design phase where the desired future state of the interaction can be discovered by using VR. By finding the desired future state of the interaction, HRC cells can be continuously improved towards that state. The overall idea of the platform is to provide the manufacturing industry with a tool that can be used in the design and evaluation of the interactions in HRC cells, and thus realise successful implementations of HRC applications to a broader extent.

The next section continues by presenting the background of this study, describing HRC and advances in the area, as well as VR and how VR has previously been used in the industry. Section 3 then describes the VR platform ViCoR in detail, listing requirements of the platform, how it was implemented, what interactions that can be modelled, and the limitations of using VR for HRC. Section 4 describes a scenario created with ViCoR based on a physical demonstrator, showing its usefulness and initial results. Section 5 finally concludes the paper by summarising ViCoR and how it can be used for future research.

2 Background

This section presents a brief overview of HRC and the definition used in this paper, followed by an introduction to VR and how VR has been used for industrial purposes.

2.1 Human-robot collaboration

The term HRC has been around for more than a decade; however, there is still little agreement on what HRC entails. Articles (Beer et al., 2014; Gustavsson et al., 2017; Kolbeinsson et al., 2018; Michalos et al., 2015; Pichler et al., 2017) define HRC from different perspectives. These are summarised at the end of this section to define how the term is used in this paper.

From a safety perspective, collaborative robots and collaborative operations are defined in the technical specification ISO/TS 15066 (ISO, 2016) focusing on the human and the robot sharing the workspace. Collaborative robots are robots that support one or more of the four collaborative operations:

1 *Safety-rated monitored stop:* A robot in a shared workspace ceases all motion before an operator enters. When no operator is in the shared workspace or if the robot is outside the shared workspace, the robot can resume its operation.

2 *Hand guiding:* The operator uses a hand-operated device to send motion commands to the robot; for example, the operator can grab the robot tool and move it directly to a location. Before this operation is activated, the robot must be in a safety-rated monitored stop. Thereafter the operator uses an enabling device to start the hand-guiding operation.

3 *Speed and separation monitoring:* The operator and robot both move in the shared workspace but the robot system monitors the distance to the operator at all times. If at any time the distance decreases below the safety threshold, the robot stops. If the distance increases above the threshold, the robot automatically resumes its operation.

4 *Power and force limiting:* Physical contact between the operator and the robot can occur without posing a safety risk because of an inherently safe design of the robot or a safety-related control system.

These operations are defined based on safety requirements. However, only hand guiding requires any kind of collaborative interaction between the human and the robot. In this paper the other three operations are considered as safety operations that may be essential when a human and a robot share workspace, but are not collaborative in nature.

Michalos et al. (2015) categorise HRC based on whether the human and robot share tasks and/or workspace, and whether the human and/or robot are active. They divide collaboration with the robot into four categories:

1. *shared tasks and workspace, robot non-active:* in this case the human is active, but the robot is inactive. The robot can still be essential for the task, for example, by acting as a fixture
2. *shared tasks and workspace, robot active:* in this case the human is inactive, letting the robot do its work but on a shared task
3. *common task and workspace:* in this case both the human and the robot are active working on a common task
4. *common task and separate workspace:* in this case the human and the robot are working on a common task but are separated by a fence or similar device.

Similarly Gustavsson et al. (2017) divide collaboration into three categories:

1. *direct HRC:* the human and the robot are both active to execute the task
2. *indirect HRC:* the human and the robot are dependent on each other but only one is active at a time
3. *non-HRC:* the human and the robot do not depend on each other but are working on the same task with no interaction.

From another perspective Pichler et al. (2017) defined levels of autonomy based on the capabilities of the robot cell and how the human and robot interact with each other.

1. *Human and robot are decoupled:* Human interacts with robot using control switches such as start/stop buttons.
2. *Human-robot coexistence:* Human and robot are located in the same workspace but are still decoupled with respect to activities.
3. *Human-robot assistance:* Human and robot synchronise activities with a clear server/client relationship between them. Robot does not need to be equipped with any cognitive abilities.
4. *Human-robot cooperation:* Human and robot work on the same work-piece and both need to be aware of the other’s current and planned tasks. The robot requires some cognitive abilities such as awareness of the situation, the external environment, and interaction with the worker.
5. *HRC:* Human and robot need high interoperability on detailed process levels using challenging interactions to deal with uncertain situations. In this situation, both the human and the robot need detailed understanding of all activities and execution time to collaborate efficiently.

In Kolbeinsson et al. (2018), interaction levels are determined by the task being executed and the human involvement. Here the author considers how the human is needed for the task to be executed, which closely correlates to the framework for levels of robot autonomy in human-robot interaction (HRI) (Beer et al., 2014; Yanco and Drury, 2004). From an autonomy point of view, following the taxonomy of Yanco and Drury (2004), HRC lies between full automation (autonomy = 100%) and fully manual (intervention = 100%). If an operation is either fully automatic or fully manual, there is no requirement for collaboration between the human and the robot because one of the agents has full control of the operation.

Wang et al. (2019) discusses that the interaction between the robot and the human often is dynamic, as a consequence of the robot having to dynamically change its pre-planned operations according to what the human doing in the shared workspace. The authors state that traditional static robot programming does not work very well for HRC, but that dynamic, multi-model methods are needed. The authors call this 'symbiotic control and communications' and describes that voice processing, gesture recognition, haptic interaction, and brainwave perception are key methods for efficient HRC.

It can be noted that in all the articles summarised in this chapter, the common denominator of HRC is that it requires human and robot involvement to complete tasks. Working with a robot at a distance can be considered HRC from the perspective of human involvement as defined in Beer et al. (2014) and Kolbeinsson et al. (2018), in the same way that humans can collaborate with each other remotely. Hongyi Liu and Wang (2020) present how remote HRC can operate and describes that it is especially useful in hazard manufacturing environment. However in this paper, collaboration when human and robot do not share any parts of a workspace is referred to as remote HRC. This distinction is necessary because remote and shared workspaces impose different sets of requirements on the HRI and the robot system's capabilities.

In this paper we consider HRC as the use of at least one human and one robot to complete tasks in a shared or common workspace that requires collaborative operations. A collaborative operation is defined as an operation that requires HRI to perform the operation. A collaborative operation requires at least some autonomy and some intervention to be considered collaborative. A station that requires no interaction between human and robot under normal operation can also be categorised as HRC if collaborative operations are used in abnormal situations, for example, hand guiding to a safe location or flexible fixture if an error occurs.

2.2 VR in HRC

VR encloses a user in a virtual environment using an HMD. The user sees the virtual environment through the HMD, which updates the content based on sensors that track the motions of the user's head. Commercial VR headsets include Oculus VR, HTC Vive, and Samsung Gear VR. There are three main types of HDMs: a HDM connected to a desktop computer that runs the VR program (e.g., HTC Vive and Oculus Rift), a smartphone dock in the HDM (e.g., Samsung Gear VR and Google Cardboard), and a stand-alone HDM with an embedded computer (e.g., Oculus Go and Oculus Quest).

