VIRTUAL REALITY PLATFORM FOR DESIGN AND EVALUATION OF THE INTERACTION IN HUMAN-ROBOT COLLABORATIVE TASKS IN ASSEMBLY MANUFACTURING

DOCTORAL DISSERTATION

VIRTUAL REALITY PLATFORM FOR DESIGN AND EVALUATION OF THE INTERACTION IN HUMAN-ROBOT COLLABORATIVE TASKS IN ASSEMBLY MANUFACTURING

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ABSTRACT

Industry is on the threshold of the fourth industrial revolution where smart factories are a necessity to meet customer demands for increasing volumes of individualized products. Within the smart factory, cyber-physical production systems are becoming important to deal with changing production. Human-robot collaboration is an example of a cyber-physical system in which humans and robots share a workspace. By introducing robots and humans into the same working cell, the two can collaborate by allowing the robot to deal with heavy lifting, repetitive, and high accuracy tasks, while the human focuses on tasks that need intelligence, flexibility, and adaptability. There are few such collaborative applications in industry today. In the implementations that actually exist, the robots are mainly working side-by-side with humans rather than truly collaborating. Three main factors that limit the widespread application of human-robot collaboration can be identified: lack of knowledge regarding suitable human-robot collaboration tasks, lack of knowledge regarding efficient communication technologies for enabling interaction between humans and robots when carrying out tasks, and lack of efficient ways to safely analyze and evaluate collaborative tasks.

The overall aim of this thesis is to address these problems and facilitate and improve interaction between humans and robots, with a special focus on assembly manufacturing tasks. To fulfill this aim, an assembly workstation for human-robot collaboration has been developed and implemented both physically and virtually. A virtual reality platform called ViCoR has been developed that can be used to investigate, evaluate, and analyze the interaction between humans and robots and thereby facilitate the implementation of new human-robot collaboration cells. The workstation developed has also been used for data collection and experiments during the thesis work, and used to extract knowledge of how the interaction between human and robot can be improved.

SAMMANFATTNING

Industrin är på väg in i den fjärde industriella revolutionen, där smarta fabriker är nödvändigt för att möta kundernas krav på ökande volymer av individualiserade produkter. Inom den smarta fabriken blir cyberfysiska produktionssystem viktigt för att hantera den varierande produktionen. Människa-robot samarbete är ett exempel på ett cyberfysiskt produktionssystem där människor och robotar delar arbetsyta. Genom att införa robotar och människor i samma arbetscell kan de samarbeta där roboten kan hantera uppgifter som kräver tunga lyft, repetitiva rörelser och hög precision medan människan kan fokusera på uppgifter som kräver intelligens, flexibilitet och anpassningsförmåga. I dagens industri är sådana samarbetsapplikationer få och I de implementationer som finns så arbetar robotarna mestadels i närheten av en människa istället för att faktiskt samarbeta. Tre huvudfaktorer har identifierats som har begränsat antal tillämpningar av människa-robot samarbete: brist på kunskap om lämpliga människa-robot samarbetsuppgifter, brist på kunskap om kommunikationstekniker som möjliggör interaktion mellan människor och robotar samt brist på effektiva och säkra sätt att analysera och utvärdera samarbetsuppgifter.

Det övergripande syftet med denna avhandling är att adressera dessa problem samt att underlätta och förbättra interaktionen mellan människor och robotar, med ett särskilt fokus på monteringsuppgifter. För att uppfylla detta mål har en arbetsstation för samarbete mellan människa och robot utvecklats och implementerats både fysiskt och virtuellt. En virtuell verklighetsplattform som heter ViCoR har utvecklats som kan användas för att undersöka, utvärdera och analysera interaktionen mellan människor och robotar och därigenom underlätta arbetet att implementera nya samarbetsceller. Den utvecklade arbetsstationen har också använts för datainsamling och experiment under avhandlingen och använts för att utvinna kunskap om hur samverkan mellan människa och robot kan förbättras.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to all my supervisors, Anna Syberfeldt, Magnus Holm, and Lihui Wang, for the continuous support in my PhD study. Their guidance and immense knowledge have greatly helped me with my research and with the writing of this thesis.

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I would like to thank all my coworkers in the Production and Automation Engineering department at the University of Skövde for all their cooperation and friendship which has made my PhD studies even more enjoyable.

PUBLICATIONS

In the course of my PhD studies, I produced the following publications, which are either published or currently in the submission process.

PUBLICATIONS WITH HIGH RELEVANCE

1. Gustavsson, Patrik, Anna Syberfeldt, et al. (2017). "Human-Robot Collaboration Demonstrator Combining Speech Recognition and Haptic Control". In: *Procedia CIRP* 63, pp. 396–401.

2. Gustavsson, Patrik, Magnus Holm, Anna Syberfeldt, and Lihui Wang (2018). "Human-robot collaboration – towards new metrics for selection of communication technologies". In: *Procedia CIRP* 72, pp. 123–128.

3. Gustavsson, Patrik and Anna Syberfeldt (2020). "The industry's perspective of suitable tasks for human-robot collaboration in assembly manufacturing". In: *International Conference on Industrial Engineering and Manufacturing Technology* (Submitted).

4. Gustavsson, Patrik, Magnus Holm, and Anna Syberfeldt (2020a). "Virtual Reality Platform for Design and Evaluation of Human-Robot Interaction in Assembly Manufacturing". In: *International Journal of Manufacturing Research* (Submitted).

5. Gustavsson, Patrik, Magnus Holm, and Anna Syberfeldt (2020b). "Evaluation of Human-Robot Interaction for Assembly Manufacturing in Virtual Reality". In: *Robotics and Computer-Integrated Manufacturing* (Submitted).

ADDITIONAL PUBLICATIONS

6 Syberfeldt, Anna, Oscar Danielsson, and Patrik Gustavsson (2017). "Augmented Reality Smart Glasses in the Smart Factory: Product Evaluation Guidelines and Review of Available Products". In: *IEEE Access* 5. Conference Name: IEEE Access, pp. 9118–9130.

7 Gustavsson, Patrik and Anna Syberfeldt (2017). "A New Algorithm Using the Non-Dominated Tree to Improve Non-Dominated Sorting". In: *Evolutionary Computation* 26.1. Publisher: MIT Press, pp. 89–116.

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ABBREVIATIONS

AR	Augmented reality
CPPS	Cyber-physical production systems
CPS	Cyber-physical system
DOF	Degrees of freedom
DSR	Design science research
HMD	Head-mounted display
HRC	Human-robot collaboration
HRI	Human-robot interaction
pHRI	Physical human-robot interaction
ROS	Robot operating system
TTS	Text-to-speech
VCC	Volvo Car Corporation
VR	Virtual reality

INTRODUCTION

CHAPTER 1
INTRODUCTION

This chapter introduces the research done for this PhD work. Section 1.1 presents the background of this PhD work and motivation for the research. In section 1.2 the problems are described, and in section 1.3 the aim and research questions are formulated based on the identified problems. The included articles are described briefly in section 1.4 with a description of their main contribution to this thesis. Finally, in section 1.5 the structure of the thesis is described.

1.1 BACKGROUND

Industry is on the threshold of the fourth industrial revolution (Hermann, Pentek, and Otto, 2016; Rojko, 2017; Kagermann et al., 2013), often referred to as Industry 4.0, which is predicted to see the conversion of industries into smart factories. The necessity for this revolution lies in customer requirements for more individualized products together with growing production volumes. The vision of smart factories in Industry 4.0 absorbs the Internet of Things and Services into the manufacturing industry. The aim is to establish global networks incorporated into industry and use cyber-physical systems (CPS) as the mechanisms and machinery to work within industry (Hermann, Pentek, and Otto, 2016; Kagermann et al., 2013; Monostori, 2014; Gorecky et al., 2014). CPS are smart systems that are capable of autonomously communicating with one another to accomplish certain tasks. By connecting CPS elements in a production line and allowing those elements to interact with its physical environment, a so-called cyber-physical production system (CPPS), a more flexible and adaptable production system can be realized.

In comparison with traditional automation schemes that focus on a centralized control system, CPPS uses a more decentralized approach by communicating with humans, machines, and products to figure out its intended task (Monostori, 2014). This approach has the advantage of adapting to changes in production at any time, be it a change in product specification, unforeseen problems, or a change in production resources. One of the challenges with CPPS is the human-machine symbiosis, that is, enabling humans and machines to successfully communicate to deal with the ever-changing production. In recent years robots have included several features that make them adaptive and aware of their surroundings (Sadrfaridpour and Y. Wang, 2017; Cherubini et al., 2016). By introducing robots into the same working cell as humans, the two can collaborate by, for example, allowing the robot to deal with heavy lifting or repetitive and high accuracy tasks while the human focuses on tasks that need the intelligence, flexibility, and adaptability of humans (J. Krüger, Lien, and Verl, 2009). Human-robot collaboration (HRC) is one aspect of Industry 4.0, where the goal is not to remove humans from the industry, but to make the tasks more suitable for humans and robots to work together (Hermann, Pentek, and Otto, 2016). Human-robot collaboration is especially interesting in assembly manufacturing, that consist of complex tasks which often require the sensory-motor ability and flexibility of a human, but also often include heavy lifting and repetitive tasks (Mikell P Groover, 2013).

To enable HRC, robot manufacturers have developed collaborative robots that include functions such as force limitation in the manipulator to make them safer to work with. Collaborative robots enable the implementation of more flexible work stations where the operators can collaborate with the robot without the need for safety fences. Instead safety is ensured by activating collaborative operations as defined in the technical specification ISO/TS 15066 (ISO, 2016). Collaborative robots are attracting an increasing interest in manufacturing industry due to to their low cost, simple programming, ease of integration, and reduced space requirements (Mandel, 2019; Sharma, 2018). With these robots, manufacturing companies can incrementally automate their production without changing the layout of the existing production lines, because they do not require safety fences as long as they fulfill the safety requirements of ISO/TS 15066:2016 (ISO, 2016). However, even though collaborative robots have existed for more than a decade, the number of HRC applications is still limited (Saenz et al., 2018). Cases have been reported where collaborative robots are used for cooperative tasks in industry (Bannat et al., 2009; Saenz et al., 2018; Sadrfaridpour and Y. Wang, 2017; Michalos et al., 2015). However, these are often limited to the human working in close proximity to the robot, with limited interaction, and no real cooperation.

1.2 PROBLEM DESCRIPTION

Three major problems in HRC in assembly manufacturing have been identified and are addressed in this thesis:

- The lack of knowledge regarding suitable tasks that humans and robots can carry out together in various scenarios, based on an efficient interaction. In order for the human and robot to fully collaborate, the two need to assist each other and work together, not only side-by-side. To explore the full potential of HRC, more knowledge of suitable tasks in various collaborative applications must be identified and evaluated.

- The lack of knowledge about efficient communication technologies to facilitate interaction in various HRC application scenarios. If the human and robot are to successfully collaborate with each other, then the two need to communicate efficiently. Many technologies could potentially be used to enable this communication. However, it is unclear which technologies are most efficient for a particular application scenario. Doing an exhaustive search to test the compatibility of each technology for every possible application is not feasible in practice. More efficient ways of identifying suitable communication technologies are needed.

- The lack of safe and efficient ways to analyze and evaluate the interaction between humans and robots. Safety requirements are one of the major reasons why HRC has not been more widely used in industry, which limits the creation of new HRC applications (Saenz et al., 2018). Currently, the way to ensure safety when testing HRC is often to limit the maximum velocity and force that the robot can exert. More efficient, but still safe, ways of testing HRC applications are needed.

1.3 AIM AND RESEARCH QUESTIONS

This thesis aims to address the identified problems with HRC and facilitate the interaction between humans and robots, thus contributing to successful HRC implementations. This thesis has a special focus on assembly manufacturing as there is much potential for HRC in this area. Based on the aim of the thesis, an overall question is formulated as follows:

How can the interaction between a human and a robot be facilitated in assembly manufacturing?

Based on this overall question four research questions were formulated that define the scope of the thesis:

RQ1 *What tasks are suitable for humans and robots to carry out together in assembly manufacturing?*

Currently there are very few industrial implementations of HRC, and more knowledge is needed regarding collaborative tasks. This question therefore focuses on identifying HRC tasks, that are suitable for assembly manufacturing or that can be adapted for assembly tasks.

RQ2 *What technologies can be used to enable communication between humans and robots, and how can these be efficiently integrated to facilitate interaction?*

There are several communication technologies for interacting with machines in general, but more investigation is needed into how these can be combined to improve HRC. This question therefore focuses on identifying what technologies are suitable for efficient interaction between humans and robots and how these can be combined, with a focus on the tasks identified in RQ1.

RQ3 *How can the interaction between humans and robots be tested in a safe and efficient way?*

As previously discussed, industrial robots introduce safety risks when sharing workspace with a human. Therefore, this question focuses on identifying how the safety of humans can be ensured when testing various ways of interacting using the communication technologies identified in RQ2.

RQ4 *How can a technical platform be designed based on the results from RQ3 in order to enable practical HRC experimentation and speed up the implementation process?*

Development and testing of HRC applications should be rapid, safe, and cost efficient. Therefore, this research question focuses on how a technical platform can be designed based on the approach identified in RQ3 which can be used in the development and testing of new human-robot collaborative tasks.

1.4 CONTRIBUTION OF THE ARTICLES

In this section the main contributions of the publications with high relevance to the thesis are briefly described. Table 1.1 shows how the papers contribute to the research questions. These publications are also attached to this thesis.

Research questions	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5
RQ1	✓	✓	✓		
RQ2	✓	✓		✓	✓
RQ3	✓			✓	
RQ4				✓	✓

Table 1.1: Relationship between the publications with high relevance and the research questions.

In addition to the publications listed in Table 1.1, two more publications (Papers 6 and 7) are described that contributed either to the thesis or to my research career.

PAPER 1

Patrik Gustavsson, Anna Syberfeldt, et al. (2017). "Human-Robot Collaboration Demonstrator Combining Speech Recognition and Haptic Control". In: *Procedia CIRP* 63, pp. 396–401

This paper describes the design of a HRC workstation that was constructed in which three communication technologies were implemented: speech recognition, haptic control, and augmented reality (AR). The task to be carried out by the operator at the workstation was to assemble a car model together with the robot. A pilot study was performed to test the usability of the workstation, with participants from technical high schools between the ages of 16 and 19. Throughout the process of creating the workstation and executing the pilot study, several challenges were identified: there were no selection criteria for communication technologies, it was time-consuming to build the workstation, it was difficult to deal with safety issues, and the maturity of the technology used at the time was still quite low to enable robust interaction.

The paper contributes to the overall aim of the thesis and also partly answers RQ1 and RQ2, as it implements typical HRC tasks and tests technologies for communication between robot and human. The paper also shows the importance of RQ3, as it became clear that it was problematic to use the workstation to efficiently test communication technologies safely. The first version of the workstation designed in the paper is an important basis for the whole thesis and was used throughout the whole project.

I was the first author and main contributor to this paper. I designed the workstation and the car model used in it together with a colleague. I took the major responsibility for the physical construction, and I implemented the robot logic. I also implemented the speech recognition and haptic control, and their integration.

PAPER 2

Patrik Gustavsson, Magnus Holm, Anna Syberfeldt, and Lihui Wang (2018). "Human-robot collaboration – towards new metrics for selection of communication technologies". In: *Procedia CIRP* 72, pp. 123–128

This paper starts with a comprehensive literature survey of existing communication technologies and their use in HRC interaction. The paper continues by proposing new metrics, and tries to simplify the process of selecting proper communication technologies based on the type of task to be executed. The proposed metrics measure the flexibility and the time taken to complete messaging of the communication technologies in typical HRC tasks. With the new metrics, the combination of communication technologies for a HRC application can be selected based on the tasks included in a specific workstation.

The paper contributes to answering RQ1 and RQ2. The literature survey results in an overview of typical HRC tasks (RQ1), and the proposed new metrics simplify the process of identifying and combining proper communication technologies for HRC (RQ2).

I was the first author and main contributor to this paper. I performed the literature review and created the new metrics which facilitates the process of selecting communication technologies for HRC.

PAPER 3

Patrik Gustavsson and Anna Syberfeldt (2020). "The industry's perspective of suitable tasks for human-robot collaboration in assembly manufacturing". In: *International Conference on Industrial Engineering and Manufacturing Technology (Submitted)*

This paper describes an interview study made to investigate the industry's perspective on tasks that they think benefits the most from HRC. Several studies have been made that implements various HRC tasks, but little is known about what the industry think as suitable tasks for HRC. This paper presents an interview study with two companies where shop-floor operators, production engineers and automation engineers were interviewed. The result of the study pinpoints a number of tasks that the participants thinks are beneficial for HRC and these were categorized to simplify the process for other manufacturing companies that is considering to implement HRC.

This paper mainly contributes to answering RQ2 by extracting knowledge from the industry on what they think are the most value-adding tasks in HRC. The interview study resulted in a categorization of tasks that the industry perceive as suitable for HRC.

I was the first author and main contributor to this paper. I organized the interview study and supervised two university students who executed the study.

PAPER 4

Patrik Gustavsson, Magnus Holm, and Anna Syberfeldt (2020b). "Virtual Reality Platform for Design and Evaluation of Human-Robot Interaction in Assembly Manufacturing". In: *International Journal of Manufacturing Research (Submitted)*

This paper describes the suggested virtual reality (VR) platform ViCoR, which has the purpose of designing and evaluating human-robot interaction for assembly manufacturing. The paper starts by describing how VR can be used within the production system life cycle of HRC cells. It shows that VR has potential to be used in the development phase to validate the HRC workstation with a human-in-the-loop. It can also be used as a training tool for operators to learn to operate the workstation during the development of the station and its productive use.

The paper continues by describing the requirements and architecture of ViCoR in detail. The purpose of the platform is to improve HRC interaction, and the workstation designed in ViCoR is therefore eventually meant to be implemented in a physical environment. Another requirement is the possibility of testing new types of interaction, so that the platform capabilities can be extended beyond those of existing robot controllers.

Unity software was selected as the development tool for ViCoR and two modes were implemented, called simulated mode and ROS mode. Features that may not exist within current robot controllers can be tested in the simulated mode. In ROS mode the same control used in the virtual world can be used in the real world. A scenario is implemented in the platform, that is an adaptation of the HRC workstation initially developed in Paper 1 to evaluate the user experience. This scenario is used to test and publicly demonstrate the possibilities of using VR for HRC. The paper also describes some of the limitations of using VR. For example, users do not experience resistance or inertia, the environment looks digital, and the virtual hands have limited degrees of freedom.

This paper contributes to answering RQ3 by describing how VR can be used to test the interaction between robot and human in a safe and efficient way. It contributes to answering RQ4 by presenting the design of a technical platform that enables practical HRC experimentation. Also, it contributes to answering RQ2 by exemplifying how different communication technologies can be combined and tested in VR.

I was the first author and main contributor to this paper. I designed and implemented the ViCoR platform, and I also set up the scenario for testing human-robot interaction in the platform, based on the workstation that I had developed earlier.I also performed the initial tests and demonstrations of the ViCoR platform as discussed in the paper.

PAPER 5

Patrik Gustavsson, Magnus Holm, and Anna Syberfeldt (2020a). “Evaluation of Human-Robot Interaction for Assembly Manufacturing in Virtual Reality”. In: *Robotics and Computer-Integrated Manufacturing (Submitted)*

The main focus of this paper is on evaluating the ViCoR platform. An experiment was set up with participants from three companies involved in assembly manufacturing. For the experiment, the scenario from paper 4 is further developed and the VR functionalities are extended to improve the user experience. A tutorial guide is added before the HRC scenario starts to ensure that participants become acquainted with using VR and become familiar with interacting in a virtual environment. The results from the experiments show that ViCoR works well. In general users of the platform feel that it provides a realistic experience and that the platform is valuable for testing HRC.

The paper mainly contributes to answering RQ4 by presenting the evaluation of a fully functional technical platform for the design, evaluation, and analysis of HRC workstations with a specific focus on the interaction between human and robot. Also, it contributes to RQ2 by showing how a combination of communication technologies has been implemented in a virtual scenario for use with HRC.

I was the first author and main contributor to this paper. I further developed the scenario to fit the experiment, and I also coordinated the experiment and analyzed the results.

SUPPORTING PAPERS

Paper 6

Anna Syberfeldt, Oscar Danielsson, and Patrik Gustavsson (2017). “Augmented Reality Smart Glasses in the Smart Factory: Product Evaluation Guidelines and Review of Available Products”. In: *IEEE Access* 5. Conference Name: IEEE Access, pp. 9118–9130

This paper presents a review of AR glasses, which are an important type of interaction in HRC. AR is also one of the interaction technologies implemented in the workstation used in the thesis. The paper analyzes the different AR glasses available at the time by comparing their specifications and their usefulness in industry. The paper does not delve into HRC, but it provides a comprehensive study of the possibilities of AR technology.

I was the third author in this paper and contributed by identifying and providing specifications for the AR glasses mentioned in the paper. This paper contributed knowledge about existing AR technologies and their capabilities for the focus area of the thesis.

Paper 7

Patrik Gustavsson and Anna Syberfeldt (2017). "A New Algorithm Using the Non-Dominated Tree to Improve Non-Dominated Sorting". In: *Evolutionary Computation* 26.1. Publisher: MIT Press, pp. 89–116

This paper presents a new algorithm that improves the performance of non-dominated sorting when using three or more objectives and larger population sizes. Non-dominated sorting is used for sorting solutions in a population according to Pareto dominance, and is usually applied in the selection stage in a multi-objective evolutionary algorithm.

I was the first author and main contributor to this paper. I developed the algorithm which reduces the optimization time of meta-heuristic algorithms that require non-dominated sorting. This paper was my first step into the academic world and laid a foundation for my career as a researcher. In the future, multi-objective optimization algorithms could potentially be used to optimize HRC scenarios. This system could become a valuable tool in the future.

1.5 OUTLINE OF THIS THESIS

Chapter 2 provides the frame of reference for this thesis, describing the basic concepts in HRC and existing communication technologies that can be used to enable interaction between human and robot. Chapter 3 explains the research approach used for this thesis. Chapter 4 describes the implemented HRC workstation. Chapter 5 describes the work that was done in identifying suitable HRC tasks, and what communication technologies can be used to facilitate HRC. Chapter 6 explains the VR platform ViCoR that was created to address the safety issues of testing physical HRC applications. Chapter 7 concludes this thesis and discusses future work.

FRAME OF REFERENCE

CHAPTER 2
FRAME OF REFERENCE

This chapter starts off with a description of assembly manufacturing and what processes may be involved in assembly. Then general concepts are provided regarding industrial robotics, collaborative robots, HRC, and its use in assembly manufacturing. To better understand how communication technologies can be used for HRC, the chapter goes into more details on state-of-the-art communication technologies, how they have been combined, and what metrics have been used. Finally, this chapter will explain how virtual commissioning is used to verify and validate production systems, together with an overview of how VR has been used to involve the human aspect in this process.

2.1 ASSEMBLY MANUFACTURING

This thesis has focused on assembly manufacturing because it often consists of complex operations that are difficult to automate and should benefit from HRC to improve existing processes. Assembly is a manufacturing process where two or more parts are attached together with either joining processes, fasteners, or interference fits (Mikell P Groover, 2013). Examples of these processes are illustrated in figure 2.1.

Joining processes such as welding, brazing, soldering and adhesive bonding form a permanent bond between the parts which cannot easily be separated. Most of the assembly on car bodies uses spot-welding.

Fasteners are separate hardware used to attach parts. There are two types of fasteners: those that allows disassembly, such as screws, bolts, nuts and clamps, and those which do not allow disassembly without damaging the fastener, for example, rivets and eyelets.

Interference fits bond parts together by mechanical interference between them. Press fitting is an interference fit where two parts are pressed together where the outer dimension of the inner part exceeds the inner dimension of the outer part. Shrink and expansion fits have an interference fit at room temperature, but when either the inner part is cooled or the outer part is heated, then the two parts can be put together. Snap fits are a variation of interference fits where the snap fit has a temporary interference during the assembly process, but once fully assembled the parts are interlocked. A retaining ring is a fastener that uses snap fit interference to be attached to a shaft, also called a snap ring, which restricts the movement of other components on the shaft.

In addition to these assembly processes, handling, controlling, and auxiliary processes (e.g., cleaning, adjustment, marking) are required to realize the assembly task (Siciliano and Khatib, 2016). The requirements of the assembly application and the type of resource required to manage the assembly change depending on production quantities, complexity of the assembled product, and the assembly processes used (Mikell P. Groover, 2014). If the production volume is relatively small, it is often more economical to have individual workstations where one or more workers assemble the product. For complex products made in medium to high volumes, a manual assembly line is often the

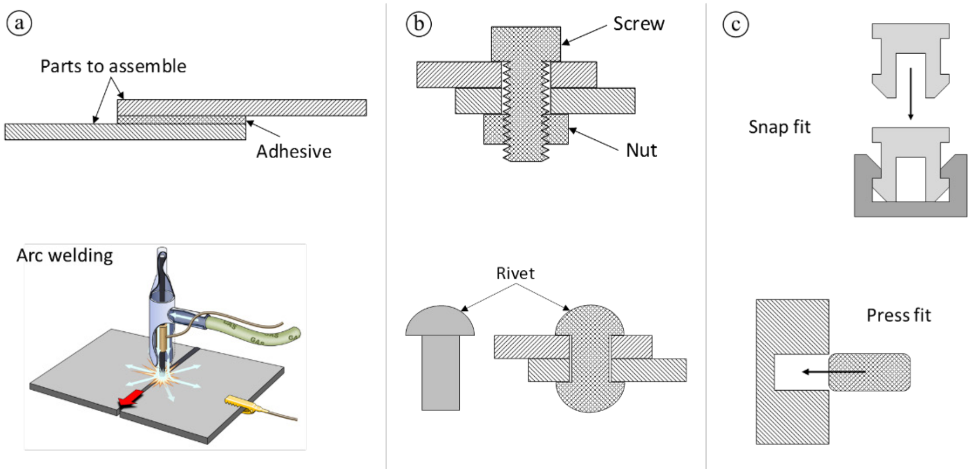

Figure 2.1: Illustration of different assembly manufacturing processes: a) Joining b) Using fasteners c) Interference fitting.

best option. For large volumes close to a million units and simple products with a dozen or so components, automated assembly lines are more appropriate.

Figure 2.2 shows an example of a fully manual assembly station where the products consist of both soft and stiff material requiring screwing, clamping, control, and handling processes. This workstation is difficult to automate because it requires high sensibility and fine motor control (which humans already possess with their sensory-motor abilities) to position the component and sense when it is in place.

Up to 80% of a product's manufacturing cost lies in the assembly processes and therefore the greatest competitive advantage can be gained by improving these processes (Siciliano and Khatib, 2016). Design for assembly is the process of designing the product in such a way that the assembly process is feasible and economical (Mikell P. Groover, 2014; Boothroyd, 2005). If a product has not been designed for automatic assembly, then manual assembly is often required.

Higher production volumes and demands for more customizable products have resulted in increasingly complex manufacturing systems with increased automation (Frohm et al., 2008). However, excessive levels of automation may result in poor system performance, and complex manufacturing systems are more vulnerable to disturbances. The concept of Industry 4.0 as the fourth industrial revolution transforms manufacturing systems by introducing smart automation which uses CPS with decentralized control (Rojko, 2017). As part of the Industry 4.0 revolution, humans are an important resource within the factory. However, the types of skills that are needed are different from the skills for traditional automated and manual stations. For tasks that are difficult to automate cost efficiently, humans can be seen as an important component of the manufacturing system (Frohm et al., 2008). Therefore, to achieve flexible, productive, and cost-efficient manufacturing, both advanced technical systems and skilled human workers are necessary.

Figure 2.2: Example of a fully manual assembly station (from a VCC plant). This image shows an operator using a screw machine to fasten a part consisting of both soft and stiff material, which is difficult to fully automate.

2.2 INDUSTRIAL ROBOTS

The definition of an industrial robot, as stated in ISO 8373:2012 (ISO, 2012), is an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes which may either be fixed or mobile for use in industrial applications. An industrial robot consists of links and joints, where joints constitute the movable axes and links constitute the rigid parts between each joint. An industrial robot's main purpose is to use a tool to execute the task at hand.

Robotics has its origin in the 1920s when Karel Čapek, a Czech writer, wrote the play R.U.R., *Rossum's Universal Robots* (Čapek, 1923). The word robot was coined in 1921 when the play R.U.R. first took the stage, but was used only in science fiction (Siciliano and Khatib, 2016; Horáková, 2011). It took some time before the first robot company, Unimation, was founded in 1954. This company installed the first robot, Unimate, into a General Motors plant for extracting parts from a die-casting machine in 1961. Later, several robot manufacturers adopted their robot design to solve complex applications, such as a painting robot application by Trallfa in 1967 and the robot IRB-6 from ASEA developed in 1974.

Today, industrial robots are used for tasks that involve repetitive or non-ergonomic movements, tasks that need to be executed in hazardous environments, and tasks requiring heavy lifting or high precision (Siciliano and Khatib, 2016; Mikell P. Groover, 2014). These can include handling, painting, welding, processing, and assembly applications. The robots used for these applications are usually large and robust, requiring fences to ensure the safety of humans. In some cases, depending on the workspace environment, the room will be sealed, for example, in painting applications.

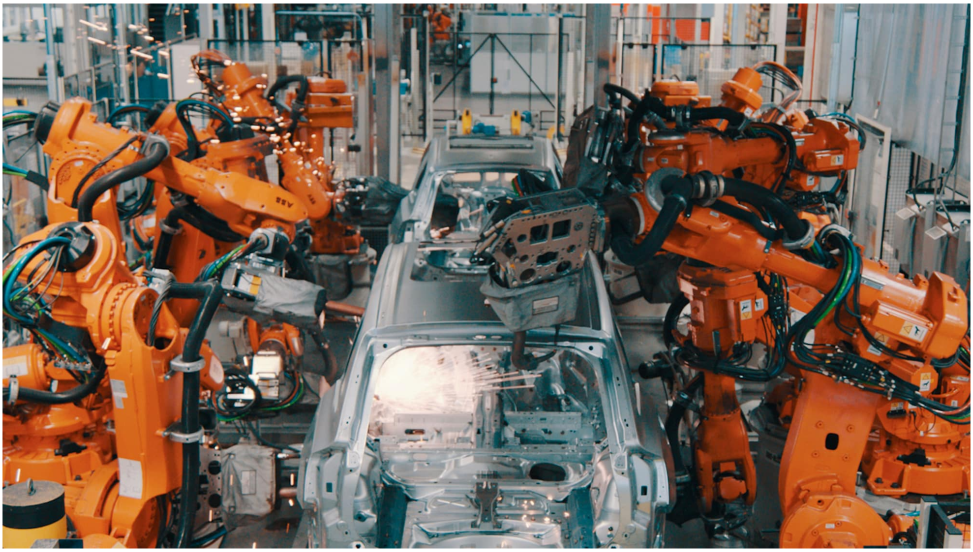

Figure 2.3: Spot-welding in VCC to join car body parts of a Volvo using ABB robots.

