Linköping Studies in Science and Technology
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On Safe Collaborative Assembly With Large Industrial Robots

Varun Gopinath

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ON SAFE COLLABORATIVE ASSEMBLY WITH LARGE INDUSTRIAL ROBOTS

VARUN GOPINATH

Division of Machine Design
Department of Management and
Engineering
Linköping University
SE-581 83, Linköping, Sweden

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ABSTRACT

This thesis pertains to industrial safety in relation to human-robot collaboration. The aim is to enhance understanding of the nature of systems where large industrial robots collaborate with humans to complete assembly tasks. This understanding may support development and safe operations of future collaborative systems.

Industrial robots are widely used to automate manufacturing operations across several industries. The automotive industry is the largest user of robots and have identified robot-based automation as a strategy to improve efficiency in their manufacturing operations.

Recently, a class of machines referred to as *collaborative robots* have been developed by robot manufacturers to support operators in assembly tasks. The use of these robots to support human workers in an industrial context are referred to as *collaborative operations*.

Presently, collaborative robots have limited reach and load carrying capacity compared to standard industrial robots. Large/standard industrial robots are widely used for applications such as welding or painting. They can, in principle support operators in assembly tasks as well.

Two laboratory demonstrators representing the final results from a series of research activities will be presented. They were developed to investigate issues related to personnel and process safety while working with large industrial robots in collaborative operations. The demonstrators were partially based on manual assembly workstations that are currently operational and these manual workstations exemplify challenges faced by the automotive industry.

Demonstrator-based Research, a methodology for *collaborative research* that emphasizes development of demonstrators as a research tool, forms the rationale for carrying out research operations presented in this thesis. An evaluation of the laboratory demonstrators by industrial participants suggests an increased interest and confidence in collaborative operations with large robots. The demonstrators have served as a tentative platform for members from the industry to identify and discuss manufacturing and safety challenges in relation to their organization.

A main outcome presented in this thesis relates to specifying requirements for introducing robots in a human-populated environment. Introducing robotic systems in new environments requires reconsideration of the nature of the hazards particular to the domain. An analysis of the laboratory demonstrators suggest that, in addition to hazards associated with normal functioning of the system, limitations in human cognition must be considered. These results will be exemplified and discussed in the context of situational and mode awareness.

This is particularly significant considering the direction of present-day research aimed at introducing robots across various industries and working environments. In response to this trend, this thesis discusses the relevance of Interactive Research and its emphasis on *joint learning* that goes on between academic researchers and industrial participants as a valuable principle for collaborative research.

KEYWORDS Industrial Safety; Interactive Research; Industrial Robots; Human-Robot Collaboration; Collaborative Operations; Human Factors

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December 2019

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APPENDED ARTICLES

- I *Design Criteria for a Conceptual End-effector for Physical Human-Robot Production Cell*
Varun Gopinath, Kerstin Johansen & Åke Gustafsson
In Swedish Production Symposium; No.47; 6 pages; Gothenborg, Sweden; 2014

- II *Risk Assessment Process for Collaborative Assembly – A Job Safety Analysis Approach*
Varun Gopinath & Kerstin Johansen
Procedia CIRP; Vol. 44; 199 – 203; 2016.

- III *Safe Assembly Cell Layout through risk assessment – An Application with Hand Guided Industrial Robot*
Varun Gopinath, Fredrick Ore & Kerstin Johansen
Procedia CIRP; Vol. 63; 430 – 435; 2017.

- IV *Risk Assessment for Collaborative Operation: A Case Study on Hand-Guided Industrial Robots*
Varun Gopinath, Kerstin Johansen & Johan Ölvander
Risk Assessment; Intech Publishers; Book Chapter 09; 167 – 187; 2018.

- V *Demonstration of Robot-Assisted Assembly on a Continuously Moving Line*
Varun Gopinath, Åke Gustafsson, Stefan Axelsson, Micael Derelöv & Kerstin Johansen
Special issue – *Robotics and Computer-Integrated Manufacturing*;
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Invited article based on conference paper (see Other Publication XVI)

- VI *Demonstrators to support research in Industrial safety – A Methodology*
Varun Gopinath, Kerstin Johansen & Micael Derelöv
Procedia Manufacturing; Vol. 17; 246 – 253; 2018.

- VII *Understanding Situational & Mode Awareness for Safe Human-Robot Collaboration: Case Studies on Assembly Applications*
 Varun Gopinath & Kerstin Johansen
 Production Engineering; Vol. 13; 1 – 9; February 2019.

- VIII *Development of Demonstrators for Industrial Safety – An Interactive Perspective*
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ADDITIONAL PUBLICATIONS

- IX *Conceptual Optimization of Aircraft Actuator Systems*
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 2012

- X *A Collaborative tool for Conceptual Aircraft Systems Design*
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- XI *Template Driven Conceptual Design of High Speed Trains*
 Varun Gopinath, Mehdi Tarkian, Johan Ölvander & William Gaziza
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 Technical Conferences & Computers and Information in Engineering
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- XII *Supporting Risk Assessment of Human-Robot Collaborative Production Layouts using Design Automation*
 Leon Poot, Kerstin Johansen & Varun Gopinath
 Procedia Manufacturing; Vol. 25; 543 – 548; 2018.

- XIII *Safe Layout Design and Evaluation of a Human-Robot Collaborative Application Cell through Risk Assessment – A Computer Aided Approach*
 Pooja Wadekar, Varun Gopinath & Kerstin Johansen
 Procedia Manufacturing; Vol. 25; 602 – 611; 2018.

- XIV *Exploring a Model for Production System Design to Utilize Large Robots in Human-Robot Collaborative Assembly Cells*
Sten Grahn, Kerstin Johansen, Xi Wang & Varun Gopinath
Procedia Manufacturing; Vol. 25; 612 – 619; 2018.
- XV *Safety-Focussed Design of Collaborative Assembly Station with Large Industrial Robots*
Varun Gopinath, Fredrik Ore, Sten Grahn & Kerstin Johansen
Procedia Manufacturing; Vol. 25; 503 – 510; 2018.
- XVI *Collaborative Assembly on a Continuously Moving Line – An Automotive Case Study*
Varun Gopinath, Kerstin Johansen, Åke Gustafsson & Stefan Axelsson
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DEFINITIONS

- Automatic Mode:** Operating mode in which the robot control system operates in accordance with the task programme.
- Collaborative Operation:** State in which purposely designed robots work in direct cooperation with a human within a defined workspace.
- Collaborative Robot:** A robot designed for direct interaction with a human within a defined collaborative workspace. (see ISO 10218-2:2011)
- Collaborative Workspace:** Workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation.
- End-effector:** Device specifically designed for attachment to the mechanical interface to enable the robot to perform its task.
- Hazard:** Potential source of harm, where harm is defined as physical injury or damage to health.
- Industrial Robot:** Automatically controlled, reprogrammable multi-purpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications.
- Operator:** person designated to start, monitor and stop the intended operation of a robot or robot system.
- Protective Stop:** Type of interruption of operation that allows a cessation of motion for safeguarding purposes and which retains the programme logic to facilitate a restart.
- Risk:** Combination of the probability of occurrence of harm and the severity of that harm. $\text{Risk} = \text{Probability} \times \text{Severity}$
- Robot System:** A system comprising robot(s), end effector(s) and any machinery, equipment, devices, or sensors supporting the robot performing its task .
- Situational Awareness:** Situational Awareness (SA) is defined as the perception of the elements in the environment within a volume of time and space, comprehension of their meaning and the projection of their status in the near future.
- Takt Time:** Average time between start of production of one unit till the start of production of next unit.

ACRONYMS

CW	Collaborative Workspace
DBR	Demonstrator Based Research
DRM	Design Research Methodology
FWC	Flywheel Housing Cover
ESPE	Electro-Sensitive Protective Equipment
HRC	Human-Robot Collaboration
IR	Interactive Research
KRC	Kuka Robot Controller
KRL	Kuka Robot Language
OSSD	Output Signal Switching Device
PLC	Programmable Logic Controller
PSPE	Pressure Sensitive Protective Equipment
RSI	Robot Sensor Interface
SPE	Sensitive Protective Equipment
TRL	Technology Readiness Level
UBP	Under-Body Panels

INTRODUCTION

An introduction to the broad research agendas that influence current manufacturing research is followed by an account of robots in manufacturing. The challenges faced by the automotive industry are presented followed by the aim and research questions pertinent to the thesis.

1.1 BACKGROUND

Industrial revolution is a term used to describe rapid technological development and the effect of industrialization on society. The first era, from 1760 – 1820 (approx) is associated with mechanization of labor and the developments during this era are attributed to the efficiency gains of the Watt steam engine. Coal powered the steam engines that were the prime mover for mechanization in the then dominant textile industry.

The second era (1830 – 1914) was characterized by acceptance of technical systems such as railways, telegram and telephones. Petroleum and electricity were introduced and proved their use as a motive force for vehicles as well as factories. The later years of this era saw the invention of assembly lines that were instrumental in manufacturing *affordable transport solutions* for the masses.

The third era (1945 – 1990 approx.) saw the development of technologies that led to the development of computing (e. g. personal computers) and communication technology. Over the last three centuries, there has been a significant increase in the global population coupled with improved living and working standards

Schwab [1] predicts the fourth industrial revolution, an era characterized by the merging of the capabilities of humans and machines. The expectation is that technologies such as artificial intelligence and robotics will drive future innovations. The development of technologies during these periods was governed by contemporary paradigms that reflected societal goals and aspirations on the one hand, and the current state of technology [1–3] on the other.

1.2 MANUFACTURING AGENDA

This thesis contributes to the ongoing technology research in automation of manufacturing processes. *Automation* drives efficiency, enables organizations to deliver products that cater to a customer's needs and meets societal goals. The developmental trajectories of industrial automation are influenced by several contemporary goals such as sustainability, improving the work environment and minimizing cost.

Reduction or elimination of *work related injury* has been the goal for researchers in ergonomic studies, human factors as well as human-machine interaction [4, 5]. The technological solution to improve the working environment is to automate tasks that are considered dangerous, induce stress or can result in injury [4, 5].

Digitalization programs aim to revolutionize manufacturing by building upon technologies that have revolutionized communication. Industry 4.0 is the umbrella term to describe digitalization research activities and as noted by Schwab [1], computer-based technology will drive innovation with substantial change in many areas such as manufacturing, bio-engineering and sustainable energy.

Manufacturing *flexibility* and the ability to adapt to market fluctuations has guided research in areas such as production, logistics and lean manufacturing [6–8]. Researchers have presented taxonomies for flexibility and have proposed technical and non-technical solutions to enable flexible and lean manufacturing processes [9–11]. Industrial robots are seen as a key technological solution that enables manufacturers to address contemporary challenges.

1.3 INDUSTRIAL ROBOTS

Since their invention in 1961, industrial robots have become prevalent across several industries such as automotive, aerospace as well as food. These are used to automate manufacturing operations such as welding, packaging, handling and painting (see fig: 1.1).

By the end of 2016, it was estimated that there are 1.8 million industrial robots in operation globally and IFR [12, 13] expects this figure to grow to over 3 million by the end of 2020 [12]. The automotive industry is the largest user of industrial robots with an estimated 125,500 units in 2017, which represents a yearly increase of 21%. During the same period, the world average saw an increase of 31%, with the highest growth in China which exceeded 50%.

Researchers aim to investigate the viability of new applications with industrial robots that address challenges faced by manufacturers [15, 16]. Researchers have demonstrated new applications with force-controlled industrial robots for de-burring of cast parts [17], automated manufacture of carbon-fiber reinforced plastics [18], and programming strategies to support the uptake of robots in small and medium sized companies [19, 20].

These examples extend the applications of traditional industrial robots by incorporating new technologies such as force-torque sensors, vision systems, etc.