VR has been in existence for several decades. At first it was used for research (e.g., Jayaram et al., 1997; Satava, 1993) and today it is used extensively in the gaming community. It is also spreading to new areas, not least because the cost of VR headsets has been falling. So VR is now used in areas like healthcare to treat mental health disorders (Freeman et al., 2017), in manufacturing to do things like programming painting robots (RobNor, 2018), and to validate ergonomics and product design (Berg and Vance, 2017).

Virtual commissioning is a method of developing and validating industrial control systems in a virtual simulation model (Dahl et al., 2016; Strahilov and Hämmerle, 2017). Using a simulation model, a control system can be integrated and tested before the physical system is in place, and the system can even be debugged virtually. Virtual commissioning is expected to reduce the cost and time of system installation, increase reliability, and enable efficient maintenance once the system is in operation (Dahl et al., 2016). The benefits of virtual commissioning can be further extended by incorporating VR (Dahl et al., 2017). VR allows for more realistic visualisation and movement tracking, so improving the validation aspect. VR also makes it possible to interact with the control system in a manner that is intuitive for humans and brings the simulation closer to reality (Dahl et al., 2017).

Malik et al. (2020) propose an approach for virtual commissioning of HRC based on a VR solution. The authors present a framework that can be used to design and validate HRC stations that is based on an integration between human-robot simulation with VR. The simulation is event-driven and estimates the human-robot cycle times, and can be used in the development of process plans, layouts and robot control programs. By using the simulation in VR, the user can interact both with the robot and the surrounding production equipment. The authors especially pinpoint the usefulness of VR-based HRC from a safety perspective, which is in line with the idea of the solution presented in this paper.

VR can also be used to setup training systems that allow employees to perform tasks that feel realistic while immersed in a virtual work environment. The goal of virtual training systems is to reduce training time, improve competence, and decrease training costs. Virtual training systems have been suggested for many different applications, including HRC. Matsas and Vosniakos (2017) present an immersive and interactive training system based on VR. Their system, called 'beWare of the Robot', is designed in the form of a serious game that simulates collaboration between a human and a robot in executing simple manufacturing tasks. Evaluation of 'beWare of the Robot' indicates that there is large potential in using virtual training systems for HRC and that users in general are positive to the approach.

In Etzi et al. (2019) VR was used in experiments to simulate and test human-robot cooperation. Here the authors take a look at how human-robot collaborative tasks can be tested through the assessment of the human psychophysical stress level. They also suggest the use of VR as a tool for designing HRC systems, performing optimisation of the production process and to train operators.

The type of headset and additional equipment used significantly impact the type of interaction that can be modelled in a VR environment. Using VR headsets with associated controllers allows the user to control the positioning of their virtual hands but restricts the control of individual fingers. The interaction support, therefore, heavily depends on the VR equipment used.

In Weber et al. (2013) the authors experimented with linking the hands of the operator with two collaborative robots to simulate weights, resistances, and inertia in the VR environment. This allowed the user to feel weight and resistance without having a physical object present. However, this introduced resistance to all motion in the VR environment. In Matsas and Vosniakos (2017) Kinect cameras were used instead of hand controllers to allow users to fully utilise their hands for gestures and grabbing motions. Some manufacturers try to overcome the limitations of force/haptic feedback in hands by using VR gloves, such as VRGluv which allows force feedback for all fingers, and HaptX which allows both force and tactile feedback to sense surface textures.

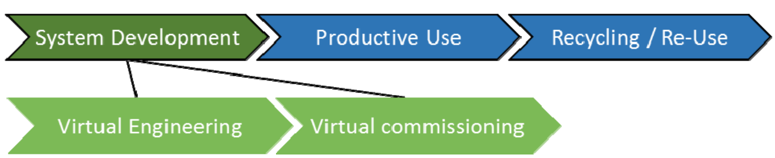
3 Virtual collaborative robot

As previously discussed, VR has the potential to improve the virtual commissioning process (Dahl et al., 2017) and in the case of HRC it can also be used in a training system (Matsas and Vosniakos, 2017). To further extend the use of VR for HRC, this paper presents ViCoR, a VR platform that can be used to design and validate the interaction between an operator and a robot in a safe way. In the following subsections, ViCoR is explained in detail, starting with its potential use in the production system development process. Thereafter the requirements and limitations of VR when used for HRC are described. Finally the implementation of the platform is described.

3.1 Production system development process

A production system lifecycle has sequential phases (Strahilov and Hämmerle, 2017) that can be categorised as system development, productive use, and recycling/re-use (Figure 1). During the system development phase, a production system is designed and later realised in the industry. After realisation the productive use phase begins, in which the production system is used for its intended purpose. In the last phase, when the production system has ended its productive use, the system is either recycled or re-used for another production process.

Figure 1 Production system development process in which virtual engineering and virtual commissioning are part of the system development phase (see online version for colours)



The system development phase has several sub-levels, but those of interest to the VR platform are virtual engineering and virtual commissioning. Virtual engineering takes place in the design phase consisting of the mechanical, electrical, and fluidic design of a production system. As pointed out by Metzner et al. (2018), HRC introduces another level of design needs, namely, the involvement of the human-in-the-loop and the need to design the interaction. Therefore, in the virtual engineering phase the interaction between the operator and the robot also needs to be designed.

The input parameters to the virtual engineering phase are the desired future state of the interaction between the operator and the robot in an HRC cell. This state describes what the company wants to achieve with HRC and may be used to guide continuous improvement toward their vision. Continuous improvement is common practice in industry, especially when working with the Lean philosophy and the improvement Kata (Rother, 2010). Working in virtual environments it is possible to evaluate a system without the constraints, associated with physical implementations. One such constraint is the safety of the operator [one of the barriers to HRC uptake (Saenz et al., 2018)]. Working in virtual environments overcomes this constraint because the operator cannot be injured by external forces. If needed, additional simplifications can be made to find the desired future state. For example, if speech recognition does not work to the operator's satisfaction, then another person can be used to interpret the intention of the operator.

When constructing an HRC cell in the virtual commissioning phase, the cell needs to be adapted to existing control systems and emulated hardware. There are several benefits to using a human-in-the-loop as part of this procedure to ensure that the system is modelled with the operators in mind (Metzner et al., 2018). Simulated manikins may not be enough to test whether the interaction is working properly.

During and after the commissioning phase, when the cell is constructed, it is beneficial to use virtual models to train new operators to reduce the training period in production. VR allows the user to experience more realistic training that resembles conditions in the real world, rather than merely training in front of a computer.