Figure 2.3 is an example of how robots can be used in industry. In this picture multiple ABB robots are spot welding parts to construct the body of a Volvo car. In general, welding operations are not suited to humans due to the hazardous environment. Dealing with several hundreds of products per day, with relatively high precision and complex poses makes this type of application highly suitable for industrial robots.

It is common for robot manufacturers to use proprietary programming language for controlling their robots (Owen-Hill, 2016). For example ABB uses RAPID for their robots, KUKA uses KRL (KUKA Robot Language), Comau uses PDL2 and Kawasaki uses AS. These languages are scripts that have been created with instructions that can execute common tasks of an industrial robot. There are other industrial robots that instead use existing general purpose programming languages to create the robot code. Examples of these are the LBR IIWA robots from KUKA that use Java, and Sawyer from Rethink Robotics that uses Python. One of the problems with industrial robot programming is that the programmer needs to learn a new language when using a robot from another manufacturer. If the programmer is going to implement more advanced features, they need to rely on the language provided to support those features.

2.2.1 COLLABORATIVE ROBOTS

Traditional industrial robots often require fences to ensure the safety of humans. In addition, these robots are quite large and intimidating, making them unfit for work in close proximity to humans, even if the robots could meet safety requirements. Robot manufacturers have, therefore, introduced collaborative robots which use a light-weight robotic structure and include certain safety features as defined by ISO/TS 15066 (ISO, 2016). Examples of collaborative robots include the UR3, UR5, and UR10 series from Universal Robot, YuMi robots from ABB, LBR IIWA from KUKA, and Baxter from Rethink Robotics. Figure 2.4 shows the YuMi and LBR IIWA robots. Collaborative robots

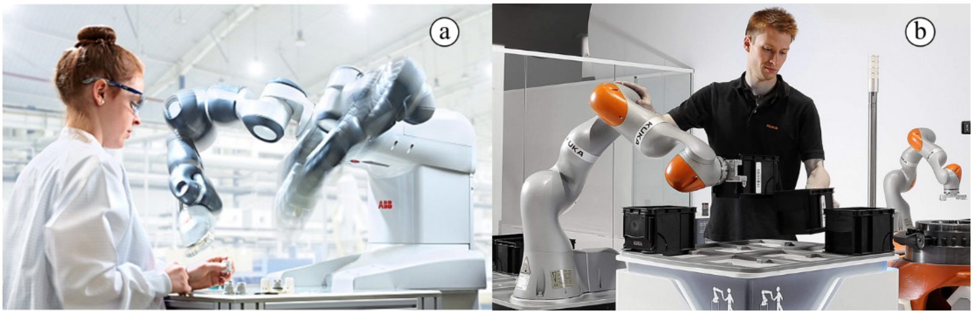

Figure 2.4: Example of two collaborative robots: a) YuMi from ABB b) LBR IIWA from KUKA.

have drawn more attention in recent years among production industries. These robots provide an easy interface to program the robots without the need for extensive training and do not require safety fences, which reduces the footprint of the robot, saving space for other machinery. These robots have also drawn the attention of the research community, as applications and prototypes can more easily be tested because the robot is inherently safe. However, even if these robots meet certain safety requirements, the robot system still needs to be CE-marked with the tools, products and workspace for the specific application.

2.2.2 ROBOT OPERATING SYSTEM

Robot Operating System (ROS) is an open source framework for implementing robot logic (*ROS.org* 2020). Quigley et al. (2009) presented ROS as a structured communication layer in which nodes send messages to each other in a network. ROS has grown significantly since then, and today it is a collection of tools and libraries that enables the creation of complex robot behavior.

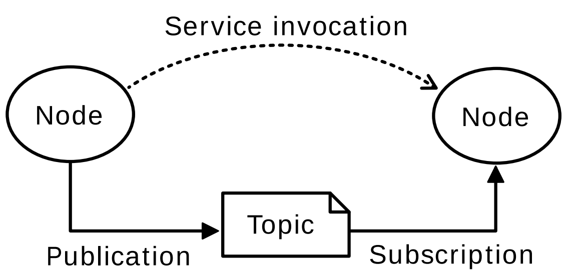

Figure 2.5: Illustration of the communication between ROS nodes, as shown in *ROS/Concepts - ROS Wiki* (2020).

The robot logic is written in the form of nodes exchanging messages with each other (*Documentation - ROS Wiki* 2020), as shown in figure 2.5. A master node is set up as a lookup service which is used to find other nodes, exchange messages, or invoke services. Each node registers its name with the master and the topics they subscribe or publish messages to. The topics are used to convey messages in a many-to-many relationship between nodes. All nodes that are publishing can send new messages to a topic, and all nodes that subscribe to this topic receive the messages sent by other nodes. The publish-subscribe pattern enables nodes to send messages without knowing who the recipients are, making it easy to hook up new nodes to the same network. However, it is not suitable for request/reply interactions, which are often required in a distributed system. Therefore, another communication protocol is used, called services, where a client node sends a request message to the node offering the service, which then replies.

A ROS node is any type of computational process that can communicate through the ROS network and is not limited to any type of device. This has allowed the framework to include a diverse set of libraries,such as speech recognition, path planning, custom sensors, motor control, artificial intelligence algorithms, and many more. ROS has libraries which can be used for industrial robots, as shown in *ROS-Industrial* (2020). ROS-Industrial has support for some industrial robots, including the universal robots series used in this thesis. Using ROS-Industrial, the same robot logic can be used for all supported robots, which makes the implementation more standardized compared to using the language of the robot provided by the manufacturers. More advanced features can also be implemented by using the libraries provided by ROS or implementing the features in Python or C++.

2.3 HUMAN-ROBOT COLLABORATION

There is major interest in human-robot collaboration in the academic community and industry (Norberto Pires, 2009; Haddadin et al., 2011). The concept of humans and robots working together opens up many possibilities, especially within the assembly industry, where it can increase the flexibility, adaptability, and reusability of assembly systems (J. Krüger, Lien, and Verl, 2009). HRC allows the strengths of both the human and the robot to be utilized by letting the human deal with tasks that require flexibility, adaptability, and intelligence, while the robot deal with tasks that require physical strength, repeatability, and high accuracy.

Collaborative robots have been produced for over a decade and could be used for collaborative tasks. However, in industry these robots are most commonly used to work in close proximity with humans with limited interaction. Recent research has shown promising results by using these robots for more collaborative work (Hietanen et al., 2020; Ragaglia et al., 2016; Cherubini et al., 2016). There are also other robotic systems in the industry (J. Krüger, Lien, and Verl, 2009) that have been used to improve ergonomics for humans. These kinds of robotic systems originated from the work of Akella et al. (1999), who introduced the concept of cobots, assisting robotic systems used for the automotive assembly line.

In the following sections HRC is explained in more detail, starting with a summary of HRC definitions and the definition used in this thesis. Then safety aspects of HRC are explained, followed by types of interaction that have been tested for HRC applications.

2.3.1 DEFINITION

Although the concept of HRC has existed for more than a decade, a common definition has yet to be established. Michalos et al. (2015) categorize HRC based on how humans and robots execute a task and whether they share workspace in doing so. They divide collaboration with a robot into four categories:

- *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.
- *Shared tasks and workspace, robot active*: In this case the human is inactive, letting the robot do its work, but on a shared task.
- *Common task and workspace*: In this case both the human and the robot are active, working on a common task.
- *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.

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

- *Human and robot are decoupled*: Human interacts with robot using control switches such as start/stop buttons.
- *Human-robot coexistence*: Human and robot are located in the same workspace but are still decoupled with respect to activities.
- *Human-robot assistance*: Human and robot synchronize activities with a clear server/client relationship between them. Robot does not need to be equipped with any cognitive abilities.
- *Human-robot cooperation*: Human and robot work on the same workpiece 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.
- *Human-robot collaboration*: 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 a detailed understanding of all activities and of execution time to collaborate efficiently.

De Luca and Flacco (2012) define coexistence as a robot's ability to share workspace with other entities. Safety must be guaranteed if humans are present in the workspace, which they refer to as safe coexistence. They define collaboration as the robot performing a complex task in coordination with a human using two different, not mutually exclusive, modalities. In physical collaboration the human and robot execute a task by intentionally exchanging forces through physical contact. In contactless collaboration, the human and robot interact by exchanging information to execute the task. This interaction can be direct through gestures and speech, or indirect through intention or attention recognition, for example, by using eye gaze recognition.

The definition used in this thesis is based on the above definitions and is most similar to the definition of De Luca and Flacco (2012), with the exception that collaboration does not require two different modalities. This means that throughout this thesis, HRC is referred to as a human and an industrial robot completing manufacturing tasks in a shared workspace that requires collaborative operations. A collaborative operation is an operation that requires interaction between the human and the robot to execute. The interaction can be through physical contact exchanging forces to manipulate an object, or through coordinated actions by exchanging information using communication technologies such as gestures and speech recognition.

2.3.2 SAFETY

One of the major barriers to developing new HRC applications is the restrictions set out in the safety standards (Michalos et al., 2015; Saenz et al., 2018). Traditional industrial robots need to be enclosed within safety fences or other barriers to ensure the safety of the human. The standards ISO 10218-1 (ISO, 2011a) and ISO 10218-2 (ISO, 2011b) are used to specify the safety requirements for constructing the robot and the robot cell respectively. Collaborative robots have been developed that can be used to work in close proximity to humans without needing safety fences. The standard ISO/TS 15066 (ISO, 2016) is the technical specification for these robots, defining the following four safeguarding 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 used to safeguard humans only when they are working in a collaborative environment and are referred to as safety operations in this thesis. Hand guiding also introduces physical interaction with the robot, and is therefore considered both a safety and a collaborative operation in this thesis. The other three operations are essential for enabling HRC, but are not collaborative in nature.

Risk assessment and risk reduction are required to ensure the safety of the cell by following the guidelines of ISO 12100 (ISO, 2010) when implementing a new robotic cell. When using traditional industrial robots, the workspace consists of the robot with auxiliary devices (e.g., robot tool, clamping devices, and conveyors). Safety for these cells is often implemented using physical barriers, such as fences, or using sensors that detect whether unknown objects enter the area. In these cases safety is ensured by separating the human from the robot, making it easier to handle safety because only the distance between the human and risk zones, as defined in ISO 13857 (ISO, 2019), needs to be considered. In these cases auxiliary devices have low impact on the safety risks. For collaborative workspaces, the human is in close proximity to the robot and auxiliary devices, and it is no longer possible to rely on ISO 13857 for distances to risk zones. Each cell presents unique risks that need to be dealt with in the risk assessment and risk reduction processes to ensure the safety of the human (Michalos et al., 2015).

The existing procedure for implementing new robotic cells and the strict safety requirements pose a difficult challenge when implementing new HRC applications (Saenz et al., 2018). Because of this there are relatively few collaborative robots in industrial applications compared to traditional robots. Collaborative robots are often implemented as traditional robots without fences (Michalos et al., 2015; Saenz et al., 2018) with limited interaction between the human and the robot to minimize safety risks. For collaborative environments, new procedures are needed to evaluate the safety to allow the process of implementing new HRC applications (Fast-Berglund et al., 2016; Saenz et al., 2018). However, improving and evaluating the safety procedures of HRC as such is not the focus of this thesis.

2.3.3 INTERACTION

For humans and robots to successfully collaborate, they need to interact with each other. With traditional robots the interaction is merely the use of buttons and displays. However, when collaborating, the interaction should be as smooth as possible; therefore a more elaborate interface is needed. Human-robot interaction (HRI) is defined as the interaction between humans and robots (Siciliano and Khatib, 2016). In this thesis, HRI is investigated to collect information on possible communication technologies, that can be considered for use in HRC.

If the interaction between a human and a robot is to be as fluent as possible, the interaction should be self-explanatory (Siciliano and Khatib, 2016). However, ”self-explanatory” can differ depending on the context and previous knowledge of the human in question. In industry everyone is required to undergo training before working on an assembly line. If, after that training, the interaction is still not self-explanatory, then the interaction will not be fluent. In addition to being self-explanatory, the interaction should also be able to communicate whether a situation is safe or dangerous using both verbal, and non-verbal communication cues, such as gestures and emotional feedback.

Interaction between a human and a robot is based on the communication technologies provided to transfer communication cues. The communication cues can be auditory, visual, and haptic (taste and smell are typically not included). By combining communication technologies, several features can be introduced such as:

- Allowing operators with no robot programming expertise to teach the robot how to execute its task, for example by using hand guidance to move the robot and speech recognition to give it commands.
- Allowing the operator to receive information superimposed on the real world. For example, augmented reality glasses can display animated instructions on how to assemble a part, or the robot’s possible movements when guiding the robot.

Human-robot interaction is not limited to communication from human to robot.An essential part of interaction is the feedback loop to the human, to facilitate the human’s understanding of decisions made by the robot (Scholtz, 2002). In addition, humans may need information from the system to know what they need to do. Therefore, communication technologies can be divided into human-to-robot and robot-to-human communication.

Papers by Rossi et al. (2013), Bannat et al. (2009), Gea Fernández et al. (2017), and Maurtua et al. (2017) discuss how multimodality improves the flexibility and robustness of HRI. Using complementary communication technologies improves the flexibility as different modalities can recognize different types of messages, which is of interest in this thesis. Using redundant communication technologies improves the robustness, as different modalities improve the recognition of the same message. This thesis does not consider the robustness of the communication technologies themselves, but rather the type of collaborative tasks in which they can be utilized and how the type of communication affects possible scenarios.

Human-to-robot communication technologies

Haptic controls such as controls with force-torque sensors, joint-torque sensors, impedance or admittance have the ability to physically control a robot by guiding it by hand (J. Krüger, Lien, and Verl, 2009; Cherubini et al., 2016; Roveda et al., 2015). This type of communication falls under physical human-robot interaction (pHRI), which refers to physical interaction where mechanical energy is exchanged between human and robot (Evrard et al., 2009). This can be by direct contact between a human body part and a robot link, or it can be by manipulating a shared object. Haptic controls can be far more efficient than traditional methods such as joysticks or buttons, and requires less training to work with. There are two main approaches to controlling a robot, using either Cartesian space or joint space. Controlling a robot in Cartesian space is natural for humans, but may produce singularities if a redundant robot arm is used. Controlling a robot in joint space will not produce such errors. Force-torque sensors mounted on end effectors can be used to control a robot in Cartesian space but not in joint space, making them less flexible. However, if torque sensors or compliance can be incorporated into each joint enabling control in both joint and Cartesian space, flexibility will be increased.

A virtual impedance control for collision avoidance to ensure the safety of the operator was tested by Lo, Cheng, and Huang (2016). This was implemented with a Kinect sensor which detects the human body and uses that information to change the robot path to avoid collision. Although virtual impedance is used in this case for collision avoidance, impedance has been used to control the robot accurately (Roveda et al., 2015). This suggests that virtual impedance could be used for guiding the robot, but this has not been tested so far.

Speech recognition is the process of converting an audio signal into recognizable sentences for the system. Speech recognition has been used in several instances in HRI to tell the robot what to do, as shown in Rossi et al. (2013), Bannat et al. (2009), Maurtua et al. (2017), Lei et al. (2014), and Green et al. (2008). It shows promise in HRC because the human can interact in a way that is natural in human-to-human communication. This technology provides a way to communicate without changing hand positions or changing focus from the current activity. Devices used for speech recognition can be divided into two categories: head-mounted and distant. Distant devices can use technologies such as omni- and unidirectional microphones and microphone arrays. Microphone arrays can also be directional, to filter out noise and other people's voices. Filtering is mainly used to improve robustness of the technology, which is not the focus of this thesis.

Gesture recognition provides an interface allowing a human to use gestures to interact with a system (Mitra and Acharya, 2007). These interactions include pointing at an object to highlight it, giving thumbs up to indicate good quality, grasping the hand to demonstrate a gripping command, or nodding to indicate agreement. Gesture recognition has been used in HRI using vision-based technologies (Rossi et al., 2013; Maurtua et al., 2017; Lei et al., 2014; Van den Bergh et al., 2011; Lambrecht and Jörg Krüger, 2012), and glove-based technologies (Lu, Yu, and Liu, 2016; Simão, Neto, and Gibaru, 2016). Several of the vision-based gesture recognition papers use the inexpensive Microsoft Kinect as the vision system. Vision-based technologies may be more flexible than glove-based systems, but they face difficulties in seeing gestures from all directions.

A multimodal HRI system tested in Bannat et al. (2009) consists of a robot, a projector, and three input modalities. The input modalities are gaze recognition, speech recognition, and so-called soft buttons. Human gaze is realized using eye-tracking glasses, speech recognition uses a head-mounted microphone, and the soft buttons are a combination of tracking the hand using vision sensors with a projector that displays buttons on a workbench. The projector can also be used to display other information, such as assembly instructions at the point of gaze of the human using eye-tracking technology. The authors also mention another application where gaze can be used to detect which button the human wants to activate.

Gesture and speech recognition were combined in Lei et al. (2014) to control an artificial robot with the following nine navigational commands: forward, back, left, right, northeast, southeast, southwest, northwest and stop. The paper demonstrates that these technologies can be used for proximate interactions, making them possible in a HRC setting. They used a Kinect camera for both gesture recognition and distant speech recognition. Robustness was greatly improved when combining the two modalities.

Screens have been used to display facial expressions (emotions) (Sadrfaridpour and Y. Wang, 2017) to improve the feedback loop to the human. The emotional states of the face can help the operator prioritize which task to execute, guiding the attention of the human. This technology improves the interaction between the human and the robot. However, by itself the technology cannot be utilized for interaction in a collaborative task.

Robot-to-human communication technologies

Augmented reality is a technology that overlays digital information onto the real world. Promising results have been seen in robot interactions (Green et al., 2008; Lambrecht and Jörg Krüger, 2012; Guhl, Tung, and Kruger, 2017). For example, with this technology instructions can be displayed where they are needed, physical objects can be highlighted, or a specific motion can be animated in the real world. To enable the technology some sort of hardware device is used. These devices can be categorized as spatial, handheld, and head-mounted devices (Syberfeldt, Danielsson, and Gustavsson, 2017). Different types of optics can be used to visualize information on the devices: video, optical and retinal optics affect the view of the user, while holograms and projection affect the visualization of the real world. AR technologies using spatial devices can be separated into spatial monitors (affects the view of the user) and spatial projection (affects the visualization of the real world). The two categories affect the type of task they can be used for.

Text-to-speech (TTS) technologies are an artificial way of providing understandable audible output for the human (Tabet and Boughazi, 2011). This technology is currently in smartphones, cars, and laptops for example, and has also been suggested for HRI (Green et al., 2008) to allow the robot to express itself using speech. Devices for TTS can be categorized as head-mounted or freestanding. The audio signal can be delivered in a non-spatial or spatial way.

Pick-by-light and pick-by-voice are common communication technologies in modern warehouses (Reif and Günthner, 2009). Pick-by-light uses small lamps installed on each storage compartment that light up to signal which compartment the human should pick from. This system is not flexible because lamps or displays need to be installed on every compartment. A pick-by-vision system has been suggested to overcome this problem, using AR glasses to highlight the different compartments. Pick-by-voice supports the worker using TTS instructions. The reliability of this technology degrades in noisy environments, and it is questionable whether humans would appreciate being told what to do in a monotone voice. However, as one objective in TTS synthesis is to make the speech indistinguishable from that produced by a human (Tabet and Boughazi, 2011), the tone of voice should not be a problem in the future.

2.4 VIRTUAL COMMISSIONING AND VIRTUAL REALITY

Commissioning is the process of testing and verifying a manufacturing system until it fulfills certain requirements (Lee and Park, 2014). Commissioning can be separated into four categories based on the use of virtual and real components:

- Real commissioning involves the real plant and real controllers, which is the process of getting production up and running in the real world. Reducing the time needed for commissioning can lead to time reductions and savings.
- Virtual commissioning involves a virtual plant and real controllers, which can test the functionality of the manufacturing system without needing to change the underlying software when transferring to the real plant.
- Reality-in-the-loop commissioning is the use of the real plant with virtual controllers.
- Constructive commissioning involves a virtual plant and virtual controllers. The use of virtual controllers may mean that the functionality differs when switching to the real controllers.

The virtual and constructive commissioning processes use a virtual plant with real or virtual controllers, which means that the PLC, robot, or simulated controllers will be acting on virtual actuators and sensors. In the absence of virtual commissioning the verification process would be dependent solely on real commissioning, which is time-consuming and expensive. The purpose of virtual commissioning is to identify and fix problems in the manufacturing system before creating the physical system. In a virtual environment the plant can be changed easily to test different solutions. Studies (Shahim and Møller, 2016; Koo et al., 2011) show that the real commissioning time can be significantly reduced, making it possible to meet customer deadlines more efficiently.

Existing virtual or constructive commissioning tools focus on the simulation/emulation of PLC, robots and other machines to act on a virtual plant. Humans can be involved in this process, but often they are either simulated or are involved by interacting with a user interface. This makes manual assembly processes difficult to commission in a virtual environment. Recent studies such as Matsas and Vosniakos (2017), Giorgio et al. (2017), and Metzner et al. (2018), have shown great potential in virtual training and testing using VR, which potentially could include the human in the commissioning process using a virtual plant.

Virtual reality involves the use of a head-mounted display (HMD) which encloses a user in a virtual environment. The virtual environment is updated based on sensors that track the motions of the user's head. Thus the user appears to be inside the virtual environment. However, the HMD alone is usually not enough for a full VR experience. Therefore, VR headsets exist that include a HMD with two displays (one for each eye),

Figure 2.6: Example of VR headsets: a) HTC Vive b) Oculus Rift c) Samsung Gear VR.

hand controllers, and sensors to track the user's motions. Examples of commercial VR headsets are HTC Vive and Oculus Rift (figure 2.6).

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 for using virtual training systems for HRC and that users in general are positive to the approach.

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

Sagardia et al. (2012) and Weber et al. (2013) present two related studies using two robots connected to the hand of the user to provide the user with force feedback. Force feedback is lacking in existing commercial VR headsets, which affects the user experience and performance. In the study three scenarios were compared using different feedback components: force feedback using two robots, vibrotactile feedback using VibroTac devices connected to the lower arm and wrist, and visual feedback highlighting parts in collision. Their evaluation showed that force feedback provided the highest precision but reduced the execution time and limited the user's ability to reach a desired position quickly. Using vibrotactile feedback was cognitively more demanding due to ambiguous feedback; however, execution times were better compared to using visual feedback. Other studies have been made using haptic feedback devices to improve the user experience, for example, using a knife-shaped device for incisions (Toda et al., 2013), using an exoskeleton for assembly tasks (Carignan, Tang, and Roderick, 2009; Gu et al., 2016), and using gloves with force feedback (Kreimeier et al., 2019).

Regardless of what equipment is used and the type of interaction implemented, using VR for HRC has proven to be feasible and has benefits in both virtual commissioning and training. Additionally, VR provides an opportunity to test a system based on concepts that are not available in existing controllers. For example, the interaction is not limited to the constraints set by physical devices. Therefore, the algorithms and sensor technologies used, for example, for haptic control can be simplified by replacing their information with the positional data of the hands. The effect on the production system life cycle is yet to be explored. Interaction with the virtual environment using standard VR headsets lacks force feedback, and has limited hand coordination. However, there is often a trade-off between user experience, performance, and flexibility when introducing more advanced equipment, as demonstrated by Sagardia et al. (2012). If the standard equipment of VR headsets can be used to design and evaluate HRC applications successfully, it could reduce the cost and time needed for setting up VR.

RESEARCH APPROACH

CHAPTER 3
RESEARCH APPROACH

This chapter describes the research approach used for this thesis, starting with a presentation of the philosophical paradigms in section 3.1. The methodology selected is discussed in section 3.2, while section 3.3 presents the type of contribution that can be expected from the approach selected.

3.1 PHILOSOPHICAL PARADIGM

It is important to understand the underlying assumptions and ways of thinking when executing a research project because the approach affects how projects are carried out and evaluated (Oates, 2005). A philosophical paradigm defines how the nature of our world is viewed (ontology) and the ways knowledge is acquired from it (epistemology).

Orlikowski and Baroudi (1991) explain three different philosophical paradigms. Of these, positivism and interpretivism are of interest in this research.

- Positivism views the world as ordered and regular, in which we can extract knowledge from this world using an objective approach. This view is closely associated with the natural sciences. The result of positivistic research should be the same, no matter who executes the research. In positivistic research new knowledge is found by formulatng a hypothesis. The hypothesis is then tested to determine whether it can be refuted. If it cannot be refuted, then a theory is formed. However, if there is one instance where the hypothesis/theory can be refuted, then the theory is proven false.
- Interpretivism views the world as multiple subjective realities, with all individuals having their own understanding of the world. There is no such thing as objectivity in interpretive research, because interpretivists believe that there will always be bias. Observations cannot be made independently because researchers have their independent view of the world. Interpretive research in information systems and computing tries to understand how a system works in a social setting.

This research has an overall interpretivistic view, in which experiments are executed to evaluate HRC based on behavior, usability, and user experience. These are interpretivistic because they all rely on information extracted from the subjective experiences of the users.

3.2 METHODOLOGY

This research follows the design and creation strategy defined by Oates (2005), which focuses on developing artifacts in information technology. The types of artifacts in information technology are constructs, models, methods, and instantiations (March and

Smith, 1995). This project aims to develop artifacts and gain knowledge from creation and experimentation using the artifacts. It is argued that novel instantiations are simple extensions of novel constructs, models, and methods. However, in computer science, instantiations are the real proof and evidence that the underlying constructs, models, and methods work.

3.2.1 FRAMEWORK

The project follows the information system research framework, as defined by Hevner et al. (2004), as the model for understanding, executing, and evaluating this research. This framework combines behavioral science and design science paradigms in order to compare and position them in the research. Behavioral science meets business needs by focusing on the development and justification of theories, while design science meets business needs by focusing on building and evaluating artifacts. Hevner et al. (2004) argue that these paradigms are inseparable, that is, building and evaluation of artifacts informs theory, while development and justification of theories informs the design of artifacts.

Figure 3.1 shows the overall definition of the information system research framework defined by Hevner et al. (2004), with specific information related to this research. Information system research is where new artifacts and theories are developed and evaluated in order to contribute to the knowledge base and at the same time satisfy the environment. This framework clarifies how different parts of a research project relate to each other. The environment specifies the need for an artifact, and it is necessary to consider the needs if the research is to be relevant. The knowledge base constitutes the foundation and methodologies to conduct research. By appropriately applying existing knowledge, the research becomes rigorous.

The process of executing a design and creation strategy is not straightforward, but instead follows an iterative cycle where new knowledge is extracted in each cycle (Oates, 2005; Hevner et al., 2004). Oates (2005) explains this iterative process in this way: development of an idea leads to increased understanding, thinking about a tentative solution increases the awareness of the problem, failure leads to new insights, and so on. This iterative process is learning by making, which is the process adopted in this research as illustrated in figure 3.1. The process starts with the development of a workstation that is used in an experiment. Once the workstation and its potential in HRC is understood, then knowledge is extracted from that work. Based on that knowledge, the workstation is further updated or another artifact is created.

The environment defines the goals, tasks, problems, and opportunities, which defines the business needs. These needs are formed based on the perception of the people in the organization. Their assessment and evaluation is based on the organizational strategies, structure, culture, and processes. The needs are then defined in relation to existing technologies with their limitations and possibilities. From the start of this project, the organizational strategy and the trend of the industry point to HRC.

The knowledge base defines the foundations and methodologies which are the building blocks used to execute information system research. The foundations consist of the theories, frameworks, instruments, constructs, models, methods, and instantiations used in the development and construction phase. Methodologies, on the other hand provide guidelines on how to justify and evaluate the artifact or theory. From the start, the current state-of-the-art technology is known within the different areas, but as the project

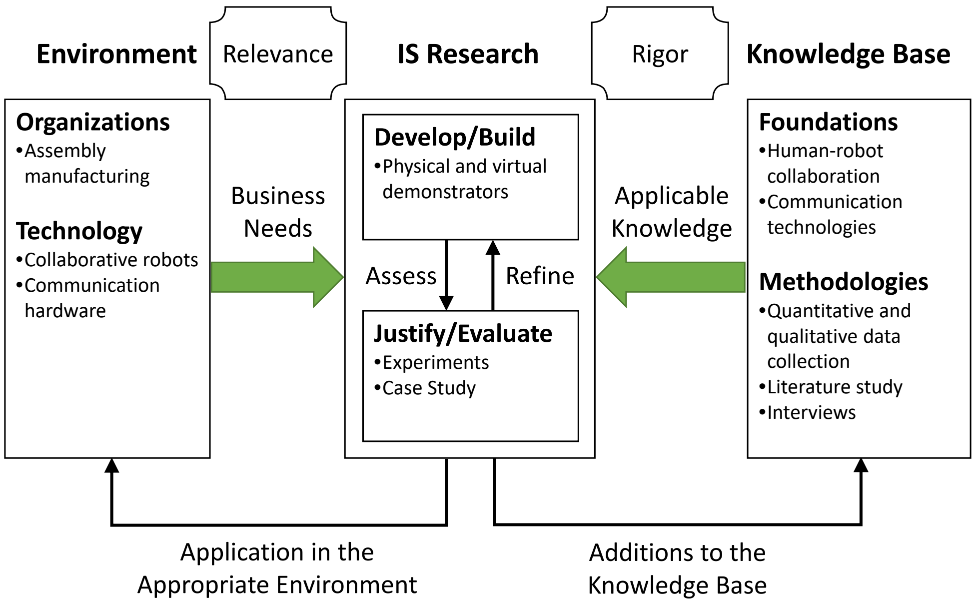

Figure 3.1: The information system research framework as defined by Hevner et al. (2004), adapted to this research by showing how the different parts of the research fit into the framework.

continues creating artifacts and possibly new theories, the project will iteratively add to the knowledge base.