Figure 1.1: Industrial robots are widely used in the automotive industry for welding and material handling.

Figure 1.2: ABB Yumi [14] is a dual-arm industrial robot designed to collaborate with humans.

Speed, precision and repeatability are characteristics of traditional industrial robots which are relied on by manufacturing firms and have made them ideal technological solutions for various manufacturing operations [16]. These characteristics pose recognized risks [21] and therefore they are installed in fenced areas – referred to as robotic cells/workstations – with interlocking devices.

Physical fences with interlocking devices are an effective risk reduction strategy as the source of hazard (e. g. fast moving robot) is removed by bringing the system to a safe state. However, the installation of fences requires additional floor space and eliminates the possibility of collaboration. In practice, robot integrators [22, 23] are responsible for the development of robotic systems that are developed off-site and integrated into manufacturing process, when requirements for function and safety are tested, verified and validated [23–25].

Recently, several manufacturers have introduced robots that can sense their surrounding. They are referred to as collaborative robots and can detect contact on their structure (see fig: 1.2). They are expected to realize an inherently different application compared to those discussed above, and such applications are referred to as human-robot collaboration (HRC) or collaborative operations [26] (fig: 1.3).

HRC aims to synergize the abilities of humans and robots for the purpose of improving the effectiveness of assembly operations [27–29]. The challenges faced by the automotive industry, as discussed in the next section, demand flexible solutions and collaborative operations have emerged as a suitable strategy.

Figure 1.3: A suggestion from ISO 10218-2 [23] to label a collaborative workstation.

Figure 1.4: An operator fastening bolts under the body of a car in the final-assembly plant.

1.4 AUTOMOTIVE ASSEMBLY PLANT

An automotive plant that manufactures vehicles such as cars, trucks, buses etc., can be broadly generalized into three facilities [30, 31]:

1. The *body-in-white* (BIW) facility, where the components that form the chassis are stamped and welded together.
2. The *paint shop*, where the welded chassis is painted and prepared for final assembly.
3. The *final-assembly* plant, where components such as drive-train, wheels, brakes, dashboards etc. are fitted to the chassis (fig: 1.4).

The ubiquity of manual labor as observed by the author in the *final-assembly* plant are attributed to operational demands such as physical dexterity and cognitive skills in terms of decision making and hand-eye coordination. It may be noted that operations in BIW and the paint shop are extensively automated with industrial robots used for material handling, painting & welding.

Advances in technology and stricter regulations are dictating design changes to the vehicle, which affects the manufacturing process. There are several ongoing design changes to a vehicle such as: 1. Improved aerodynamic efficiency, 2. Electrification of the drive-train and 3. New materials such as carbon composites.

It was noted that automotive manufacturers strategically introduce these changes concurrently with maturing technologies. To illustrate this point, a path to full electrification for some manufacturers has been to introduce hybrid vehicles – with internal combustion engines and electric motors – first and continue development with a goal of producing a fully electric vehicle in the near future.

Evolution of an automotive product, with tentative but promising technology (sometimes referred to as Incremental Innovation [2]), is a strategy for automotive companies that competes in a globalized market. This incremental strategy determines the changes in the manufacturing process of the automotive plant.

In addition to changes brought about by advances in technology, end-users seek customized products. These customizations are integrated into the vehicle at various stages during production. As noted by Diffner [30], a significant portion of the optional customization selected by the final-user is integrated into the vehicle during final-assembly.

1.5 AIM & RESEARCH QUESTIONS

Attempts at introducing automation to support operators in assembly applications (e.g. cobots [32, 33]) have resulted in custom machinery that functions as ergonomic support. Safety for operators with collaborative robots – robots designed for collaboration – has been of significant interest for both practitioners and the research community.

Researchers have proposed several technical solutions which include space monitoring with 3D camera; path planning with vision systems and gesture control for interacting safely with robots [34–38]. The solution space for the majority of research emphasizes robots specifically designed for collaboration.

Large industrial robots such as KUKA KR210 [39] are widely used in industrial automation and are designed to function with minimum human intervention. They are referred to as standard robots [40], large robots [41] or manipulators [22]. The body of research that focuses on the application of large industrial robots in collaborative operations is limited, though their physical performance can be valuable in assembly operations [40].

Literature concerning large robots in collaborative operations has discussed real-time safety system [40], speed and separation monitoring [42, 43] and concepts for collaborative cells [44]. As discussed in section: 1.3, the safety of systems with large robots is well-understood, with considerable practical knowledge of non-collaborative operations.

This thesis aims to enhance our understanding of robotic systems where large robots collaborate with humans to complete assembly tasks. This understanding may support development and safe operations of future collaborative workstations.

As noted earlier, final-assembly within the automotive plant is reliant on manual labor. Collaborative solutions imply the introduction of industrial robots where the working environment has been organized and designed for humans. In order to plan and design a robot-assisted workstation in a populated environment, there is a need to understand the constituents of a collaborative workstation.

RQ.I: What constitutes a collaborative assembly workstation?

The process of designing, developing and maintaining a safe automated robotic solution is well defined and standardized. However, there is a lack of understanding about issues related to safety in collaborative operations.

RQ.II: What are the relevant safety issues for collaborative operations in automotive assembly plants?

Safety in an automotive assembly plant encompasses a wide range of issues that include organizational factors, security, laws etc. Therefore, this research question can be further elaborated as follows:

RQ.II.A: What are the hazards when industrial robots are operated collaboratively?

RQ.II.B: What are the safety solutions to mitigate risks associated with these hazards?

1.5.1 *Delimitations*

As the definition of industrial robot indicates, a robot can take various physical forms. However, a six-degree-of-freedom articulated industrial robot, a widely used type of manipulator, forms the basis for discussions and demonstration.

Normal functioning refers to the sequence of tasks carried out by the system. Procedures that accompany normal operations such as maintenance, production ramp-up etc., were not considered. Additionally, systems such as laser scanners, robot controllers etc., were expected to function as intended and the effects of their failure were not considered during risk assessment.

Research was designed to showcase safety solutions in assembly applications. The approach was to develop industrial-grade safety solutions in a laboratory environment, whereas the assembly operations were approximated. That is, prevailing research trends that included machine learning to avoid collision, protective skins, rgb cameras, ROS [45] etc. were considered and were phased out when minimum requirements on equipment and operating procedures were developed.

The concept of *change process* (sec: 2.2) stems from Action Research and refers to research activities (i.e. *Action*) applied in practice. In this thesis, the possibility of practice-oriented action (introduction of robots in collaborative operations) in currently functioning workstations is limited.

Practitioners expressed several reasons including: 1. insufficient knowledge in identifying appropriate applications, 2. limited commercial vendors that can deliver collaborative solutions and 3. limited understanding of return on investment. Therefore, research was directed towards addressing the critical challenge of safety, a feature that determines the viability of collaboration operations with large robots.

1.6 THESIS OUTLINE

This is a compilation thesis and is composed of two parts: 1. A logical list of chapters (fig: 1.5) that summarizes the results and 2. An appended list of articles presented according to the date of publication.

Figure 1.5: Map of the chapters presented in this thesis.

This chapter has introduced the reader to industrial robots and automotive assembly plants, followed by the aim and research questions pertinent to this thesis. Chapter 2 will present the methodology that has guided activities to answer the research questions.

Chapter 3 will present a frame of reference that will form the basis for understanding and the interpreting results presented in chapter 4. Chapter 4 presents two laboratory demonstrators:

1. Hand-guided robots to assist in the assembly of a flywheel housing cover (sec: 4.1) and
2. Robot-assisted assembly of under-body car panels on a continuously-moving line (sec: 4.2).

In chapter 5, a model of a collaborative workstation is presented and is based on: 1. The demonstrators, 2. Literature and 3. Reflections & observations made during the PhD studies. Chapter 6 will discuss the approach to research and elaborate on the contributions to the research questions. Finally, section: 6.3 summarizes the thesis by answering the research questions along with concluding remarks and suggestions for future work.

Part two of this thesis consists of eight articles appended to support the arguments made in this thesis. There are five (5/8) conference proceedings, one (1/8) book chapter and two (2/8) journal articles. The following section briefly discusses the relevance of each publication to the thesis and its contribution to answering the research questions.

1.6.1 Summary of Appended Papers

For all the appended articles, the first author has been responsible for: 1. Defining, planning and conducting research activities in collaboration with industrial partners, 2. Research and preparation of the written material, and 3. Presentation at conferences as needed. The co-authors have supported these activities to

Table 1.1: Appended articles & their relationship to research questions (RQ).

RQ	Appended Articles							
	I	II	III	IV	V	VI	VII	VIII
RQ.I	✓		✓	✓	✓	✓		✓
RQ.II.A		✓	✓	✓	✓		✓	
RQ.II.B		✓	✓	✓	✓		✓	

varying degrees. Table 1.1 depicts the contribution of the appended articles with the research questions (sec: 1.5).

Paper-I

Design Criteria for a Conceptual End-effector for Physical Human-Robot Production Cell; Varun Gopinath, Kerstin Johansen & Åke Gustafsson; In Swedish Production Symposium; Gothenborg, Sweden; 2014. [Conference Proceeding]

This article presents a concept for a collaborative workstation for the assembly on a continuously moving line (RQ.I). The concept describes the placement of the components in the workstation, robot and operator tasks and the interface to support assembly operations. The article also describes a concept of a smart end-effector that functions as a nut-runner and an interface device.

Paper-II

Risk Assessment Process for Collaborative Assembly – A Job Safety Analysis Approach; Varun Gopinath & Kerstin Johansen; Procedia CIRP; Vol. 44; 199 – 203; 2016. [Open-Access; Conference Proceeding]

A concept for a device to hand-guide an industrial robot is presented. This device demonstrates the ergonomic and interaction function of the hand-guiding tool and contributes to knowledge on how to safely undertake hand-guided collaborative operation (RQ.II). The article also contributes to knowledge on the nature of hazards (RQ.II) that should be considered while carrying out risk assessment.

Paper-III

Safe Assembly Cell Layout through Risk Assessment – An Application with Hand Guided Industrial Robot; Varun Gopinath, Fredrick Ore & Kerstin Johansen; Procedia CIRP; Vol. 63; 430 – 435; 2017. [Open-Access; Conference Proceeding]

A concept for a workstation where operators can safely hand-guide a robot to assemble a flywheel housing cover is presented. The development was carried out in collaboration with industrial participants and contributed to knowledge

of the constituents of a collaborative workstation (RQ.I). Risk Assessment was employed to manage risks during concept development and contributed to a better understanding of the hazards pertinent to a workstation where large robots are hand-guided for assembly operation (RQ.II).

Paper–IV

Risk Assessment for Collaborative Operation: A Case Study on Hand-Guided Industrial Robots; Varun Gopinath, Kerstin Johansen & Johan Ölvander; Risk Assessment; Intech Publishers; Chapter 09; 167 – 187; 2018. [Open-Access; Book Chapter]

The book chapter presents a laboratory demonstrator developed to showcase assembly of a flywheel housing cover (RQ.I). The development of the demonstrator provided insight into physical and cognitive requirements for safety in hand-guided collaborative operations. These requirements relate to ergonomics, safeguarding measures as well as human factors that can be considered while carrying out risk assessment (RQ.II).

Paper–V

Demonstration of Robot-Assisted Assembly on a Continuously Moving Line; Varun Gopinath, Åke Gustafsson, Stefan Axelsson, Micael Derelöv & Kerstin Johansen; Submitted to Robotics and Computer-Integrated Manufacturing; Vol. xx; xxx–xxx; 2019. [Open-Access; Invited article]

This article builds on the approach discussed in Papers III & IV and presents results from activities carried out with industrial partners. It details a laboratory demonstrator that meets industrial safety requirements for the assembly of under-body panels on a continuously-moving line (RQ.I). The article elaborates on the hazards of collaborative operations and discusses measures to mitigate critical risks (RQ.II). The article also discusses the sequence of tasks (performed by the operator) synchronized with the automation system that can enable operators to safely assemble under-body panels.