3.2 Requirements

ViCoR was developed to create a VR platform to be used in the phases explained in the previous section. Thus the basic requirements for the VR platform are as follows:

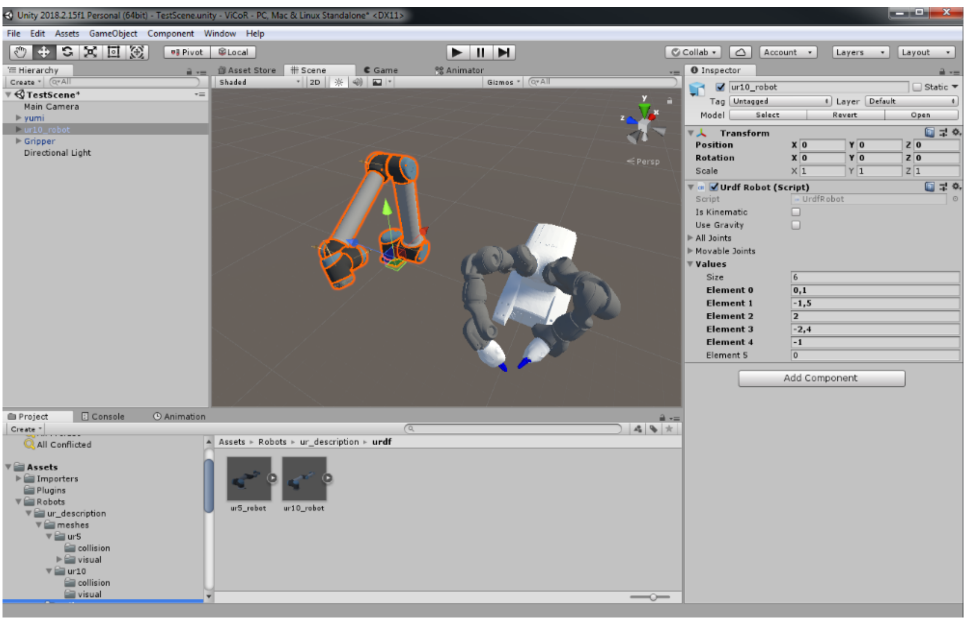
- *VR headsets:* It should support one or several VR headsets so that interaction can be tested. The more VR headsets that are supported the more flexible the platform becomes.
- *Robot connection:* It should be compatible with one or several robot controller emulators to facilitate the process of converting a conceptual implementation into a real implementation.
- *Custom robot control:* It should have the ability to create a variety of features that may or may not exist within current robot controllers to allow the development of conceptual ideas.
- *VR interaction:* It should have the possibility to control the type of interaction that is used with the VR headset and in the virtual environment. This enables the development of new types of interaction with the robot.

Table 1 lists some tools that can be used to build prototypes or robot applications that include VR support. Out of these tools, Unity was selected as the most compatible development tool for ViCoR given the basic requirements set out in Table 1. Unity is a game development tool that supports most VR headsets, including Oculus Rift/Quest, HTC Vive, and Google Cardboard. However, unity has limited support for connection with robot controllers.

Table 1 Features of tools for developing the VR platform

Tools	*VR headsets*	*Robot connection*	*Custom robot control*	*VR interaction*
Unity	Most VR headsets	ROS using ROS# or RosBridgeLib	Scripting using C#	Scripting using C#
ROS and Gazebo	Oculus DK1 and DK2	ROS	ROS node	Limited built-in
Process Simulate	Computer connected	Native and simulated	No	Limited built-in
RobotStudio	Computer connected	ABB full integration	No	Limited built-in

Figure 2 Unity development tool showing imported robots using ROS# (see online version for colours)



Notes: The left robot is a UR10 robot from Universal Robots, and the right robot is a YuMi robot from ABB.

Robot Operating System (ROS) is an open source framework for implementing robot logic (ROS, 2020). ROS began in 2009 as a structured communication layer in which nodes sends messages to each other in a network (Quigley et al., 2009), but has since significantly grown and is today a collection of tools and libraries for creating complex robot behaviour. Although Unity has limited support for robot connections there are libraries that can be used for connecting Unity with ROS, e.g., ROS# (Siemens, 2019) and RosBridgeLib (Thorstensen, 2019). With these libraries the platform can establish connection with simulated or real robot controllers through ROS. ROS# also provide means to import robots into Unity using the unified robot description format (URDF). Figure 2 shows an example of two robots that were imported into the Unity development tool using ROS# based on URDF files. The main advantage of Unity for the platform is the ability to create custom VR interactions in the virtual environment. Using custom VR interaction facilitates the process of finding a future desired state of the interaction between the human and robot.

VR headsets come with the full set of equipment which enables a user to step into a virtual environment and interact with virtual objects. But there are limitations on existing VR headsets that impacts the user experience, which restrict what can be tested in VR. In the following list, some of these limitations of current VR equipment are described:

- The field-of-view and resolution of HMDs are less than those of the human eye.
- All objects look like digital objects, which lacks realism for full presence. This affects testing interaction intended for AR because it may be difficult to distinguish representations of physical objects and AR objects in the virtual environment.
- The resistance/inertia of hand-guiding the robot cannot be tested using VR controllers. That would require an actuator adding external force on the hand, like the robots attached to the hands in Weber et al. (2013).
- Sensing the stiffness, surface, and heat of objects is limited. The glove HaptX could address this problem and would be useful if the interaction relies on this kind of sensing.
- Moving and rotating an object directly in the hand is difficult. So far, even though some of the VR gloves have many degrees of freedom (DOF) (e.g., VRGluv and HaptX), such an operation requires the full sensory-motor abilities of the hand.

These limitations impact the immersion/presence of testing HRC applications in VR and it is important to evaluate how the perceived realism is affected by these limitations. Therefore, this platform should be used to evaluate how these limitations impact the user experience.

3.3 Implementation

Based on the requirements listed in Section 3.2, Unity was selected as the development tool for ViCoR. Because Unity is a game development platform, it supports most gaming functionality, including VR. To speed up the development process, computer-connected VR headsets were used to reduce the time between coding and testing the VR application. A runtime system is needed to enable VR headsets to be used on the computer and an asset is available for Unity that supports SteamVR, a runtime system for VR headsets used in the gaming platform Steam. With SteamVR the same VR application is compatible with multiple VR headsets, including HTC Vive and Oculus Rift, the two headsets tested with ViCoR.