3.2.2 DATA COLLECTION

This research is divided into several objectives in the form of research questions, with different objectives requiring different data collection techniques. In this research three data collection techniques have been used: observations, interviews, and questionnaires, as explained by Oates (2005).

Observation as a data collection technique is the process of recording observations made in a study. Observations can be highly systematic by only observing predefined types of events, or the observations can include anything and everything going on within the study. In this thesis observations was used to collect data on the participants behavior and for empirical data by observing or measuring the performance of combinations of communication technologies.

Interviews are used to obtain more insight from participants by conversation. The interviewer can obtain detailed information, ask complex questions, and explore the emotions and experiences of the participant. There are three main approaches to interviews: structured (predefined questions are asked), semi-structured (a predefined set of questions are prepared, but the ordering of the questions may differ and additional questions may be asked), and unstructured (start off with a topic and then the interview proceeds freely). Interviews will be used to gain the user's understanding of collaborative tasks in assembly manufacturing. In this case a semi-structured interview will be used, because more interesting tasks may be found depending on the operator's answer.

Questionnaires are a data collection technique involving a set of predefined questions. This data collection technique is mainly used to understand the usability of the created artifacts. Usability can be measured with the system usability scale (SUS) developed by Brooke (1996), which is a simple ten-point Likert scale questionnaire to assess the usability of a system. SUS has been used in numerous projects and has proven to be a good tool for usability tests (Bangor, P. T. Kortum, and J. T. Miller, 2008).

3.2.3 DATA ANALYSIS

The data of the observations, interviews, and questionnaires needs to be analyzed before conclusions can be drawn based on the data (Oates, 2005). Data analysis examines data and tries to find patterns within the data to draw conclusions.

Quantitative analysis can find patterns within numerical data by using visual aids or statistics. Visual aids can show the patterns by plotting the data in different type of charts and graphs. For example, pie charts can show proportions, scatter graphs can show relationships between two variables, and bar charts can show frequencies of phenomena. Visual aids are good tools to help organize empirical data. However, they are dependent on the researcher's individual interpretation. Statistics can be used to ensure that the analysis of the data remains objective.

Qualitative analysis can find patterns in non-numeric data such as words, images, and sounds. In this project qualitative analysis is used for the semi-structured interviews, which mainly contain textual data. The interviews are planned to discover what collaborative tasks are possible in assembly manufacturing by involving operators from the assembly line.

Textual data can be analyzed based on themes. Following the procedure of Oates (2005), the initial step has the following three themes: segments that bear no relation to the research, segments that provide general descriptive information about the research context, and segments that are directly relevant to the research. The focus here is mainly on the third theme, since the other two are not directly relevant to the research objective or research question. Then the data are categorized based on categories found within the data or literature. The categorization can be refined further by breaking it down into smaller sub-categories. When the categorization is satisfactory, it is time to find connections between the different segments to determine patterns within the data.

3.3 CONTRIBUTION

Oates (2005) defines the contribution of design and creation research in three ways: research where the IT application is the main focus, research where the IT application is used as a vehicle for something else, or research where the IT application is a tangible end-product where the focus is on the development process. This thesis intends to develop a fully functional artifact (IT-based application) and demonstrate the technical viability of this artifact.

The contribution of this project can be best explained using the design science research (DSR) knowledge contribution framework, as shown in figure 3.2. The framework defines the type of contribution based on the research solution maturity and application domain maturity. Four different knowledge contributions are illustrated in figure 3.2.

Improvement: When the application context is known but the solution artifacts are either non-existing or sub-optimal, then the goal of DSR in the improvement quadrant is

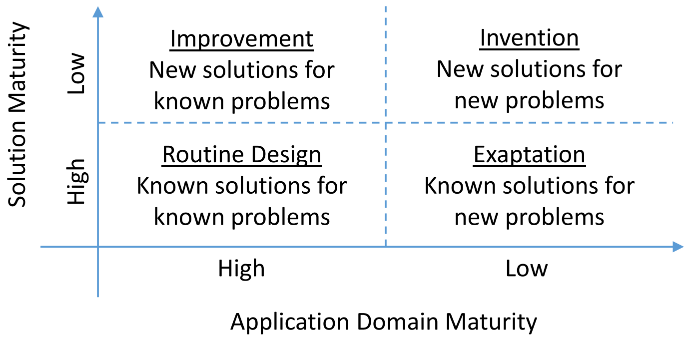

Figure 3.2: Design science research knowledge contribution framework as defined by Gregor and Hevner (2013).

to create better solutions. ”Better” in this case means more efficient and effective products, processes, services, technologies, or ideas.

Invention: Those projects that invent a new type of solution in new and interesting applications fall into the invention quadrant of DSR. The invention type of research most often falls into the artifact/instantiation level. The typical knowledge flow of inventions is: first a new artifact is invented as prescriptive knowledge, then other researchers see the use of such artifacts and they then formulate descriptive knowledge.

Routine Design: Applying known solutions to known problems rarely requires research methods. Both the solutions and the problems are well understood, and therefore the knowledge already exists. However, there have been cases where routine work has led to surprises and other discoveries.

Exaptation: In exaptation research, known solutions in one field are applied/adapted to new problems in another field. Exaptation research is common in information system research because individuals who have experience in multiple disciplines can more easily see whether knowledge from one field can be applicable in another. In exaptation research the researcher needs to demonstrate why the adaptation of the solution is nontrivial and interesting.

In this thesis existing technologies will be adapted to new application areas, which fits the definition of exaptation. Exaptation mainly contributes to prescriptive knowledge in the form of artifacts. These artifacts are constructs, models, methods, and instantiations. Exaptation can also in some cases contribute to descriptive knowledge via a greater understanding of the artifacts in use. The expected contributions of this thesis are:

- Better understanding of how HRC can support assembly manufacturing.
- Simplified/improved test approach for communication technologies in HRC.
- Improved selection process to find combinations of communication technologies for collaborative tasks.

DESIGN OF A HUMAN-ROBOT COLLABORATION SOLUTION

CHAPTER 4
DESIGN OF A HUMAN-ROBOT COLLABORATION SOLUTION

At the start of the project a HRC workstation was created as a platform for prototyping typical human-robot collaborative tasks. This work laid the foundation of this thesis by identifying challenges in HRC through the creation and evaluation of the workstation. The HRC workstation had the following requirements:

1. It needs to be safe for humans to use. This part is the most critical aspect of any workstation: if it is not safe, then no human should use it.
2. It should be mobile to move around so that the workstation can be demonstrated in different locations, making it easier to display at public events. Making the workstation movable also makes it easier to get more participants, since the participants will not need to travel; instead the workstation is moved to them.
3. The task on which the human and the robot collaborate should be simple yet relevant, and it should involve communication technologies that enable interaction between the human and the robot.

At the time the workstation was created, no selection criteria or frameworks were used to select the type of interaction. Instead the focus of the work was on combining three types of interactions: speech recognition, haptic control, and augmented reality.

4.1 SETUP

The setup shown in figure 4.1 was used to meet the requirements of the HRC workstation:

- UR3 robot (a) and controller (b) from Universal Robots
- Flexible 85mm 2-finger tool (c) from Robotiq
- Sennheiser ME 3 EW microphone with Steinberg UR12 USB audio interface (d)
- Computer (e) with Microsoft Speech API 11 and EasyModbusTCP, connected to the microphone and the robot controller
- A movable cart, containing components (a–e)
- A TV as the graphic user interface, mounted on a movable stand

The UR3 robot was selected because it is certified for working in close proximity to humans, and is also one of the cheapest industrial robots on the market. It is a six-axis light weight articulated robot that can lift up to 3 kg. It has joint-by-joint haptic control,

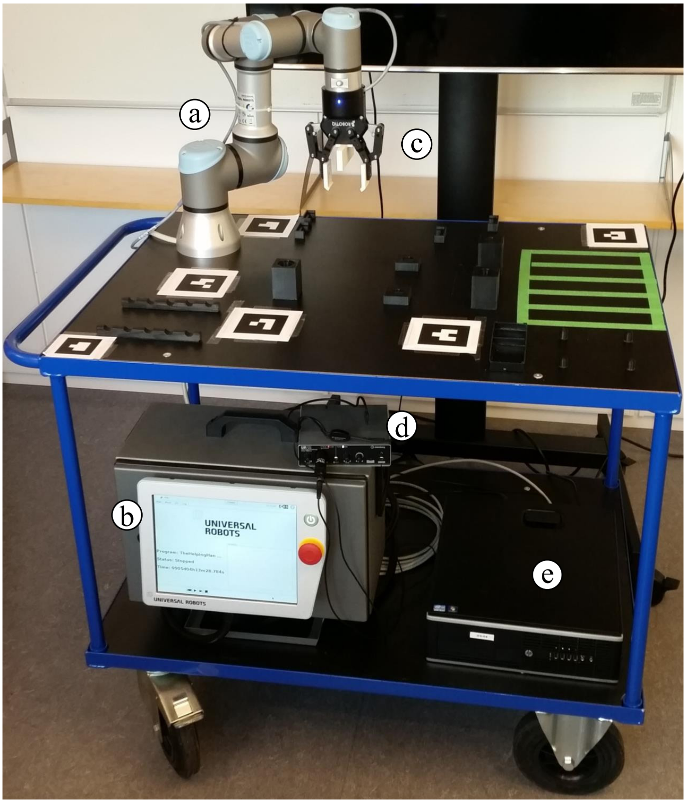

Figure 4.1: HRC workstation setup: (a) robot, (b) robot controller, (c) robot tool, (d) microphone and USB audio interface, (e) computer. All components are on a movable cart.

called freedrive mode. The freedrive mode uses impedance/back-drive control which allows a human to move the robot by hand.

The 85 mm 2-finger tool from Robotiq was selected because it is highly flexible. The fingers can open 85 mm wide and close to 0 mm. This tool can also control the speed and force with which it grips an object. The speed of the tool has been reduced in the workstation to reduce the possibilities of someone being pinched.

The computer is the central system controlling what is displayed on the interface, listening to commands spoken by the user, and controlling robot execution. Control was implemented using a custom made C# program to enable multi-modal communication. This control was selected because at that time standard industrial equipment such as industrial PLCs and robot controllers, provided limited support for multi-modal communication.

The interface is a TV which displays a live feed from a camera mounted above the workspace. Digital information was superimposed on the live feed. This enables spatial AR which gives instructions to the user by highlighting objects on the live feed (figure 4.2). In addition, the TV displays instructions to the user on what to do and what to say when a task is complete. The display is controlled by the computer. Unity software was used to display the interface, using Vuforia as the AR technology.

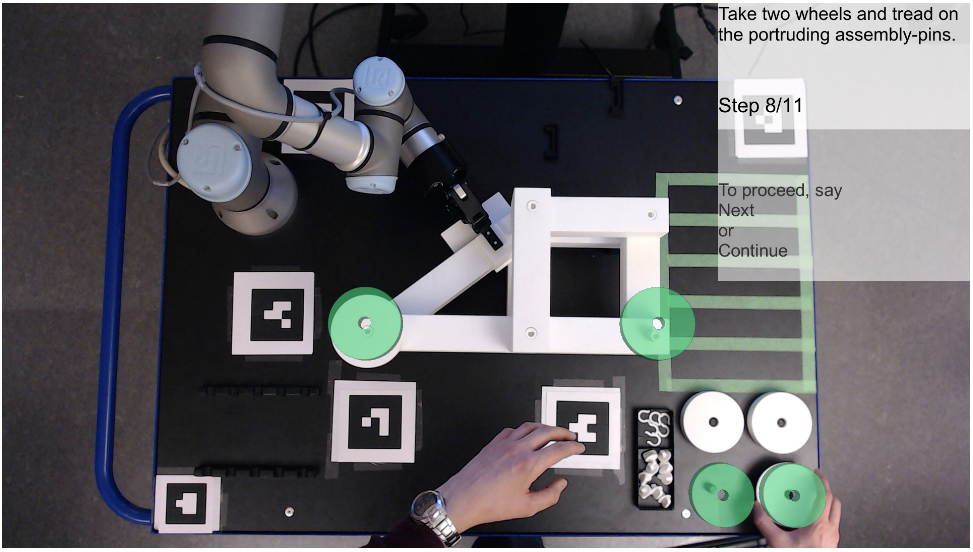

Figure 4.2: Example of the interface on the TV used to display instructions in text format and spatial AR by highlighting objects to pick and where to assemble them.

The speech recognition system combines Microsoft Speech API 11, the Sennheiser ME 3 EW microphone, and the Steinberg UR12 USB audio interface. Microsoft Speech API 11 is not cloud-based, which is an advantage because Internet access might not be available, depending on the location. The Steinberg UR12 USB audio interface connects the microphone to the computer. This was necessary because the Sennheiser microphone plug is not directly compatible with the computer.

Robot execution is controlled from the computer, through the EasyModbusTCP, which acts as a Modbus server. Several signals are defined in the Modbus server: reset, start, next, open, close, and handshake. The handshake signal is used to ensure good communication between the robot and the computer. The other signals are used for different commands controlling the execution of the robot.

4.2 TASK

A simple yet relevant task was created in which the human and robot collaborate to assemble a car model. The car model has the advantage of having a real world connection to uses of HRC. In the task the robot acts as a flexible fixture, providing parts when needed close to the assembly operation. This ensures that the operator only deals with tasks that require the sensory-motor ability of humans. This is similar to the situation in operating rooms in hospitals, where the room is prepared and tools are delivered to the surgeon when needed.

Creating the task was done in two iterations. The first iteration used a wooden car, figure 4.3 on the left, and the second iteration used a 3D printed car, on the right.

Friction was used to hold the structure of the wooden car together. This resulted in difficulties when assembling the parts, because some parts required the human to apply

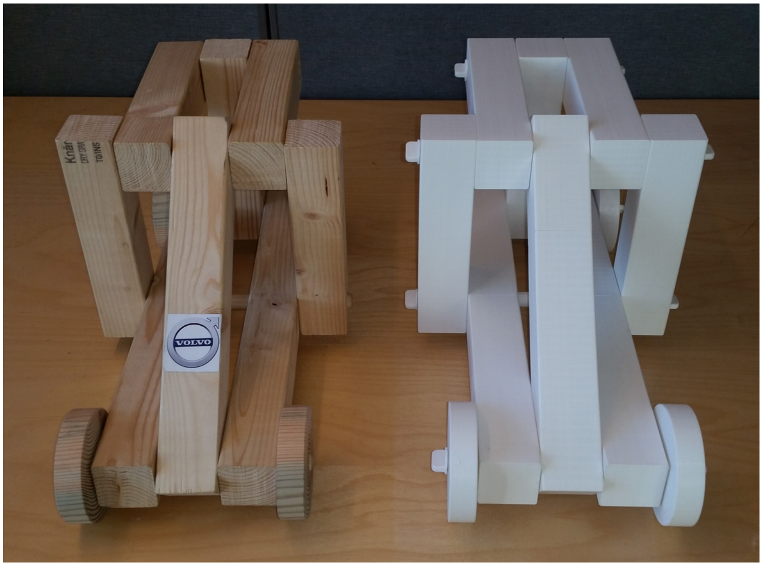

Figure 4.3: The two iterations of car models, to the left the wooden car, and to the right the 3D printed car.

more force to assemble them. Because friction holds the car together, no fasteners were used, which is unrealistic in a real-world assembly task. For these reasons the 3D printed car was developed. This car had approximately the same model and measurements as the wooden car, but used locking rings and thumbscrews to hold the car together. Because of these changes, different fixtures and custom tool parts were created to work with the car model.

There is also another major difference between the tasks created in the two iterations. In the first iteration the whole car was assembled, while in the second iteration only a portion of the car was assembled. The second iteration focused on a more realistic work station, where parts of a product are assembled, not the whole product. The sequence of steps to assemble the car consisted of three types of operations:

- HRC operations: The human and robot work actively together using physical interaction to assemble parts (see figure 4.4 image a).
- Manual operations with robot as fixture: The human works while the robot holds the partially assembled car, acting as a fixture (see figure 4.4 image b).
- Manual operations: The human works without the support of the robot. In some of these operations the robot prepares for the next step, working in parallel with the human.

The speech recognition system filtered out commands that did not have at least 85% confidence. This was to make sure that the system did not misinterpret the words spoken. The speech recognition in the first iteration used “Start” to begin the demonstration, and “Next” to continue to the next step. For the second iteration the speech recognition used words and sentences connected to the task at hand, for example, “Rotate car”, “Open”, and “Next step”.

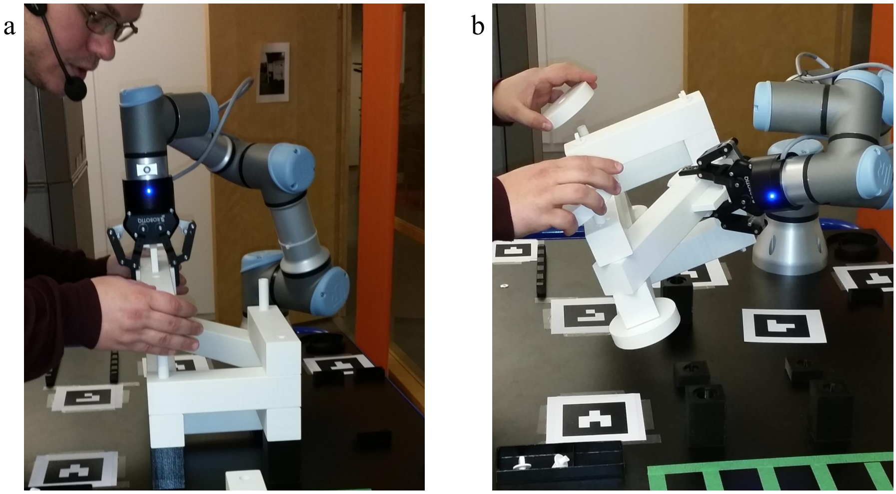

Figure 4.4: Operations used in the workstation: a) HRC operation, where the human guides the robot using haptic control, b) manual operation with robot as fixture, where the the robot holds the car while the human assembles parts onto the car.

4.3 PILOT STUDY

The workstation was used in a pilot study with the purpose of measuring the performance and usability of the system. For this pilot study, students aged 16 – 19 yearsfrom technical high schools between 16 and 19 were invited. These students, who had chosen a technical subject, are likely to work in the manufacturing industry and were therefore suitable for the pilot study. The pilot study set out to investigate the usability and performance of the implemented HRC workstation.

The system usability scale (SUS) developed by Moultrie (2015) is a usability questionnaire which is simple yet efficient (Bangor, P. Kortum, and J. Miller, 2009) and was used to measure the usability of the HRC workstation. It is divided into ten questions. Each question uses a five-point Likert scale, from ”strongly agree” to ”strongly disagree”. The result of the SUS is a score between 0 and 100 that correlates to the usability of a system. A score above 73 is a good system, while a score above 85 is an excellent system (Bangor, P. Kortum, and J. Miller, 2009). Every odd-numbered question has a positive point of view while every even-numbered question has a negative point of view. All questions were translated into Swedish and focused on speech recognition and haptic control.

To measure the performance of the system, the following metrics were selected to identify problems with the HRC workstation:

- *Errors*: Number of errors made when following the instructions, including missing parts, loose fasteners, and steps not fully executed.
- *Drops*: Number of parts that were dropped onto the cart or the floor during the experiment, as an indication of how well the parts are designed.

- *Questions*: Number of questions that the participant needed to ask the instructor, as an indication of how intuitive the interface is.
- *Misinterprets*: Number of missed interpretations of the speech recognition engine including commands that fell below the 85% threshold and commands that were interpreted as a different phrase.

The pilot study used the HRC workstation with the 3D printed car model. Four programs were prepared to test two variants of the speech recognition and two variants of the user interface. The speech recognition variants tested one-word commands and multi-word commands, to study which are more suitable. The graphical user interface variants tested non-blinking and blinking highlights for the AR instructions, to study how these affect user performance. Unfortunately, a mistake was made in the study and only one group tested the multi-word commands.

Four groups of between 26 and 31 students participated. For each group three students (called the participants) were selected to test the HRC workstation, while the remaining students watched. Two of the participants were asked to leave to ensure they did not learn by watching. Then one by one, the participants were informed about how to work with the HRC workstation. Then they worked their way through the steps assembling the car model and filled in the SUS.

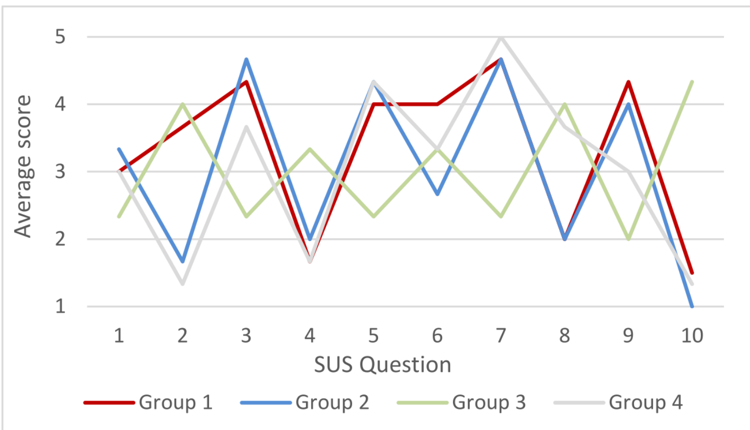

Figure 4.5: Results from the SUS in the pilot study, average score per question for each group.

Group	Program	Errors	Dropped parts	Questions	Misinterpreted commands
1	one word, blinking	5.7	0.3	1.7	6.3
2	one word, non-blinking	11.7	0.7	2.0	3.7
3	one word, non-blinking	11.3	0.0	1.0	15.7
4	multiple words, blinking	9.3	0.3	1.7	2.7

Table 4.1: Observations made in the pilot study.

The results from the pilot study are listed in Table 4.1 and figure 4.5. The results show that the HRC workstation was not yet intuitive enough to work with. In total there were

Figure 4.6: The upgraded HRC workstation equipped with aluminum profiles, 3D printed fixtures, and the UR5 robot. The image was taken at a public event to showcase research in production and manufacturing technologies.

eleven steps to assemble the car model. Each participant in groups 2 and 3 averaged one error per step. This clearly indicates that the system needed improvement. The speech recognition had more difficulties interpreting the participants in group 3. However, it is important to mention that group 3 also had the most background noise, such as chatter and laughter. Program 1 and 2 tested one word commands, but the number of misinterpreted words were mostly connected to the background noise. The implemented speech recognition is clearly not ready for industrial use because the word error rate is too high.

The score from the SUS between the groups varied from 30.8 to 72.5. The sample size of each group was three, and therefore the results cannot be statistically proven, but can be used as an indication of usability. There is a clear difference between the score of group 3 and that of the rest of the groups. From observation there were many external disturbances for group 3, where the students at the back talked and laughed. This is believed to be the reason for the large differences in the SUS scores. In groups 1, 2, and 4 the SUS scores vary between 65.8 and 72.5.

4.4 FURTHER IMPROVEMENTS

After the pilot study the HRC workstation was further improved based on the pilot study and the requirements of this thesis to test HRC applications in a safe and efficient way. The top of the cart was equipped with slotted aluminum profiles to make it easier to replace fixtures, making it more usable (figure 4.6). All fixtures were upgraded to 3D printed parts and the UR5 robot was installed instead of the UR3 model.

Up to that point the HRC workstation had been implemented using custom C# code for the control logic. However, to show that this application with speech recognition, haptic control, and augmented reality can be used in industrial systems, the workstation needed to be implemented using a system that can be used in industry. Björkenstam et al. (2013) showed it is possible to use ROS for industrial applications. It has the potential to do the path planning automatically, and at the same time reduce energy consumption. Dahl et al. (2019) also presents a sequence planner for industrial use cases where ROS is used as the backbone of the system. Furthermore, as shown in *ROS-Industrial* (2020), a multitude of industrial robots are supported in ROS, including the UR5 robot used in the latest iteration of the HRC workstation.

The custom C# control logic was replaced by ROS, with a ROS node that communicated with all devices using code written in Python. Pocketsphinx was used as the speech recognition engine to listen to the user (*pocketsphinx - ROS Wiki* 2020). The library MoveIt was used as the trajectory path planner to move the robot (*MoveIt Motion Planning Framework* 2020). The Robotiq 2-finger gripper was controlled via USB with the robotiq_2f_gripper_control drivers (*robotiq - ROS Wiki* 2020).

4.5 IDENTIFIED CHALLENGES

Several challenges were identified during construction, execution of the pilot study, and improvements to the HRC workstation:

1. The communication technologies were selected based on experience and common sense but lacked a proper selection criterion.
2. It was time consuming to build the physical workstation, and the workstation was limited to one setup. Even if the workstation could be constructed with more flexibility, reconfiguring between different applications would require a lot of resources.
3. Due to safety issues, it is difficult to build a safe workstation for trying new concepts. This is especially the case as the workstation needs to be safe enough to be used by participants who may not have previous experience with robots. This meant using the maximum safety setting on the collaborative robot, which also resulted in low speed.
4. The maturity of the technology used for interaction at the time was quite low, which resulted in misinterpreted communication. The haptic control used joint-based control, which was difficult to deal with as it is more natural to move in Cartesian space. In some cases the speech recognition engine had difficulty understanding the participant.

SUITABLE TASKS AND INTERACTION IN HUMAN-ROBOT COLLABORATION

CHAPTER 5
SUITABLE TASKS AND INTERACTION IN HUMAN-ROBOT COLLABORATION

This thesis aims to facilitate interactions between humans and robots, and thereby support successful implementations of HRC. Two of the problems identified in this thesis are a lack of tested communication technologies for HRC and a lack of HRC applications. This chapter focuses on explaining the research done to address these problems. Section 5.1 describes finding suitable tasks for HRC using an interview study. In section 5.2 selection metrics are described to facilitate the process of selecting suitable communication technologies for HRC interaction.

5.1 SUITABLE TASKS FOR HUMAN-ROBOT COLLABORATION

Human-robot collaboration combines the strengths of both humans and robots in a hybrid production cell (Sadrfaridpour and Y. Wang, 2017). If using humans and robots is to improve the cell so that it involves more than just a human and robot working in sequence, they need to work on tasks suitable for HRC. Collaborative robots are often put into the same assembly cell where a human operator is already working, but with limited interaction between the two (Fast-Berglund et al., 2016) to ensure the safety of the human. However, there are several application areas where HRC seems to offer an advantage (Villani et al., 2018), assembly manufacturing being one of those areas.

To further investigate which tasks are suitable for HRC, the literature study was supplemented with an interview study with subject matter experts. This study is explained in more detail in the following sections.

5.1.1 PARTICIPANTS OF THE INTERVIEW STUDY

This study wanted to extract knowledge from persons who are either working with tasks that can be collaborative, or who are planning and/or constructing cells with similar tasks. This thesis has focused on HRC in assembly manufacturing, therefore this study focused on assembly tasks. The following professions were considered for this study:

Automation engineer: Persons in this profession can provide knowledge of the automation process, what can and cannot be constructed, and the capabilities of robots including collaborative robots.

Production engineer: Persons in this profession have an overall knowledge of, and responsibility for the production line. They can therefore provide insight into the production and technical aspects of assembly and what can be improved with the help of an assistant, such as a collaborative robot. Production engineers know the process as well as its history and development over time in the factory, which gives them a different perspective to automation engineers.

Operators working with assembly: Persons in this profession are relevant because their daily work consists of assembly, and they are therefore experts on the process as well as its shortcomings and possibilities. They have experience of the process beyond that of automation and production engineers and should be able to provide good insight into the current process and opportunities for improvement. Since they work with assembly daily, they can also provide information on what parts of the assembly process feel inefficient, stressful or present ergonomic issues.

Two companies participated in this study, one an automation company and the other company working with assembly manufacturing. In total there were ten participants: four automation engineers, three production engineers, and three operators. These participants are referred to as A1-A4 for the automation engineers, P1-P3 for the production engineers, and O1-O3 for the operators.

5.1.2 STRUCTURE OF INTERVIEW STUDY

The study used a semi-structured interview, with core questions focused on identifying tasks suitable for HRC. A semi-structured interview approach was selected because it gives the participants more freedom to discuss the topic as they want, but still restricts them to the main theme if they stray too far (Oates, 2005). The questions were open-ended to avoid guiding the thought processes of the participants. They were also adapted to the occupational role of the participant.

Trost (2010) states that the language used during an interview is very important, and that a good interviewer should be able to adapt their language to the interview subject without mimicking or imitating people in any way. The interviewer should thus be able to adapt in such a way that the question and the message become clear without making the situation unnatural. This is why the questions were varied depending on the occupational role.

All interviews started with an introduction presenting the interviewers, explaining the purpose of the interview, obtaining permission to record, and assuring confidentiality. Three interview forms were created for this study, one for each occupational role. They consisted of the following four phases (phase 2 was not used for automation engineers):

1. *Introduction*: In the introduction phase, the interview subject were asked questions that had simple answers. This was to ease them into the questions, which according to Kylén (2004) and Oates (2005) helps making them more comfortable answering questions. The questions used for this phase were, ”What is your occupation?”, ”How long have you worked in your current occupation?”, ”How long have you worked in this company?” and ”What was your previous occupation?”