Paper–VI

Demonstrators to Support Research in Industrial Safety – A Methodology; Varun Gopinath, Kerstin Johansen & Micael Derelöv; Procedia Manufacturing; Vol. 17; 246 – 253; 2018. [Open-Access; Conference Proceeding]

This article details the methodological approach in developing the robot-assisted workstations in collaboration with industrial partners. The article contributes to validation of the approach and the demonstrator (described in Paper III & IV) based on a series of interviews of members from the participating organization (RQ.I).

Paper–VII

Understanding Situational & Mode Awareness for Safe Human-Robot Collaboration: Case Studies on Assembly Applications; Varun Gopinath & Kerstin Johansen; Production Engineering, Dec 2018. [Open-Access; Journal Article]

This article evaluates the hazards and their constituents (presented in paper IV and paper V) with the aim of identifying the underlying mechanism that can lead to an accident. The contribution highlights cognitive factors (loss of situational & mode awareness) must be considered in order to introduce collaborative workstations in human-populated environment (RQ.II).

Paper–VIII

Development of Demonstrators for Industrial Safety – An Interactive Perspective; Varun Gopinath, Micael Derelöv, Johan Ölvander & Kerstin Johansen; submitted to International Journal of Occupational Safety and Ergonomics; 2019.

This article develops the methodological approach presented in paper VI based on the two laboratory demonstrators. The article contributes to Interactive Research with insights into practical challenges of this approach (RQ.I).

1.7 A BRIEF HISTORY OF INDUSTRIAL ROBOTS & SAFETY

On June 13 1961, a patent related to automatic operation of machinery, considered the first modern approach to robot design, was awarded to George C Devol Jr titled *Programmed Article Transfer* [46, 47]. Joseph Engelberger and George Devol formed Unimation, which developed the world's first industrial robot called Unimate and sold it to General Motors (1961).

The first industrial robot in Europe was installed by Unimation at Metallverken, Uppsaland Väsby, Sweden 1967. In 1974, ASEA (now ABB AB [14]) developed the IRB 6 (fig: 1.6), which was the first all-electric microprocessor-controlled industrial robot. IRB 6 is an articulated robot which possesses rotary joints and accounts for majority of sales.

There have been several technological developments that have influenced the development of collaborative operations. In an article published in 1996, Colgate et al. [32] defined the term Cobot, referring to a system which manipulates objects in collaboration with operators. These are passive machines and do not enhance human strength (see fig: 1.7). That is, the steering of the Cobot is controlled by a motor where the operator provides motive force to manipulate an object.

Intelligent Assist Devices are a class of machines that combines the passive motion-guidance of Cobots with power-assist systems. These devices were based on ideas presented by Colgate et al. [32], but can complement an operator's physical ability [33]. Presently, constrained motion or motion-guidance are available in modern robotic systems and can be configured relatively easily. This

Figure 1.6: ASEA IRB 6, the first microprocessor-controlled electric industrial robot.

Figure 1.7: A tricycle cobot with a three-dimensional workspace. Picture courtesy of Michael Peshkin [48].

is achieved using computer-aided control systems which permit elimination of mechanical solutions.

In a PhD thesis authored by Townsend [49] in 1988, a technique for whole-arm manipulation (WAM) was presented. The technique was intended to allow a robotic arm to manipulate an object using the entire arm in addition to the end-effector. The links of the manipulator cannot sense their surroundings but infer contact forces based on torque at the joints [49]. This technique is still under research to realize its initial objective, Although several robot manufacturers have commercialized the principle of collision detection in the form of collaborative robots.

Though robotic automation has improved manufacturing productivity, personnel and process safety has been a concern for several decades [25, 50]. There have been several documented fatal accidents as well as numerous injuries that are often not documented [21].

During this period, an international effort to standardize safety features in industrial robots took the form of ISO-10218 in 1992 and its development was coordinated by several national standardization bodies. Currently, a majority of installed robotic systems are operated within fenced workspaces, whose design and development are shaped by suggestions documented in the safety standards.

METHODOLOGY

A description of the research approach designed to achieve the aim and answer the research questions is presented. A presentation of the research orientation (sec: 2.1) is followed by 1. Interactive Research (sec: 2.2); 2. Design Research Methodology (sec: 2.3) and 3. Demonstrator-based research (sec: 2.4). These form the theoretical basis for the approach presented in section: 2.5.

2.1 RESEARCH ORIENTATION

The purpose of conducting research is to discover answers to questions through the application of scientific procedures with the aim to find out the truth which is hidden and not yet discovered [51]. Leedy and Ormrod (Chapter 1 [52]) define research as follows:

Research is a systematic process of collecting, analyzing and interpreting information (data) in order to increase our understanding of a phenomenon about which we are interested or concerned.

This thesis can be characterized as qualitative research, which is primarily used to gain an understanding of underlying reasons, opinions, and motivations [53]. It is also used to uncover trends in thought and opinion, and dive deeper into the problem.

This thesis can also be characterized as Applied Research with a focus on Technology. Applied Research aims at finding solutions to an immediate problem facing society or a business organization [51]. Technology research places an emphasis on the development of useful techniques for an immediate problem [51, 52]. There are several definitions of technology and in this chapter, the following definition by Nordin [54] will be used.

Technology can be seen as the activity directed towards producing useful techniques for solving practical problems.

This activity involves research, innovation and refinement of techniques. According to Nordin [54], Functionality and Usefulness are two qualities that a technique must possess. The notion of being useful implies two conditions.

- 1. In order to be useful, a technique must function as intended. That is, functionality is a precondition for usefulness and this judgement can be measured based on probability.
- 2. The functionality of the technique must be useful for some people. This is a subjective condition and demonstrates a qualitative aspect of a technique.

As noted by Nordin [54], research devoted to creation of technique can exist over a wide spectrum. One measure to quantify this spread is Technological Readiness Level (TRL), which is defined on a scale from one to nine [55]. In this thesis, research activities were directed towards TRL levels of less than six, which refers to demonstration of systems/subsystems in a relevant environment [55, 56].

2.2 INTERACTIVE RESEARCH

The research activities presented in this thesis are directed towards addressing industrial challenges and this approach is referred to as collaborative research. In collaborative research, academic researchers and industrial participants (*participants* going forward) collaborate in carrying out research activities to address industrial challenges. In this thesis, Interactive Research (IR) is seen as an approach to manage the complexity that arises when academics and participants collaborate to create techniques that address industrial challenges.

As noted by Nielsen and Svensson [57], Interactive Research (IR) was developed in recognition of deficiencies in collaborative research (specifically action research [57, 58]), where researchers were solely responsible for several activities including planning and executing actions, documenting the change process and maintaining academic requirements. This places demands on researchers who may not be equipped to carry them out within the permitted time-frame.

Figure 2.1: Illustration of roles & interests of the participants and researchers in Interactive Research. Adapted from Svensson et al. [59].

To deal with issues related to efficiency, IR recognize the dual role of researchers and participants but encourages division of labor. Svensson et al. [59] state that the ambition of IR is to conduct research *with* participants who own the change process. The change process is the introduction of new techniques that address perceived industrial challenges. Figure: 2.1 shows the role of researchers and participants in IR based on their individual goals.

Action and Interactive research does not represent a specific method and can be understood as an approach to research. Svensson et al. [59] state that *Interactive*

Research is characterized by a continuous joint learning that goes on between the researcher and the participants. Joint learning occurs during the entire research process, from the definition of the problems to the analysis as well as dissemination of the results.

Table 2.1: Features of Interactive Research [60–62]. Adapted from Paper VIII.

Features	Description
Division of labor	Research operations are delegated between researchers and participants based on expertise and interest.
Mutually beneficial outcome	Researchers contribute to theory and method development. Practitioners own the change process which facilitates identification of practice-oriented problems and development of useful techniques to solve them.
Issue of validity	Interest in valid research is high for researchers and participants. Participants with different perspectives emphasize different aspects and therefore can affect the outcome.
Efficiency in operation	Organizing joint-learning activities for knowledge gathering and critical analysis. Researcher is responsible for organizing events with the understanding that active participation in various research activities results in continuous joint learning for researchers and participants.

Ellström [61] discusses the notion of IR in terms of two interacting cyclic systems driven by problems and issues particular to them. These are the research and practice systems depicted in figure: 2.2 and show a typical model for knowledge creation in IR [61].

As noted by Ellström [61], the interactive process is assumed to produce a common conceptualization and interpretation of the research object, shown as a shaded box at the intersection of the two systems, which is fed back as *cognitive input* into the next cycle of problem solving activities.

Product and production innovation research projects that were carried out interactively have been reported to:

- Narrow the theory-practice gap with emphasis on broader research results;
- Give researchers the role of moderators for companies to devote resources to various research phases;
- Place additional demands on both researchers and participants as it requires frequent communication between them [63].

The increased frequency in communication, according to Hermans and Castiaux [64], is the mechanism by which tacit knowledge is transferred in collaborative research.

Figure 2.2: A model of knowledge creation through Interactive Research. Adapted from Ellström [61]

2.3 DESIGN RESEARCH METHODOLOGY

Design Research Methodology (DRM) was proposed by Blessing & Chakrabarti [65] in order to provide rigor in design research. They define design as *those activities that actually generate and develop a product from a need*. In this thesis, the activities are focussed on generating designs of collaborative systems that are safe for use.

The need can be formally expressed as requirements and for a collaborative system encompasses issues such as 1. Ergonomics of a hand-held tool (e. g. nut-runners, hand-guiding tool), 2. Procedures for initiating a system for production or maintenance.

DRM has been mainly associated with research on product development. It is a systematic and iterative application of the following four stages (fig: 2.3 [65]):

1. Research Clarification – The researchers try to formulate goals based on the current and desired understanding of the research object. This activity can be complemented by literature review, interview.
2. Descriptive Study I – The researchers attempt to make a detailed description of crucial factors that describe the current situation. To support this activity, a detailed literature study can be undertaken along with specification of success factors that can characterize desired results.
3. Prescriptive Study – The aim is to develop design supports to realize the desired situation. They note that design support includes all possible tools

Figure 2.3: Illustration of the iterative approach in Design Research Methodology aim to provide rigor in design research. Adapted from Blessing & Chakrabarti [65].

and methods that can be used to improve design. These are prescriptions, suggesting ways by which design tasks should be carried out.

4. Descriptive Study II – The main focus is the application and evaluation of the previously selected methods.

In this thesis, DRM is seen as an approach to systematically design a demonstrator (see sec 2.4) supported by appropriate and valid design support, which according to Blessing and Chakrabarti [65] is the purpose of design research.

2.4 DEMONSTRATOR-BASED RESEARCH

Demonstrator-Based Research (DBR) is a multi-methodological approach to research developed to address challenges faced by a manufacturing organization [17]. According to Jonsson [17], DBR was inspired by two methodological approaches. They are:

1. Industry as a laboratory [66] – The approach emphasizes close collaboration between researchers and organisations to identify industrial challenges, formulate research questions and develop solutions that offset the identified challenges.
2. System development in information systems [67] – It was developed to support multi-methodological research where the development of the information system is the mechanism for knowledge production and theory development. It is based on a framework where research activities, with foundations on a body of knowledge, contribute back to the development of the knowledge base.

Figure 2.4: The multi-methodological approach to research with emphasis on research activities centred on demonstrator development [17].

Figure 2.4 illustrates DBR, where the Industrial Challenge, Knowledge Base and the Research Objectives form the basis for carrying out research activities. They provide the rationale for the four different research stages with the Demonstrator stage as the main source of information for conceptualization, evaluation as well as feedback.