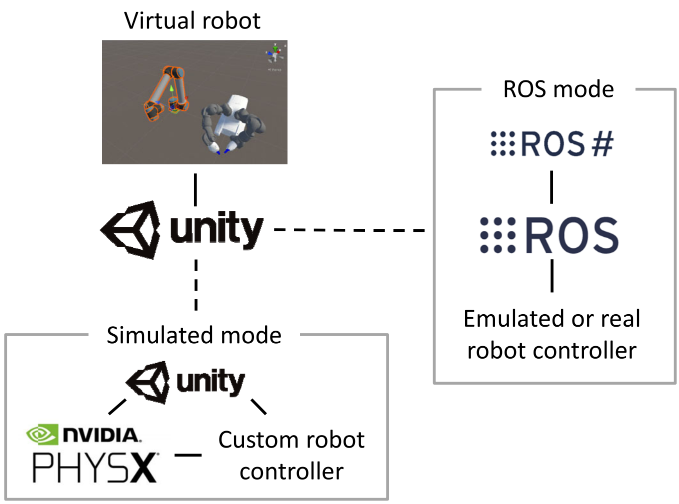
Applications built using ViCoR should eventually be used for physical industrial systems. Therefore, robots used in the virtual environment should be possible to connect with a controller system that could be used in the physical world. Therefore, the platform was implemented with the ability to switch between robot controllers as shown in Figure 3. The following two modes were implemented for robots in ViCoR:

- *Simulated mode:* This mode uses a custom robot controller, and the robot program (which moves the robot) is written in Unity. This allows testing HRC with features beyond the limitations of existing robot controllers.

- *ROS mode:* This mode connects the virtual robot to a robot controller through a ROS node supporting both ros_control and the action interface follow_joint_trajectory. This allows the same program to be used for both a virtual robot and a physical robot.

In the following subsections the implemented interaction in the virtual environment are described in more detail.

Figure 3 Illustration of the components used within ViCoR and how they relate to the two modes (see online version for colours)



Notes: The dashed lines represent the ability to switch between simulated and ROS mode.

3.3.1 Hand interaction

In assembly manufacturing operators mainly use their hands and vision to perform tasks. There are exceptions where the operator is required to listen for certain sounds, use their body for support in executing the task or the foot for pressing on a pedal or a bumper. However, in this work the focus is on assembly tasks that only require hands and vision to execute them. During an assembly process, an operator uses many hand operations to assemble parts. The following are some of the most common hand operations:

- *grabbing:* using the hand to grab an object to manipulate it
- *pinching:* grabbing an object between thumb and index finger, often used with smaller parts
- *reorienting:* moving an object with one hand, using the hand and fingers to get the correct rotation or displacement of the object relative to the hand
- *twisting:* using fingers to rotate a pinched object
- *turning:* using the hand to rotate a grabbed object
- *sensing:* using the tactile and kinesthetic senses of the hand and fingers to feel the geometry of an object, its surface stiffness, and its roughness.

The implementation of the hands in the VR environment used the standard hand controllers of the VR headset. This reduces the possible DOF of the hand to approximately one third in the virtual environment. The location (position and rotation) has the same number of DOF for the hand and the controllers. However, instead of individual control of each finger in the virtual environment, the controllers have buttons, joystick, touchpad, and analog triggers. With the reduced finger control, only a subset of the hand operations could be implemented. To ensure that the motions are somewhat similar to those in the real world, only the grasp button/trigger and index finger trigger are used when picking and placing objects, because the motions for activating these inputs resembles that of the real-world hand. The implemented hand operations are: grabbing using the grip button, pinching using the trigger button, turning by grabbing and rotating the controller, and twisting by pinching and rotating the controller. The hand motions for twisting and turning are quite different in the physical world, but due to the limitations of the hand controller the same rotation motion was used for both these hand operations in ViCoR.

The only way to sense an object in the virtual environment is through the geometry of the controller and its built-in vibrotactile sensing. The controller's shape does not change, and therefore the feeling of grabbing a screwdriver with a small cylindrical shape will be the same as that of grabbing a large cube. As reorientation is not supported due to the limitations of the controllers, predefined grab poses are needed for each object. For users to sense that they are correctly grabbing an object, vibrotactile feedback is used whenever the pose of the hand differs from the predefined grab pose. This happens when two hands are used to grab the same part or if a partially assembled part is grabbed by one hand. The further away the pose of the hand is from the predefined grab pose (considering both position and rotation), the more it vibrates. This signals the user whether the object lies correctly in the hand. When the distance reaches a certain threshold, the hand releases the part, in case both hands are used only one hand drops the part.

To visualise the hands correctly grabbing a part, either predefined hand and finger animations or an inverse-kinematics solver can be used to display that the user is grabbing an object in the correct way. In this implementation of ViCoR, Unity's animation system was used to animate the hands to obtain visual feedback of the hand grasping objects. There is no force feedback when moving the controllers, which makes all forces of the hands in the virtual environment infinite. In some cases, this results in the hand passing through objects. With no force feedback and limited DOF, the VR system needs to provide semi-automatic assembly operations, e.g., guiding objects when close to the assembly operation and grabbing objects even if the hand is not fully oriented for lifting.

3.3.2 Speech recognition

Speech Recognition is the process of converting an audio signal received by a microphone into recognisable sentences and commands for the system. Speech recognition has successfully been used to showcase how humans and robots can interact (Bannat et al., 2009; Green et al., 2008; Lei et al., 2014; Maurtua et al., 2017; Rossi et al., 2013). It has great potential in HRC, because the human can interact in a way that is natural when communicating with other humans. This technology provides an interface where the human can give commands to the robot without losing focus from the task at hand.

With VR headsets a microphone is commonly embedded in the HMD, but if needed other microphones can be used as well. In ViCoR the Microsoft Azure speech-to-text engine is used as the speech recognition feature. Using the microphone embedded in the VR headset, then speech recognition can be tested for head-mounted microphones. If, however, remote speech recognition is the aim for an eventual HRC application, more work may be required to apply the program in a physical environment. The reason is that the program may need to cope with a noisy environment and the location of the speaker may be important.

3.3.3 Haptic control

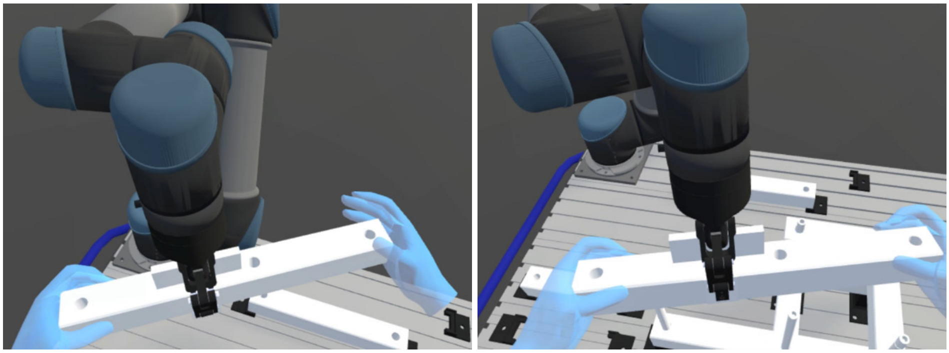
A hand-guiding mode was added to allow the user to move the robot by hand. This mode can be activated from both the simulated mode and ROS mode. The hand-guiding mode allows the user to control the robot in joint or Cartesian space using constraints such as constrain joints 1–3, constrain rotation about the x- and y-axis, and constrain all but motion in the x- and z-axis. The tool centre point and frame of reference need to be set to enable the hand-guiding mode in Cartesian space.