2. *Current status*: In this phase, questions were asked about existing problems on the assembly manufacturing line. (As the automation engineers were not connected to a specific line or station, this phase was excluded for them.) The questions in this phase were used to determine the interview subject’s perception of the current situation. Here answers were expected to relate to specific tasks that were perceived as time consuming, requiring high precision, working with small or heavy objects, working with difficult to handle parts, ergonomically stressful parts, or with other complexities. The questions were also asked in sequence to provide an image of the

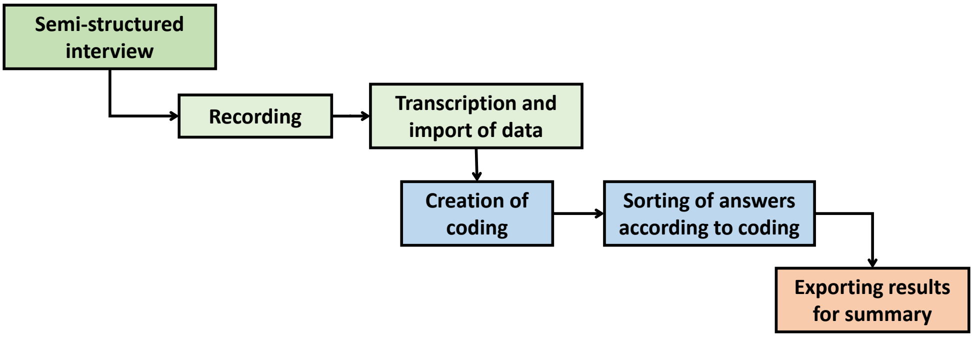

Figure 5.1: The process of collecting and analyzing data to extract knowledge of tasks suitable for HRC.

interview subject's work and to prepare the interview subject to think about tasks that might be relevant to the core question.

3. *Core questions*: This was the main phase of the interview study, where the purpose was to gain knowledge about what tasks are suitable for HRC. This question was carefully worded because not everyone who works with assembly or production in general has experience of the possibilities with collaborative robot and HRC. Therefore, the question used with the production engineers and operators were formulated as what a colleague or an extra person could have assisted with in the task to facilitate or simplify it.

   The automation engineers were directly asked about identifying possible HRC tasks. They were first asked whether they had previously worked with implementing HRC or collaborative robots. If they had, they were asked for more information about that implementation; otherwise they were asked in which tasks in assembly manufacturing they could see possibilities using HRC.

4. *Future analysis*: In this phase, questions were asked about what the interview subject thought the future would look like. For production engineers and operators, questions were asked about their perception of HRC. If they had no idea what HRC could look like, the interviewers gave a brief explanation. For automation engineers, questions were asked about how they would want to work with collaborative robots and HRC, how HRC could be tested virtually, and how robots need to be developed to become a more common solution in industry.

After the interview, the interview subjects were asked whether they had anything else to add.

5.1.3 RESULTS

The procedure shown in figure 5.1 was used to extract relevant data from the interviews. First the interviews were conducted according to the structure in section 5.1.2, and were recorded. Then the recorded data were transcribed, which according to Oates (2005) simplifies the process of searching through and analyzing the data. The transcribed text was imported into Dedoose, an online app used for analyzing qualitative and mixed methods research with text, photos, and audio. Codes were created to categorize each interview subject's answers. The results of this process are described and summarized in this section.

Based on the results, six categories were identified where support for the operator would be suitable. These categories are listed in Table 5.1. The table shows the opinions of the interview subject's listed in each row, where a checkmark is added for each category of tasks that they mentioned can benefit from HRC.

	A1	A2	A3	A4	P1	P2	P3	O1	O2	O3
Difficult to operate	✓				✓		✓		✓	
Logistic inefficient			✓	✓	✓	✓	✓	✓	✓	✓
Non-ergonomic	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Product variation			✓					✓		✓
Time consuming		✓	✓		✓				✓	
Uneven quality	✓	✓	✓			✓				

Table 5.1: Interview subjects' opinions on potential collaborative tasks. The areas are listed on the left and the interview subjects are in the columns. A1–A4 are automation engineers, P1–P3 production engineers, and O1–O3 operators.

Difficult to operate

Automation engineer 1 mentioned that in tasks that are perceived as ”pilliga” (a Swedish word meaning that a task requires skill and manual dexterity), a collaborative solution could have assisted the operator. These are tasks which are difficult to perform using another machine or tool. Operator 2 also mentioned ”pilliga” tasks, such as inserting small screws. Two out of the three production engineers also mentioned tasks where it is difficult to reach, as possible tasks for a collaborative robot.

Logistic inefficient

Most interview subjects mentioned that a collaborative robot could assist in tasks related to logistics around the assembly work. All operators discussed material preparation and preparation for the next product as an example, and said that assistance with surrounding equipment could facilitate the work. Operator 3 mentioned that assistance in loading material and preparing for the next product could reduce downtime and improve productivity. Production engineer 2 mentioned tasks that involve placing details in the station for identification. Production engineer 1 suggested that a collaborative robot should function as a third hand, even in logistics. Automation engineers 3 and 4 talked about a HRC cell that had previously been built where they used a mobile solution to drive materials to the station. This too could have been in the form of an intelligent collaborative robot in the future.

Non-ergonomic

All participants mentioned that collaborative robots might offer ergonomic relief for the human is a good potential use case for, as seen in Table 5.1. One specific task that they discussed was the non-ergonomic inserting of screws. Production engineer 1 told us that the inserting of screws is hard on the wrists and has affected the employees negatively. Automation engineers 2 and 3 also mentioned specific insertion tasks in the assembly line. A recurring feature repetitive heavy lifting. Automation engineer 4, who had also participated in a project which involved a HRC cell, mentioned a task at their station where the collaborative robot and the human being together help to lift a heavy metal piece. Operator 3 also mentioned the possible benefits of a collaborative robot where the operator is otherwise forced to work at an uncomfortable height.

Product variation

During the interviews, all automation and production engineers talked about how future production will require increased flexibility. One of the reasons for this is the increased customer demand for product variation in the market. Automation engineer 3 hoped that the collaborative solution would be able to cope with the preparation process even if the product changes. The robot should be intelligent enough to be updated automatically and be aware of the product type it should adapt to. Automation engineer 3 explained that in future production where more robots and complex systems will be present, it will be difficult for humans to have all the information in their head. Therefore, it would be advantageous if the robot could take more responsibility regarding product changes and preparation for new details. Operator 1 and 3 did not mention any specific tasks but said that smooth assistance in complicated switches between products is something that would have facilitated their work.

Time-consuming tasks

Regarding tasks that are time consuming for the operator, both automation engineer 2 and 3 mentioned parts where a large number of screws must be tightened. Automation engineer 2 thought that such a task could just as easily be done by a robot. Automation engineer 3, who had participated in the project with the HRC cell, said that one of the tasks that the collaborative robot performs at the test station is tightening 24 screws. Both operator 2 and production engineer 1 stated that a collaborative robot could contribute to efficiency in the tasks at the stations as it involves several parts during assembly.

Uneven quality

Regarding quality, automation engineer 2 mentioned a collaborative solution that their company provided which glued dashboards. This was a task previously performed manually, but in order to achieve the uniform product quality required, a collaborative robot was implemented. Production engineer 2 also mentioned an existing solution in the company's production. A YUMI robot checks the quality of the product as one of the station's tasks before the part continues. Neither automation engineer 1 nor 3 mentioned any specific task. However, automation engineer 1 mentioned that in general automation is used to achieve better product quality. Automation engineer 3 also mentioned improvement in product quality.

5.2 SELECTING COMMUNICATION TECHNOLOGIES FOR HUMAN-ROBOT INTERACTION

One of the problems identified by working with the HRC workstation was the lack of proper selection criteria for communication technologies.

A considerable number of papers present HRC applications combining different communication technologies (Green et al., 2008; Bannat et al., 2009; Lambrecht and Jörg Krüger, 2012). Several papers also summarize various communication technologies used in HRI. However, these papers either focus on technologies that have been tested together (Chandrasekaran and Conrad, 2015; Green et al., 2008) or on how metrics can be used when evaluating a combination of technologies (Steinfeld et al., 2006; Murphy and Schreckenghost, 2013). These papers use metrics based on:

- *Reliability*, that is, how well the technology functions in normal conditions.
- *Robustness*, that is, how the technology functions in adverse conditions.
- *Cognitive load*, that is, the amount of mental effort when using the technology.
- *Delay*, that is, processing time before the action is interpreted by the system.

These characteristics consider the performance of specific technologies, however, they do not consider how technologies match different tasks in HRC applications. Therefore, additional metrics were created to facilitate the process of selecting communication technologies for HRC. Proper selection metrics will enable end-users to efficiently identify suitable technologies for a specific scenario.

A new set of metrics has been suggested for selecting communication technologies in different HRC applications. This metric set is based on how a technology conforms to specific HRC tasks. These metrics are displayed in Table 5.2. The following categorization was used:

- *Extent of use*, that is, how many HRC tasks the technology can be used for.
- *Flexibility*, that is, how the technology can be extended with more features.
- *Duration*, that is, how long an action takes from start to end.
- *Additional classification*, that is, classification of the technology based on how it affects HRC applications.

These metrics have not yet been fully evaluated to determine whether they can be used to select appropriate communication technologies. In its current state, it does not go into detail on exact performance measures which would improve the metrics.

Extent of use

Extent of use is defined by how many typical HRC tasks the technology can be used for. The more capabilities the technology has, the more HRC applications it can be used for. Depending on the task, one or several communication messages are needed for the human and robot to understand each other. These messages are categorized based on the information they contain. The message types were derived from the use of communication technologies in HRI, with a view to covering all possible HRC tasks. The message types are categorized as follows:

1. *Command messages*: Communicate what the robot or human should do, for example, next, reject, and stop commands.
2. *Data messages*: Communicate data to the human or robot, such as quantity, dimension, and text.
3. *Highlighting messages*: Communicates where in the environment the robot or human should execute its work.

	Wearable	Limited coverage	Hand use	Command messages	Data messages	Highlighting messages	Demonstration messages	Guidance messages	Option messages
Human-to-robot									
Gesture recognition									
Vision-based		✓	✓	◑	–	●	●	○	
Glove-based	✓		✓	◑	–	●	●	○	
Automatic speech recognition									
Head-mounted	✓			●	●			–	
Distant		✓		●	●			–	
Haptic control									
Joint-based			✓	–				●	
End effector based			✓	–				◑	
Virtual impedance control [1]			✓	–				◑	
Gaze recognition									
Head-mounted	✓			–		◑			
Stationary		✓		–		◑			
Buttons/joystick									
Stationary			✓	◑	◑			◐	
Soft buttons		✓	✓	◑	○	◑		○	
Robot-to-human									
Augmented reality									
Spatial monitor		✓		●	●	●	◑		◑
Spatial projection		✓		●	●	●	○		◑
Hand-held			✓	●	●	●	●		●
Head-mounted	✓			●	●	●	●		●
Text-to-speech									
Head-mounted	✓			●	●	○			◐
Distant				●	●	○			◐
Pick-by-light									
Lamp based				◑		◑			◑

[1] Has not been tested

	Not applicable	✓	Applicable
●	Good flexibility and good duration	○	Poor flexibility and poor duration
◐	Good flexibility and poor duration	◑	Poor flexibility and good duration
–	Special use cases		

Table 5.2: The metrics created to facilitate the process of selecting communication technologies for HRC. The symbols used in the table are described at the bottom.

4. *Demonstration messages*: Communicate a continuous work flow of how to execute a specific task, for example, showing the human or robot how an object needs to be assembled.

5. *Guidance messages*: Communicate how the robot should move to execute its task by physically moving the robot, for example, to teach a motion, to move to a safe location, to calibrate the robot, or use robot as a flexible fixture.

6. *Option messages*: Communicates to the human what alternative options are available depending on the scenario, for example, alternative motion constraints, or alternative processes.

Most of the tasks in HRC applications can probably be communicated With these message types. Therefore, it should be enough to measure the performance based on the type of task instead of specific applications.

Message types 1–4 are suitable for conveying messages to both robots and humans, but the type of communication technology may differ. Command messages using audio may, for instance, use speech recognition for robots and TTS for humans. Guiding messages are, however, only suitable for robots, because humans have enough sensory-motor skills and intelligence to know how to move based on highlighting and/or demonstration messages. Therefore, guiding messages for humans are excluded from the table of robot-to-human communication technologies. Similarly, option messages are only suitable for humans because the robot already has full knowledge of what can be done in a specific scenario, but the human can be presented with different options to know what they can do. Therefore, option messages are excluded from the table of human-to-robot communication technologies.

Flexibility

By flexibility is meant whether the communication technology can be used for multiple features of the specific task. Flexibility is classified in four ways:

1. *Not-applicable*: For technologies that cannot be used in that specific task.

2. *Special use cases*: For technologies that can only be used in a few instances, for example, joint force control can be used to push the robot and thus imply that the robot should continue.

3. *Poor flexibility*: For technologies that can be used for general purposes, but cannot easily be extended to support most features. For example, gesture recognition can be used for a smaller set of commands because humans have limited ability to produce gestures.

4. *Good flexibility*: For technologies that can easily be extended for most features. For example, head-mounted AR can be used for most highlighting messages because it can produce any visual artifact for humans.

Duration

Duration requires empirical studies to be quantified for a specific task. However, this information can still be estimated based on the literature using the following classification scheme:

1. *Not-applicable*: For technologies that cannot be used in that specific task.

2. *Poor duration*: For technologies that can execute the specific task but require considerably more time than low-duration technologies. For example, buttons and joysticks for guidance messages require considerably more time than using haptic control.

3. *Good duration*: For technologies that can execute the specific task in approximately the same time as low-duration technologies. For example, gesture recognition, gaze recognition, and soft buttons all have equal duration for highlighting messages because the recognition processing for all these technologies has similar performance.

Additional classification

In some cases the metrics will produce the same results, even if the hardware changes. To further improve the selection process, three additional classifications are defined in this research, based on how technologies affect HRC applications:

- *Wearable*: Whether the technology requires the user to wear the hardware, which affects the requirement of protection gear.
- *Limited coverage*: Whether the position of the user or the shape of the workspace/-workpiece affects the readability of the message.
- *Hand use*: Whether the users hand(s) are necessary to use the technology, which removes hand(s) from the work task.

VIRTUAL REALITY PLATFORM FOR DESIGN AND EVALUATION OF HUMAN-ROBOT COLLABORATION

CHAPTER 6
VIRTUAL REALITY PLATFORM FOR DESIGN AND EVALUATION OF HUMAN-ROBOT COLLABORATION

As previously discussed, a safe and efficient way to test HRC scenarios and the interaction between human and robot is needed. VR has been shown to provide good results in testing manual assembly tasks, and has also to some extent been used for HRC applications. Furthermore, VR is inherently safe, because there are no external forces that can injure the user (assuming that the VR equipment does not contain any device that can exert forces on the user). The environment in VR uses digital objects, which are easier and quicker to replace when new scenarios need to be implemented. These advantages mean that VR technology meets the criteria of RQ3 to test communication technologies in a safe and efficient way. To extend that use case, this thesis argues that VR can be used throughout the whole production system life cycle of a HRC cell. This includes research and development, creation of conceptual cells, virtual commissioning and training of operators. Therefore, this work aims at constructing a VR platform which can be used to develop and evaluate human-robot collaborative tasks for assembly manufacturing. The constructed platform is called Virtual Collaborative Robot (ViCoR), and from now on this name will be used to refer to the VR platform.

The following sections begin by explaining how VR can be used in the production system life cycle of a HRC cell. Then ViCoR is described in detail including the requirements, architecture, and evaluation of the platform.

6.1 VIRTUAL REALITY FOR HUMAN-ROBOT COLLABORATION

A production system life cycle consists of a set of phases (Strahilov and Hämmerle, 2017). It can be simplified to three sequential phases: system development, productive use, and recycling/re-use, as in figure 6.1. During the system development phase a production system is designed and later realized in industry. After realization 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.

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

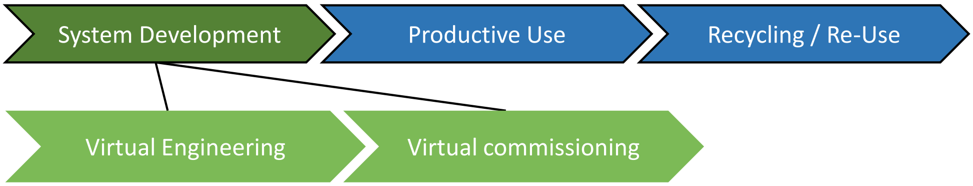

Figure 6.1: Production system development process. Virtual engineering and virtual commissioning are part of the system development phase.

The desired future state of the interaction between the operator and the robot in a HRC cell are input parameters to the virtual engineering phase. This state describes what the company wants to achieve with HRC, and may be used to guide continuous improvement toward their vision. This is a common practice in industry, especially when working with Lean philosophy and the Kata improvement method (Rother, 2010). Working in virtual environments makes it possible to try a system without the constraints that come with physical implementations. One such constraint is the safety of the operator (one of the barriers to HRC uptake according to 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 a HRC cell in the virtual commissioning phase, the cell needs to be adapted to existing control systems and emulated hardware. During the virtual commissioning procedure, there are several benefits to involving a human-in-the-loop to ensure that the system is modeled 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 in industry, it is beneficial to use virtual models for training new operators to reduce the training period for production. Virtual reality allows the user to experience more realistic training that resembles the real world, which could improve the training in comparison to training in front of a computer.

6.2 REQUIREMENTS

The concept of ViCoR was to develop a VR platform that can be used for the development and evaluation of HRC throughout the production system life-cycle, as explained in section 6.1. Thus the following basic requirements were formulated for the VR platform:

- *VR headsets*: It should support one or several VR headsets, so that existing commercial VR technologies can be used. The more VR headsets 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 the conceptual implementation into a real implementation as part of the virtual commissioning process.

Tools	VR headsets	Robot connection	Custom robot control	VR interaction
Unity	Most VR headsets	ROS using ROS#	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

Table 6.1: Features of tools for developing ViCoR.

- *Custom robot control*: It should be possible to create a variety of features without being limited by the constraints of existing robot controllers. This is to facilitate the process of research and development, and the implementation of conceptual ideas.
- *VR interaction*: It should be possible 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.

Several development tools can be used for this purpose. Table 6.1 lists some tools that can be used for building prototypes or robot applications that also have VR support. The table compares the tools based on the four previously mentioned features needed in ViCoR.

Unity was selected as the development tool for ViCoR because it has better compatibility with the required features, as seen in Table 6.1. Unity is a game development tool which supports most VR headsets, for example, Oculus Rift/Quest, HTC Vive, and Google Cardboard. Unity has, however, limited support for robot connections, but Siemens has created an open source library called ROS# (Siemens, 2019) which includes libraries so that Unity can use ROS to communicate with simulated or real robot controllers. The main advantage of Unity in this project is the possibility of creating custom VR interactions in the virtual environment. By using custom VR interactions, it should be possible to find a future desired state for how the interaction between human and robot should work.

6.3 IMPLEMENTATION

Because Unity is a game development platform, it supports most gaming functionalities, including VR support. 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 on the computer. An asset (software plugin) is available for Unity to support SteamVR, a runtime system for VR headsets used in the gaming platform Steam. The same VR application is compatible with multiple VR headsets with SteamVR, including HTC Vive and Oculus Rift, which were the two headsets tested with ViCoR.

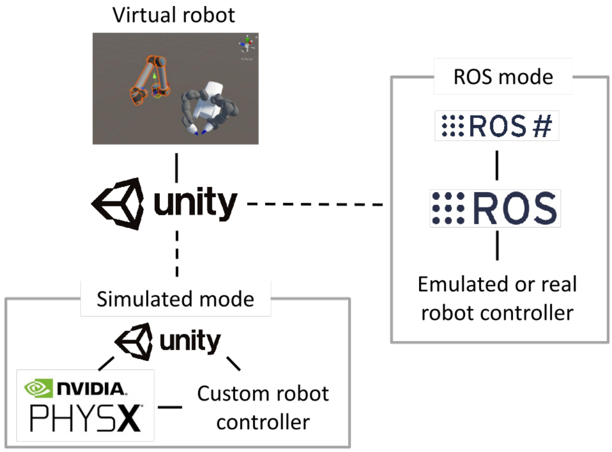

Figure 6.2: Illustration of the components used in ViCoR and how they relate to the simulation and ROS modes. The dashed lines represent the ability to switch between simulated and ROS mode.

The HRC workstation was implemented in ViCoR as an example of collaborating with a robot. In the following sections, the implementation for the VR environment and the specific interaction with the robot is explained in detail.

6.3.1 ROBOT CONTROLLERS

Since the robot is eventually going to be used in industrial systems, the workstation should be able to connect to a robot in the virtual environment with a controller system that could be used in the physical world. Therefore, the workstation was implemented with the ability to switch between robot controllers, see figure 6.2. ViCoR has the ability to switch between the two following modes:

- *Simulation mode*: In this mode a custom robot controller is used and the robot program is written in Unity. This makes it possible to test human-robot interaction beyond the limitations of existing robot controllers.
- *ROS mode*: In this mode the virtual robot is connected to a robot controller through a ROS node supporting both *ros_control* and the action interface *follow_joint_trajectory*. Using this mode the same program can be used for both a virtual robot and a physical robot. This mode was created to ensure that the system could be connected with the physical HRC workstation.

6.3.2 HAND CONTROLLERS

ViCoR was built with the intention of being used for assembly scenarios. During an assembly process, the operator is required to use many hand operations to assemble pieces. The following are some of those hand operations:

- *Grabbing*: Using a hand to grab an object in order to move it.
- *Pinching*: Gripping an object between thumb and index finger, often used with smaller parts.

- *Reorienting*: Moving an object within a hand, using the hand and fingers to obtain 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 controllers of the available VR headsets reduce the possible degrees of freedom (DOF) of the hand and do not allow sensing an object except with the geometry of the controller and built-in vibrotactile sensing. The following hand operations are implemented in ViCoR: 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 operations for twisting and turning are very different in the physical world, but due to the limitation of the controller, the same rotation motion was used for both these hand operations in ViCoR. Sensing is limited to vibrotactile feedback and the geometry of the controller. 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 grabbing a large cube.

The reorientation operation is not supported due to the limitations of the controllers. Therefore, predefined grab poses are needed for each object. If the user correctly grabs an object, the system continues operation. However, vibrotactile feedback is used whenever the pose of the hand differs from the predefined grab pose. This is to simulate the senses that an object lies correctly in the hand. The virtual hands either need to use predefined hand and finger poses or an inverse-kinematics solver to visualize that the user is grabbing an object in the correct way.

6.3.3 SPEECH RECOGNITION

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

If distant speech recognition is a requirement for an eventual product, then more work may be required when using the program in a physical environment. This is because the program may need to cope with a noisy environment, and the location of the speaker may be important to the task.

6.3.4 HAPTIC CONTROL

Haptic control was implemented to allow the user to move the robot by hand. This will be called the hand-guiding mode. The hand-guiding mode allows the user to control the robot in joint or Cartesian space using constraints. For example, constrain joints 1–3,

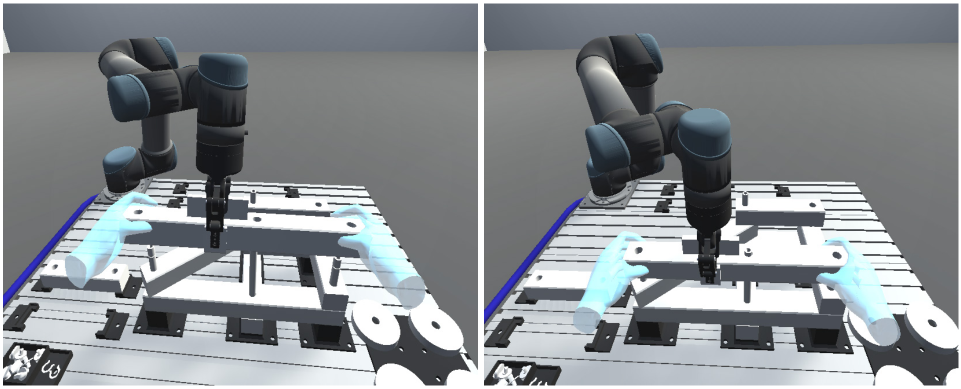

Figure 6.3: The user (light blue hands) can grasp the part directly to assemble it together with the robot.

constrain rotation about x- and y-axis, and constrain all but motion in x- and z-axis. In Cartesian space, the TCP and frame of reference need to be set. The Robotiq force-torque sensor was installed in the HRC workstation but never used due to its oscillating behavior. In ViCoR, it is possible to use the hand-guiding mode in both Cartesian and joint space, because simplifications were made to remove the oscillating behavior.

In addition to grabbing the robot, the user can directly grab the work piece to move it around while the robot is still holding it, as seen in figure 6.3. The implemented hand-guiding mode uses the grab poses described in section 6.3.2. The desired location of the work piece is calculated based on the location of the hands holding the work piece. A maximum velocity in joint and Cartesian space is defined, which limits the robot's velocity when approaching the desired location.

6.3.5 AUGMENTED REALITY

Augmented reality is the technology for displaying digital information onto the real world. In AR, the tracking and placement of digital information is a demanding task because the AR device needs to track all objects that have individual movements and require augmentation. To improve the performance of AR tracking, it is quite common to add markers, for example, a sticker with a QR-code which is recognized by the software and makes tracking easier and more accurate. In VR the tracking needs to consider the movements of the user's body (most commonly the head and hands) in relation to the physical environment. To accomplish this tracking, the system uses specialized sensors embedded into the VR headset. Inside the virtual environment there is no need to track objects, because the positional data of each object is already known. Additional information and animations can therefore easily be attached to the objects, creating the perception of perfect tracking when using VR.

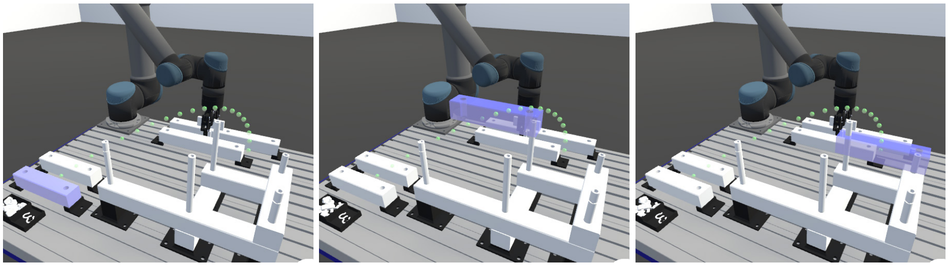

Figure 6.4: The animation intended for AR glasses visualized in the virtual environment. The animation consists of a static trajectory of small green spheres with the motion of the part highlighted in blue.

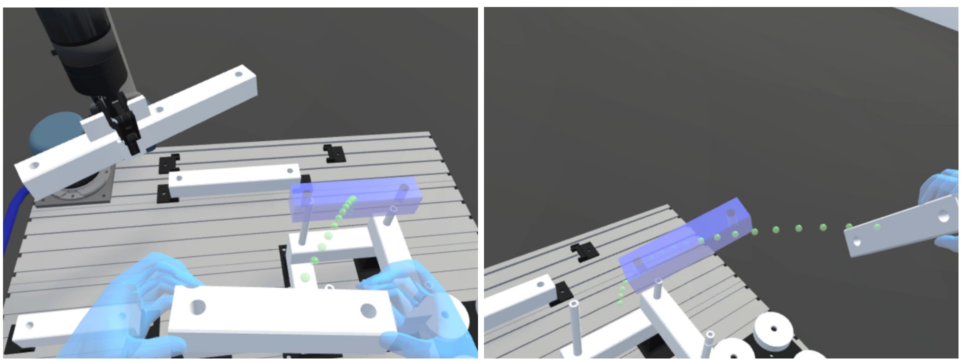

Figure 6.5: Visualization of perfect tracking of the part, allowing the animation intended for AR glasses to follow the part with any position and orientation.

ViCoR uses real-time animations, intended to be used for AR glasses, to show the track of the part to its destination, as seen in figure 6.4. In the figure, opaque objects represent physical objects that the user should work with, while the transparent objects represent AR instructions. The figure illustrates the animation of an assembly operation involving a white box-like object with holes at each end that needs 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, and 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 6.5 further illustrates how the animation is dynamically updated by continuously moving the start of the trajectory to the part's location. The animation, therefore, seems to be attached to the part at all times. 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.

This type of animation allows the user to receive 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.

Figure 6.6: Participants being introduced to the HRC workstation and ViCoR. In the left image the observer explains the HRC workstation to the participant. In the right image the participant is being introduced to the VR headset and interacting with the virtual environment.

6.4 EVALUATION

A controlled experiment was executed in ViCoR to investigate user experience and behavior. To ensure that the participant is aware of physical HRC, the HRC workstation was included in the experiment. The experiment collected data using a questionnaire, observations, and recordings in ViCoR.

In the following sections, the evaluation is explained in more detail, starting with the scenario that was used, and then the experiment structure. Finally the results based on the different data collection techniques are presented.

6.4.1 SCENARIO

There were differences between the physical scenario (in chapter 4) and the virtual scenario, such as using pHRI and AR. The more stable and tested solution was used in this experiment, with the C# program and Iteration 2 of the car model. Two scenarios were created to compare the physical environment with the virtual environment. These two scenarios were set up to use the same task and the same type of interaction with the robot. The left image in figure 6.6 shows a participant being introduced to the HRC workstation, while the participant in the right image is being introduced to the VR headset in a tutorial.

The same assembly task is executed in both scenarios, in which the operator and robot collaborate to partly assemble a car model. The assembly consists of four steps in total, two collaborative and two manual, that the participant follows during the experiment.

- Two of the steps require assembling parts that are considered too heavy for an operator to handle. Instead the robot lifts these parts and places them close to the assembly position. The operator then guides the robot (by grasping the part directly) so that these parts can be assembled correctly. This process represents an operation that cannot be fully automated because the complexity of the task requires the full sensory-motor skills of the human. The car model itself has internal flexibility which does not ensure that the shafts are always in the same position. This makes the task especially difficult to automate and therefore needs an operator.

- Two of the steps are fully manual during which the robot prepares for the next step by moving to the next part and grasping it. In these steps the parts are light, which the operators can handle without ergonomic issues.

Oculus Quest was used as the VR headset for the VR scenario. This headset is a standalone unit with a computer built into the headset. The tracking used is solely based on sensors within the headset and does not require additional tracking base stations. As a result, moving to a new location for demonstrations is quick and easy. Unity software was used as the development tool for the VR platform, and supports Android. Android is used as the operating system in Oculus Quest, so adapting ViCoR to the Oculus Quest did not require much effort.

To enable collaboration, the operator and the robot interact with each other using three types of communication: speech recognition, haptic control, and augmented reality. The following sections describe in more detail how these were used in the scenarios, and the reasons for using them.