Björnsson [18] notes that a demonstrator can serve two purposes: 1. A platform for experimentation to build new theories and gain insights into issues related to research objectives and 2. A communication tool between the researcher and the industry.

Jonsson [17] and Björnsson [18] also note that a demonstrator can be developed in many forms such as prototype, virtual or physical demonstrators. They also note that the development is iterative where the process might look as follows: 1. initial specification based on research questions refined through collaboration with the industry. 2. development of low fidelity demonstrators such as scaled-prototypes or simulations. 3. These concepts can then be realized as laboratory or physical demonstrators. The choice of form depends on the nature of the research questions and what insights are sought from the demonstrator.

2.5 RESEARCH METHODOLOGY

This section discusses the methodological approach pertinent to this thesis.

Figure 2.5: Time line for activities directed towards evaluating the possibilities for establishing a collaborative robot-operator team in an assembly system.

2.5.1 Research Environment

The role of the researcher or the participants in activities such as developing design support (sec: 2.3) or developing demonstrators (sec: 2.4) is not explicitly stated. The assumption in collaborative research is that the researcher is primarily responsible for these activities, whereas participants support researchers' in research operations.

Interactive Research assumes that knowledge and the ability of participants can be valuable for these tasks and therefore encourages a division of labor. The research operations relevant for this thesis were carried out interactively. That is, the specification of tasks was developed through discussions and delegated based on individual goals and expertise.

As noted in section 2.2, participants' principle task is the identification of industrial challenges, since they are knowledgeable in practical domain. These challenges can then be redefined with discussions with academic researchers to gain insight into state of the art solution strategies. These discussions resulted in broad research challenges and formulation of studies directed towards addressing them. Formally, these studies took the form of research projects ToMM [68], followed by ToMM 2 [69] (fig: 2.5).

ToMM – Collaborative Team of Man and Machine (ToMM) was designed to evaluate the possibilities and requirements for establishing a robot-operator team in an assembly system.

ToMM 2 – ToMM was followed by ToMM 2, aimed at improving the TRL and demonstrating solutions in a laboratory environment.

A laboratory environment provides an opportunity to test concepts and guide the design towards a practically feasible solution. The research project consisted of members from three automotive companies, one research institute and one research university. The author is part of the research university and the research projects were funded by Vinnova within the FFI (Fordonsstrategisk forskning och innovation) program [70]. These projects forms the basis for the results and discussions presented in this thesis.

Figure 2.6: The methodological development of demonstrators to enhance understanding of issues related to safety in collaborative operations.

Additionally, the author has been involved in the following research projects:

1. SCOR [71] was aimed at developing a model to facilitate identification and selection of safety strategies for collaborative workstations.
2. SWEDEMO [72], a project aimed at introducing collaborative robots for automating application of sealants in aircraft structures. Participation in these projects has contributed to validation of the results presented in this thesis.

Figure 2.6 depicts the research approach taken to understand the challenges faced by the industry and to develop demonstrators to address them. It attempts to illustrate what Ellström [61] refers to as *waves* of understanding and problem solving for research participants whose ambition was to address safety-related challenges in collaborative operations with large industrial robots.

The path to understanding the problem and finding solutions can be understood as *interactive* (sec: 2.2), where both researchers and participants carry out the activities (presented in the following sections) together with an emphasis on joint-learning.

2.5.2 Case Studies & Data Collection

A case study is a research method that includes procedures & tools and is used to investigate a contemporary phenomenon in its context. A unit of analysis defines the case and aids researchers in determining parameters that explain the nature of the phenomenon under investigation [73].

A case refers to currently operational assembly workstations that are introduced by participating organisations based on their individual challenges. The cases are 1. Assembly of flywheel housing cover (sec: 4.1.1), 2. Assembly of under-body panels (sec: 4.2.1) and 3. Assembly of a dashboard [74].

The normal operations of an assembly station were studied to understand how participants interact with a workstation. A two step strategy was undertaken, first to describe the essential constituents of an assembly system and then to explain the interactions of these elements. Yin [73] describes these as exploratory and explanatory case studies.

Direct observation of the workstation during normal functioning permits the researchers to document the interactions of the operators with various elements of the workstation. There were observations on the sequence of tasks, logistics of the part from the storage to the workstation, part geometry and dimensions, equipment to support assembly operations, and how these sub tasks are arranged for efficiency. In addition to manual assembly cells, automated robotic workstations were observed and studied in parallel with the case studies.

A deliberate and frequent dialogue with various stakeholders, whose daily responsibility is to maintain a productive and efficient plant, has allowed researchers to validate observed phenomenon. These dialogues can be characterized as semi-structured interviews with potential benefactors of the research results.

The interviewees (operators, line managers, maintenance engineers) [52] can clarify and complement the observed data with insights that are not easily perceived during observation. Additionally, this presents an opportunity for the researchers to: 1. communicate the intention of their presence and the purpose of the research, and 2. perform the assembly of a part which has allowed the author to understand the nuances of assembly operations.

A literature review (academic articles, safety standards, equipment documentation) forms a theoretical basis that permits researchers to interpret and discuss findings gathered during observation and interview phases. Additionally, it allows researchers to identify knowledge gaps and contribute to academic development [75].

Review of safety standards such as ISO 12100 [76], ISO 10218-1/2 [22, 23] allows researchers to: 1. interpret current workstations under observation; 2. prescribe requirements for personnel and process safety; and 3. select, evaluate and design equipment viable for industrial use. Training on machinery (e.g. programming robots) and process (risk assessment) provides deeper insights on requirements for the functioning of industrial systems.

Trade shows (e.g. Automatica – Trade fair for industrial robots) and workshops at robot manufacturers can be seen as state of the art studies that allow the research team to gauge development trajectories of the manufacturing industry. These venues demonstrate off-the-shelf solutions that encourage discussions within the research team.

The data collection activities, augmented by scientific/practice knowledge, aid in understanding the problem and are the foundation for formulation of research activities to develop demonstrators that address challenges faced by the organization.

2.5.3 Demonstrator Development

As noted by Blessing and Chakrabarti [65] (sec. 2.3), the conceptualization phase overlaps with activities for understanding and formulating research questions and can be attributed to the pragmatic research purpose. That is, activities devoted to

developing concepts raise questions about the nature of the problem and parallel actions might be needed to address it.

The case studies and conceptualization of solutions was carried out during ToMM and development of physical demonstrators were carried out during ToMM 2. Based on the concepts, two cases (assembly of FWC and UBP) were selected for further investigation by developing them as laboratory demonstrators.

Laboratory demonstrators demand resources in terms of time and technical expertise. Therefore, two separate working groups, composed of members from the research project, were organized to develop the demonstrators. The author participated actively in both groups. The objective for the working groups was to develop demonstrators that showcase industrially viable solutions that meet current safety practices. Workshops, organized by the author, were used by the groups to plan and discuss relevant issues.

Workshops facilitated activities such as: 1. Project planning (driven by participants) to determine the tasks and the responsible, 2. Developing design requirements for demonstrators 3. Selection of appropriate tools (e.g. Risk assessment) and 4. Identifying lack of expertise and actions to tackle this issue. These frequent workshops provided opportunities for the members to learn, understand and clarify the research object. Paper VIII discusses the role of researchers and participants in the development of demonstrators.

Student projects were employed to methodologically develop concepts, evaluate designs and develop demonstrators (sec: 2.3). This provided the students with an opportunity to engage with the research team and contribute with problem solving and product development skills. The author and the participants have been responsible for: 1. Specifying student projects; 2. Mentor/supervision of the students and 3. Analyzing results from the student projects.

Paper VIII discusses the application of the presented research approach (fig: 2.6) and it is further discussed in chapter 6, while the outcome of the research work – interactive development of demonstrators – is presented in chapter 4.

FRAME OF REFERENCE

A frame of reference is presented to support the interpretation of a *safe collaborative assembly workstation*. Beginning with a presentation on automation & safety, this chapter details industrial robots, practices in industrial safety and a description of an assembly workstation.

Figure 3.1: Knowledge domains to support interpretation of a safe collaborative assembly system.

3.1 AUTOMATION

This section attempts to characterize automation and presents design issues and approaches to address these challenges.

3.1.1 Characteristics of Automation

Automation is the use of control technologies that enable machines to carry out tasks automatically [77]. Operators are responsible for ensuring that machines function as intended and this role, referred to as supervisory control, places humans in control through interaction [78]. In its simplest form, interaction between automation and humans occurs [79] when it is necessary to 1. Start &

Table 3.1: Level of Automation (LoA) taxonomy. Adapted from Sheridan & Verplanck [78].

NO.	DESCRIPTION
1.	Human does it all.
2.	Automation offers alternatives.
3.	Automation narrows alternatives down to a few.
4.	Automation suggests a recommended alternative.
5.	Automation executes alternative if human approves.
6.	Automation executes alternative; human can veto.
7.	Automation executes alternative and informs human.
8.	Automation executes selected alternative & informs human only if asked.
9.	Automation executes selected alternative & informs human only if it decides to.
10.	Automation acts entirely autonomously.

stop the system, 2. Specify the goals & tasks and 3. Recognize the system state through feedback devices.

The nature of interaction can be more complex and is dependent on the functions that will be automated or carried out by humans. Sheridan & Verplanck [78] introduced the Level of Automation (LoA), (see table 3.1), which is a hierarchical taxonomy that has allowed designers and researchers to discuss the characteristics of automation [80]. LoA consists of ten levels where the end-points represent either manual work or full automation, whereas the remaining levels require some form of interaction between humans and automation.

Task delegation is a requirement when automation is introduced to support manual work [81–83]. It is the process of assigning roles and responsibility for the subtasks of a parent task. That is, certain functions previously carried out by a human operator can be automated. This led to the development of a model that considers: 1. Level of automation and 2. Functions (type) to automate.

To address the issue of the function/type to automate, Parasuramen et al. [81] introduced a generic information processing model. It is based on four steps that a human goes through to understand a problem and take action. This model is comparable to Rouse's conceptual model (fig: 3.2) of an operator. The four steps a human takes to complete tasks are: 1. Sensory processing 2. Perception/Working memory 3. Decision making and 4. Response selection.

Figure 3.2: Conceptual Model of a Human Operator. Adapted from Hollnagel [84].

Parasuramen et al. [81] extended the LoA (Table: 3.1) to include *automation types* and stated that 1. The four human processing stages have their equivalent in system function, 2. The four functions in a system need not be automated at the same automation level and can vary [85]. The four functions are:

1. Acquisition Automation – A monitoring function that takes into account all relevant information about system status.
2. Information analysis – The acquired information is analyzed and the operator formulate options for achieving goals.
3. Decision & action selection – Based on the initial information analysis, a particular option or strategy is decided.
4. Action implementation – Carrying out the chosen option through control actions at an interface.

Systems that are designed at fixed automation level are termed *Static Automation*. Systems where automation levels across the four functions change are of two types: Adaptive and Adaptable Automation. Adaptive Automation [79] refers to context-aware systems that can change their behavior dynamically, where the division of labor between human workers and the automation system is not fixed. However, in Adaptable Automation, the operator is always in charge of changing the behavior of the automation system.

3.1.2 Challenges in Automation

Though automation has been responsible for many of the productivity gains, introducing automation has associated problems. Machines can be designed to function reliably. However, reliability is not a good measure for a safe system [86]). Errors in operation that have occurred under human control, have historically been judged and labelled as *human error*, and have resulted in serious accidents [86]). These are challenges that have to be considered in addition to machines operating reliably.

Researchers have attempted to understand the reasons for human error. According to Parasuraman et al. [83], 1. Situational awareness, 2. Work load and 3. Trust in automation are constructs that are aimed at better understanding and predicting human performance in complex systems.