In ViCoR, it is possible to use the hand guiding mode that allows the user to control the robot in both Cartesian space and joint space, as described in the previous sections. In addition to grabbing the robot, the user can directly grab the work piece, as seen in Figure 5, to move it around while the robot is still holding it. This feature for guiding the robot is called haptic control. Haptic controls for physical robots use force torque sensors, joint torque sensors, impedance or admittance (Gustavsson et al., 2017). However, in VR, when finding a desired future state, the control mechanism can be simplified by ignoring the inputs of the force torque sensor and instead focus on the behaviour of the robot when moving it by hand, e.g., speed, responsiveness, constraints in Cartesian and joint space.

Figure 4 Physical demonstrator to the left and the virtual model to the right (see online version for colours)

Notes: The model is shown in the Unity editor.

Figure 5 Images show how the part can be grabbed and moved while the robot holds it, showing haptic control (see online version for colours)



Notes: The hands are animated to look as if they are grabbing the part.

The implemented haptic control uses the grab poses as described earlier. The desired location of the work piece is calculated based on the location of the hands holding the work piece. A maximum velocity and acceleration in joint and Cartesian space is defined, to limit the robot's speed and responsiveness when approaching the desired location. With this setup, the speed and responsiveness of the robot can easily be changed to evaluate its impact on the user's experience.

3.3.4 Augmented reality

AR is a technology that overlay digital information onto the real world and has shown promising results when interacting with robots (Green et al., 2008; Guhl et al., 2017; Lambrecht and Krüger, 2012). Augmented reality comes in different forms, it can be spatial AR using a display, see-through camera with the use of a hand-held device and projected AR with a HMD (Syberfeldt et al., 2017). In AR, the tracking and placement of digital objects is a demanding task compared to using VR where tracking of objects is perfect since the same frame of reference is used for tracking and for rendering.

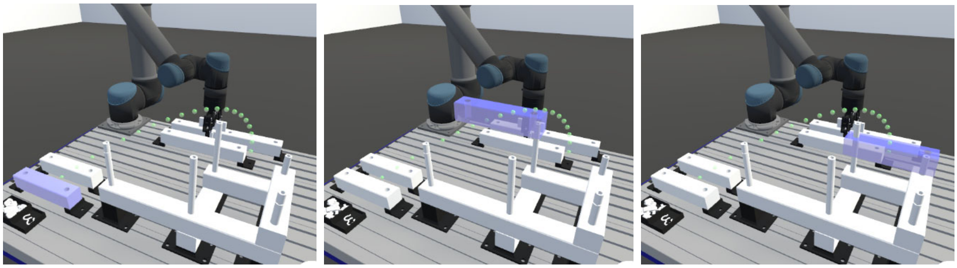
ViCoR uses real-time animations intended for AR glasses to show the track of the part to its destination, as seen in Figure 6. In Figure 6 the opaque objects represent physical objects that the user should work with, while the transparent objects represent animations intended for AR usage. Figure 6 illustrates the animation of an assembly operation involving a white box-like object with holes at each end that need to be placed over two cylindrical pins. The animation consist of two parts:

1 a trajectory of small green transparent spheres between the part and the assembly position

2 a blue transparent object of the same shape as the part, which moves from the part's position to the assembly position following the trajectory.

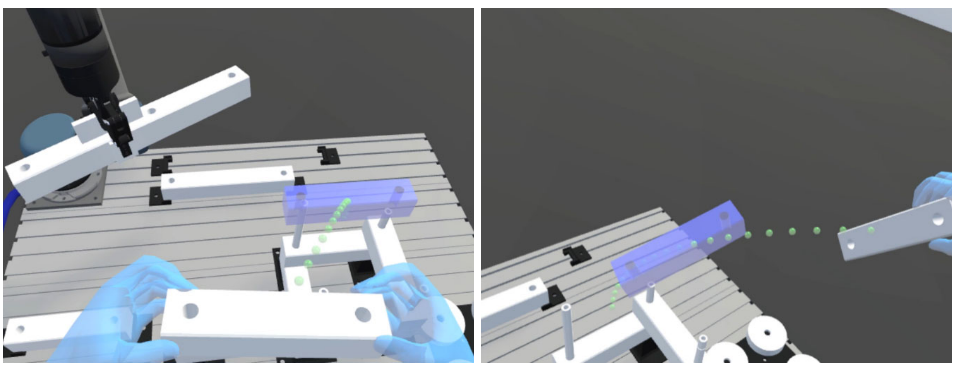
Figure 7 further illustrates how the animation is dynamically updated by continuously moving the start of the trajectory to the part's location. The animation, therefore, always seems to be attached to the part. This is possible because the virtual environment is already responsible for placing all objects within the scene, and therefore the animation can obtain the exact location of the moving part.

Figure 6 AR animation visualised in the virtual environment (see online version for colours)



Notes: Animation consists of a static trajectory of small green spheres with motion of the part highlighted in blue (screen shot from ViCoR).

Figure 7 Visualisation of perfect tracking of the part allowing the AR animation to follow the part with any position and orientation (see online version for colours)



Notes: Screen shot from ViCoR.

This type of animation allows the user to get instructions without moving their focus away from the task, which is not the case with traditional work instructions based on text and images. Even if more details are necessary, such as measuring tolerances and the torque of a screwdriver, those details can be displayed close to the assembly operation.

4 Experiment

An initial experiment was made to investigate the perceived realism of using ViCoR for HRC, to establish if the platform has potential to be useful in the design and evaluation of HRC applications and worth to put more development efforts into. In the experiment a scenario was created in ViCoR based on an upgraded version of the physical demonstrator (Figure 4) used in the study of Gustavsson et al. (2017). Ten operators and technicians from a company working with assembly manufacturing participated in the experiment. The participants were first introduced to the purpose and structure of the experiment, then they tested the physical demonstrator (hereafter referred to as the physical scenario), then they executed the same task in a virtual scenario using ViCoR and finally they filled in a questionnaire.

In addition to the experiment ViCoR has been demonstrated on multiple occasions to potential users and stakeholders, including several industrial companies such as Volvo Cars, AB Volvo, and ABB Robotics, and also to senior academic researchers. Knowledge gained from each demonstration feeds into ongoing improvement to ViCoR.

In the following subsections the setup of the virtual and physical scenarios of the HRC task and the initial results are described.

4.1 Setup

The physical scenario consisted of a HRC application which combines speech recognition, haptic control, and AR to interact with a UR5 robot to build a model car (Figure 4). The UR5 from Universal Robots is a collaborative robot that can lift 5 kg. The car model, tool fingers, and fixtures were 3D-printed based on CAD models created in-house. Aluminum profiles were mounted on the wagon to make the demonstrator more flexible. In the virtual scenario, all models of the 3D-printed parts were imported by converting the CAD models to .obj files. The UR5 robot was imported with a modified script based on the ROS# (Siemens, 2019) urdf importer. The rest of the models were available from the manufacturers' own websites and was either imported through .stl file or by converting them to .obj files.