6.4.2 EXPERIMENT

The VR platform ViCoR is meant to be used in existing engineering processes for designing and evaluating human-robot interaction in assembly manufacturing. To evaluate this, experiments were undertaken in which the VR platform was studied in a controlled environment to extract measured data on user behavior and user experience. The intended users for ViCoR are R&D staff, engineers, and operators. Three Swedish companies who work with assembly manufacturing were thus asked to participate. In total there were 28 participants, 1 R&D person, 6 engineers, 16 operators, and 5 with other roles. Two scenarios were created for the experiment, a VR and a physical scenario. The purpose of the physical scenario was to enable the participant to develop a frame of reference to compare with the VR scenario.

In the experiment the participants were asked to work with the HRC workstation and its implemented scenario in ViCoR, so they could compare VR with reality. In a trial run with two participants, the experiment started with the VR scenario and then moved to the physical scenario. However, the VR scenario was not intuitive enough, so the participants did not understand that they were supposed to manually assemble the parts based on the animations alone. Therefore, the sequence was changed so that the experiment instead started with the physical scenario. In the experiments one participant was invited at a time. Each was asked to perform the following sequence of steps:

1. First the participant was introduced to the experiment and its purpose. They were also told that they could stop the experiment at any time they chose, if for example they felt dizzy because of VR or were uncomfortable working close to the robot.

2. They were informed that the data collected consisted of a questionnaire, observations made during the experiment, and a recording of the experiment. The participant signed a consent form to allow the data collected from the experiment to be used in this study.

3. The participant went through the physical scenario to understand how to use HRC in assembly manufacturing, and also to get a feel for working with a physical robot.

4. The participant went through the tutorial and VR scenario (figure 6.7), which consisted of four steps. The first step was the tutorial, in which the participant be-

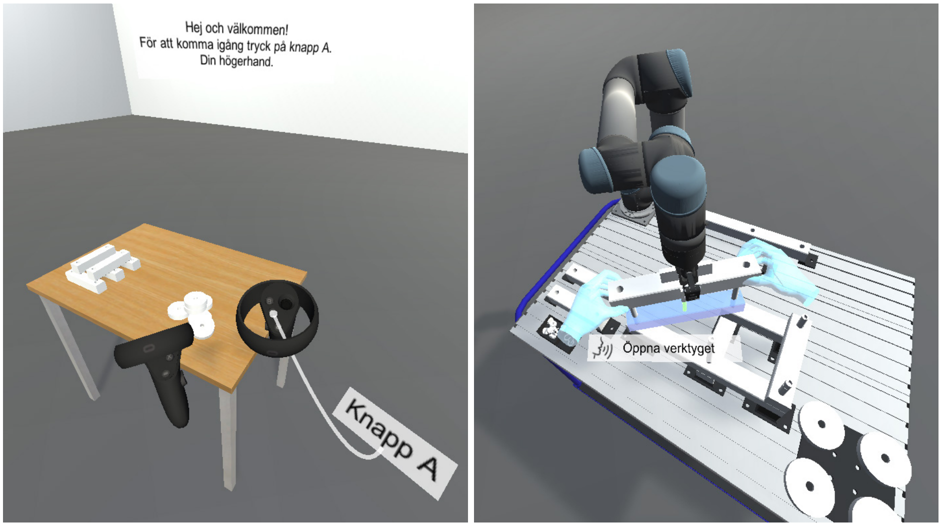

Figure 6.7: The two scenes used in the VR platform during the experiment. The tutorial is shown on the left, where the user becomes acquainted with the controls and how to manipulate objects. The VR scenario is shown on the right where the user assembles a car model.

came acquainted with VR and how to use the hand controllers. If the observer noticed that the participant misunderstood anything during the tutorial, the observer would give directions. In the second step the participant started with the VR scenario to assemble the car virtually, without any guidelines. In the third step, the participant repeated the same scenario, but the observer gave directions if anything was misunderstood in the second step. In the last step, the participant repeated the same scenario but again without any prompting.

5. After the participant had gone through both scenarios, they filled out a questionnaire about their user experience.

6.4.3 RESULTS

The experiment yielded results from several data collection methods. A questionnaire investigated the subjective experience from each participant. Observations were made during the experiment, by examining how the user was using the VR headset, and whether the participant needed assistance or explanation. All participants motions using VR were recorded so that the session could be replayed afterwards.

A questionnaire, divided into three main parts, was used to obtain data from the participants. In the first part, age and working role were requested to identify whether there is any correlation between the answers and the role or age of the person. In the second part, statements were presented with a five point Likert-scale to determine the participant's opinion. In the third part, the participants had the option of writing additional comments as free text to pick up additional information from the participants.

The statements in the second part are listed in Table 6.2, which was divided into three categories. Statements 1–4 asked about their experience using the VR system. Whether they felt immersed in the VR world or not greatly impacts the experience of working

	Questions	Answers
1	It felt like I was really moving in the virtual world	10 18
2	I had no problem keeping my concentration throughout the experiment	6 22
3	It felt like I was moving objects with my hand, even though the objects did not have physical mass (actual weight)	1 2 14 11
4	It felt realistic to be in the virtual world	1 1 15 11
5	It was easy to understand what to do with the instructions presented by animations	9 19
6	It was easy to understand the robot's intentions and where it was going to move	9 19
7	The robot felt safe to work with	1 5 22
8	It was easy to assemble parts together with the robot	1 14 13
9	It felt realistic to assemble parts together with the robot	2 16 10
10	It was easy to assemble parts manually	4 4 20
11	It felt realistic to assemble parts manually	1 4 10 13
12	It was easy to tell the robot what to do	1 5 13 9
13	Talking to the robot to give it instructions was a quick alternative	2 2 13 11
14	It felt like my behavior in the virtual world was the same as my behavior in the real world	2 21 5
15	It felt like I was participating in an entertainment game rather than a human-robot collaboration training environment	1 8 4 7 7 1
16	I think a virtual environment like this is good for training	1 10 17

■ No answer ■ Strongly disagree ■ Disagree ■ Neutral ■ Agree ■ Strongly agree

Table 6.2: List of statements in the questionnaire with the results visualized as a stacked bar diagram. The colors represent the Likert-scale answers, shown in the legend at the bottom of the table.

with the virtual robot. Statements 5–13 asked about their experience assembling and interacting with the robot in VR, while statements 14–16 asked for additional information relevant to the study. The statements and the results from the questionnaire are summarized in Table 6.2. The results for each statement are presented as a stacked bar diagram to the right. As can be seen in the table, most of the participants agree or strongly agree with the statements in the questionnaire, except for question 15.

The participants' ability to handle the hand controllers was observed when they were working in VR. Some had great difficulty using the hand controller and some had no problems at all. Participants were therefore asked about their previous experience with VR. One person had somewhat more experience with VR, some had tested it on occasion, and some had barely heard of it at all. The user who had more experience with VR had no difficulty at all with the hand controller, but was trying to manipulate objects in a different way than the rest of the participants. In VR games picking up objects is often made easier by just aiming at an object; even if the hand is not close to the object, the object will automatically teleport to the hand. This participant expected this to happen, which made their experience different. On the other hand, those who did not have any experience with any hand controllers for games had difficulty navigating the hand controllers. They did not know where the buttons of the controllers were located, and had difficulty remembering where the buttons were after not using them for a while.

During the experiments all motions of the controllers and HMD were recorded together with the state of all buttons, triggers, and joysticks, as well as the output from the speech recognition engine. These were stored in JSON format. For each frame, the entire state was stored in a log file so that the experiment could be repeated. The data were stored this way to reduce the impact on performance when recording. The stored data made

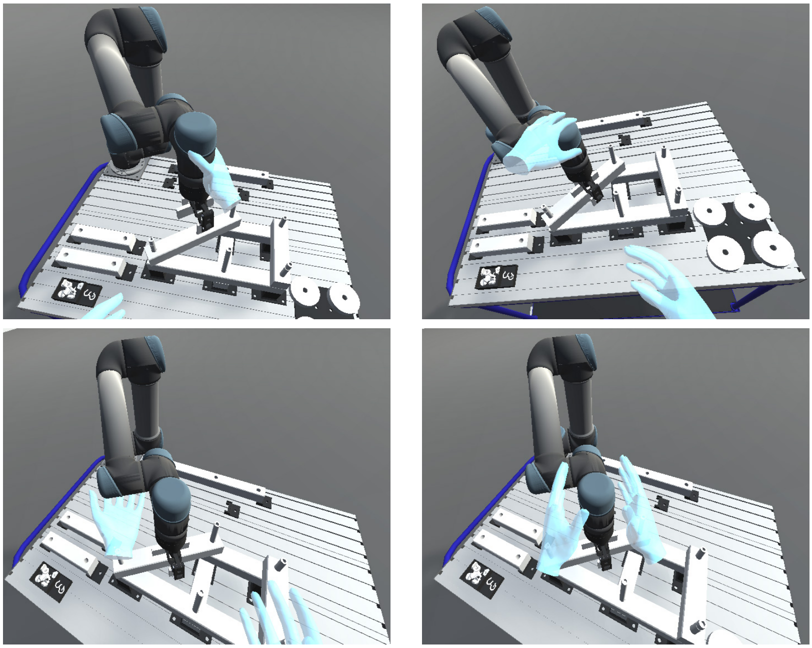

Figure 6.8: The images show how participants approached grasping the robot to move the tool upwards. The top left image shows the predefined pose, and the remaining images show the poses that some participants used before knowing the predefined pose.

it possible to repeat the recorded experiment and be able to inspect the scene from different angles. All participants were recorded. Each run took 10–20 minutes, totaling approximately 1 GB of recorded data.

The results from the questionnaire indicate that the participants had similar opinions about all statements, except for statement 15. Twenty-two or more participants out of 28 agreed with all statements, except statement 15. Statement 15 asks whether the VR scenario felt like a game rather than a training environment.

There was a clear difference between the answers to statement 5 in the trial run and in the experiment. During the trial run, the participants started with VR and did not understand that they were supposed to do some work manually. The participants in the trial run, therefore, answered ”Strongly Disagree” and ”Disagree” based on whether they could understand the animations or not. (This is why the sequence was changed to physical and then virtual.) All participants in the experiment answered either ”Agree” or ”Strongly Agree”. Since the participants in the experiment had already assembled parts in the physical scenario, they partly knew what they were supposed to do, which affects the result. Further investigation is therefore needed to determine whether it is enough that the participants understand that they are supposed to do manual work, or if the animations themselves need to be improved, for example, by showing hands with orientations to guide the operator.

All motions were recorded so that phenomena missed during the experiment could be observed afterward. The following observations were made when reviewing the recorded material:

- The predefined pose for grasping the robot to move it upward had the center of the hand grasping the cylindrical geometry between thumb and fingers, see figure 6.8. In the experiments, before knowing the predefined pose, several participants assumed they should grasp the robot on the top cap, or below the third link, or use two hands to move the tool upwards. The desired interaction for vertical motion heavily depends on ergonomics, resistance, and the height of the robot. The results show several poses that could be investigated.
- When assembling the square prism–shaped parts with cylindrical holes, several of the operators tried to grip them from above, covering the holes. The cylindrical holes are assembled onto shafts, which means that the shafts will protrude through the holes. Therefore, the predefined grip poses were located so that the hands would not cover the holes. When asked, the operators said that gripping from above was the natural choice since they could push down on the object. This resembles realistic behavior, but since this was not the case with the physical scenario, the reason for this behavior is not that simple. A possible reason is that the assumed grasp resembles the physical environment. However, because VR does not have force feedback and therefore no immediate impact on the operator, operators do not see the consequences of this behavior. In the physical scenario the consequence would be a shaft sticking into the hand. In the VR scenario the shaft has no impact and the consequence is disregarded. This leads to behavior based on first instincts which leads, in this instance, to a position that covers the holes. Further experiments are required, however, to fully analyze the reason for this behavior.

Four of the participants did not react in VR when parts were falling, but they did in the physical scenario. After reviewing the recorded material, several participants moved the robot back and forth without regard to collisions between the robot and the parts. This is probably because virtual objects do not experience forces when they collide, and have no real impact when they fall to the ground, or at least it seems that the user did not experience that impact.

CONCLUSIONS AND FUTURE WORK

CHAPTER 7
CONCLUSIONS AND FUTURE WORK

This chapter concludes the work done in this thesis with a summary of the thesis, contributions to knowledge, and discussions of future work to extend the research.

7.1 SUMMARY OF THESIS

Human-robot collaboration is a hot research topic and the combination of the advantages of a human with the advantages of a robot has great potential. However, the implementation of HRC in the manufacturing industry is still limited and only a few industrial applications have been reported. Furthermore, in most of the reported cases there is limited interaction between the human and the robot and minimal contact, mainly to satisfy the requirements set in safety standards. In this thesis, three main factors that limit widespread application of HRC are identified: lack of knowledge regarding suitable HRC tasks, lack of knowledge regarding efficient communication technologies to enable interaction between human and robot when carrying out the tasks, and lack of efficient ways to safely analyze and evaluate collaborative tasks. Regarding the third factor, it could be mentioned that creating new HRC applications always introduces safety issues. Even if collaborative robots have been created to be safe in close proximity to humans, safety issues inevitably arise related to the tools, type of interaction, and products that are used at the workstation.

This thesis has aimed at addressing the identified problems and investigating how the interaction between a human and a robot can be improved to facilitate the process of successfully implementing HRC applications in assembly manufacturing. Based on the aim and the problems identified in the thesis, the following research questions were formulated:

RQ1 What tasks are suitable for humans and robots to carry out together in assembly manufacturing?

RQ2 What technologies can be used to enable communication between humans and robots, and how can these be efficiently integrated to facilitate interaction?

RQ3 How can the interaction between humans and robots be tested in a safe and efficient way?

RQ4 How can a technical platform be designed based on the results from RQ3 in order to enable practical HRC experimentation and speed up the implementation process?

7.2 CONCLUSIONS

To fulfill the aim of the thesis, design science was used as the selected research strategy in which two artifacts were created to conduct experiments and to disseminate the research results. The first artifact is referred to as the HRC workstation, a physical station at which a human can collaborate with a robot. In this workstation, speech recognition, haptic control, and augmented reality were implemented as a combination of communication technologies to experiment with how humans and robots can interact. The second artifact is referred to as ViCoR, a VR platform used to design and evaluate HRC applications for assembly manufacturing. The physical HRC workstation was also modeled in ViCoR. Both artifacts have been used in experiments to collect data for the thesis and gather insights on user experience and behavior.

An interview study was conducted with industrial participants working in assembly manufacturing to identify tasks suitable for HRC in assembly manufacturing. A literature search was also performed. The analysis in the interview study together with the literature found on the subject constitute the main contribution to RQ1. All interview subjects mentioned ergonomic relief was a good potential use for HRC. This was the task selected for the scenario used in the HRC workstation. More specifically, the workstation was designed to let the robot deal with lifting heavy parts while the human uses their sensory-motor skills to position the parts.

A literature review was undertaken to identify communication technologies that can be used to enable interaction between robots and humans. In the literature review, a gap was discovered in that metrics for assessing communication technologies used in typical HRC tasks were missing. Therefore, new metrics were suggested as part of this thesis. A list of communication technologies that can be used in HRC was derived, and their issues and performance for typical HRC tasks were analyzed. The suggested metrics can simplify the process of selecting and combining suitable communication technologies for specific HRC applications. The literature review together with the new metrics constitute the main contributions to RQ2.

The challenges of ensuring the safety of the users and at the same time having a flexible and efficient way to test the interaction between a human and a robot led to the creation of the VR platform ViCoR. ViCoR is intended to be used for designing and evaluating the interaction in HRC, with a special focus on assembly manufacturing. In VR the user is safe from external forces as the robot is not able to physically injure the user. Applications can be changed quickly to test new concepts in ViCoR. With the creation of ViCoR the interaction between humans and robots can be tested in a safe and efficient way, as compared to a physical HRC workstation, which answers RQ3.

ViCoR was evaluated in an experiment with three companies working with assembly manufacturing. In this experiment the participants worked with a scenario of building a car model together with a robot in both the physical and virtual HRC workstations, the latter realized within ViCoR. Knowledge about the user experience and behavior of the participants was extracted from this experiment. Most of the participants felt that the experience and the interaction with the robot were realistic. The evaluation indicates that the platform can be successfully used for HRC experimentation, which answers RQ4.

Since the platform is virtual, rapid changes can be made and are cost efficient when compared to a physical station. This speeds up the implementation process, contributing to the overall aim of the thesis.

7.3 CONTRIBUTION TO KNOWLEDGE

The following main contributions of this research can be summarized as follows:

- Suitable HRC tasks for assembly manufacturing were identified using interviews and a literature review to provide new insights to show what tasks are suitable for humans and robots to carry out together.
- Novel metrics simplify the process of selecting communication technologies for HRC applications and facilitate an optimal interaction between human and robot.
- The VR platform supports safe and efficient design and evaluation of the interaction in HRC for assembly manufacturing and makes it possible to test new types of interactions between humans and robots without any risk of injury.
- A general contribution to knowledge of the interaction between humans and robots in assembly manufacturing, and how this interaction can be facilitated in order to support successful HRC implementations.

7.4 FUTURE WORK

The VR platform ViCoR described in this thesis has not yet been integrated into existing engineering processes. It is predicted that it will be useful in the whole production system life cycle, including research and development, virtual engineering, virtual commissioning, and training of operators. Each of these use cases needs further investigation to ensure VR can improve existing engineering processes. To evaluate the potential of using ViCoR, future research should also investigate how ViCoR can be integrated in existing engineering tools.

There were some differences in the behavior of the participants between working in the HRC workstation and in ViCoR. For example, some participants started a maneuver in the same way as they would have done in the physical environment. However, they did not consider the consequences of the said maneuver, which would have resulted in a different behavior. In this case, the consequences would have been shafts poking into the hand. The question is whether the virtual environment can be designed in a way that ensures that the behavior of the participants is consistent with behavior in the physical environment. Further research should therefore identify tasks where the behavior differs between virtual and physical environment, and investigate the reason. There are also limitations to what can be tested in ViCoR. The most problematic is the inability to accurately test full hand coordination, weight and resistance. It is worth investigating how to overcome these limitations in the future.

The majority of the participants agreed or fully agreed that the implemented scenario in ViCoR was realistic. However, the physical interaction with the robot was limited to hand guiding the robot either by grabbing the work piece or the robot tool. The work pieces were of similar size, shaped like square prisms. It is not clear how realistic the virtual environment feels when using other shapes and sizes. This too should be further investigated.

The new metrics can be used to simplify the process of selecting communication technologies for HRC tasks. However, the actual impact of using the metrics was not investigated in this thesis. This should be further investigated to evaluate the improvement when using the metrics.

INCLUDED PAPERS

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PAPER 1

Patrik Gustavsson, Anna Syberfeldt, et al. (2017). "Human-Robot Collaboration Demonstrator Combining Speech Recognition and Haptic Control". In: *Procedia CIRP* 63, pp. 396–401

PAPER 2

Patrik Gustavsson, Magnus Holm, Anna Syberfeldt, and Lihui Wang (2018). "Human-robot collaboration – towards new metrics for selection of communication technologies". In: *Procedia CIRP* 72, pp. 123–128

PAPER 3

Patrik Gustavsson and Anna Syberfeldt (2020). "The industry's perspective of suitable tasks for human-robot collaboration in assembly manufacturing". In: *International Conference on Industrial Engineering and Manufacturing Technology (Submitted)*

PAPER 4

Patrik Gustavsson, Magnus Holm, and Anna Syberfeldt (2020b). "Virtual Reality Platform for Design and Evaluation of Human-Robot Interaction in Assembly Manufacturing". In: *International Journal of Manufacturing Research (Submitted)*

PAPER 5

Patrik Gustavsson, Magnus Holm, and Anna Syberfeldt (2020a). "Evaluation of Human-Robot Interaction for Assembly Manufacturing in Virtual Reality". In: *Robotics and Computer-Integrated Manufacturing (Submitted)*

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The 50th CIRP Conference on Manufacturing Systems

Human-Robot Collaboration Demonstrator Combining Speech Recognition and Haptic Control

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Abstract

In recent years human-robot collaboration has been an important topic in manufacturing industries. By introducing robots into the same working cell as humans, the advantages of both humans and robots can be utilized. A robot can handle heavy lifting, repetitive and high accuracy tasks while a human can handle tasks that require the flexibility of humans. If a worker is to collaborate with a robot it is important to have an intuitive way of communicating with the robot. Currently, the way of interacting with a robot is through a teaching pendant, where the robot is controlled using buttons or a joystick. However, speech and touch are two communication methods natural to humans, where speech recognition and haptic control technologies can be used to interpret these communication methods. These technologies have been heavily researched in several research areas, including human-robot interaction. However, research of combining these two technologies to achieve a more natural communication in industrial human-robot collaboration is limited. A demonstrator has thus been developed which includes both speech recognition and haptic control technologies to control a collaborative robot from Universal Robots. This demonstrator will function as an experimental platform to further research on how the speech recognition and haptic control can be used in human-robot collaboration. The demonstrator has proven that the two technologies can be integrated with a collaborative industrial robot, where the human and the robot collaborate to assemble a simple car model. The demonstrator has been used in public appearances and a pilot study, which have contributed in further improvements of the demonstrator. Further research will focus on making the communication more intuitive for the human and the demonstrator will be used as the platform for continued research.

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Keywords: Human-robot collaboration; Speech recognition; Haptic control

1. Introduction

The fourth industrial revolution, Industry 4.0, is a top priority for many research institutes, universities and companies [1], because this ultimately shapes the future within the industry. In this revolution human-machine collaboration is one important aspect, and therein Human-Robot Collaboration (HRC). HRC means that a robot and a human work closely together to solve a task related to for example assembling or quality control. By HRC, the unique strengths of a human (such as flexibility and intelligence) can be combined with the unique strengths of a robot (such as strength and the ability to exactly repeat the same a movement an infinite number of times).

Most of the existing industrial robots all over the world require safety fences, because it is not safe to walk close to these robots. However, some of the major industrial robots suppliers, such as ABB and KUKA, have developed new collaborative robots that can be used without a safety fence and thereby make HRC possible. Another supplier is Universal Robots, officially founded in 2005, which focuses on bringing lightweight, flexible industrial robots to the global market. Universal Robots has today three variants of collaborative robots, UR3, UR5, and UR10. HRC is the next step in the development of robots as seen with the prediction of Industry 4.0 and the new collaborative robots.

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The common way of interacting with industrial robots is with a teaching pendant. A teaching pendant is a tool connected to the robot which can be used to move and program the robot. However, the teaching pendants way of moving the robot is with either a joystick or buttons, which is both difficult and time consuming for someone not familiar with the controls. The new collaborative robots offer another way to interact with the robot, namely through guidance by hand. This simplifies the way a human can move a robot but is in most cases not enough to achieve an intuitive interaction. To realize a more intuitive way of interacting with the robot, this work attempts to combine haptic control with speech recognition.

There are plenty of research within speech recognition, including some of the largest companies in the world, Google, Apple, and Microsoft. Haptic control have also been thoroughly researched, and there are several focused on robotics, e.g., [2, 3]. However, research on the combination of the two technologies to achieve a more intuitive industrial HRC is limited.

2. Human-Robot Collaboration demonstrator

The research in focus is the combination of speech recognition and haptic control to create an intuitive HRC. A design and creation approach [4] is suitable for this research, because a physical artifact is necessary to evaluate the technologies. Therefore, a demonstrator was planned, because a demonstrator can be used for multiple purposes [5], within and outside the scientific domain. The demonstrator serves as platform for prototyping, and for disseminating the concepts to potential users.

The main requirements considered when designing the demonstrator were: (1) it needs to be safe for humans to use, (2) it should be mobile to move around, (3) the task to carry out in collaboration between the human and the robot should be simple yet relevant, and (4) it should involve both haptic control and speech recognition. In the following subchapters, the implementation of the demonstrator is described in further detail.

2.1. Setup of the demonstrator

The following setup was used, as shown in Fig. 1, to meet the requirements of the demonstrator:

- UR3 robot (a) and controller (b) from Universal Robots.
- Flexible 85mm 2 finger tool (c) from Robotiq
- Sennheiser ME 3 EW microphone with Steinberg UR12 USB audio interface (d)
- Computer (e) installed with Microsoft Speech API 11 and EasyModbusTCP, connected to the microphone and the robot controller
- A movable wagon, containing components (a-e)
- A TV as the graphical user interface, mounted on a movable stand

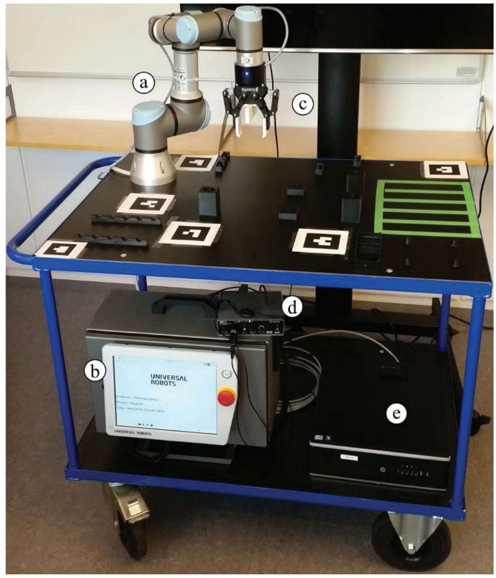

Fig. 1. HRC demonstrator setup, (a) robot, (b) robot controller, (c) robot tool, (d) microphone and USB audio interface, (e) computer. All components placed on a movable wagon.

The UR3 robot was selected because it is certified for working in collaboration with a human, in combination with being one of the cheapest robots for HRC on the market. It is a six axis light weight articulated robot that can lift up to 3 kg. It has joint-by-joint haptic control, called freedrive mode. The freedrive mode uses the impedance/back-drive control which allows a human to move the robot by hand.

The 85mm 2finger tool from Robotiq was selected because it is highly flexible, where the fingers can open 85mm wide and close at 0mm. This tool can also control the speed and force with which it grips an object. In the demonstrator the speed of the tool has been reduced, limiting the possibilities of someone getting stuck.

The computer is the central system controlling what will be displayed on the graphical user-interface, listening to commands by the human and controlling the robot execution. The speech recognition system combines Microsoft Speech API 11, Sennheiser ME 3 EW microphone and Steinberg UR12 USB audio interface. Microsoft Speech API 11 is not cloud based, which is an advantage because depending on the location, Internet access might be unavailable. The Steinberg UR12 USB audio interface connects the microphone to the computer, and this was necessary because the Sennheiser microphone plug is not compatible directly with the computer.

The robot execution is controlled from the computer, through EasyModbusTCP, which acts as a Modbus server. Several signals are defined in the Modbus server, which are: reset, start, next, open, close, and handshake. The handshake signal is used to ensure a good communication between the robot and the computer. The other signals are used for different commands controlling the execution of the robot.

2.2. Task to be carried out in the demonstrator

A simple, yet relevant, task was created where the human and robot collaborate to assemble a toy car. The toy car also has the advantage of having a real world connection of what HRC can be used for. Creating the task was done through two iterations, where the first iteration used a wooden car, Fig 1 to the left, and the second iteration used a 3D printed car, Fig 1 to the right.

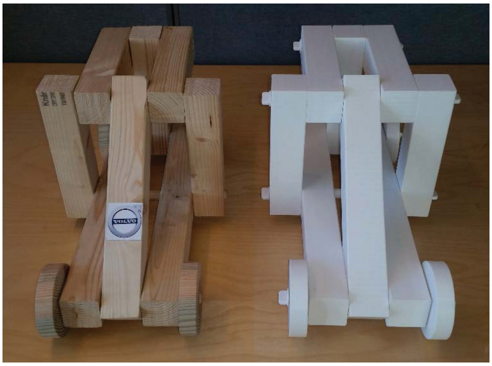

Fig. 2. The two iterations of car models, to the left the wooden car, and to the right the 3D printed car.

The graphical user-interface displayed information of the task and speech commands. The task was described with both plain text and augmented reality by highlighting both the pick and assembly position. The available speech commands were displayed with plain text and when the user spoke the interpreted command were displayed along with the speech-recognition confidence.

The speech recognition system filtered out commands that did not have at least 85% confidence. This was to make sure that the system did not misinterpret the spoken words. The speech recognition in the first iteration used "Start", to begin with the demonstration, and "Next" to continue on each step. On the second iteration the speech recognition used words and sentences connected to the task at hand, e.g., "Rotate car", "Open", and "Next step".

Friction was used to hold together the structure of the wooden car. This resulted in difficulties when assembling the parts, because some parts required the human to apply more force to assemble. Because friction holds the car together no fasteners were used, which is unrealistic in a real-world assembly task. For these reasons the 3D printed car was developed. This car used approximately the same model and measurement as the wooden car, but instead used locking rings and thumbscrews to hold the car together. Because of these changes, different fixtures and custom tool parts were created to work with the car model.

There were also another major difference between the tasks created in the two iterations, in the first iteration the whole car was assembled, while in the second iteration only parts of the car were assembled. The second iteration focused more on a realistic work station, where parts of a product are assembled, not the whole product. Both iterations of the tasks have been separated in several steps, and each step could be categorized into three different levels of HRC, direct, indirect, and no HRC.

- Direct HRC refers to steps when both the human and the robot actively work together on the same part.
- Indirect HRC refers to steps when the human or the robot support each other but only one of them is actively working on the part.
- No HRC refers to steps when the human and the robot can work without support from each other.

Fig. 3 illustrates direct HRC and indirect HRC steps used in the demonstrator. Direct HRC (a) has been used when the human guide the robot using haptic control. Indirect HRC (b) has been used when the robot holds the car while the human assembles parts onto the car. In these cases the robot has been stiff to ensure that the user have no problem assembling the parts.

a

b

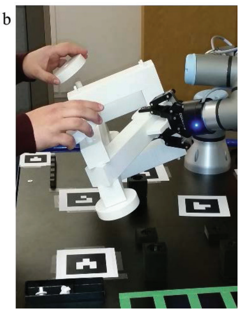

Fig. 3. Steps with (a) direct HRC and (b) indirect HRC.