Situational Awareness (SA) refers to a person's perception of their surroundings which enables them to make decisions, and according to Kaber & Endsley [85], there are two types of problems associated with SA: 1. Failure to detect a problem and 2. failure to understand the problem. A loss of SA can result in the operator taking a bad decision based on the system state and can be attributed to factors such as changes in vigilance and complacency, assumptions or misunderstanding on the part of the operator, or changes in the design of the system [80, 87, 88],

Current technologies allow designers to develop automation systems that can change their behavior and this is referred to as mode of operation. Sarter & Woods [89] note that, in complex systems, operators must keep track of the current mode,

know when & how to change the mode and understand the function of each mode, which can increase the cognitive demands on the operator.

Therefore, maintaining mode awareness can be particularly challenging in systems that can change their mode based on environmental input or for protection purposes. The effect of systems with multiple modes of operation can result in accidents due to the higher risk of inadvertent activation of modes (mode error) by the operator. Mode error can also occur if an operator attempts to change the mode but instead activates an unanticipated function because of a lack of awareness of the system state [89].

Additionally, there are several known problems associated with using automation that have to be recognized and addressed. Some of them are 1. over-reliance, 2. under-reliance, 3. compliance, 4. distrust, 5. misuse & disuse, 6. human-out-of-loop and 7. automation bias.

3.1.3 *Human-Automation Interfaces*

An interface is a device that enables communication between a human and a machine (e. g. buttons, lights, displays) and forms part of a system. A characteristic of a well-designed system is the ease of use [90], where information concerning automation modes, current system and future states can potentially enhance system performance – provided it does so in good etiquette [79].

With an increase in automation, inappropriate feedback can be the source of the problem [91]. As noted by Sarter et al. [89, 92], appropriate feedback is a prerequisite for operators to maintain awareness of the system state in order to take suitable actions. Interfaces can help to reduce the occurrence of an accident through effective warning signals or displays [93]. Literature presents several suggestions for guiding the design of interfaces such as:

1. Present information necessary for the operators to respond to events quickly. That is, information that best describes the current system state [79, 94] .
2. Feedback on the state of the system is important to reduce stress. The tools for feedback can be chosen to improve confidence and reduce the cognitive load of the operator [89, 92].
3. Interfaces can be designed to support anticipated and unanticipated events [94, 95].

3.2 INDUSTRIAL SAFETY

A presentation of hazard theory and industrial robots is followed by a discussion of safeguarding strategies and Risk Assessment.

3.2.1 Hazard Theory

The meaning of a hazard, hazardous situation and risk are often used interchangeably in spoken English. Hazard is a potential source of harm [76], whereas risk is a probability measure associated with a hazard [96] ($\text{Risk} = \text{Probability} \times \text{Severity}$). The term *probability* refers to the frequency of the hazard transitioning to an accident whereas the *severity* accounts for the overall consequence of the accident.

Ericson [96] states that an accident is an event which occurs when a hazard, or more specifically hazardous element, is actuated upon by an initiating mechanism. That is, a hazard is a prerequisite for an accident to occur and is composed of three basic components, which form the hazard triangle (fig: 3.3). These components are:

1. Hazardous Element (HE) – A resource that has the potential to create a hazard. Examples include end-effector failure, vibration induced loosening of fasteners, etc.
2. Initiating Mechanism (IM) – An event that triggers a hazard.
3. Target/Threat (T/T) – This is the people or equipment directly affected when the hazardous element is activated.

Figure 3.3: A hazard triangle consisting of the three essential components (Adapted from Ericson [96]).

Figure 3.4: The domino accident model was influential in shifting the emphasis to human error.

Ericson [96] notes that a *hazard description* contains the three hazard components. A well articulated hazard description can enable risk assessors to make better judgements about the nature of the hazard – its severity as well as its effect. A hazard description is a statement that predicts the occurrence of an accident: e.g. an operator (T/T) accidentally (IM) enters the collaborative workspace and collides with a fast moving robot (HE) (from Paper V, Table 2.).

Leveson (page 16 [86]) notes that the domino accident model (fig: 3.4) by Heinrich [97] was influential in shifting the emphasis in system safety to human

error. In the domino model, the general sequence of an accident is compared to five domino standing end on end. When the first domino falls, it knocks down the neighboring domino until an injury occurs.

3.2.2 Industrial Robots & Safety

Robots designed for industrial use are referred to as industrial robots and are formally defined as *Automatically controlled, reprogrammable multi-purpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications* [98].

An articulated robot has three or more independent rotational joints as shown in fig: 3.5 [22] and includes the arm, control system and the interface of the control system [22]. To perform tasks, robots are fitted with an end-effector – a device attached to the wrist [22] such as grippers, nut runners, glue dispenser etc.

Figure 3.5: An example of an industrial robot along with the control box and the teach pendant [39].

```
DEF KUKA_Sample()
INI
SPTP HOME VEL= 10[%] DEFAULT
LIN P3 VEL= 1 m/s CPDAT1 Tool[5] Base[10]
LIN P4 VEL= 1 m/s CPDAT2 Tool[5] Base[10]
SPTP HOME VEL= 10[%] DEFAULT
END
```

Figure 3.6: Sample KRL code for KUKA KRC4 Controller [39].

Safety Standards

ISO (International Organization for Standardization [99]) publish robot safety standards that are widely accepted across many countries. They document recommended safety practices and are revised according to market demands. The development of the standards is a coordinated effort by members from participating countries and business organizations. The following are standards for robot safety:

ISO 10218-1 : Aimed at robot manufacturers and specifies minimum design requirements for safe operations.

ISO 10218-2 : Targeted at system integrators who develop custom robotic solutions for the manufacturing industry.

ISO 12100 : This is a general safety standard that details risk assessment & risk reduction for machine safety.

Additionally, ISO/TS 15066 [100] is a technical specification intended to support risk assessment of collaborative operations. Recently, ISO/TR-20128 [101], a technical report was released to support the development of end-effectors.

Programming Robot Motion

Industrial robots are programmed either using a teach pendant or specialized software on a computer, (off-line programming). The common method is to teach a robot poses, where each pose refers to a combination of orientation and positions of the robot arm. A robot program can then be thought of as a set of poses and the robot path is the motion between the poses. Each pose is defined with respect to an axis (robot, tool or any other arbitrary axis) and the path between each pose is explicitly defined by the programmer.

A sample program in KRL (a programming language for KUKA robots) is shown in figure: 3.6. After initializing *INI*, the robot moves to the HOME position at 10% of the rated speed with a spline point-to-point path. Then the robot moves to points P₃ and P₄ at 1m/sec before moving back to the HOME position.

The robot path can also be based on external sensors integrated into the robot. Robot manufacturers include specialized software to develop custom applications based on force/torque, vision & proximity sensors. Programs are tasks to be carried out by the robot and play a crucial role in the safety of the system.

Safety & Modes of Operation

For programs such as those shown in figure: 3.6, an industrial robot can be operated in three modes of operations and are standardized in ISO 10218-1 (page 12 [22]). They are:

Automatic: In this mode, the system functions as set, running at programmed speeds and the safeguarding measures are active.

Manual reduced-speed: This mode permits programming using the teach pendant. The speed is limited to 250mm/sec and can be used without safeguarding measures.

Manual high-speed: This mode is used to test and verify program code. The motion is initiated by a human, provided enabling devices on the teach pendant are activated.

During automatic mode, two kinds of signals can be issued by the controller to stop robot motion. These are protective stops and emergency stops, as detailed in table: 3.2. In order to limit access to a hazardous region, safeguarding solutions are employed. Fixed, flexible or moving guards block entry to a unsafe area (robot workspace) and is a widely practised safeguarding strategy.

The selection, positioning, configuration and commissioning of sensitive protective equipment (SPE) are detailed in IEC 62046 [102], which aims to define the performance requirements for this equipment. They include provisions for two specific types: 1. ESPE and 2. PSPE. They automate monitoring of a pre-defined area and are used as part of the safety-related system [43, 102].

Electro-Sensitive Protective Equipment (ESPE) uses optical, microwaves and passive infra-red techniques to detect operators entering a hazard zone. That is, unlike physical fences, where the operators and the machinery are physically

Table 3.2: Comparison of emergency & protective stop (Adapter from ISO: -10218-1 [22]; page 10).

NO.	PARAMETER	EMERGENCY STOP	PROTECTIVE STOP
1.	Location of initiation means	Operator has quick, unobstructed access	For protective devices, the location is determined by the min. (safe) distance formulas described in ISO 13855
2.	Initiation	Manual	Manual or automatic
3.	Reset	Manual only	Manual or automatic
4.	Use frequency	Infrequent	Variable; from every operation to infrequent
5.	Purpose	Emergency	Safeguarding or risk reduction
6.	Effect	Remove energy to all hazards	Safely control the safeguarded hazard

separated, ESPE relies on the operators entering a specific zone for the sensor to be triggered (see fig: 3.7). Pressure-Sensitive Protective Equipment (PSPE) has been standardized in part 1 to 3 of ISO 13856, and works on the principle of an operator physically actuating a specific part of the workstation [103–105].

Figure 3.7: A laser scanner (left) & a light curtain (right) are examples of safety-rated sensors.

Figure 3.8: Three color stack light (left). A point source LED lamp (right) with several colors.

3.2.3 Collaborative Operations

Collaborative operation is defined as a *state in which purposely designed robots work in direct cooperation with a human within a defined workspace* [22]. Collaborative operations can only be employed when: 1. tasks are predetermined, 2. protective devices are active and 3. the robots have features that support collaborative operations as specified in ISO 10218-1:2011. A combination of one or more of the following *types* can be employed to develop collaborative workstations:

Safety-rated monitored stop: Stipulates that the robot ceases its motion, if the operator enters the collaborative workspace.

Hand guiding: Allows the operator to send position commands to the robot with the help of a hand guiding tool attached at or close to the end-effector.

This operation is permitted when the robot is at the hand-over position and signals a safety-rated monitored stop.

Speed and separation monitoring: Allows the operator and the robot to move concurrently in the collaborative workspace provided a minimum safe distance is maintained.

Power and force limiting by inherent design or control: Generally refers to robots designed to be intrinsically safe. It allows contact with the operator provided the exerted force is less than the safe threshold limit.

Manipulators designed for collaboration are referred to as collaborative robots and employ sensors or control schemes that enables them to detect and react to collision with the physical structure [35, 106–108].

3.2.4 Risk Assessment & Risk Reduction

Risk assessment is the systematic process of identifying hazards and evaluating risks associated with them. It is standardized in ISO 12100 [76], where the scope is to evaluate risks associated with industrial machinery (fig: 3.9). They are also referred to as MSRA (Machine Safety Risk Assessment [109]) or Job Safety Analysis. Risk assessment is a two step process: 1. Risk analysis and 2. Risk evaluation. Risk analysis consists of the following three steps:

1. *Determination of the limits of machinery*: – Limits in terms of space, use, and time are identified and specified for the machine for which risk assessment is to be carried out. This boundary include the physical space and can also includes environmental conditions, operators as well as all phases of the machine's life-cycle.
2. *Hazard identification*: – At this stage, reasonably foreseeable hazards are identified. Ericson [96] notes that this is a cognitive process backed by the experience of the investigators. Investigators should consider human interaction with all phases of machine's life-cycle, possible states of the machine and unintended behavior of the operator such as misuse of equipment.
3. *Risk Estimation*: – Risks are estimated based on two risk constituents – *severity of harm* and *probability of occurrence of that harm*. Severity of harm is based on the severity of injury and extent of harm that can result from the hazard being considered. Probability of occurrence of that harm is a function of a) Exposure of persons, b) Occurrence of a hazardous event, and c) Possibility to avoid or limit the harm (fig: 3.10).

Risk analysis provides information required for the risk evaluation and results in specifying the risk level in terms of *Negligible, Low, Medium High and Very High*. If risks are deemed unacceptable, *risk reduction* measures should be taken to either eliminate or mitigate the effects of the risks [76]. Risk reduction strategies can follow three stages and should result in elimination of hazards or mitigation of associated risks to an acceptable level.