The physical robot was equipped with a force torque sensor from RobotiQ. However, that sensor was not used for the physical demonstrator because the algorithms for controlling the robot started oscillating the tool to an extent that could potentially damage parts in the demonstrator. This was due to too much compliance between the grabbed object and the tool, which introduced backlash that the algorithm could not cope with. Instead the freedrive mode available in the UR5 robot was used to manually guide the robot. With freedrive the tool can only move in joint space, not in Cartesian space making it difficult to move the tool in a straight line (Gustavsson et al., 2017). This is the case for the UR5 version but the UR5e series includes a built-in force torque sensor that can be used to move in Cartesian space, similar to using the RobotiQ force torque sensor. However, this feature has not yet been used for the physical demonstrator. The virtual platform did, however, implement the behaviour of using force torque sensing with the hand guidance mode described in Section 3.3.3. In this case, the force torque sensor algorithms were not considered in the virtual environment. In an initial phase to find a desired future state, this is preferable. However, in a virtual commissioning step it is necessary to model the force torque sensor to ensure that the virtual model has the same functionality as the physical equipment.

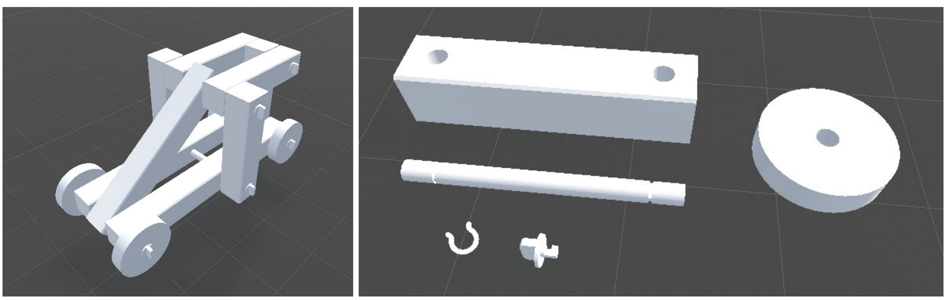
A headset with microphone was provided for the physical scenario and in the virtual scenario the VR headset has a built-in microphone. Because the microphones used in both scenarios are headset variants, no extra programming is required when moving between physical and virtual environments, assuming the same speech recognition engine can be used. However, depending on the device and operating system, the available speech recognition engines may differ, as was the case in this instance. The computer running the physical demonstrator was installed with Windows 7 using Microsoft Speech Platform SDK 11, while the VR scenario was installed with Windows 10 with Microsoft Azure speech-to-text engine.

Instructions was made for AR in both the physical and virtual scenario, however, the represented AR device used in virtual scenario was significantly different with the AR device used in the physical scenario. In the virtual scenario animations instructions were used intended for AR glasses. In the physical scenario digital information was added on top of a live camera feed displayed on a TV, which highlighting parts to be assembled and their destination.

4.2 Assembly sequence

In the virtual scenario the user assembles the car model shown in Figure 8, which is the same car model assembled in the physical demonstrator. The model consists of blocks, cylinders, and wheels that are interlocked using locking rings and thumbscrews. This car model does not require any additional tools to assemble; for example, no screwdriver is needed.

Figure 8 (a) Car model that is assembled in the scenario (b) Some of its base components (see online version for colours)



(a) (b)

Notes: Screen shot from ViCoR.

The car is only partly assembled in this scenario to make this station represent one part of an assembly line. The original workflow is divided into eleven steps. Two steps require haptic control, two steps require the robot as a fixture, and the rest are manual assembly operations. Since this work focuses on the usage of VR for HRC tasks, the assembly sequence was reduced to four steps, two using haptic control and two with manual assembly. In the two steps with haptic control, the human guides the part to the correct position while the robot holds the part to represent lifting a heavy object. This part cannot be assembled by the robot alone because of variances in the positioning. If the object is too heavy, a human cannot lift the part without specialised fixtures. In this case the robot acts as a specialised fixture that can also initially position the parts close to where they are needed.

4.3 Initial results

The results from the questionnaire are shown in Table 2. Based on the answer of the questionnaire most of the participants agree or fully agrees that the VR environment felt realistic and that their behaviour in the VR environment felt similar to that of the real world. These results indicate that the users of the platform will have a realistic experience when testing new HRC applications even if the standard hand controllers of the VR headset are used. However, a more thorough investigation is needed to cover more user experience aspects. The purpose of this paper is to present ViCoR, its architecture and the potential use-case in the HRC production system lifecycle, and the next step will be to perform a full analysis from the users' perspective.

Table 2 Answers from the questionnaire regarding the user experience in ViCoR

Questions	*NA*	*SD*	*D*	*N*	*A*	*SA*
It felt like I was really moving in the virtual world	0	0	0	0	5	5
I had no problem keeping my concentration throughout the experiment	0	0	0	0	2	8
It felt like I was moving objects with my hand, even though the objects did not have physical mass (actual weight)	1	0	0	1	4	4
The virtual world felt realistic	0	1	0	0	6	3
It was easy to understand what to do with the instructions presented by animations	0	0	0	0	5	5
It was easy to understand the robot's intentions and where it was going to move	0	0	0	0	4	6
I felt safe when working with the robot	0	0	0	0	3	7
It was easy to assemble parts together with the robot	0	0	0	1	6	3
It felt realistic to assemble parts together with the robot	0	0	0	2	4	4
It was easy to assemble parts manually	0	0	0	1	2	7
It felt realistic to assemble parts manually	1	0	0	1	4	4
It was easy to tell the robot what to do	0	0	0	2	3	5
Talking to the robot to give it instructions was a quick alternative	0	0	0	2	6	2
It felt like my behaviour in the virtual world was the same as my behaviour in the real world	0	0	0	0	10	0
It felt like I was participating in a game rather than in a HRC training environment	0	2	0	3	4	1
I think a virtual environment like this is good for training	0	0	0	0	3	7

Notes: No answer (NA), strongly disagree (SD), disagree (D), neutral (N), agree (A) and strongly agree (SA).

Observations made when demonstrating ViCoR for potential users and stakeholders indicate that VR has good potential as a platform for testing HRC. For instance, we have learned:

- there is interest in using VR technology for virtual commissioning and training, not only for HRC but for all processes requiring manual tasks
- it is difficult to differentiate between the objects that should represent physical entities and the objects that should represent AR entities.