3. Testing the demonstrator publically

To test the functionality of the demonstrator it has been publically exposed at several occasions. One of the main purposes of the demonstrator is also to disseminate the concepts and the research to potential users and stakeholders, which goes hand-in-hand with exposing it publically. It has been quite popular in these occasions, and it has been especially useful to show the industry what is possible using HRC.

During these public appearances the first iteration of the task was used, with the wooden car model. Anyone at these occasions was allowed to test the demonstrator. At least one instructor was always available to help them get started and to help them when problems occurred. The instructor was also necessary to ensure that there were no safety risks during the demonstration. The first time a person reached a step with direct HRC, when parts were assembled in collaboration with the robot, then the instructor guided the person on how they should execute that step.

The knowledge gained from these occasions helped to develop the second iteration of the task. Some of the problems learned from these public appearances were:

- Limited speech recognition usage, in the first iteration only the word "Next" was used to step through the program.
- Too much force required to assemble some parts, because friction was used to hold the car together.
- Too many steps of the task did not include HRC, because the whole car was assembled.
- The steps with direct HRC were difficult to move in a straight line, because the freedrive mode of UR3 is limited to joint-by-joint control, see Fig. 4.

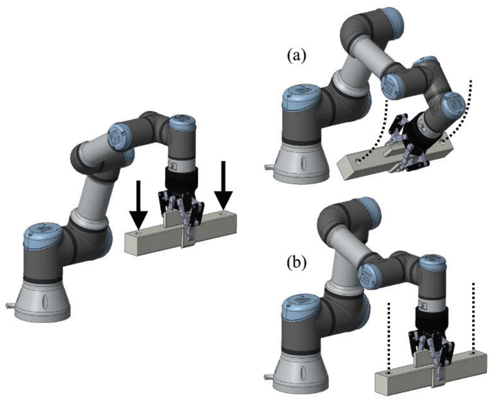

Fig. 4. Illustration of (a) UR3 freedrive mode and (b) linear motion, when applying force onto the part held by the tool.

This demonstrator has also been shown in both local and regional newspaper, to inform the general public about ongoing research at the university.

4. Pilot Study

During the previously mentioned public appearances the instructor guided the users completely in order for them to use the demonstrator. However, the main purpose of the research is to create a more intuitive interaction using speech recognition and haptic control. Therefore, the demonstrator has also been used for a pilot study, where the aim was to study the performance of the system. This pilot study invited students from technical high schools between ages 16-19. These students make good test-subjects, because they are likely to work in the future in the manufacturing industry. The pilot study had three goals:

- Comparing the accuracy of the speech recognition system when using one-word and multiple-word commands.
  - By comparing the accuracy when using one and multiple words, it is possible to determine whether the current speech recognition system is more suited for one or the other.
- Gaining insights on how the demonstrator is working and the test subjects are performing without interference from instructors.
  - With these insights, it is easier to find which problems the system has, which ultimately leads to future improvements of the demonstrator.
- Gather the interests of technical high school students toward human-robot collaboration.
  - The interests of the students, is mainly an indicator whether the students would in the future want to work with HRC. This knowledge is useful for both academia and industries, because academia want to attract new students to study HRC, while industries want to attract new employees.

4.1. Structure of the pilot study

In the pilot study the second iteration of the task was used, with the 3D printed car. The study took place in a classroom, and the demonstrator was placed on the floor in front of the seats so that all participants could see what the test-person was doing.

There were three instructors in total in this study. One instructor was tasked to handle all questionnaires, giving the correct questionnaire to each person. One instructor was tasked to introduce the students to the experiment, select the test-persons, and observe the test-person while filling in an experiment protocol. One instructor was tasked to help the test-persons getting started, intervene when a problem occurred, answer questions from the test-person, and switch programs between the groups.

Four programs were prepared. The programs were created to test two variants of the speech recognition system, and two variants of the graphical user-interface. The speech recognition variants tested one-word commands, and multiple-word commands, to study which one is more suitable. The graphical user-interface variants tested non-blinking and blinking highlights, to study how it affects the user performance.

The following programs were prepared:

1. One-word commands and blinking highlight
2. One-word commands and non-blinking highlight
3. Multiple-word commands and blinking highlight
4. Multiple-word commands and non-blinking highlight

4.2. Execution of the pilot study

Four groups, ranging between 26-31 technical high school students, participated in the experiment separately. For each group, three students were selected as test-persons by asking for volunteers. Two of the selected test-persons were asked to leave the classroom, to ensure they did not learn by watching the other test-persons. The remaining test-person was asked to stand in front of the demonstrator. The instructor gave information on how to put on the microphone and about the graphical user interface, containing all instructions. After the first test-person finished, that person received a user questionnaire, and then the audience received a public interest questionnaire. Then the second test-person was brought in to start the demonstration, the same information was given to this person. After the second test-person finished, that person received a user questionnaire. This was repeated with the third test-person. When all questionnaires were completed they were collected and the group left the room. The next prepared program was loaded in the demonstrator and then the next group was brought in.

The experiments became hectic, because some groups required more time, leaving less time to prepare for the next group. Therefore a mistake was made where two groups tested the same program. This resulted in group 1 using program 1, group 2 and 3 using program 2, and group 4 using program 3.

4.3. Experiment protocol

For this experiment certain type of events were of interest, therefore a systematic observation [4] was used to count these events. An experiment protocol was therefore created; the protocol was used to study the graphical user-interface, haptic control, speech recognition, and combination thereof. This protocol logged for each step:

- Number of errors, when following the instructions, including missing parts, untightened fasteners, and not fully executed steps.
- Dropped parts, all parts that were dropped onto the wagon or the floor.
- Number of questions from the test-person.
- Misinterpreted commands, including commands that fell below the 85% threshold and commands that were interpreted to a different phrase.

Table 1 lists the average result from each group. The results from the protocol may have some errors, because at some occasions the instructor, responsible for the protocol, needed to tell the audience to stop laughing or to lower their voices. However, these results can still give indications to what needs improvement.

Table 1. Average and standard deviation results from the experiment protocol rounded to one decimal, each group had three test-persons.

Group	Program	Errors	Dropped parts	Questions	Misinterpreted commands
1	1	5.7	0.3	1.7	6.3
2	2	11.7	0.7	2.0	3.7
3	2	11.3	0.0	1.0	15.7
4	3	9.3	0.3	1.7	2.7

From the results, it is clear that the system is not yet intuitive enough to work with. There were in total 11 steps for this demonstration, each test-person in group 2 and 3 did in average one error per step. This clearly indicates that the system needs improvements. The speech recognition had more difficulties interpreting the test-persons in group 3. However, it is important to mention that group 3 also had the most noise in the background, i.e., chatter and laughter. Program 1 and 2 tested one word commands, but the number of misinterpreted words were mostly connected to the background noise. The implemented speech recognition is clearly not ready for industrial use, because the word error rate is too high.

4.4. User questionnaire

The System-Usability-Scale (SUS) developed by [6], was used to get an indication of the usability of the demonstrator. This questionnaire is a simple yet efficient tool for assessing a system's usability [7]. It is divided into ten questions, each question uses a five level Likert scale; from strongly agree to strongly disagree. Every odd numbered question has a positive point of view while every even numbered question has a negative point of view. Each question was translated to Swedish, and focused on the haptic control and speech recognition. The result of the SUS is a score between 0 and 100 that correlates to the usability of a system. A score above ~73 is a good system, while a score above ~85 is an excellent system [7].

The average score per question from each group is illustrated in Fig. 5. The score from the SUS varied from 30.8 to 72.5, between the groups. The sample size of each group was three, and therefore the results cannot be statistically proven, but can be used as an indication of usability.

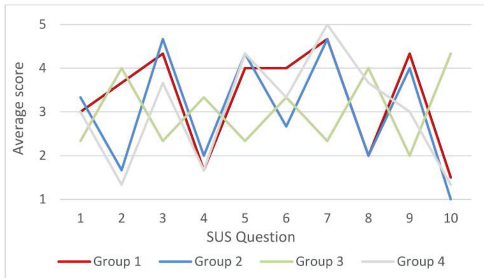

Fig. 5. Results from the SUS, average score per question for each group.

There is a clear difference between the score of group 3 and that of the rest of the groups. From observations, there were a lot of external disturbances for group 3, where the students in the back talked and laughed. This is believed to be the reason for the large differences in the SUS-scores. In the groups 1, 2, and 4 the SUS scores vary between 65.8 and 72.5. This indicates that without external disturbances, the system is close to being good, but needs clarification from a larger sample size.

4.5. Public interest questionnaire

A questionnaire was developed for the audience, to get indications of the public interest. A questionnaire was selected because it provides an efficient way of collecting data from many people [4]. This questionnaire had 11 questions, each question using a five level Likert scale; from strongly agree to strongly disagree. The following questions were used:

1. I am interested in technology
2. I am interested in robotics
3. It would be interesting to work with this robot
4. It would be interesting to develop systems with this robot
5. I thought the system seemed practical to work with

6. The system seems to be safe to work with
7. I use speech recognition in my daily life
8. I think I would like to use speech recognition for work
9. I thought the speech recognition seemed practical
10. I think I would like to use the control by hand for robot programming
11. I thought the control by hand seemed practical

Question 5 had an average result between 4 and 5, question 7 had an average result between 2 and 3, and all other questions had an average result between 3 and 4. These results indicates that the kind of technology used in the study is interesting for students in a technical high school, and that they might be interested in working with this technology in the future. The results also show an indication that speech recognition is not used in the daily life, but that the technology itself might be interesting to work with.

5. Conclusions

This study aimed to investigate the combined use of haptic control and speech recognition for human-robot collaboration. A demonstrator has been developed that combines speech recognition and haptic control and serves as a platform for prototyping and experimentation. The demonstrator has been used both for public dissemination of the research concepts and for undertaking a pilot study of the concepts. During the public appearances anyone was allowed to test the system, which helped improving the demonstrator.

From the pilot study, important knowledge of the system was gathered. It was shown that the system has great potential, but that too many errors and misinterpretation occurred which indicates that the system needs improvements. A SUS was used to measure the usability of the system and the results showed a clear indication that external sources, in this case chatter and laughter, affected the user experience heavily. An important finding from the study is therefore that external disturbance can largely affect the results from user experiment to render unusable and careful measures should be taken to avoid this. To draw further conclusions from the study, more participants need to be involved and doing this is included in the plans of the near future.

Even though the system has some problems, there seems to be an interest of working with this kind of system amongst technical high school students. This is important knowledge for both academia and industries, where the academia wants to attract more students, and the industry wants to attract more workers.

6. Future work

Future experiments require more participants testing the demonstrator because three participants are not enough to make any statistical proofs, although it gave valuable insights. The pilot study had two controlled variables, variation of speech recognition and graphical user-interface. However, the results might be affected depending on the combination, therefore future experiments should focus on one controlled variable. Future experiments should also have a more controlled environment, isolating the user with the HRC demonstrator to avoid disturbances like chatter and laughter.

For the pilot study 16-19 years old high school students were selected because they are potential future workers within an industrial manufacturing setting. However, future studies need to consider using actual workers within a manufacturing industry. Their perspectives could provide insight on applications where HRC could be implemented. They also make good test-subjects for future experiments when evaluating improvements with HRC, because they have experience working in the manufacturing industry.

The speech recognition in its current form is not good enough for industrial use, therefore different speech recognition engines and microphones needs to be tested. Further experiments also needs to apply controlled noise, since within certain industries noise is quite common. The misinterpretation results from the experiment protocol in the pilot study were not perfectly accurate. The reason was because the instructor got distracted, and also it was difficult to keep track of everything that happened. Therefore, in the future, an automatic way of logging the accuracy or word error rate needs to be developed.

All direct HRC steps, that included some form of haptic control, were inconvenient because the freedrive mode of the UR3 robot moves joint by joint. Therefore, future work should look into implementing technologies where haptic control can be used to move the robot with linear motions. One such technology is the ActiveDrive developed by Robotiq, which allows a human to control the robot with, translation movements, tool orientation, etc.

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HUMAN-ROBOT COLLABORATION – TOWARDS NEW METRICS FOR SELECTION OF COMMUNICATION TECHNOLOGIES

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Human-robot collaboration – towards new metrics for selection of communication technologies

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Abstract

Industrial robot manufacturers have in recent years developed collaborative robots and these gains more and more interest within the manufacturing industry. Collaborative robots ensure that humans and robots can work together without the robot being dangerous for the human. However, collaborative robots themselves are not enough to achieve collaboration between a human and a robot; collaboration is only possible if a proper communication between the human and the robot can be achieved. The aim of this paper is to identify and categorize technologies that can be used to enable such communication between a human and an industrial robot.

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Keywords: human-robot collaboration; human-robot interaction

Nomenclature

AR	Augmented Reality
ASR	Automatic Speech Recognition
HRC	Human-Robot Collaboration
HRI	Human-Robot Interaction
TTS	Text-To-Speech

1. Introduction

Interaction with industrial robots have historically been limited to simple control panels with displays. The robots were either controlled by human guidance or operated almost independently from the user. Human-Robot Collaboration (HRC) tries to close the gap between robots and humans by introducing a shared workspace that enables a human and a robot to execute a specific task together [1, 2]. This combination utilizes the strengths of both the human and the robot, where the human has flexibility, adaptability and intelligence, while the robot has physical strength, repeatability and accuracy [3]. There are currently several industrial robot manufacturers that offer collaborative robots, e.g., [4-6], which have greatly advanced the research in HRC the last couple of years. However, to fully utilize the potential of HRC there are several issues that remains to be considered. One such issue is to achieve a proper communication between the robot and the human, which is a necessity to truly realize HRC. Today, robot manufacturers use the term "collaborative" mainly in the sense of force limitation required by the safety standard, which allows humans to work in the same area as the robot. Force limitation does, however, not enable collaboration but there must also be a way of communicating between the robot and the human. The collaborative robots generally support programming-by-guidance, which is without doubt an important feature for HRC, but not enough for enabling full two-way communication.

The research area of HRC belongs to the field of human-robot interaction (HRI), which covers all types of interaction between a human and a robot. HRI can be divided into two general categories: remote and proximate interaction [7]. In remote interactions the human and the robot are spatially separated from each other, while in proximate interaction the human and the robot are co-located sharing the same area. Since industrial HRC is focused on the collaboration between a

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human and a robot in the same working cell, only proximate interaction is of interest for this paper. Specifically, the paper focuses on communication technologies for enabling proximate interaction and how to successfully select the proper technologies for a specific scenario. For aiding the selection, the paper suggests a number of metrics to be used for identifying the best technologies. The paper targets technologies used for communication between a human and a robot, and excludes technologies for safety, social interaction, and trust factors.

A considerable number of papers presents HRI applications combining different communication technologies [8-10] and several papers also summarizes various communication technologies used in HRI. However, these papers either focuses on technologies that have been tested together [1, 7, 8], or how metrics can be used when evaluating a combination of technologies [11, 12]. These papers uses metrics based on characteristics such as:

- **Reliability**, that is, how well the technology functions in nominal condition
- **Robustness**, that is, how the technology functions in adverse conditions
- **Cognitive load**, that is, amount of mental effort when using the technology
- **Delay**, that is, processing time that is necessary before the action is interpreted

These characteristics consider performance of specific technologies, however, they do not consider how technologies matches different tasks in HRC applications. Therefore, this paper aims to improve and extend the current use of metrics by considering also the type of task to be carried out. As far as the authors are aware, there are no previous metrics or classification scheme that aid the selection of communication technologies for specific tasks within HRC applications, which make this paper unique. With proper selection metrics, the idea is to enable end-users to efficiently identify the most optimal technologies for a specific scenario.

The next chapter continues by listing state-of-the-art communication technologies that have been tested in HRI and HRC applications. Chapter 3 then proposes a metric set needed to reliably select communication technologies for HRC applications and categorizes the technologies found in chapter 2. Chapter 4 finally concludes the paper and discusses future work.

2. HRI communication technologies

HRI is not only limited to communication from human to robot, but an essential part of interaction is the feedback loop to the human, to facilitate the human's understanding of the decisions made by the robot [13]. In addition, the human may need information from the system to know what he or she needs to do. Therefore, communication technologies can be separated into human-to-robot and robot-to-human communication.

The papers [9, 14-16] discusses how multimodality improves flexibility and robustness of HRI. The flexibility is improved using complementary communication technologies where different modalities recognizes different type of messages. The robustness is improved by using redundant communication technologies where different modalities improve the recognition of the same message. This work categorizes technologies and does not consider the robustness, therefore, the separate technologies are considered. There could, however, be a situation where the combination of technologies generates a unique message, not possible by the individual technologies. In that case those technologies are considered as one entity. As an example the soft-buttons mentioned in [9], is such an entity.

In the next two subchapters, the human-to-robot and robot-to-human communication technologies are described in further detail.

2.1. Robot-to-human communication technologies

Augmented reality (AR) is a technology that overlay digital information onto the real world and demonstrates promising results in HRI [8, 10, 17]. The technology provides several advantages such as displaying information where it is needed, highlighting different objects, showing how a motion can be executed, etc. To enable the technology some sort of hardware device is used, these devices can be categorized into: spatial, hand-held and head-mounted devices [18]. Different types of optics can be used to visualize information on the devices: video, optical and retinal affects the view of the user, while hologram and projection affects the visualization of the real world. AR technologies using spatial devices can be separated into spatial monitor (affects the view of the user) and spatial projection (affects the visualization of the real world), because these two categorization affects the type of task that they can be used for. AR using hand-held and head-mounted devices only uses optics affecting the view of the user and does not require additional categorization.

Text-To-Speech (TTS) technologies provides an artificial way of providing understandable audible output for the human [19]. This technology is used today in smartphones, cars, laptops, etc. TTS has also been suggested for HRI [8], to allow the robot to express itself using speech. Devices for TTS can be categorized into head-mounted or freestanding. The audio signal can be delivered in a non-spatial and spatial way. Spatial sound allows the user to locate it in a three dimensional space, which has been useful when searching and navigating through AR environments [20]. Both head-mounted and freestanding technologies can be used for spatial and non-spatial sound and do not need additional classification.

Pick-by-light and pick-by-voice are communication technologies common in modern warehouses [21]. Pick-by-light uses small lamps installed on each storage compartment. This aids by lighting up the compartment that the human should pick from. However, this system is not flexible because lamps or displays needs to be installed on every compartment. Therefore, a pick-by-vision system is suggested to overcome these problems, using AR glasses to highlight the different compartments. Pick-by-voice supports the worker using TTS instructions. The reliability of this technology degrades in noisy environment, and it is questionable whether the human would appreciate being told what to do with a monotone voice.

However, one objective with TTS synthesis is to make the speech indistinguishable from that produced by human [19], in which case the monotone voice will not be a problem.

2.2. Human-to-robot communication technologies

Haptic controls such as controls using force-torque sensors, joint-torque sensors, impedance or admittance, have the ability to physically control a robot by guiding it with the hand [3, 22, 23]. In comparison to traditional methods such as joystick or buttons, the efficiency can be increased by a multitude, and require less training to work with. There are two main approaches of controlling a robot, in Cartesian space and in joint space. Controlling a robot in Cartesian space may produce singularities if a redundant robot arm is used. However, controlling a robot in joint space will not produce such errors. Force-torque sensors mounted on end effector can be used to control a robot in Cartesian space but not in joint space, making them less flexible. Torque sensors, or compliance can be incorporated into each joint enabling control both in joint and Cartesian space, making them more flexible. Haptic control is therefore divided into two categories, end effector based and joint based.

A virtual impedance control has been tested in [24] for collision avoidance to ensure the safety of the operator. This was implemented with Kinect sensor using the detected skeleton to change the robot path to avoid collision. Although virtual impedance is used in this case for collision avoidance, other instances of impedance has been used to control the robot accurately such as [23]. This suggests that virtual impedance could be used for guiding the robot, but this has not been tested so far.

Automatic speech recognition (ASR) is the process of converting an audio signal into recognizable sentences for the system. ASR has been used in several instances in HRI to tell the robot what to do [8, 9, 14, 16, 25]. It shows good promise in HRC, because the human can interact in a way that is natural in human-to-human communication. This technology provides a way to communicate without removing hand or focus from current activity. Devices used for ASR can be divided into two categories, head-mounted and distant. Distant devices can use technologies such as omni- and unidirectional microphones, microphone arrays, etc. Microphone arrays can provide additional information such as direction of the speech, to filter out other voices. However, such filtering information is mainly used to improve robustness, which is not the focus of this paper. Therefore, ASR is divided into distant and head-mounted devices.

Gesture recognition provides an interface allowing the human to use gestures to interact with a system [26]. Such interaction includes pointing at an object to highlight it, giving thumbs up to indicate good quality, grasping the hand to demonstrate a gripping command, nodding the head to indicate affirmative decision, etc. Gesture recognition has been used in HRI using, vision based technologies [10, 14, 16, 25, 27], and glove based technologies [28, 29]. Several of the vision-based gesture recognition papers uses the inexpensive Microsoft Kinect as vision system. Vision based technologies may have better flexibility in comparison to glove based systems, but they face difficulties in covering gestures from all directions.

A multimodal HRI system has been tested in [9] that consists of a robot, a projector, and three input modalities. The input modalities are gaze recognition, ASR, and so called soft-buttons. Human gaze is realized with eye-tracking glasses, the ASR uses a head-mounted microphone, and the soft buttons are a combination of tracking the hand using vision sensors, i.e., hand gestures, with a projector that displays buttons onto a workbench. The projector can also be used for displaying other information, such as assembly instructions at the gaze of the human using eye-tracking technology. The authors also mention another application where the gaze can be used to detect which button the human wants to activate.

Gesture and ASR have been combined in [25] to control an artificial robot with nine navigational commands, such as forward, back, stop, northeast, etc. The paper demonstrates that these technologies can be used for proximate interactions, making them possible in a HRC setting. In this case a Kinect camera is used for both gesture recognition and distant ASR. Using this setup the robustness is greatly improved when combining the two modalities.

Screens have been used to display facial expressions (emotions) [30], to improve the feedback loop to the human. The emotional states of the face can help the operator prioritize which task to execute, guiding the attention of the human. This technology improves the interaction between the human and the robot. However, by itself the technology cannot be utilized and is therefore excluded from the paper.

3. HRC task-based metrics

A new, more sophisticated set of metrics is suggested in this paper for selecting communication technologies in different HRC applications. This metric set is based on how a technology conforms to specific HRC tasks based on the following categories:

- **Extent of usage**, that is, how many HRC tasks that the technology can be used for
- **Flexibility**, that is, how the technology can be extended with more features
- **Duration**, that is, from the time an action starts until it ends
- **Additional classification**, that is, classification of the technology based on how it affects HRC applications

In subchapter 3.1-3.4 these categories are described further. In subchapter 3.5, different communication technologies are summarized based on the four categories.

3.1. Extent of usage

Extent of usage is defined by how many basic tasks that a technology can communicate, the more tasks the higher extent of usage that technology has. Depending on the task, one or several communication messages are needed for the human and robot to collaborate. These messages are categorized into several types based on the information they contain. The message types were derived from the usage of communication technologies in HRI, described in chapter 2, with the mindset to cover all possible HRC tasks. The message types are categorized as follows:

1. **Command messages** communicates what the robot or human should do, e.g., next, reject and stop commands. These messages do not require any real-world information or additional data.
2. **Data messages** communicates data to the human or robot, such as quantity, dimension, strings, etc.. The data could contain, quantity of products to produce, article number, instruction, etc. These messages contain data without real-world information.
3. **Highlighting messages** communicates where in the physical world the robot or human should execute its work. For example, to point out an object to work with, or to visualize from where a component should be collected. These messages require real-world positional information.
4. **Demonstration messages** communicates a continuous work flow of how to execute a specific task, e.g., showing the human or robot how an object needs to be assembled. These messages require real-world positional information with recording of motion.
5. **Guidance messages** communicates how the robot should move to execute its task by physically moving the robot, e.g., teach a motion, move to safe location, calibrate robot, flexible fixture. These messages require a continuous flow of robot and real-world positional/force information
6. **Option messages** communicates to the human what alternative options are available depending on the scenario, e.g., alternative motion constraint, alternative processes. These messages require context information from the current state of the system.

With these message types, the authors believe most of the tasks within HRC applications can be communicated. Therefore, it should be enough to measure the performance based on the tasks instead of a specific application.

Message types 1-4 are suitable for both robots and humans, but the type of communication technology may differ. For example: command messages using audio as communication media may use ASR for robots and TTS for humans. Guiding messages are, however, only suitable for robots, because humans have enough sensory-motor skills and intelligence to know how to move based on highlighting and/or demonstration messages. Therefore, guiding messages for humans are excluded from table with robot-to-human communication technologies. Similarly, option messages are only suitable for humans because the robot already has full knowledge of what can be done in a specific scenario, but the human can be presented with different options to know what he or she can do. Therefore, option messages are excluded from table with human-to-robot communication technologies.

Communicating the identity of the operator is a special case that is important in the industry for traceability. However, technologies developed for identification, e.g., voice recognition, face recognition, RFID tags, can generally not be used for the previously mentioned communication tasks. They may use the same hardware as another technology, but the purpose of the technologies differs so they cannot be used in each other's context.

Depending on the application multiple message types may be necessary to complete a task. In [9] it is demonstrated how positioning of information at humans gaze can be used, which is the combination of human-to-robot highlighting message (gaze of human), and robot-to-human data message (projecting info on workbench).

3.2. Flexibility

Flexibility is defined by whether the physical interface can be used for multiple features within a specific task. The flexibility is classified in four levels based on the findings in chapter 2:

- **Not-applicable –** for technologies that cannot be used in that specific task, e.g. ASR cannot be used for demonstration messages because it cannot contain a recording of motion.
- **Special use-cases –** for technologies that can only be used in few instances, e.g., joint force control can be used to push robot and therefore implying that the robot should continue.
- **Poor flexibility –** for technologies that can be used in a general purpose, but cannot easily be extended to support most features, e.g. gesture recognition can be used for a smaller set of commands, because the human has limited ability to produce gestures.
- **Good flexibility –** for technologies that can easily be extended for most features, e.g. head-mounted AR can be used for most highlighting messages, because it can produce any visual artifact for the human.

3.3. Duration

Duration requires empirical studies to be quantified for a specific task. However, this information can still be estimated based on the findings in chapter 2 using the following classification scheme:

- **Not-applicable –** for technologies that cannot be used in that specific task.
- **Poor duration –** for technologies that can execute the specific task but requires considerable more time in respect to low-duration technologies. E.g. buttons and joystick for guidance messages require considerable more time than using haptic control, as mentioned in chapter 2.
- **Good duration –** for technologies that can execute the specific task, in approximately the same time in respect to low-duration technologies. E.g. Gesture recognition, gaze recognition, and soft-buttons all have equal duration for highlighting messages, because the recognition processing for all these technologies have similar performance.

3.4. Additional classification

In some cases the metrics will produce the same results, even if the hardware changes. To further improve the selection process of technologies, three additional classifications are defined, based on how technologies affect HRC applications:

- **Wearable**, that is, whether the technology requires the user to wear the hardware, which affects requirement of protecting gear
- **Limited coverage**, that is, whether the position of the user or the shape of the workspace/workpiece affects the readability of the message
- **Hand usage**, that is, whether the users hand(s) are necessary to use the technology, which removes hand(s) from work task

These categories do not require quantification measures and are simply stated yes (symbol ✓) or no (without symbol).

3.5. Suggested metrics to be used for selecting communication technologies

To guide the end-user in the selection of communication technologies, the various technologies are classified for each message type based on the scheme presented in Table 1.

Table 1. Scheme used for estimating a technology measurement values based on flexibility and duration.

Meaning	Symbol
No or Not applicable	
Good flexibility and good duration	●
Good flexibility and poor duration	◐
Poor flexibility and good duration	◑
Poor flexibility and poor duration	○
Special use cases	-
Yes	✓

Table 2 and 3 presents the communication technologies discussed in chapter 2 with the classification suggested in the paper, that is, the new metrics. Technologies for human-to-robot are presented in Table 2, while Table 3 presents technologies for robot-to-human communication. Using these two tables, the idea is that an end-user can easily select the proper communication technologies for a specific scenario.

Table 2. Categorization of human-to-robot communication technologies.

	Wearable	Limited coverage	Hand usage	Command messages	Data messages	Highlighting messages	Demonstration messages	Guidance messages
Gesture recognition								
Vision based		✓	✓	◑	-	●	●	○
Glove based	✓		✓	◑	-	●	●	○
Automatic speech recognition								
Head-mounted	✓			●	●			-
Distant		✓		●	●			-
Haptic control								
Joint based			✓	-				●
End effector based			✓	-				◑
Virtual impedance control [1]			✓	-				◑
Gaze recognition								
Head-mounted	✓			-		◑		
Stationary		✓		-		◑		
Buttons/Joystick								
Stationary			✓	◑	◑			◐
Soft-buttons		✓	✓	◑	○	◑		○

[1] Has not been tested

Table 3. Categorization of robot-to-human communication technologies.

	Wearable	Limited coverage	Hand usage	Command messages	Data messages	Highlighting messages	Demonstration messages	Option messages
Augmented reality								
Spatial monitor		✓		●	●	●	◑	◑
Spatial projection		✓		●	●	●	○	◑
Hand-held			✓	●	●	●	●	●
Head-mounted	✓			●	●	●	●	●
Text-To-Speech								
Head-mounted	✓			●	●	○		◐
Freestanding				●	●	○		◐
Pick-by-light								
Lamp based				◑		◑		◑

4. Conclusions

This paper presents state-of-the-art communication technologies for HRC. Shortcomings of current metrics for the selection of communication technologies in HRC have been identified. This paper, therefore, suggests new metrics to classify different communication technologies for use in HRC applications. The new metrics focuses on three characteristics; extent of usage, flexibility, and duration. Extent of usage is measured by how many communication message types a technology can be used for. The message types are divided into six categories; command, data, highlighting, demonstrating, guidance, and option messages. The performance of the technologies when used in each message type is then classified based on flexibility and duration. The communication technologies are additionally classified into wearable, limited coverage, and hand usage to further improve the selection process.

Using the two tables defined in the paper, that cover various technologies for human-to-robot and robot-to-human communication and their various strengths and weakness, the work task of selecting the proper communication technologies for a specific HRC scenario is simplified. The long-term ambition is to extend the results further in the future and eventually provide a comprehensive document that future researchers, developers and integrators can utilize for selecting communication technologies in HRC applications.