1. *Inherently safe design measures* – If possible, design changes are specified that result in the elimination of risks.
2. *Safeguarding and/or complementary protective measures* – Safeguarding includes use of barriers, and protective devices can be used in cases where a change in design does not accomplish the goal of risk reduction.
3. *Information for use* – Residual risks after design changes and safeguarding measures should be documented in Information for use. This is complemented by operator training and safe operational procedures.

Figure 3.9: Overview of risk assessment & risk reduction [76].

Severity of Injury	Exposure to the Hazard	Avoidance of the Hazard	Risk Level
S1 Minor	E1 - Low	A1 - Likely	Negligible
		A2 – Not Likely	Low
		A3 – Not Possible	
S2 Moderate	E2 - High	A1 - Likely	Medium
		A2 – Not Likely	High
		A3 – Not Possible	
S3 Severe	E2 - High	A1 - Likely	High
		A2 – Not Likely	
		A3 – Not Possible	Very High

Figure 3.10: Risk level decision matrix. Adapted from RIA/TR R15.306 [110].

To realize a safe system, a system safety program (SSP) [96] is carried out, which is a coordinated effort that includes participants with various levels of expertise such as operators, maintenance, line managers etc. Risk assessment is conducted in conjunction with the development of a system or to verify that a system is safe for operation when changes are made in a design or process [22, 76].

Risk assessment is carried out by a team participating in workshops with helpful aids such as sketches, pictures or visits to the installation. As noted by Marvel [43], the discussions are held in plain language in order to describe hazardous situations and the interpretation of relevant standards.

Hazardous situations are identified for a task performed by the system or the operator. To identify hazards, the team can refer to: 1. a list of common hazards documented in ISO 10218-1/2, 2. hazards that can be postulated based on the working environment or 3. operator model to complete tasks (fig: 3.2). Risk estimation and evaluation are judgements made by the team and supported by a risk matrix such as shown in figure: 3.10.

3.3 ASSEMBLY OPERATIONS

An assembly plant is an industrial facility that functions to assemble components that constitute a product such as a vehicle [111]. They are made up of two or more assembly workstations/cells – discrete and well-defined workspaces – that function to assemble a finite number of parts to form a product.

According to Hales (ch. 40 [112]), physical, procedural and personnel are three aspects that must be addressed when planning an assembly cell. They consist of infrastructure such as workspaces, part handling systems, machinery, and devices to display information. Predefined tasks are carried out by workers and are allocated to specific workstations that require operating procedures for efficiency, quality, maintenance etc.

The design, management and functioning of an assembly cell is coordinated at the plant level and is regulated by national laws supported by appropriate standards. The human capital responsible for these activities is organized according to various functions (e.g. maintenance, safety, quality etc.) and have a direct/indirect stake in the overall performance of each workstation. Therefore, Risk Assessment (see sec 3.2.4) suggests various stakeholders to participate in this process.

The assembly of a vehicle begins with the painted chassis and continues along the line where parts are added sequentially [30]. The arrangement of the workstations takes various forms [112] and is dependent on the complexity of the assembly, takt time, level of automation etc.

Assembly lines are designed either as a set of *Stop & Go* workstations or continuously-moving line. In a *Stop & Go* workstation, the assembly line stops at the point where operations are performed whereas the assembly does not stop in a continuously moving line.

Two reasons are attributed to the higher cost of a continuously moving line and challenges the introduction of robot-based automation [113]. It requires a robust and automated part handling system that moves the chassis along the line. It also demands handling of a greater quantity of parts that will be assembled due to the lower takt time associated with such systems.

Figure: 3.11 shows a generic layout of an automotive assembly cell where operators assemble parts on the chassis which is either moving continuously or stops at each workstation. Logistics functions to deliver parts from the warehouses to the workspace, where they are stored in storage bins. The operator picks up the part from the bins manually or using an assist device.

Assembly plants are manual-labor intensive, which implies that the design of assembly lines and workstations caters to the requirements of workers. These include: 1. shorter distance between workstations which facilitates communication and interaction, 2. easy entry and exit from workstations and 3. reduced requirements concerning handling, cycle times, inventory as well as physical space compared to automated solutions (ch 40 [112]).

Figure 3.11: A generic layout of an assembly cell where operators complete a sequence of tasks.

The sequence of tasks carried out in a cell is designed to adhere to the overall efficiency requirements [112]. Luczak & Mueller [5] (ch 16) state that the main functions are automated, whereas the secondary functions that support the main function (e.g. preparation, start/stop etc.) are carried out manually.

The assembly function can be analyzed into smaller subtasks using methods such as Hierarchical Task Analysis [114] or MTM [115]. The feasibility of introducing automation (e.g. nut-runners) or ergonomic evaluation of manual tasks or a combination of both (e.g. ergonomic support) also determines the sequence of tasks to be performed [33, 116, 117]. Tasks that require cognitive skills (e.g. take decisions and adapt to new situations, hand-eye coordinations) are difficult to completely automate and influence the analysis.

LABORATORY DEMONSTRATORS

This chapter presents two physical demonstrators that represent the final results from a series of research activities carried out interactively. They contribute to a general understanding on the nature of collaborative systems with large industrial robots. They are: 1. Hand-guided assembly of a Flywheel Housing Cover (FWC) and 2. Collaborative assembly of Under-body panels (UBP).

They exemplify workstations based on 1. the nature of the *assembly operations* (hand-guided robots & assembly on a continuously-moving line) and 2. the nature of the *assembly task* (heavy & light/flexible component).

4.1 HAND-GUIDED ASSEMBLY OF FLYWHEEL COVER

A description of the workstation as observed at the manufacturing facility is followed by a discussion on the development of the end-effector and a presentation of the tasks, layout and safeguarding strategy of the laboratory demonstrator.

4.1.1 Case Study – Assembly of Flywheel Cover

The task is the assembly of a flywheel housing cover (FWC) on an engine block (fig: 4.1). The FWC weighs approx. 20kg and is made of cast metal that is machined before being transported to the workstation. Figure: 4.2 illustrates the tasks currently carried out manually to assemble the FWC. The sequence of operations observed at the manufacturing facility is:

1. From position P₁, the operator picks up the FWC from the material rack using a lifting device. The operator manipulates the object by exerting force on the FWC that is hanging on the lifting device and secured by a manual clamp.
2. The operator physically moves the FWC to the integrated machinery (P₂) where the part is prepared for assembly. The auxiliary task includes application of sealant and pre-installation of bolts on the FWC.
3. The operator then moves the FWC to position P₃ and mates it to the engine block. The FWC is guided into position using two pre-mounted guide pins. The bolts are fastened using powered nut-runners by one or more operators.

Figure 4.1: Picture of a flywheel housing cover (silver) mounted on the engine block.

Figure 4.2: Illustration of the layout and tasks from picking the FWC (P1) to assembly on the engine (P3).

The workstation is part of the engine assembly facility and the cycle time varies between 3 and 5 minutes (approx.) depending on the orders to be processed during the day. This affects the number of operators (three were observed during the afternoon shift) that are responsible for this workstation.

The entry to and from the workstation is free from physical barriers, but the boundary is marked by equipment supporting the workstation. Operators who have experience of working at the facility undergo additional training for this workstation as the demands are high. Bolts that fall to the ground are not used and are removed from the workstation. Workers are required to wear safety shoes and gloves to protect their hands and feet.

4.1.2 *Designing the Hand-Guiding Device*

The decision to control the movement using a force-torque (F/T) sensor was based on two reasons: 1. An F/T sensor can allow the user an intuitive hand-guiding experience. 2. Off-the-shelf solutions to control the robot with a F/T sensor from the robot manufacturer was available.

Additionally, ergonomic simulation of the case carried out by Ore et al. [117] supported the use of F/T sensor to hand-guide the robot (fig: 4.3). The selection of an F/T sensor (Schunk/ATI [118] sensor model: Gamma SI 130 – 10) was made through discussions with the sensor manufacturer.

The act of manipulating the FWC around the workstation has two parts: carrying a heavy load and moving it around. The robot's task is to carry the heavy load while the operator guides the robot, and thus the FWC, to the correct location. The hand-guiding tool is mounted on the F/T sensor and this assembly is mounted on the end-effector of the robot (Paper III).

The force and torque values from the sensor are processed using RSI (Robot Sensor Interface), a software package for KUKA KRC4 to control motion based on sensors (sec: 3.2.2). The sensor-guided motion can be initiated and executed from KRL.

Figure 4.3: Ergonomic evaluation of the case carried out by Ore et al. [117].

Figure 4.4: CoCo – Collaborative Controller developed in a student project to hand-guide an industrial robot (Paper II).

Figure: 4.4 shows a demonstrator developed to understand the design requirements of a hand-guiding tool (Paper II) achieved through a student led development projects. An analysis of the hand-guiding tool by the investigators highlighted the importance of:

1. Interaction using physical devices (e.g. enabling switches) coupled with visual interfaces (e.g. lamps, status light) mounted on the end-effector or in the vicinity.
2. Inability of a human to accurately position the robot must be considered during risk assessment.
3. Ergonomics of the hand-guiding tool are critical to avoid injury. Physical ergonomics include the shape of the grip, width between the grips and tensions to actuate enabling switches.
4. The speed of the robot while hand-guiding is critical to safety.
5. The rigidity and damping of the end-effector is critical to avoid feedback to the sensor. That is, movement of the robot might induce vibrations on the sensor as they are coupled.
6. The system should guide the operator to the target location. That is, the movement of the robot should be constrained within a safe volume. Within this volume, the robot can be hand-guided at the discretion of the operator.

These insights led to the development of a revised concept for an end-effector and a hand-guiding tool, as shown in figure: 4.5 and discussed in detail in Paper IV. The changes support the operator in aligning the FWC with the engine-block and take into account the requirements specified in ISO 10218-1/2 [22, 23].

4.1.3 *Developing & Safeguarding the Layout*

Risk Assessment guided research activities devoted to developing the layout of the collaborative workstation shown in figure: 4.7 (Paper III) and the hand-guiding tool (fig: 4.5) (Paper II–III). During this iterative process, the workstation

Figure 4.5: Hand-guiding tool with enabling switches & an emergency button.

Figure 4.6: Block code to enable hand-guiding using a force-torque sensor.

boundaries were determined along with the sequence of tasks to be performed by the operator and the robot.

A result of risk assessment is the specification of the robot, operator and collaborative workspaces. The collaborative tasks were specified to be carried out in the collaborative workspace (cw) as suggested in ISO 10218-1/2 [22, 23]. Similarly, in the robot workspace, the intention is that the robot tasks can be programmed to move at high speeds. Operators can prepare for upcoming tasks in the operator workspace.

Safeguarding the system was realized through the use of physical fences, pressure sensitive mats and light curtains (fig: 4.7). Fences form a physical barrier and require a deliberate action by the operator to enter the robot workspace, which is a hazard zone due to the fast moving robot. Therefore, physical fences eliminate hazards associated with loss of situational awareness (Paper VII).

To hand-guide the robot, the operator must enter the robot area to access the hand-over position (P3 in fig: 4.7). While the robot is in automatic mode, light curtains and pressure sensitive mats monitor the system for safety. The change in state of the system and the safety function enabled by these sensors are discussed in Paper III. The hazards identified during risk assessment have been reported in Paper IV along with the risk reduction measures.

Additionally, warning lamps were installed to communicate the state of the system to the operators or nearby personnel. It may be noted that in the concept presented in figure: 4.7 (Paper III), pressure sensitive mats monitored the robot workspace. Due to practical limitations, they have not been used in the laboratory demonstrator shown in figure: 4.8.