5 Conclusions and future work

This paper presents ViCoR, a VR platform used for designing and evaluating HRC. With ViCoR, users can interact with a robot to simulate HRC without the safety risk of using physical robots. The platform was implemented with the game development tool Unity using ROS to connect with industrial robots. The platform has two modes. One enables the user to work with simulated robots through Unity, while the other connects with emulated or real robots through ROS. ViCoR provides additional interaction possibilities compared to existing VR tools, such as the ability to use hand guiding, and speaking to the robot.

VR has been used to test HRC in other projects, however, the novelty of this paper is the development of a VR platform that considers the research and development phase where a desired future state of the interaction can be tested. Using the simulated mode, a HRC station can also be tested without the limitations of existing production systems, which enables to evaluate state-of-the-art features and technologies not yet mature enough to be adopted in running production. To showcase the possibilities of ViCoR a scenario was implemented in which AR, speech recognition and haptic control was implemented with features beyond existing technologies. Animations intended to be used for AR glasses was tested with perfect tracking and higher field-of-view than existing AR glasses can provide. A hand guiding feature was implemented in Cartesian space with a specific responsiveness, without the need to implement the control using force-torque sensors.

An initial experiment was made with ten participants who tested the same task in both a physical and a virtual scenario. Most of these participants agreed or strongly agreed that that working inside ViCoR was realistic, even if the standard hand controllers from the VR headset was used. This suggests that ViCoR may be used with VR headsets without additional equipment with success, however, a deeper analysis is needed in this subject.

The long-term goal is to integrate ViCoR with engineering tools to facilitate the workflow of implementing HRC cells. New interactions could then be tested using VR without safety issues during research and development. In the design and commissioning phase, operators could test the production system at an early stage and provide input to improve the system. Training of operators could be done during the commissioning phase and during the operation of the cell. VR is therefore predicted to be useful throughout the whole production system life cycle of an HRC cell. To achieve this goal further investigation is needed on the performance difference of using ViCoR in comparison to a physical counterpart and the user experience. The performance relates to the execution time of tasks in virtual and physical environment, and the closer these are the better results are gained when evaluating the production system. The user experience focuses on the human perception in terms of ease of use, mental effort, and similarity to real environment.

Besides being used for testing interaction, ViCoR could potentially also be useful for evaluating safety aspects of HRC. Future work includes to investigate how the functions of ViCoR could be extended to include built-in support for safety evaluations, so that the user of ViCoR ultimately gets an online risk assessment when evaluating various types of interaction. Considering safety, another idea is to use ViCoR to analyse the consequences of typical distractions that happens at the industrial shop floor. This can be done by randomly inject moments of distraction in the virtual scenario and see how this affects the operator from a safety perspective and also estimate the risks of accidents. If ViCoR is to be used for safety evaluations, it is important to also look further into the inevitable differences between the real world and the virtual world and investigate what impact these differences might have in the risk assessment process.

References

Bannat, A., Gast, J., Rehrl, T., Rösel, W., Rigoll, G. and Wallhoff, F. (2009) 'A multimodal human-robot-interaction scenario: working together with an industrial robot, in *International Conference on Human-Computer Interaction*, Springer, pp.303–311.

Beer, J.M., Fisk, A.D. and Rogers, W.A. (2014) 'Toward a framework for levels of robot autonomy in human-robot interaction', *J. Hum.-Robot Interact*, Vol. 3, No. 2, pp.74–99, https://doi.org/10.5898/JHRI.3.2.Beer

Berg, L.P. and Vance, J.M. (2017) 'Industry use of virtual reality in product design and manufacturing: a survey', *Virtual Reality*, Vol. 21, pp.1–17, https://doi.org/10.1007/s10055-016-0293-9.

Dahl, M., Albo, A., Eriksson, J., Pettersson, J. and Falkman, P. (2017) 'Virtual reality commissioning in production systems preparation', presented at the *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation* (*ETFA*), pp.1–7, https://doi.org/10.1109/ETFA.2017.8247581.

Dahl, M., Bengtsson, K., Bergagård, P., Fabian, M. and Falkman, P. (2016) 'Integrated virtual preparation and commissioning: supporting formal methods during automation systems development', *IFAC-PapersOnLine*, Vol. 49, pp.1939–1944, https://doi.org/10.1016/j.ifacol.2016.07.914.

Etzi, R., Huang, S., Scurati, G.W., Lyu, S., Ferrise, F., Gallace, A., Gaggioli, A., Chirico, A., Carulli, M. and Bordegoni, M. (2019) 'Using virtual reality to test human-robot interaction during a collaborative task', presented at the *ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers Digital Collection, https://doi.org/10.1115/DETC2019-97415.

Freeman, D., Reeve, S., Robinson, A., Ehlers, A., Clark, D., Spanlang, B. and Slater, M. (2017) 'Virtual reality in the assessment, understanding, and treatment of mental health disorders', *Psychological Medicine*, Vol. 47, No. 14, pp.2393–2400, https://doi.org/10.1017/S003329171700040X

Garcia, C., Montalvo-Lopez, W. and Garcia, M. (2020) 'Human-robot collaboration based on cyber-physical production system and MQTT', *Procedia Manufacturing*, Vol. 42, pp.315–321, https://doi.org/10.1016/j.promfg.2020.02.088.

Green, S.A., Billinghurst, M., Chen, X. and Chase, J.G. (2008) 'Human-robot collaboration: a literature review and augmented reality approach in design', *Int. J. Adv. Robot. Syst.*, Vol. 5, No. 1, pp.1–18, https://doi.org/10.5772/5664.

Gualtieri L., Palomba I., Wehrle E.J. and Vidoni R. (2020) 'The opportunities and challenges of sme manufacturing automation: safety and ergonomics in human–robot collaboration', in Matt D., Modrák V. and Zsifkovits H. (Eds.): *Industry 4.0 for SMEs*, Palgrave Macmillan, Cham, https://doi.org/10.1007/978-3-030-25425-4_4.

Guhl, J., Tung, S. and Kruger, J. (2017) 'Concept and architecture for programming industrial robots using augmented reality with mobile devices like microsoft HoloLens', in *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation* (*ETFA*), presented at the *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation* (*ETFA*), pp.1–4, https://doi.org/10.1109/ETFA.2017.8247749.

Gustavsson, P., Syberfeldt, A., Brewster, R. and Wang, L. (2017) 'Human-robot collaboration demonstrator combining speech recognition and haptic control', *Procedia CIRP*, Vol. 63, pp.396–401.

Hongyi Liu, H. and Wang, L. (2020) 'Remote human–robot collaboration: a cyber-physical system application for hazard manufacturing environment', *Journal of Manufacturing Systems*, Vol. 54, pp.24–34, https://doi.org/10.1016/j.jmsy.2019.11.001.

ISO (2016) *ISO/TS 15066: Robots and Robotic Devices – Collaborative Robots* (Standard), International Organization for Standardization.

Jayaram, S., Connacher, H.I. and Lyons, K.W. (1997) 'Virtual assembly using virtual reality techniques', *Computer-Aided Design*, Vol. 29, No. 8, pp.575–584, https://doi.org/10.1016/S0010-4485(96)00094-2.