This paper uses a classification scheme for determining measurement values, but further work should focus on how to quantify the measurements values. Empirical studies should then be used to evaluate the real-world effectiveness of the metrics.

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THE INDUSTRY'S PERSPECTIVE OF SUITABLE TASKS FOR HUMAN-ROBOT COLLABORATION IN ASSEMBLY MANUFACTURING

The industry's perspective of suitable tasks for human-robot collaboration in assembly manufacturing

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ABSTRACT

Human-robot collaboration (HRC) is the concept of combining a human and a robot into the same production cell and utilize the benefits of both. This concept has existed for more than a decade, but there are still quite few implementations of HRC within the manufacturing industry. One reason for this is the lack of knowledge when it comes to suitable tasks for HRC. Current research studies on the topic are mainly based on theoretical reasoning and/or research experiments, and little is known about what the industry perceive as suitable tasks for HRC. Therefore, this paper aims to investigate this and find out what industrial actors thinks are the most value-adding tasks for a human and a robot to carry out together. An in-depth interview study is undertaken with two companies and shop-floor operators, production engineers and automation engineers are interviewed. The result of the study pinpoints a number of tasks that the companies thinks are beneficial for HRC, which can serve as a guideline for other manufacturing companies considering to implement HRC.

Keywords

Interview study; human-robot collaboration; assembly manufacturing; ergonomics

1. INTRODUCTION

Human-robot collaboration combines the strengths of both humans and robots into a hybrid production cell [1]. There are several application areas in which HRC are advantageous, of which assembly manufacturing is one of the major [2]. In current implementations of HRC there are, however, often a limited interaction between the human and the robot in order to ensure the safety of the human [3]. This is a drawback since to fully utilize the potential of HRC, the human and the robot should interact and not only work side-by-side or in sequence with each other. To realize work cells in which the human and the robot are truly working together with each other it must be known what tasks that are suitable for such collaboration. There are a number of research papers that presents studies on the topic, but these are mainly based on theoretical reasoning and/or research experiments that investigate the suitability of various tasks. There is not much knowledge about what manufacturing companies perceive as suitable tasks for HRC, and this paper therefore aims to address this question. The paper is specifically focused on assembly manufacturing as this is a main application area for HRC. An in-depth interview study is undertaken with one manufacturing company and one automation integrator company. In these companies, shop-floor operators, production engineers and automation engineers are asked to give their view on what they perceive as suitable tasks for HRC. The manufacturing company is a large company producing quick connect couplings having production sites in several different countries around the world. The study takes place in one of their sites where these couplings are assembled. The automation integrator company produces automation solutions for manufacturing industries all over Sweden. At the site of focus, automation and robotic solutions are designed and implemented.

In the next chapter, more information about HRC is given for the reader not yet familiar with the topic. The paper then continues by describing the set-up for the interview study in chapter 3 and 4. The results from the interviews are presented and analyzed in chapter 5. Chapter 6, finally, summarized the conclusions from the study.

2. BACKGROUND

Research has been done in the area of HRC for many years and involves multiple disciplines such as interaction, safety, path-planning and task allocation to mention but a few. This chapter gives the basic knowledge of HRC necessary to understand the paper, and also describes examples of research studies in which HRC workstations have been implemented.

In HRC a human and a robot share workspace to complete a task, and the idea is to combine the benefit humans and robots into one workstation. Since traditional industrial robots pose a danger to a human when they share the same workspace, industrial robot manufacturers have started to produce collaborative robots to overcome this safety issue. Collaborative robots are robots that can be used in collaborative operations as defined in the technical specification ISO/TS 15066 [4], created by the International Organization for Standardization. Collaborative robots are generally lightweight industrial robots that include force limitations on all joints to make them suitable for HRC. In the literature, there are plenty of studies on HRC and some of the most interesting of these are presented in the following of this chapter.

Sadrfaridpour and Wang [1] presents a framework for human-robot interaction and showcase this framework in a workstation where a human and a robot collaborates. The task that the human and robot executes is to assemble three parts. The human fetches one part and places it in the workspace, the robot then fetches two other parts and places them onto the first part, and finally the human screws the parts together.

Hietanen et al. [5] presents another study in which augmented reality-based interaction is used for collaborating with a robot. The authors propose an interactive user interface for displaying digital information that is projected onto the real world. A workstation is implemented in which part of an engine is to be assembled, adopted from a real-world case. The task consists of five sub-tasks, of which three are manual, one is handled by the robot and one requires the collaboration of both human and robot. In the collaborative sub-task the robot brings a component and activates hand-guidance,

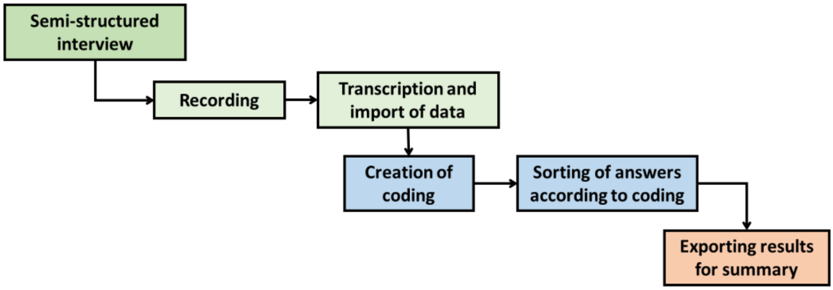

Figure 1. The process of collecting and analyzing data in the interview study to extract knowledge of tasks suitable for HRC.

which allows the human to guide the robot by hand to position the component.

Peternel et al. [6] presents and demonstrates a multi-modal robot teaching framework which is used to train a robot to physically perform cross-cut sawing motions with a companion human. Their work is an interesting example of when a human and a robot physically interacts to execute a task. In the task, the human and the robot are on opposite sides of the saw only exerting force in a dragging motion. While the robot is dragging the saw, the human mainly follows, and while the human is dragging the saw, the robot mainly follows.

De Gea Fernández et al. [7] presents a multimodal whole-body tracking system used for gesture recognition, intention recognition and collision avoidance. These technologies are implemented on a HRC workstation combining two collaborative robot arms where. In the task, adopted from a real-world case, the human signals the robotic system with gestures to either start or pause the process, or activating a collaboration mode. When the robot cell starts, the two robots assembles the parts while ensuring the safety for the operator by tracking the human and actively avoiding collision. If an inspection is needed, the operator activates the collaborative mode in which the robot picks up the last assembled product and positions it in a comfortable position for the operator to inspect it.

The summarized papers are some examples of studies that show the great potential of HRC in different application areas, and that the technological advancement in robotic platforms have made it possible to implement HRC within the manufacturing industry [2], [8]. So far, the identified tasks within HRC are, however, mainly based on theoretical reasoning and/or research experiments, and as previously discussed more investigation is needed to further identify tasks that will be beneficial for HRC.

3. INTERVIEW SUBJECTS

When it comes to relevant interview subjects for the study there are two types of persons that are of interest: (a) persons that are working with assembly tasks that can potentially be made collaborative, and (2) persons that are working with the planning and/or construction of HRC cells. As previously mentioned, the study is focused on assembly tasks specifically. When identifying interview subjects, three categories of professions were identified:

Automation engineer: Persons with this profession can provide knowledge of the automation process, what can and cannot be constructed, and the capabilities of robots including collaborative robots. In the study, automation engineers with knowledge of automation and development of collaborative solutions were sought after.

Production engineer: Persons with this profession have an overall knowledge and responsibility for the production line. They can therefore provide insight into the production and technical aspects of assembly and what can be improved with the help of an assistant, such as a collaborative robot. Production engineers know the process, the history and development over time in the factory, which gives them a different perspective to that of the automation engineer.

Operators working with assembly: Persons with this profession are relevant because their daily work consists of assembly and they are therefore experts on the process as well as its shortcomings and possibilities. They have hands-on experience of the process beyond that of automation and production engineers and should be able to provide good insight into the current process and its opportunities for improvement. Since they work with assembly daily, they can also provide information on what parts of the assembly process that feel inefficient, stressful, or present ergonomic issues.

In total there were ten participants: four automation engineers, three production engineers and three operators. These participants are further on referred to as A1-A4 for the automation engineers, P1-P3 for the production engineers and O1-O3 for the operators.

4. INTERVIEW STRUCTURE

The overall interview study was conducted according to the procedure in Figure 1. The study used a semi-structured interview approach, with core questions focused on identifying tasks suitable for HRC. A semi-structured interview approach was selected because it gives the participant more freedom to discuss the topic as they want, but still restricts them to the main theme if they stray too far [9]. The questions were open-ended to avoid guiding the thought processes of the participants. The questions were also adapted to the occupational role of the participant.

It is well known that the language used during an interview is important, and a the interviewer must be able to adapt the language to the interviewee without mimicking or imitating people in any way [10]. The interviewer should thus be able to adapt in such a way that the question and the message become clear without making the situation unnatural. Having this in mind, the interview questions were adapted depending on the professional role (see chapter 3) of the interview subject.

All interviews started with an introduction presenting the interviewers, the purpose of the interview, obtaining permission to record, and assuring confidentiality. Three interview forms were created for this study, one for each occupational role. All forms consisted of the following four phases, with the exception that phase 2 was not used for automation engineers:

Introduction: In the introduction phase, the interviewees were asked questions with simple answers. This was to warm them up and make them more comfortable in answering the more complex questions that were following [9], [11]. The questions used in this phase were the following: "What is your occupation?", "How long have you worked in your current occupation?", "How long have you worked in this company?" and "What was your previous occupation?".

Current status: In this phase, questions were asked about existing problems within the assembly manufacturing line. As the automation engineers were not connected to a specific line or station, this phase was excluded for them. The questions in this phase were used to get an understanding of the interviewee's view of the current situation. The answers were expected to pinpoint specific tasks that are perceived as time consuming, requiring high precision, working with small or heavy objects, working with parts that are difficult to handle parts, ergonomically stressful tasks, or other similar complexities. The questions in this phase are also asked to provide an image of the interviewee's work and to prepare the interviewee to think about tasks that may be relevant to the core question.

Core questions: This was the main phase of the interview, where the purpose was to gain knowledge about what tasks that are suitable for HRC. The core question needed to be carefully formulated for the production engineers and operators since it could not be expected that these were familiar with the possibilities of collaborative robot and HRC. Therefore, the question used for these two categories were formulated as “What could a colleague or an extra person assist you with to facilitate or simplify your task?”.

The questions for the automation engineers directly asked about identifying possible HRC tasks, as this profession were known to have prior knowledge about HRC. They were first asked whether they had previously practically worked with implementing HRC or collaborative robots. If they had, they were asked for more information about that implementation, otherwise they were asked in which tasks in assembly manufacturing they could see possibilities using HRC.

Future analysis: In this phase, questions were asked on how the interview subjects thought that the future would look like. For production engineers and operators, questions were asked about their perception of HRC. If they had no idea what HRC could look like, the interviewers gave a brief explanation. For automation engineers, questions were asked on how they would want to work with collaborative robots and HRC, how it could be tested virtually, and how the robot needs to be further developed to become a more common solution in industry.

After the interview, the interview subjects were asked if they had anything else to add. All interviews were recorded for the purpose of transcribing and analyzing the interviews, see Figure 1.

5. RESULTS

After the interviews had been conducted all recordings were transcribed, which simplifies the process to search through and analyze the data [9]. The transcribed text was imported into Dedoose, an online app used for analyzing qualitative and mixed methods research with text, photos, and audio. Codes were created to categorize the answers of each interview subject. The information extracted from the interviews was then carefully analyzed.

Based on the results from the analysis, six main categories of tasks were identified where support for the operator would be suitable. These categories are listed in Table 1 in alphabetical order. The categories are derived from the type of problems that were discussed during the interviews. The table shows the opinions of the interview subjects listed in each column, where a checkmark is added for each category of tasks that they mentioned can benefit from HRC.

Table 1. The interview subjects’ opinions on potential tasks that can benefit from HRC divided into six categories.

	Difficult to operate	Logistic inefficient	Non-ergonomic	Product variation	Time consuming	Uneven quality
Automation engineer 1	✓		✓			✓
Automation engineer 2			✓		✓	✓
Automation engineer 3		✓	✓	✓	✓	✓
Automation engineer 4		✓	✓			
Production engineer 1	✓	✓	✓		✓	
Production engineer 2		✓	✓			✓
Production engineer 3	✓	✓	✓			
Operator 1		✓	✓	✓		
Operator 2		✓	✓		✓	
Operator 3		✓	✓	✓		

5.1 Difficult to operate

Automation engineer 1 mentioned that in tasks that requires skill and dexterity with the fingers, a collaborative robot could assist the operator – especially if the task is difficult to perform using another machine or tool. Operator 2 also mentioned the same aspect and gave the entering of small screws as example. Two out of the three production engineers also mentioned tasks where it is difficult to reach as possible tasks when a collaborative robot could be beneficial.

5.2 Logistic inefficient

Most participants mentioned that a collaborative robot could assist in tasks related to logistics around the assembly stations. All operators discussed material preparation and preparation for the next product as an example, and that assistance with surrounding equipment could facilitate such work. Operator 3 mentioned that assistance in loading material and preparing for the next product could reduce downtime and improve productivity. Production engineer 2 mentioned tasks that involve placing details in the station for identification. Production engineer 1 suggested that a collaborative robot could function as a third hand, even in logistics. Automation engineers 3 and 4 talked about a HRC cell that had previously been built and that they used a mobile solution to drive materials to the station. This too could be in the form of an intelligent collaborative robot in the future.

5.3 Non-ergonomic

All participants mentioned that ergonomic relief for the human is a good potential utilization of a collaborative robot, as seen in Table 1. One specific task that they discussed was the non-ergonomic entering of screws. Production engineer 1 mentioned that the entering of screws is tiring for the wrists and has affected the employees negatively from an ergonomic perspective. Automation engineer 2 and 3 also mentioned similar entering tasks in their assembly lines. A recurring example of tasks that were mentioned are those that involve repetitive heavy lifting. Automation engineer 4, who had also participated in a project which involved a HRC cell, said that there is a task at their station where the collaborative robot and the human together lift a heavy metal piece. Operator 3 also mentioned that possible tasks for a collaborative robot include when the operator is forced to work at an uncomfortable height.

5.4 Product variation

During the interviews, all automation and production engineers talked about how future production will require increased flexibility. One of the reasons for this was the increased customer demand for product variation in the market. Automation engineer 3 said that the vision for collaborative solutions should be that they are able to cope with the preparation process even if the products change. The robot should be intelligent enough to be updated automatically and be aware of the product type it should adapt to. Automation engineer 3 explained that in future production where more robots and complex systems will be present, it will be difficult for humans to have all the information in their head. Therefore, it would be advantageous if the robot could take more responsibility regarding product changes and preparation for new details. Operator 1 and 3 did not mention any specific tasks but said that smooth assistance in complicated switches between products is something that would facilitate the work.

5.5 Time consuming tasks

Regarding tasks that are time-consuming for the operator, both automation engineer 2 and 3 mentioned parts where many screws must be tightened. Automation engineer 2 thought that such a task could just as easily be done by a robot. Automation engineer 3, who participated in the project with the HRC cell, said that one of the tasks that the collaborative robot performs at their test station is tightening 24 screws. Both operator 2 and production engineer 1 stated that a collaborative robot could contribute to efficiency in the tasks at the stations as it involves several parts during assembly.

5.6 Uneven quality

Regarding quality, automation engineer 2 mentioned a collaborative solution that their company provided which glued dashboards. This was a task previously performed manually, but to reach a uniform product quality, a collaborative robot was implemented. Production engineer 2 also mentioned an existing solution in the company's production. A YUMI robot checks the quality of the product as one of the station's tasks before the product continues in the production line. Neither automation engineer 1 nor automation engineer 3 mentioned any specific task. However, automation engineer 1 mentioned that in general automation is used to achieve better product quality. Automation engineer 3 also mentioned improvement in product quality.

6. CONCLUSIONS

This paper presents an in-depth interview study that investigated what industrial actors think are the most value-adding tasks in HRC. Research on HRC has been active for many years but despite this, there are still little knowledge of what tasks are suitable for HRC and the results from this interview study can serve as guideline for other manufacturing companies that consider implementing HRC. Two companies participated where shop-floor operators, production engineers and automation engineers were interviewed. From these interviews, six categories of tasks were identified as being beneficial for the human and robot to carry out together. These categories are tasks that are difficult to operate, logistic inefficient, non-ergonomic or time consuming and tasks that have product variation or uneven quality.

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VIRTUAL REALITY PLATFORM FOR DESIGN AND EVALUATION OF HUMAN-ROBOT INTERACTION IN ASSEMBLY MANUFACTURING

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

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Abstract: This paper presents the Virtual Collaborative Robot (ViCoR), which is a virtual reality platform for designing and evaluating collaboration between operators and industrial robots. Human-robot collaboration scenarios can be created in ViCoR in which 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 indicates that ViCoR can be used to successfully test new applications with the standard equipment of virtual reality headsets.

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

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1 Introduction

Human-robot collaboration (HRC) is the combination of a human and an industrial robot in a hybrid production cell. The goal is to improve quality and productivity by combining the human's sensory-motor abilities, intelligence, and flexibility with the robot's strength, accuracy, and repeatability (Michalos et al., 2014). However, industrial robots pose a danger to humans if they share the same workspace. Collaborative robots are robots that can be used in collaborative operations (safe operations) as defined in the technical specification ISO/TS 15066 (ISO, 2016) created by the International Organization for Standardization. They are generally lightweight industrial robots that include force limitations on all joints to make them suitable for HRC. There is growing interest in the use of such robots in manufacturing due to their low cost, simple programming, ease of integration, and reduced space requirements because safety fences can be eliminated (Mandel, 2019, Sharma, 2018). Industries can use them to incrementally automate their production and implement more flexible cells where operators can co-operate (collaborate) with robots. Several cases of the use of collaborative robots for co-operative tasks in industry have been reported (Saenz et al., 2018), but it is clear that the full potential of the technology is not being used. In the cases reported, there is often limited interaction between the human and the robot and minimal contact in order to conform to safety regulations. There is no true collaboration between a human and a robot; all they do is share a common workspace. The main factors limiting the use and development of collaborative robots that work side-by-side with humans are the restrictions set in safety standards (Michalos et al., 2015; Saenz et al., 2018). Because of these restrictions, the development of human-robot collaborative applications has not been fully explored. This study set out to investigate how to simplify the process of trying new collaborative applications without safety issues.

In HRC the fact that a user is working close to a robot introduces safety issues. These issues can be overcome if virtual reality (VR) is used to test HRC applications (Etzi et al., 2019; Metzner et al. 2018). VR 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. Using VR as an engineering tool, 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 engineering tools have the ability to test HRC (Matsas and Vosniakos, 2017; Dahl et al., 2017; Etzi et al., 2019) and these tools can be used to partially test the interaction between operators and robots, but these are still few. This paper presents ViCoR, a platform that can be used to test interaction in HRC using VR. In addition to previously mentioned tools an additional design phase is proposed where the desired future state of the interaction can be discovered by using VR. With VR the production system can be tested without the limitations of the existing control systems. By finding the desired future state of the interaction, HRC cells can be continuously improved towards that state. The platform presented in this paper is an initial step to provide engineers with tools that can be used in the design and evaluation of the interactions in HRC cells, and thus realize successful implementations of HRC applications in industry.

Section II presents the background to this study, describing HRC and advances in the area, as well as VR and how VR has been used in industry. Section III describes the VR platform ViCoR in detail, listing requirements of the platform, how it was implemented, what interactions can be modeled using ViCoR, and the limitations of using VR for HRC. Section IV describes a scenario created with ViCoR based on a physical demonstrator, showing its usefulness and initial results. Section V concludes this paper by summarizing 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 (Kolbeinsson et al., 2018; Michalos et al., 2015; Gustavsson et al., 2017; Beer et al., 2014; Pichler et al., 2017) define HRC from different perspectives. These are summarized 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) categorize 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 synchronize 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 workpiece 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 **Human-robot collaboration:** 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) (Yanco and Drury, 2004; Beer et al., 2014). 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.

The common denominator of HRC in all these articles is that HRC 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 (Kolbeinsson et al., 2018; Beer et al., 2014), in the same way that humans can collaborate with each other remotely. 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 categorized 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 Virtual reality in human-robot collaboration

Virtual reality 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. Based on the hardware used, commercial VR headsets fall into the following categories:

- A desktop computer runs VR programs connected to a HMD with a built-in screen, controllers to navigate in the virtual environment, and sensors to track the head, controllers, and possibly other body parts. HTC Vive and Oculus Rift are in this category.
- A smartphone can be docked in the HMD so that the screen of the smartphone is used to display the VR environment. The built-in sensors in the smartphone are used to track head movements. Samsung Gear VR and Google Cardboard are in this category.
- A computer is embedded in the HMD, which is a standalone device that includes a screen, sensors, and controller(s) to navigate in the virtual environment. Oculus Go and Oculus Quest are in this category.

Virtual reality 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 (Strahilov and Hämmerle, 2017, Dahl et al., 2016). 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 visualization 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).

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 human-robot collaboration systems, performing optimization 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 modeled 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 support of an interaction, 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 utilize 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.

An exoskeleton can be used as a haptic interface with full immersion. Carignan, Tang, and Roderick (2009) demonstrated that rehabilitation could be facilitated using VR combined with an exoskeleton. The VR generated a virtual environment where a basic wall painting task was performed. The exoskeleton enabled the user to “feel” the force when the roller brush painted the wall. Another example of VR combined with an exoskeleton is presented in Lugo-Villeda et al. (2010), also in the context of rehabilitation. An exoskeleton can be used for motion capturing as well as force feedback. An example of an exoskeleton for a human hand is presented in Gu et al. (2016). Though exoskeletons enable force feedback to the users and other functionalities, they also occupy considerable space, thus limiting movement and interaction.

3 Virtual collaborative robot

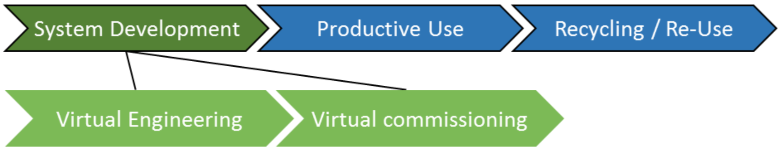
Virtual reality has the potential to improve the virtual commissioning process (Dahl et al., 2017). In the case of HRC, it can also be used in a training system (Matsas and Vosniakos, 2017). To further extend the use of VR for HRC, this paper presents ViCoR, a VR platform that can be used to design and validate the interaction between an operator and a robot in HRC.

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 categorized as system development, productive use, and recycling/re-use (figure 1). During the system development phase, a production system is designed and later realized in the industry. After realization 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.



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 modeled 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.

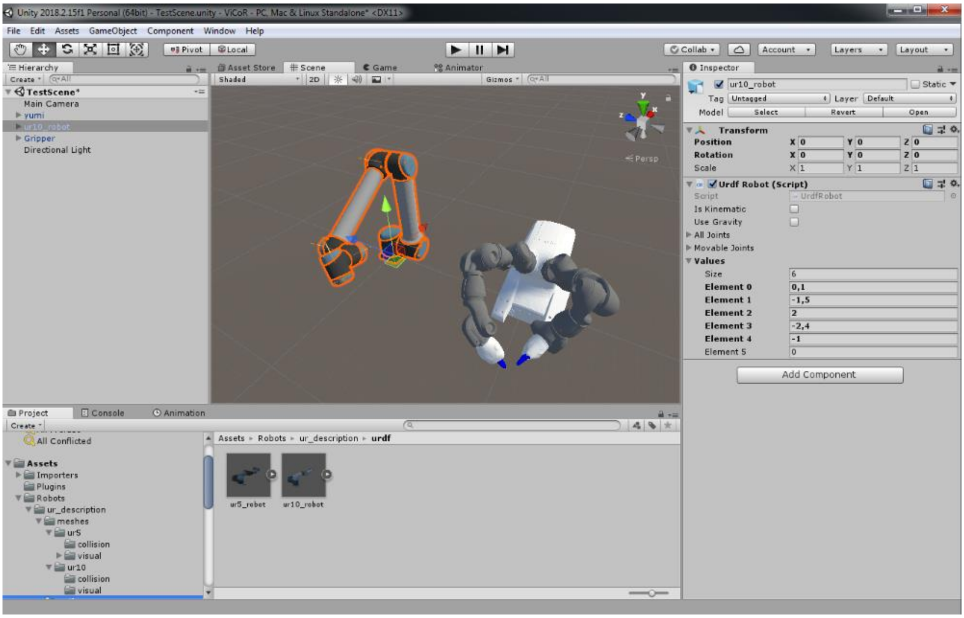
Table 1 lists some tools that can be used to build prototypes or robot applications that include VR support. Out of these tools, Unity was selected as the most compatible development tool for ViCoR given the basic requirements set out in Table 1. Unity is a game development tool that supports most VR 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

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, 2009), but has since significantly grown and is today a collection of tools and libraries for creating complex robot behavior. 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, 2020). 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.

Figure 2 Unity development tool showing imported robots using ROS#. The left robot is a UR10 robot from Universal Robots, and the right robot is a YuMi robot from ABB.



Virtual reality 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 augmented reality (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 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.

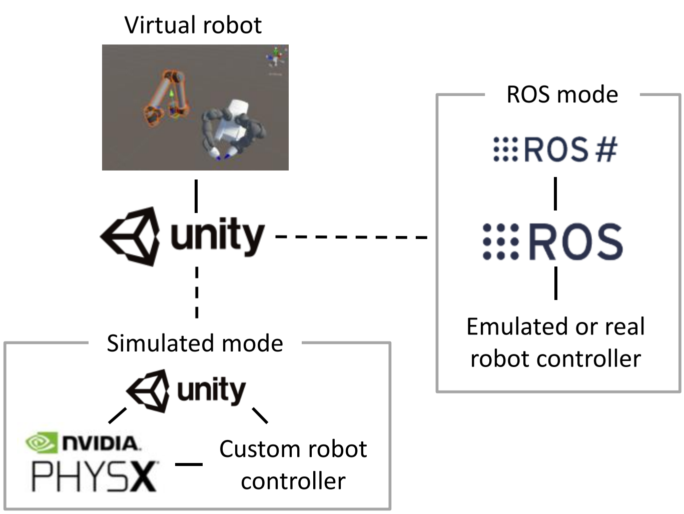
3.3 Implementation

Based on the requirements listed in section 4.2, 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 was 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 human-robot collaboration 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.

Figure 3 Illustration of the components used within ViCoR and how they relate to the two modes. The dashed lines represent the ability to switch between simulated and ROS mode.



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

3.3.1 Hand interaction

In assembly manufacturing an operator mainly uses their hands and vision to perform all 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 those 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 within a 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 degrees of freedom (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 visualize 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

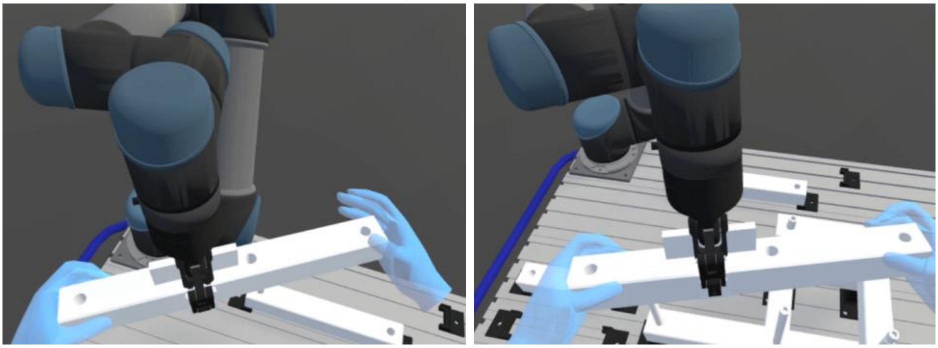
Speech Recognition is the process of converting an audio signal received by a microphone into recognizable sentences and commands for the system. Speech recognition has been used in Rossi et al. (2013), Bannat et al. (2009), Maurtua et al. (2017), Lei et al. (2014), and Green et al. (2008) to showcase how humans and robots can interact. 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 center point and frame of reference need to be set to enable the hand-guiding mode in Cartesian space.

Figure 5 Images show how the part can be grabbed and moved while the robot holds it, showing haptic control. The hands are animated to look as if they are grabbing the part.



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 virtual reality, 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 behavior of the robot when moving it by hand, e.g., speed, responsiveness, constraints in cartesian and joint space.

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

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; Lambrecht and Jörg Krüger, 2012; Guhl, Tung, and Kruger, 2017). 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, Danielsson, and Gustavsson, 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.

Figure 6 Augmented reality animation visualized in the virtual environment. Animation consists of a static trajectory of small green spheres with motion of the part highlighted in blue (screen shot from ViCoR).

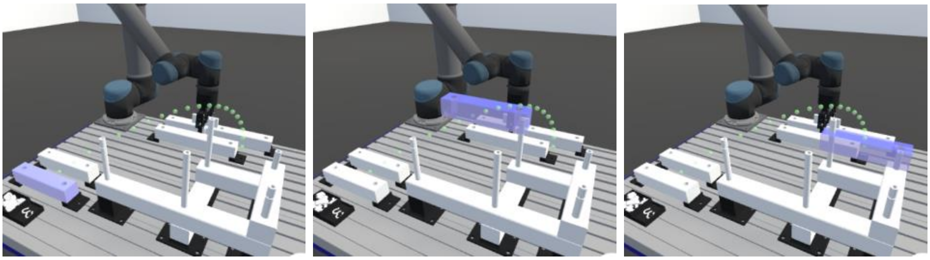
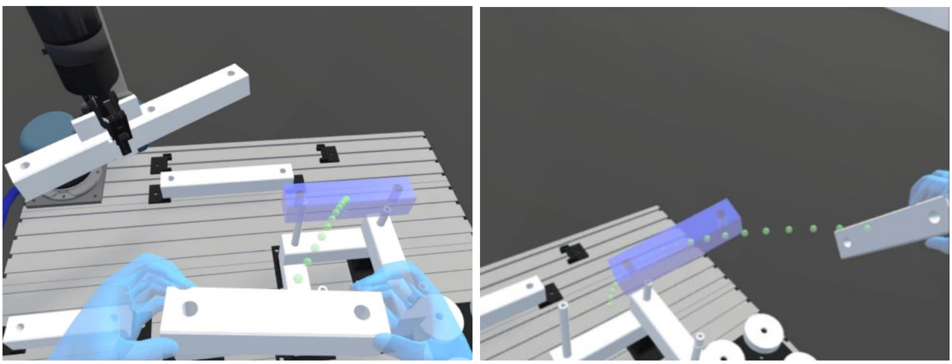


Figure 7 Visualization of perfect tracking of the part allowing the augmented reality animation to follow the part with any position and orientation (screen shot from ViCoR).