The hand-guiding tool (fig: 4.5) is integrated with an enabling switch, the absence of which can lead to the following hazardous situations (Paper VII):

1. While hand-guiding the operator can be momentarily distracted and forget that the sensor-based motion is active.
2. Other operators in the vicinity or nearby process disturbance can initiate robot motion.

In addition, the design ensures that

Figure 4.7: Plan view of the layout conceptualized to enable operators to safely hand-guide a robot (Paper III).

the operator's hands are at a predefined and safe location, thereby eliminating the risk of crushing and/or clamping of hands or other body parts.

4.1.4 Collaborative Assembly of Flywheel Cover

The physical demonstrator realized in a laboratory environment is shown in figure: 4.8 and the task sequences are described in figure: 4.10. The assembly cycle begins with the robot moving at high speed completing robot tasks. These tasks were simulated to include picking up the FWC from the rack and carrying out auxiliary jobs. Once the robot tasks are complete, the robot stops at the hand-over position (fig: 4.8 [No.10]) and the warning lamp (fig: 4.8 [No.2]) changes from red to green. This informs the operator that the hand-guiding operation can be initiated. The operator monitoring the system recognizes this change and enters the collaborative workspace to hand-guide the robot. Hand-guiding is activated when both the enabling switches on the hand-guiding tool (fig: 4.5) are engaged and will allow the operator to move the robot towards the engine-block (fig: 4.8 [No.11]).

After mating the FWC with the engine-block, the operator returns the robot back to the hand-over position. The operator engages the three-button switch and then leaves the collaborative workspace. The operator starts the next cycle by engaging the mode-change button (fig: 4.8 [No.6]) after exiting the collaborative workspace.

INDUSTRIAL WORKSHOPS

Industrial workshops were organized to allow members from the industry to experience working collaboratively with large robots. Attendees were allowed to carry out the task sequence presented in figure: 4.10. The demonstrations were carried out in *manual-reduced speed* (Max speed = 250mm/sec) where the programming of the system (coordination of robotic system with sensors and lamps) was written in KRL.

Figure 4.8: Picture of the demonstrator developed to showcase safety of hand-guided collaborative operation.

Figure 4.9 is a picture from one of a series of workshops organized to gain valuable feedback through discussions with the attendees. This workshop was attended by 26 representatives from 6 organizations. Interviews and surveys of the attendees were carried out to gather data about their experience from hand-guiding the robot and these results have been presented in Paper VI.

These results point at the usefulness of physical demonstrators to practicing engineers in the following ways: 1. The demonstrator facilitated internal discussions on the feasibility of hand-guided robots at their organizations, 2. Improved confidence in the safety of collaborative operations with large industrial robots and 3. Validation of ergonomic simulations of hand-guided industrial robots. Additionally, the final workshop functioned as a mechanism for dissemination of research results to the manufacturing community [119].

Figure 4.9: Demonstration of hand-guided assembly of a FWC. [Photo: Sofia Hägg, 15th-Feb, 2017]

Figure 4.10: Description of the task sequence (a – f) where a robot is hand-guided to assemble a flywheel cover on an engine block. Figure adapted from Paper IV and the sequence can be viewed online at [120].

4.2 COLLABORATIVE ASSEMBLY OF UNDER-BODY PANELS

This section summarizes contributions made to improve knowledge in collaborative assembly on a continuously moving line with large industrial robots.

This section begins with a description of the assembly workstation as observed at the manufacturing facility. A presentation of the end-effector development is made to give the reader insights into 1. design challenges related to safety and 2. the nature of Interactive Research operations.

The result is the laboratory demonstrator (sec: 4.2.4), which is presented to exemplify functioning of a collaborative workstation where an industrial robot is used to aid operators in the assembly of under-body car panels.

4.2.1 Case Study – Under-body Panel Assembly

The task is the assembly of under-body panels (UBP) on a car that is moving at a height of 1800mm with a speed of 100mm/sec (fig: 4.11). The plastic panels are light (less than 1kg) and flexible (see fig: 4.12).

Figure 4.11: Illustration of the current work process for the operator from reading information to assembly of an under-body panel (Paper I).

The sequence of tasks carried out by the operator at the manufacturing facility is as follows:

1. The operator identifies the car model moving on the assembly line by reading the information label kept on the body of the car.
2. The operator proceeds to select the correct plastic panel from the storage box and inserts clips in the panel.
3. The operator picks up the panel, walks to the moving line and places it under the car using the previously installed clips.
4. The operator walks to the pneumatic screwdriver (marked as a blue circle), picks it up and adopts a position under the car.
5. The operator manually secures approximately 8-10 bolts under the car. The bolts are kept in a belt-pouch.

One operator is responsible for tasks at this workstation, with similar operations being carried out downstream. The workstations located upstream

and downstream are easily accessible and allow easy restocking of the storage bins. The takt time is 59sec (approx.) and the number of panels to be installed is dependent on the model of the car. It may be noted that certain models do not require under-body panels. However, the expectation is that the number of panels/car will increase in future models.

4.2.2 *Safe End+Effector*

As noted before, the panels are light and flexible. The surface of the panel that faces the ground is smooth as it serves to improve the aerodynamic efficiency of the vehicle. The opposite side of the panel contains design features to improve the structural rigidity and features to support manufacture and assembly of the panel.

The choice of suction cups to grip the panel was based on two reasons: 1. Suction cups are used for applications where the part can be gripped on one side. 2. Suction cups can adapt to minor changes in part location (in the storage rack) and part variations in terms of geometry.

Figure: 4.12 is a picture from a workshop organized to develop a concept for an end-effector and specify general requirements for safe functioning. These requirements guided student-led development of the end-effector. Student projects were the primary mechanism for designing, purchasing, installing and testing the end-effector with the robotic system.

Figure 4.12: Workshop to specify requirements for end-effector to grip a panel. The panel is shown resting on a prototype.

Figure 4.13: The end-effector mounted on the robot. The blue cover reduces the risk of accidents.

The blue cover (fig: 4.13) is a passive safety measure that envelops the structural elements that contain suction cups and pneumatic tubes. Three suction cups grip the panel and are controlled by a *piCOMPACT 23 1-Channel* controller [121] that has the ability to activate/deactivate vacuum and blow-off air pressure. The cover is soft and has the ability to move 5cm (approx.) in all directions and is meant to protect the operator from sharp edges. It reduces the probability of body parts (e.g. hair) getting stuck in the moving end-effector.

Simulating a Moving Line

In practice, the automotive chassis is mounted on a moving line where parts are added sequentially. In the laboratory environment, the moving line was simulated

using a linear actuator from Festo [122]. A belt driven ELGA-TB-RF-70-3000-0H linear actuator with a CMMO-ST-C5-1-DIOP [122] motor controller was integrated with the robotic system. A fixture mounted on the moving line approximated the mounting holes of the car body. Figure: 4.18 [No.10] shows a structure designed to support the linear actuator that moves at a constant speed of 100mm/sec for 3000mm .

Figure 4.14: Virtual demonstrator developed by the participating organization (left) that simulates assembly of UBP. A scaled demonstrator facilitated discussions during risk assessment (top right). Prototype of a nut-runner with an enabling switch (bottom right).

4.2.3 *Developing & Safeguarding the Layout*

The assembly task was delegated as follows: 1. The process of picking and placing the panel using vacuum cups can be automated. 2. The task of securing the panel with bolts using a nut-runner can be carried out manually. Workshops were organized to further separate these tasks into subtasks that fulfill the goal of the workstation. Risk Assessment was carried out to analyze these tasks and this process was documented using official risk assessment templates.

Demonstrators (top right in figure: 4.14) supported these activities and were valuable in technical discussions with personnel who were not familiar with the case. That is, it acted as a cognitive support for discussions and clarifying design intent. The discussions were directed towards understanding the problem, specifying requirements for the end-effector, specifying type and location of safety sensors etc.

These discussions formed the basis for the virtual demonstrator (left in figure: 4.14; Paper V) developed by the participating organization and served to communicate research results internally and in discussions with members from safety standards and potential suppliers. Paper V presents hazards associated with collaborative assembly on a continuously moving line that were recognized during risk assessment.

Figure 4.15: Control architecture of the system where the safety controller (fig: 4.16) orchestrates functioning of the sub-systems. Adapted from Paper V.

Figure: 4.15 illustrates the safety architecture of the system shown in figure: 4.18. The safety controller functions as a master device that controls the operations of the collaborative workstation. The control box shown in figure: 4.16 contains components designed to adhere to industrial safety requirements such as safety CPU (*central processing unit*), input/output (I/O) modules and safety relays.

Table 4.1: Tabulation of Safe/Not Safe signals from light curtain (LC), laser scanner (LS) and the emergency button (EB) and its effect on the system.

LS	LC	EB	System Status
Safe	Safe	Safe	Normal function
Safe	Safe	Not Safe	Emergency Stop
Safe	Not Safe	Safe	Emergency Stop
Not Safe	Safe	Safe	Protective Stop

To begin a cycle, the laser scanner and light curtain are active and broadcast a safe signal to the safety controller which allows the system to function normally. As shown in table: 4.1, normal functioning of the system can be initiated when the safety sensors broadcast safe signals to the safety controller. This permits the system operator to manually initiate the robot program. The robot program is run from the robot controller, which controls the suction cups and the moving line.

Figure: 4.17 is a screen shot of the configuration tool to define the monitoring area of the laser scanner (SICK S30A-4011CA [123]). This figure shows the monitoring area (in red), which includes the collaborative workspace (fig: 4.18 [No.5]) and the robot workspace within the fenced area (fig: 4.18 [No.4]). The blue ragged lines are nearby objects detected by the sensor. Current technologies allow specification of multiple monitoring areas that can be switched on/off based on requirements or modes of operations.

If the operator fails to complete the assembly task on time, the light curtain (fig: 4.18 [No.8]) will be triggered and will result in an emergency stop. If an operator triggers a protective-stop by entering the collaborative workspace when

Figure 4.16: Master safety controller [123] along with I/O modules and safety relay.

Figure 4.17: Picture of the scanning field monitored by safety scanner (fig: 4.18.6).

the robot is in automatic mode, a reset-button (fig: 4.18 [No.9]) can be used to restart the next cycle. Warning lamps placed at two ends of the workstation communicate the state of the system to the operator.

Physical fences (fig: 4.18 [No.4]) separate the robot and the collaborative workspace. The work process requires that the end-effector moves out of the fenced area in order to place the panel under the car (fig: 4.20c). However, the physical fences are placed so that only the end-effector moves into the collaborative workspace. Additionally, the boundary of the collaborative workspace is marked appropriately.

Figure 4.18: Picture of the laboratory demonstrator developed to showcase safe collaborative assembly on a moving line.

4.2.4 Collaborative Assembly of Panels

The physical demonstrator realized in a laboratory environment is shown in figure: 4.18 and the task sequences are described in figure: 4.20. In the demonstrator, the assembly cycle begins with the robot in automatic mode picking up the panel using suction cups. The robot moves to the collaborative workspace and synchronizes with the moving line. Then the system initiates collaborative

mode by: 1. The warning lamp changes from red to green and 2. The laser scanner mutes the monitoring of the collaborative workspace.

The operator monitoring the system enters the collaborative workspace and begins fastening the panel to the simulated car body while following the moving line. The bolts are fastening using the electric nut-runner shown in figure: 4.14. When the bolts are fastened, the operator moves out of the collaborative workspace and engages the mode-change button. The button directs the operator's attention by signaling with blinking lights when the robot is nearing the end of the line. When the operator engages the mode-change button, 1. The light stops blinking, 2. The laser scanner activates monitoring of the collaborative workspace, 3. The lamp turns from green to red and 4. The robot moves to the end of the line and then proceeds to move out of the collaborative workspace.

INDUSTRIAL WORKSHOPS

The system shown in figure: 4.18 employs a industry-compliant approach to managing safety that mirrors current practices. The integration of the system along with the programming of the robot was carried out by certified professionals. Therefore, this demonstrator shows that collaborative systems with large industrial robots are a possibility with current off-the-shelf products and integration practices.