Kolbeinsson, A., Lagerstedt, E. and Lindblom, J. (2018) 'Classification of collaboration levels for human-robot cooperation in manufacturing', presented at the *Advances in Manufacturing Technology XXXII: Proceedings of the 16th International Conference on Manufacturing Research*, incorporating the *33rd National Conference on Manufacturing Research*, September 11–13, University of Skövde, Sweden, IOS Press, p.151.

Lambrecht, J. and Krüger, J. (2012) 'Spatial programming for industrial robots based on gestures and augmented reality', presented at the *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.466–472, https://doi.org/10.1109/IROS.2012.6385900

Lei, Z., Gan, Z.H., Jiang, M. and Dong, K. (2014) 'Artificial robot navigation based on gesture and speech recognition', presented at the *Proceedings 2014 IEEE International Conference on Security, Pattern Analysis, and Cybernetics* (*SPAC*), pp.323–327, https://doi.org/10.1109/SPAC.2014.6982708

Malik, A.A., Masood, T. and Bilberg, A. (2020) 'Virtual reality in manufacturing: immersive and collaborative artificial-reality in design of human-robot workspace', *International Journal of Computer Integrated Manufacturing*, Vol. 33, pp.22–37, https://doi.org/10.1080/0951192X.2019.1690685.

Mandel, M. (2019) *Demand For Collaborative Robots Continues To Grow*, WWW Document [online] https://www.forbes.com/sites/michaelmandel1/2019/11/01/demand-for-collaborative-robots-continues-to-grow/ (accessed 2.17.20).

Matsas, E. and Vosniakos, G-C. (2017) 'Design of a virtual reality training system for human-robot collaboration in manufacturing tasks', *International Journal on Interactive Design and Manufacturing* (*IJIDeM*), Vol. 11, pp.139–153, https://doi.org/10.1007/s12008-015-0259-2.

Maurtua, I., Fernández, I., Tellaeche, A., Kildal, J., Susperregi, L., Ibarguren, A. and Sierra, B. (2017) 'Natural multimodal communication for human-robot collaboration', *International Journal of Advanced Robotic Systems*, Vol. 14, p.1729881417716043, https://doi.org/10.1177/1729881417716043.

Metzner, M., Bönig, J., Blank, A., Schäffer, E. and Franke, J. (2018) ''Human-in-the-loop' – virtual commissioning of human-robot collaboration systems', in *Tagungsband Des 3*, Kongresses Montage Handhabung Industrieroboter, Springer, Berlin, Heidelberg, pp.131–138.

Michalos, G., Makris, S., Spiliotopoulos, J., Misios, I., Tsarouchi, P. and Chryssolouris, G. (2014) 'ROBO-PARTNER: seamless human-robot cooperation for intelligent, flexible and safe operations in the assembly factories of the future', *Procedia CIRP*, Vol. 23, pp.71–76, https://doi.org/10.1016/j.procir.2014.10.079.

Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D. and Chryssolouris, G. (2015) 'Design considerations for safe human-robot collaborative workplaces', *Procedia CIRP*, Vol. 37, pp.248–253, https://doi.org/10.1016/j.procir.2015.08.014.

Pichler, A., Akkaladevi, S.C., Ikeda, M., Hofmann, M., Plasch, M., Wögerer, C. and Fritz, G. (2017) 'Towards shared autonomy for robotic tasks in manufacturing', *Procedia Manufacturing*, Vol. 11, pp.72–82, https://doi.org/10.1016/j.promfg.2017.07.139.

Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R. and Ng, A.Y. (2009) 'ROS: an open-source robot operating system', in *ICRA Workshop on Open Source Software*, Kobe, Japan, p.5.

RobNor (2018) *RobNor AB – Virtual Reality*, WWW Document [online] https://www.robnor.se/virtual-reality (accessed 2.17.20).

Robot Operating System (ROS) (2020) [online] https://www.ros.org/ (accessed 4.12.20).

Rossi, S., Leone, E., Fiore, M., Finzi, A. and Cutugno, F. (2013) 'An extensible architecture for robust multimodal human-robot communication', presented at the *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.2208–2213, https://doi.org/10.1109/IROS.2013.6696665.

Rother, M. (2010) *Toyota Kata: Managing People for Improvement, Adaptiveness, and Superior Results*, Mc Graw Hill Education, USA.

Saenz, J., Elkmann, N., Gibaru, O. and Neto, P. (2018) 'Survey of methods for design of collaborative robotics applications – why safety is a barrier to more widespread robotics uptake', presented at the *Proceedings of the 2018 4th International Conference on Mechatronics and Robotics Engineering, ACM*, pp.95–101.

Satava, R.M. (1993) 'Virtual reality surgical simulator', *Surg Endosc*, Vol. 7, pp.203–205, https://doi.org/10.1007/BF00594110

Sharma, A. (2018) *Collaborative Robot Market to Grow by 60% in 2018*, WWW Document [online] https://www.interactanalysis.com/collaborative-robot-market/ (accessed 2.17.20).

Siemens (2019) WWW Document [online] https://github.com/siemens/ros-sharp (accessed 2.17.20).

Strahilov, A. and Hämmerle, H. (2017) 'Engineering workflow and software tool chains of automated production systems', in *Multi-Disciplinary Engineering for Cyber-Physical Production Systems: Data Models and Software Solutions for Handling Complex Engineering Projects*, Springer International Publishing, Cham, pp.207–234, https://doi.org/10.1007/978-3-319-56345-9_9.

Syberfeldt, A., Danielsson, O. and Gustavsson, P. (2017) 'Augmented reality smart glasses in the smart factory: product evaluation guidelines and review of available products', *IEEE Access*, Vol. 5, pp.9118–9130.

Thorstensen, M.C. (2019) *MathiasCiarlo/ROSBridgeLib*.

Wang, L., Gao, R., Váncza, J., Krüger, J., Wang, X.V., Makris, S. and Chryssolouris, G. (2019) 'Symbiotic human-robot collaborative assembly', *CIRP Annals*, Vol. 68, pp.701–726, https://doi.org/10.1016/j.cirp.2019.05.002.

Weber, B., Sagardia, M., Hulin, T., Preusche, C. and Preusche, C. (2013) 'Visual, vibrotactile, and force feedback of collisions in virtual environments: effects on performance, mental workload and spatial orientation', in *Virtual Augmented and Mixed Reality. Designing and Developing Augmented and Virtual Environments*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp.241–250.

Yanco, H.A. and Drury, J. (2004) 'Classifying human-robot interaction: an updated taxonomy', presented at the *2004 IEEE International Conference on Systems, Man and Cybernetics*, IEEE Cat. No.04CH37583, Vol. 3, pp.2841–2846, https://doi.org/10.1109/ICSMC.2004.1400763.