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 the figure the opaque objects represent physical objects that the user should work with, while the transparent objects represent animations intended for AR usage. The figure 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, and 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.

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 Evaluation

An initial experiment was made to investigate the perceived realism of using ViCoR for HRC. 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.

Figure 4 Physical demonstrator to the left and the virtual model to the right. The model is shown in the Unity editor.

In addition to the experiment ViCoR has been demonstrated on multiple occasions to potential users and stakeholders, including stakeholders in the Swedish production academy and employees at ABB Robotics. It made a public appearance at a production technology event at ASSAR. 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 augmented reality 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 behavior 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.

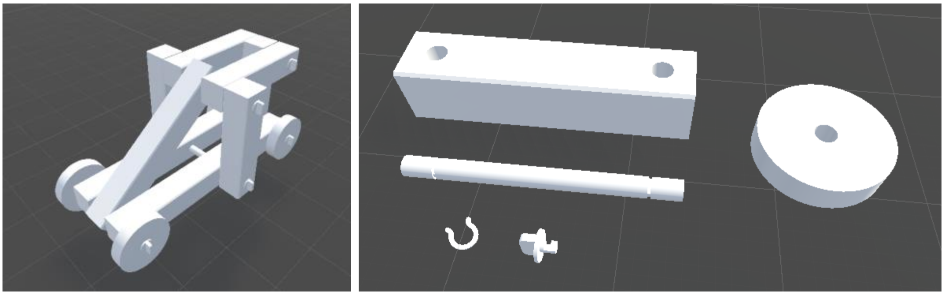
A headset with microphone was provided for the physical scenario and in the virtual scenario the VR headset has a built-in microphone. Because the microphones used in both scenarios are headset variants, no extra programming is required when moving between physical and virtual environments, assuming 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 augmented reality 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 Left: Car model that is assembled in the scenario; Right: Some of its base components (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 specialized fixtures. In this case the robot acts as a specialized fixture that can also initially position the parts close to where they are needed.

4.3 Initial results

The results from the questionnaire is 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. The full analysis from this experiment has not been covered in this paper since it is part of a larger study.

Observations made when demonstrating ViCoR for potential users and stakeholders indicate that VR has good potential as a platform for testing HRI. 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.

Table 2 Answers from the questionnaire regarding the user experience in ViCoR. No answer (NA), Strongly Disagree (SD), Disagree (D), Neutral (N), Agree (A) and Strongly Agree (SA).

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
The robot felt safe to work with	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 behavior in the virtual world was the same as my behavior in the real world	0	0	0	0	10	0
It felt like I was participating in a game rather than in a human-robot collaboration 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

5 Conclusions and future work

This paper presents the Virtual Collaborative Robot (ViCoR), a virtual reality (VR) platform used for designing and evaluating human-robot collaboration. With ViCoR, users can interact with a robot to simulate human-robot collaboration 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.

Virtual reality has been used to test HRI 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, the system can be tested without the limitations of existing production systems, which enables the use of more advanced features and easier implementations. 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. Virtual reality 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.

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EVALUATION OF HUMAN-ROBOT INTERACTION FOR ASSEMBLY MANUFACTURING IN VIRTUAL REALITY

Evaluation of Human-Robot Interaction for Assembly Manufacturing in Virtual Reality*

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ABSTRACT

Human-robot collaboration (HRC) combines the benefits of humans and robots in one hybrid cell. Although this concept is becoming more common within the manufacturing industry, there is a lack of engineering tools that can be used for HRC. Using virtual reality (VR) it is possible to simulate a production system with a human-in-the-loop, which has the potential to improve the whole production system life-cycle of a HRC cell. To validate that theory, this paper presents a study which was made with participants from three Swedish manufacturing companies, to use a VR platform in which a HRC scenario was created. The study investigated the user experience in the form of a questionnaire, and behavior of the participants based on recorded data and observations. The results from the study indicates that the participants had a realistic experience when interacting with the robot in VR, however, additional questions arose based on the behavior of the participants.

1. Introduction

Human-robot collaboration (HRC) utilizes the benefits of a human and an industrial robot in a hybrid production system. The production system combines the flexibility, intelligence, and motor-sensory abilities of humans with the strength, accuracy and repeatability of the robot [1]. Traditionally industrial robot cells have been constructed with safety fences that separates the workspace of industrial robots and operators. But since the production of collaborative robots started, cells where robots and human share workspace are becoming more common in the industry. Collaborative robots are industrial robots that include safety related control systems or inherently safe design which allows them to work side by side with an operator without posing danger. Even if collaborative robots exist the uptake of HRC have been limited because of the safety issues that are introduced and the restrictions set in the safety standards [2, 3].

Virtual reality (VR) is a technology which lets a user step into a virtual environment by putting on a head mounted display (HMD). The HMD updates the content based on the movements of the head which makes the digital content appear as if the user is in the virtual environment. To interact within the virtual environment the user have hand controllers which can be used to grip object, navigate user interfaces, using equipment, etc. The set consisting of HMD, tracking sensors, and hand controllers are refered to as VR headset and in the day of writing several commersial VR headsets exists, e.g., HTC Vive, Oculus Quest, Valve Index, and many more. These VR headsets are widespread in the gaming community due to their low cost and the increasing amount of games released for VR. Virtual reality was in the past mostly used for the development of premier products [4], but since the cost has significantly been lowered, VR has become more common for manufacturing industries, e.g., teaching robot to paint [5], teaching robot to weld [6], validating ergonomics and product design [7].

When using VR there are no safety issues of external forces in the virtual environment, i.e., there is no risk of crushing, cutting or puncturing injuries from digital entities in VR. Virtual reality is therefore suitable, from a safety point of view, for testing new concepts of HRC. A VR platforms has, therefore, been developed that can be used to design and evaluate human-robot interaction without safety risks. The VR platform is called Virtual Collaborative Robot (ViCoR), in which a user steps into a virtual environment and interacts with a robot in a HRC cell. With this platform it is possible to create new scenarios of HRC which is predicted to be useful in research and development, the design of new cells, in the virtual commissioning phase, and also as a virtual training system for new operators.

The VR platform ViCoR has yet to be integrated in engineering processes, and it needs to undergo experiments to validate its usefulness in the production system life cycle. This paper, therefore, presents a study made on ViCoR, in which a scenario was created where the user assembles a car model by interacting with the robot using speech recognition, haptic control and augmented reality (AR). Another scenario was setup in a physical demonstrator, using the same type of interaction as in the virtual scenario. With these two scenarios an experiment was conducted to compare virtual environment with physical environment, collect data on the behavior and user experience with ViCoR, and get information on how ViCoR can be improved.

In section 2 related work is presented on recent advances in HRC and the usage of VR for training and commissioning. In section 3 the structure of the experiment is explained in detail with the selected participants, description of the scenarios, and how the experiment was conducted. In section 4 the results are listed with the answers from each participant

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and observations that was made during the experiment. In section 5 the collected data and observations are analysed. Finally in section 6 the article is summarized with the conclusions made from the analysis and future direction of research with ViCoR.

2. Related work

Already in the 1990:s Virtual reality was used for researching how VR could be used for manufacturing tasks. Examples of these studies are Jayaram et al. [8] and Gomes de Sá and Zachmann [9] who presented how VR could be used in the design process of manufacturing tasks. This has since been realized to some extent, e.g., [5], [7], and has been integrated in commercial simulation systems used for manufacturing, e.g., Process Simulate and RobotStudio.

Virtual commissioning is the process of developing and testing industrial control systems using simulation models [10, 11]. With virtual commissioning the physical system is tested and validated before being built in the factory. This is expected to reduce the cost because issues in the design can be identified in an early phase which leads to reduced installation time. Simulation of a process is possible when the behavior of the system is deterministic, however, when humans are needed for part of or the whole process, the simulation model becomes more complex. To further extend the virtual commissioning process Dahl et al. [12] proposes the use of VR to validate the design of the production system and use it for training of, e.g., maintenance technicians. Metzner et al. [13] argues, that for processes involving humans, specifically HRC, then simulation models of the operators behavior may not be enough. They therefore present a simulation system that involves the human-in-the-loop to further enhance the simulation with real-like behavior.

Using VR for HRC systems have been studied by Matsas and Vosniakos [14] presenting the design of a virtual reality training system called "beWare of the Robot". This system was further evaluated for effectiveness and acceptability in Matsas et al. [15]. In the evaluation of the system, a questionnaire was used for analysing the user experience when using their VR training system. de Giorgio et al. [16] created a VR application first meant as an informal pilot study, but conclusions were made that using VR for HRC provides the possibilities for the operator to learn how to perform manufacturing processes. The VR systems presented in [14, 15, 16] are not used for the design and evaluation of the interaction between the human and operator, and that is the purpose of ViCoR and this study.

Hietanen et al. [17] describes the use of AR for interaction in human-robot collaborative manufacturing. They take a look at different AR techniques and their impact on the user experience. For their study a questionnaire is used for evaluating the user experience and comparing the user experience between different AR techniques. They conclude that existing wearable AR (HoloLens was tested) are not yet suitable for industrial use, partly due to weight and narrow field of view. In ViCoR, AR is used within VR and although the weight remains an issue with VR, the field of view is increased to that of the VR headset. This makes VR a suitable platform to analyse the user experience when AR glasses have larger field of view.

Figure 1: Participant in the physical scenario getting introduced to the system.

3. Experiment

The purpose of the VR platform ViCoR is to be used in existing engineering process for designing and evaluating human-robot interaction in assembly manufacturing. Before this can be achieved, evidence needs to be provided that VR can be used for such purpose. This study therefore intends to evaluate this platform to gain knowledge about the behavior and user experience of using VR for HRC. Hevner et al. [18] states that knowledge and understanding of a problem domain and its solution are achieved during the process of building an artifact and evaluating the usage of said artifact. In this study the artifact is the VR platform, and the study focuses on the evaluation of this platform.

The selected method of evaluation for this study is a controlled experiment, in which the VR platform is studied in a controlled environment to extract measured data on the behavior and user experience. The intended users for ViCoR are R&D, engineers and operators, therefore, three Swedish industries who work with assembly manufacturing participated and in total the experiment had 28 participants. Amongst these participants there were 1 R&D, 6 engineers, 16 operators, and 5 with other roles. Two scenarios were created for the experiment, a virtual reality and a physical scenario. The purpose of the physical scenario was for the participant to get a frame of reference to compare with the virtual reality scenario.

In the following subsections the two scenarios are described in more detail and then the structure of the experiment is explained.

3.1. Virtual reality and physical scenario

Two scenarios were created to compare the physical environment with the virtual environment. These two scenarios were setup to use the same task and the same type of in-

Figure 2: Participant in the virtual reality scenario working with the tutorial.

teraction with the robot. In figure 1 the physical scenario is shown, where the participant is being introduced to the system. Figure 2 shows a participant getting introduced with the VR headset in a tutorial.

In the two scenarios, the same assembly task is executed in which the operator and robot collaborate to partly assemble a car model. The assembly consist of four steps in total, two collaborative and two manual steps, that the participants executes during the experiment.

- Two of the steps require the assembling of parts that are considered heavy objects, too heavy for an operator to handle. Instead the robot lifts these parts, places them close to the assembly position, then the operator guide the robot (by grabbing the part directly) so that these parts can be assembled correctly. This process represents an operation that cannot be fully automated because of a complexity of the task that requires the full sensory-motor skills of the human. The car model itself has an internal flexibility which does not ensure that the shafts are always in the same position, making this task especially difficult to automate and is therefore in need of an operator.
- Two of the steps are fully manual during which the robot prepares for the next step by moving to the next part and grab it. In these steps the parts are light, which the operators can handle without ergonomic issues.

Oculus Quest was used as VR headset for the VR scenario. This headset is a standalone unit with built in computer into the headset. The tracking used is solely based on sensors within the headset and does not require additional tracking base stations. Because of this the setup when moving to a new location was quick and easy. Android is used as the operating system in Oculus Quest, because Unity was used as the development tool for the VR platform and Unity already has support for Android, adapting ViCoR for the Oculus Quest did not require that much effort.

To enable collaboration, the operator and the robot interacts with each other using three types of communication, speech recognition, haptic control and augmented reality. Following, these are described in more detail on how they were used in the scenarios and the reason for using them.

3.1.1. Speech recognition

The operator speaks to the robot to give it a command using a speech recognition engine. It was used as an alternative way to inform the system to continue to the next step. Usually buttons are used for this type of command, however, that requires the operator to switch focus to find the specific button, while using speech it is possible for the operator to continue working without losing focus on what they are working with. Three phrases were used to tell the robot system to continue, representing commands in relation to what the operator is currently working on.

The speech recognition engine used for the VR scenario was not the same as the one in the physical scenario. The reason for this was that the selected VR headset used Android as operating system and the speech recognition used for the physical scenario was Microsoft Speech API 11, which is not compatible with Android. Instead, Microsoft Azure Speech to Text was used in the VR scenario, which is an online speech recognition service, that can be used for Android and Windows. Although the speech recognition engine differed between the scenarios, the usage of said engines were the same.

3.1.2. Haptic control

By directly grabbing the robot or part attached to the robot, the operator is able to steer the robot towards its destination. This type of collaborative operation has the advantage of separating the required strength to lift an object, and the flexibility to assemble the part. The robot in this case becomes an ergonomic assistant, which assist in some heavy operations. Specialized fixtures are often constructed for this type of feature, however, a robot can provide additional help by preparing most of the operation so that the operator only do the necessary part which the robot cannot do itself.

In the VR scenario the user could manipulate the robot in Cartesian coordinates, however, with limited maximum velocity of the robot's joints and end-effector. In the physical scenario, the built in freedrive functionalty of the UR5 robot was used. This freedrive allows the operator to manipulate the robot directly by grabbing the robot, but is limited to moving it in joint space, making it difficult to move the end-effector with a linear motion.

3.1.3. Augmented reality

Using AR, digital information and instructions can be placed in a position where it is more accessible for the operator to see them. This allows the robot to efficiently communicate with the operator without them needing to switch focus, e.g., by looking at a computer screen. From earlier observations with ViCoR, all objects within VR look like digital objects, i.e., they look equally unreal. Therefore, it

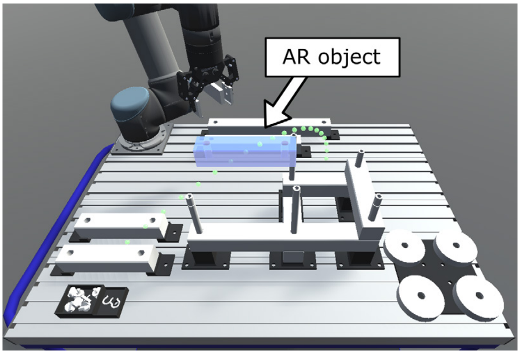

Figure 3: In the VR scenario entities that represent physical objects are rendered opaque while entities represent AR objects are rendered transparent. Image show a snapshot of an AR animation where the blue box moves along the trajectory of small green spheres.

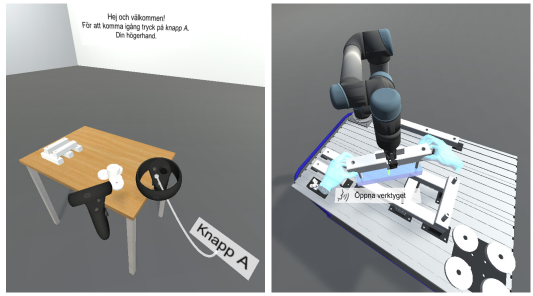

Figure 4: The two scenes used in the VR platform. The tutorial is shown to the left where the user gets acquainted with the controls and how to manipulate objects. The VR scenario is shown to the right where the user assembles a car model.

is difficult to know which objects represents real objects and which does not. This heavily impacts AR testing because with AR in real environment it is clear what objects are real and what are digital (with current technology), but in VR it is not clear. The approach for the scenario was instead to let all "real" objects appear opaque, while all AR objects and animations appear partly transparent, see figure 3.

The AR used in VR differed significantly between the AR used in the physical scenario. In VR AR smart glasses was simulated, in which animations could be added directly on to the "real" objects. In the physical scenario, a TV was used to display a live feed from a camera mounted above the shared workspace and digital information was added on top of the live feed.

3.2. Structure

In the experiment the participants were supposed to work with the two scenarios presented in section 3.1, so they could compare VR with reality. In a trial run with two participants, the experiment started with the VR scenario and then moved to the physical scenario. However, the VR scenario was not intuitive enough, so the participants did not understand that they were supposed to manually assemble the parts based on the animations alone. Therefore, the sequence was changed for the experiment to instead start with the physical scenario. The experiment was structured as follows, one participant was invited at a time and each time had the following sequence:

1. First the participant gets an introduction to the experiment and its purpose. They are also told that, if at any time the participant choose to, they can stop the experiment, e.g., if they feel dizziness because of VR or if they feel uncomfortable working close to the robot.
2. Then the participant signs a form of consent that the data collected from the experiment can be used for this study. They are informed that the data collected consist of a questionnaire, observations made during the experiment and recorded film.
3. Then the participant goes through the physical scenario to get an understanding of the usage of HRC in assembly manufacturing, and also to get a feeling on working with a physical robot.
4. Then the participant goes through the tutorial and VR scenario, see figure 4, which consist of four steps. The first step is the tutorial, in which the participant gets acquainted with VR and how to work with the hand controllers. If the observer notices that the participant misunderstood anything during the tutorial, the observer will give directions. In the second step the participant start with the VR scenario assembling the car virtually, without any guidelines. In the third step, the participant repeat the same scenario, but the observer gives directions if anything was misunderstood in the second step. In the last step, the participant repeats the same scenario but again without any guidelines.
5. After the participant has gone through both scenarios, they fill in a questionnaire about their user experience.

4. Result

The experiment yielded results from several data collection methods. A questionnaire was used to get the subjective experience from each participant. Observations were made during the experiment, by looking at how the user was using the VR headset and if needed a discussion was had with the participant to further ask about the observed phenomena. All motions made by the participants using VR were recorded so it could be replayed afterwards.

4.1. Questionnaire

A questionnaire, divided into three main parts, was used to get data from the participants . In the first part, age and working role was asked for, to identify whether any correlation exists between the answers and the role or age of the person. In the second part statements were given with a five level Likert-scale on whether the participant agree or not. In the third part the participants had the option of writing

Table 1
List of statements in the questionnaire with the results visualized as a stacked bar diagram. The colors represents the likert-scale answers, shown in the legends at the bottom of the table.

	Questions	Answers
1	It felt like I was really moving in the virtual world	10 18
2	I had no problem keeping the concentration throughout the experiment	6 22
3	It felt like I was moving objects with my hand, even though the objects did not have physical mass (actual weight)	1 2 14 11
4	It felt realistic to be in the virtual world	1 1 15 11
5	It was easy to understand what to do with the instructions presented with animations	9 19
6	It was easy to understand the robot's intentions and where it was going to move	9 19
7	The robot felt safe to work with	1 5 22
8	It was easy to assemble parts together with the robot	1 14 13
9	It felt realistic to assemble parts together with the robot	2 16 10
10	It was easy to assemble parts manually	4 4 20
11	It felt realistic to assemble parts manually	1 4 10 13
12	It was easy to tell the robot what to do	1 5 13 9
13	It was a quick alternative to talk to the robot to give it instructions	2 2 13 11
14	It felt like my behavior in the virtual world was the same as my behavior in the real world	2 21 5
15	It felt like I was participating in an entertainment game rather than a human-robot collaboration training environment	1 8 4 7 7 1
16	I think a virtual environment like this is good for training	1 10 17

■ No answer ■ Strongly disagree ■ Disagree ■ Neutral ■ Agree ■ Strongly agree

additional comments as free text, to pick up additional information from the participants.

The statements in the second part are listed in table 1, which was divided into three categories. The statements 1-4 asked about their experience of using the VR system. Whether they felt immersed into the VR world or not, heavily impacts the experience of working with the virtual robot. The statements 5-13 asked about their experience of assembling and interacting with the robot in VR. The statements 14-16 asked for additional information with relevance to the study. The statements and the results from the questionnaire are summarized in table 1. The results are presented per statement as a a stacked bar diagram to the right. As seen in the figure, most of the participant agrees or strongly agrees with the statements in the questionnaire, with the exception of question 15.

4.2. Observations

When the participants was working in VR their ability to handle the hand controllers was observed. Some had great difficulties handling the hand controller and some had no problems at all. Participants were therefore asked about their earlier experience with VR, whereof one had longer experience with VR, some had tested it on occasion and some had barely heard of it at all. The user who had longer experience with VR had no difficulties at all with the hand controller but was trying to manipulate objects in a different way than the rest of the participants. Often in VR games picking up objects are made easier by just aiming at an object and even if the hand is not close to the object, the object will automatically teleport to the hand. This participant expected this to happen, which made their experience different because of this. On the other hand, those who did not have any experience with any hand controllers for games, had difficulties navigating the hand controllers. They did not know where the buttons of the controllers were located and had difficulties remembering where the buttons were after not using them for a while.

With a couple participants a phenomenon was discovered where the user in the virtual environment behave significantly different in comparison with working in the physical environment. These four participants did not fully understand on the first turn that they should manually assemble the parts together with the robot. These participants stepped through each step without manually assembling the parts first. In the physical demonstrator, the participants were reacting as if they wanted to intervene when parts were falling, while in VR they had no reaction than to just continue stepping forward.

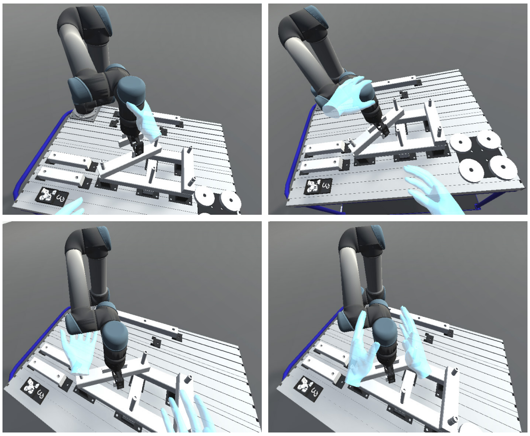

Figure 5: The images show how the participants approached grabbing the robot to move the tool upwards. The top left image show the predefined pose, and the remaining images show the poses that some participants used before knowing the predefined pose.

4.3. Recorded data

During the experiments all motions of the controllers and HMD were recorded together with the state of all buttons, triggers and joysticks, and the result from the speech recognition engine. These were stored in JSON format and for each frame, the whole state was stored in a log file so that the experiment could be repeated. The reason for storing the data this way was to reduce the impact of the performance when recording the data and at the same time be able to repeat the recorded experiment and be able to look at the scene from different perspectives. All participants were recorded, each time took between 10-20 minutes totaling approximately 1 GB of recorded data.

5. Analysis

The results from the questionnaire indicates that the participants have similar opinion about all statements, with an exception of statement 15. For all statements except 15, 22 or more participants out of 28 agrees or strongly agrees. For statement 15, which asks the participant whether the VR scenario felt like an entertainment game rather than a training environment, the participants did not have the same opinion.

There was a clear difference between the answers for question 5 between the trial run and the experiment. During the trial run, the participants started with VR and did not understand that they were supposed to manually do work. The participants in the trial run, therefore, answered strongly disagree and disagree on whether they could understand the animations or not, while all participants in the experiment answered either agree or strongly agree. Since the participants of the experiment had already assembled parts in the physical scenario, they partly knew what they were supposed to do, which impacts the result. Further investigation is, therefore, needed to see whether it is enough that the participants understand that they are supposed to do manual work, or if the animations themselves need to be improved, e.g., showing hand with orientation to guide the operator.

All motions were recorded so that phenomenon which may be missed during the experiment can be observed afterward. The following observations were made by looking through the recorded material:

- The predefined pose for grabbing the robot was located at the center of the wrist grasping the cylindrical geometry, see figure 5. When looking at the experiments, before knowing the predefined pose, several participants assumed they should grab the robot on the top cap, below the third link or using two hands to move the tool upwards, see figure X. The desired interaction for vertical motion heavily depends on ergonomics, resistance and height of the robot, but with this information several poses are of interest to investigate.
- When assembling the square prism shaped parts with cylindric holes, several of the operators tried to grip them from above, i.e., covering the holes. The cylindric holes are assembled onto shafts, which leads to the shaft sticking out from the holes. Therefore, the predefined grip poses were located so that the hands would not cover the holes. When asked the operators said that gripping from above was the natural choice since they should push down the object. This resembles a real-like behavior, but since this was not the case with the physical scenario, the reason for this behavior is not that simple. Further experiments are required to fully analyze the reason for this behavior. Following are two possible reasons for that behavior.
  - The assumed grab position resembles that of the physical environment, but because VR does not have force feedback and therefore no immediate impact on the operator, they do not see the consequences of said behavior. In the physical scenario the consequence would be a shaft sticking into the hand. In the VR scenario the shaft have no impact and the consequence is disregarded leading to a behavior based on the first instinct which is, in this instance, a grab position that covers the holes.
  - During the tutorial they were asked to grab these parts and because they started working with them without the context of assembling these parts. They learned the wrong behavior which then led them to do the same thing in the VR scenario.

Four of the participants, had no reaction in VR when parts were falling but they did in the physical scenario. After looking through the recorded material, several of the participant moved the robot back and fourth without considering the collision between the robot and the parts. This indicates that the participants did not feel that the robot and parts were realistic. This is probably because virtual objects has no real impact if they fall to the ground, or at least it seems that the user did not experience that impact. There could be several factors to this behavior:

1. During the tutorial of the VR scenario, the user were asked to pick up and throw away objects to get acquainted with the controls. This could lead to the feeling that there is no impact of dropping parts.
2. All objects look digital and therefore lacks realism, which could impact their attitude toward such objects.

If the presence in VR is improved, specifically the realism of the simulation, then the behavior could approach a real-like reaction of the user. If the behavior of the user matches the behavior in the real environment, then the usage of VR as an engineering tool improves, which leads to reduced commissioning time and reduced training time.

During discussion with one of the participants, they gave a comment that they had already started to build muscle memory by the second try of the assembly process in the virtual environment. Muscle memory is motor memory stored in the primary motor cortex [19], which allows the person to execute a task with little conscious effort. Virtual training already exist for several industrial use cases [20, 21, 6, 22] and has improved the training process. To further enhance the training process some of these training systems utilizes specialized equipment to get the same feeling as the physical environment. According to Stefan et al. [19] evidence exist that it is possible to gain motor memory by observation alone. Allowing the user to perform motions that resembles that of the physical environment while observing the visual environment and assembly animations, we believe that the operator could gain motor memory, accurate for the physical task, using the VR platform. If the operators can gain motor memory accurate to the task in the physical environment, that would result in reduced lead time of training operators and may reduce the need for specialized training equipment.

Predefined grab poses were used for each object because of the limits of the VR controllers. Assuming that VR could be used for muscle memory training, could predefined poses, quicken the training period for the operators by leading them to grab an object in a standardized way? This assumes that every worker has the optimal hand orientation in the same way, otherwise individualized training programs would be needed.

One of the participants that neither agreed or disagreed on whether the manual assembly felt realistic, also commented that the "snap functionality" was easy to work with but made the experience less realistic. The "snap functionality" refers to the use of semi-automated assembly features in the VR platform, which snaps the part in place to simplify the procedure. This was added because the controllers have reduced number of degrees-of-freedom in comparison to the hand and there is no force feedback. With physical objects that are assembled, the objects are attached to each other, while in VR, this all depends on the ability of the physics engine. Since the hands in VR does not have any resistances, i.e., infinite strength, the "snap functionality" was added to ensure that the operator can assemble parts. In addition to the parts snapping in place, the user gets vibrotactile feedback if they stray too far from the part when assembled. Even though the "snap functionality" was added which potentially reduces realism, most of the participants partly or fully agreed that it felt realistic to assemble the parts.

The questionnaire indicates that speech recognition is a good alternative for giving instructions to the robot. But during discussion with some of the participants, they felt that the speech recognition was too slow and in some cases too unstable to be used for the normal sequence. However, they pointed out that speech recognition could be used as a flexible user interface, where the operator can easily access functionality that otherwise need navigation in a human-machine interface panel.

6. Conclusion and future work

This paper presents a study that investigated the behavior and user experience when using the VR platform ViCor for a HRC assembly task. In the study the participants first assembled a car model together with a robot in a physical scenario and then they executed the same task in a virtual scenario using VR. Afterwards they filled in a questionnaire about their experience with the VR scenario. The results from the questionnaire indicates that the experience in the VR scenario was realistic. However, from discussions with the participants and observations made when they were working in VR, suggests that the behavior in VR partly deviates from behavior in the physical environment.

For ViCoR to be fully accepted as an engineering tool, evidence needs to be provided that the behavior, performance and user experience of the operator are significantly indifferent in the virtual environment when compared to an equivalent physical environment. The conducted experiment in this study has started this journey by evaluating the behavior and user experience of the participants. The discoveries made in this study has opened up further research questions that needs to be answered:

- The behavior of the participants partly matched the behavior of the physical environment. But further investigation is needed to identify how the VR platform can be enhanced to establish real-like behavior of the users. If the behavior of the user matches the behavior in the physical environment, then the usage of VR as an engineering tool improves, which leads to reduced commissioning time and reduced training time.

- Whether the operator can gain accurate motor memory for the physical task in VR with limited embodied motions, e.g., reduced DOF because of hand controllers, requires further investigation. The challenge is to find the required level of sensory input for the user to reach the desired learning outcome of the training. If the existing hand controllers for the VR headsets can be used, this would reduce the need for specialized equipment.

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