This research result was presented at a workshop (fig: 4.19) (one of several workshops) where 46 representatives from 11 organizations attended the demonstration of a robot assisted assembly of under-body panels. Attendees were allowed to carry out the task sequence presented in section: 4.2.

Additionally, the workshop also presented 1. Results from a parallel research project (Virtual ToMM) that investigated methods to virtually simulate a collaborative system 2. Current state of the art collaborative systems and 3. Safety systems for collaborative operations. This public event was carried out as a research dissemination activity [124].

Figure 4.19: Demonstration of collaborative assembly of UBP. [Photo: Mikael Sönne, 6th Sep 2018]

Semi-structured interviews with the attendees, supported by surveys, indicate that the demonstrator facilitated broader discussions on the feasibility of collaborative operations at their organizations. Additionally, clarity in safety requirements, in terms of workspaces and safety sensors, was expressed by the attendees.

Figure 4.20: Description of the sequence of tasks to assemble plastic panels under the body of a car on a moving line. Figure adapted from Paper V and the sequence can be viewed online at [125].

5

MODEL OF A COLLABORATIVE CELL

A model that describes a collaborative workstation will be presented where a model is a representation of a system using general rules and concepts. The model is shown in figure: 5.1 and is based on an analysis of the two demonstrators (chapter 4) and consists of three elements – Workspaces, Tasks and Interaction – which will be examined in the following sections.

Figure 5.1: Workspaces, Tasks & Interaction are the elements of a model that describes a collaborative workstation.

5.1 COLLABORATIVE, ROBOT & OPERATOR WORKSPACES

Workspaces are physical spaces allocated to install machinery and/or perform tasks. The physical workspace that makes up a collaborative system can be conceptualized as collaborative, operator & robot workspaces (see Table 5.1) as illustrated in figure: 5.2 (Paper II). This categorization is a result of recognizing that:

1. There are two primary resources that can carry out tasks: an operator and an industrial robot. This is in contrast to robotic and manual workstations where the robot and the operator are the primary resources respectively.

Figure 5.2: A generic layout of a collaborative workstation in terms of robot, operator and collaborative workspaces (paper II).

2. The workspaces (fig: 5.2) together form the *limits of machinery*. As noted in section: 3.2.4, establishing the limits of machinery is the first step in carrying out risk assessment.

5.1.1 Collaborative Workspace

Collaborative workspace is defined as a *Workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation* [22]. The perimeter of the workspace is dependent on the space required to complete collaborative tasks as well as movement of the part through the workstation.

To exemplify this point, consider the assembly of UBP (fig: 4.18), where the collaborative workspace, adjacent to the robot and operator workspaces, is a function of factors such as: 1. The time required by the operator to enter, carry out the collaborative task and exit the workspace, 2. The programmed path of the robot's arm and 3. The location and geometry of the assembly in the workstation. These factors are applicable to the assembly of FWC (fig: 4.7). However, the collaborative workspace is dynamic, as discussed in section: 5.1.4.

5.1.2 Robot Workspace

A robot workspace is understood as the spatial limit for the robotic system. This workspace is safeguarded as suggested in ISO 10218-2 [23], where the tasks delegated to the robot can be carried out to fulfil productivity goals. That is, the robot can move at speeds significantly faster during automatic mode within this workspace. Based on research activities presented in chapter 4, the perimeter is affected by various factors:

- The minimum floor space required by the robot is the projection (on the horizontal plane) of the programmed path and corresponds to robot tasks (figures: 4.10a & 4.20b).

Table 5.1: Descriptions of collaborative, operator and robot workspaces that form the limits of the collaborative system.

Workspaces	Description
Operator	Tasks delegated to the operator are designed to be performed within this workspace. Operators have access to the collaborative workspace and can monitor the system (paper III, IV & V).
Collaborative	Workspace within the safeguarded space where the robot & a human can perform tasks simultaneously during production operation [23].
Robot	A space where a robot can be programmed to move at speeds that meet process requirements. The space includes robot-path & machinery that supports the workstation (paper III, IV & V).

- The placement of equipment that performs auxiliary functions (e.g. fixtures, sealant, logistics) affects the footprint of the workstation (paper III, IV & V).
- Safeguarding measures (e.g. physical fences) are installed at calculated distances, determining the extent of the robot workspace (paper III, IV & V).

5.1.3 Operator Workspace

An operator workspace is an area where: 1. Operators can monitor the robotic system. The physical space and the process can be observed directly or through monitoring devices. 2. An area allocated for parts and equipment required by the operator to complete tasks (e.g. nut-runner). 3. Operators has safe and easy access to functions related to the system (e.g. nemergency stop, enabling devices, robot start etc).

Additionally, based on observations and interviews carried out during the research phase, an operator workspace should allow the operator: 1. To plan and discuss activities with other co-workers; 2. Free movement out of the plant in case of an emergency and 3. An unobstructed path to the collaborative workspace.

5.1.4 Temporal Nature of Collaborative Systems

In addition to the spatial aspect, Krüger et al. [31] present a temporal characteristic to describe a collaborative workspace (also see Paper: IV & Paper: V). That is, a collaborative workstation can be understood as: 1. a space sharing system or 2. a space and time sharing system [31].

In a space sharing system, two forms of collaboration are envisioned: 1. The operator carries out handling task while the robot carries out assembly tasks or 2. The robot carries out handling task while the operator carries out assembly tasks. In the space-time sharing system, both the human and the robot carry out tasks either independently or together.

The temporal nature of a collaborative workspace (CW) implies a time-frame within which collaborative tasks should be completed. This introduces a few challenges for system designers:

1. Understanding and specifying a set of conditions that leads to an event upon which the CW can be occupied by a robot or an operator. This challenge implies specification of: a) how long a CW can be occupied. b) appropriate reaction if these conditions were to be violated. c) a sensor system that can monitor the CW for the specified time.
2. Specification of appropriate feedback devices for relaying information between human and the robotic system.

Figure 5.3: Operator & robot complete tasks together (left). Robot moves at high speed in the monitored robot workspace (right).

Figure 5.4: The monitored workspace (marked red) represents the volume within the CW that constrains the robot path.

A mode of operation termed *collaborative mode* (sec: 5.3) was proposed as a predetermined state, where operator and robot can safely complete tasks together in the collaborative workspace. The dynamic nature of the collaborative workspace (fig: 5.3) creates the possibility for designers to switch a collaborative workspace on or off either partially or fully as and when needed.

That is, the safety-sensor that monitors the collaborative workspace can be muted during collaborative mode provided the system is in the safe state as specified by the system designers. To illustrate this point, in the assembly of UBP (sec: 4.2), the monitoring activity of the laser scanner is muted during collaborative mode and the path of the robot is constrained as shown in figure: 5.4. Whereas, in the assembly of FWC (sec: 4.1), the monitored workspace is within the fenced area and is muted during collaborative mode.

5.2 TASKS IN COLLABORATIVE WORKSTATION

The assembly task can be broadly distinguished as collaborative, operator and robot tasks (Paper II). It is valuable to highlight that collaborative tasks are carried out by the operator and robot in the collaborative workspace. Tasks delegated to a robot, regardless of the intended spatial location, are a set of preprogrammed instructions. Similarly, operator tasks are predefined and carried out by an operator(s).

The term *collaborative task* is introduced for clarity in discussing interaction and safety. Methods such as Hierarchical Task Analysis (HTA) have been used to analyze assembly tasks in the context of a collaborative system [108]. Table 5.2 illustrates sequence of subtasks delegated to an operator and a robot for the demonstrators discussed in chapter 4.

In the context of developing a collaborative solution from a manual workstation, task delegation does not imply an even separation of labor between automation and the human worker. As noted by several authors [90, 91, 126–128], task delegation results in specification of different forms of task (e.g. supervisory control). That is, operators responsible for carrying out assembly tasks might be required to monitor the robotic system, in addition to operator task.

As noted by Miller and Parasuramen [82], introduction of automation requires task delegation. That is, in a collaborative system, tasks that were carried out manually are delegated between an operator and the robot. Literature provides guidelines for task delegation, such as:

1. Luczak & Mueller [5] notes that in the design of work in advanced manufacturing systems, the main functions are carried out by machines whereas the secondary functions that support the main function are carried out manually.
2. Tasks to be automated should be technically feasible and repeatable [5].
3. Tasks that may lead to injury can be automated.
4. Tasks that may be dangerous to humans can be automated [5].

Table 5.2: Preliminary decomposition of tasks delegated to operator & robot.

Assembly of FWC (sec: 4.1)	Tasks	Assembly of UBP (sec: 4.2)
Robot picks up Flywheel cover & carries out auxiliary tasks	– Task 1 –	Robot picks up Under-body panel
Robot waits at the hand-over position.	– Task 2 –	Robot synchronizes with moving line.
Operator begins hand-guiding the robot to assemble FWC.	– Task 3 –	Operator fastens the panel with bolts.
Operator returns robot to hand-over position.	– Task 4 –	Operator prepares for upcoming task.

5.3 INTERACTION

The term collaboration makes it explicit that operators and robots collaborate in some form to carry out a task. This section discusses the phenomenon of interaction, which is an inherent action for collaboration.

Collaboration is an act of doing something with someone to achieve a goal. On the other hand, interaction refers to the act of communication between

two participants that intended to collaborate. In human-robot interaction, this is enabled by interface technologies such as displays, gesture and voice control, buttons and lamps etc.

5.3.1 *Initiating Modes of Operation*

A benefit of computer based systems is the possibility to specify *modes of operation*. A mode of operation refers to a set of behaviors exhibited by a system that can be triggered when predefined parameters are activated. In this thesis, a *collaborative mode* (CM) was proposed and can be defined as a state in which operators can safely enter the collaborative workspace. This mode is pertinent to systems defined by ISO-10218 [22, 23] as *collaborative operations*. Considering the temporal nature of a collaborative workspace (sec: 5.1.4), designers are faced with the following dilemmas:

- Who decides when the collaborative mode can be initiated?
- Who decides when the collaborative mode can be reverted?

That is, is it the human or the machine that should be tasked with this decision? These dilemmas can be interpreted as a reformulation of the safety guideline from ISO 10218-2 (sec: 5.11.4 in [23]) which states that *The change point between autonomous operation and collaborative operation is a particularly critical part of a collaborative application. It shall be designed in a way that the robot cannot endanger personnel when changing from the autonomous operation to the collaborative operation and back to the autonomous operation.*

That is, specification of a *collaborative mode* emphasizes safety in initiating and resetting CM. In the demonstrators presented in chapter 4, the task of initiating CM is automated. That is, the automation was designed to automatically initiate CM and inform the operator of the change to CM, which was achieved by turning the lamp from red to green. In both demonstrators, this is a cue for the operator to act and respond by carrying out collaborative tasks.

Table 5.3: The role of the operator and the robotic system in initiating and resetting collaborative mode (CM) during normal operations.

	Demonstrator 1	Demonstrator 2
Initiating CM	Robotic system	Operator/Robotic system
Interface to initiate CM	Warning lamp	Warning lamp
Resetting CM	Operator.	Operator.
Interface to reset CM	Three-button switch, Mode-change button	Mode-change button

The task of resetting CM, i. e. changing state back to automatic mode, is carried out manually at the discretion of the operator. The role of the operator and the

robotic system in initiating and resetting CM, based on the process detailed in sec: 4.1 and sec: 4.2, has been summarized in table 5.3.

DEMONSTRATOR 1 CM is initiated when: 1. The robot is at the hand-over position, 2. Light curtain is muted and 3. Lamp turns red to green. The operator can now enter the collaborative workspace (fig: 5.5a) and take control of the robot by engaging both the enabling devices (fig: : 5.5b).

To reset CM back to automatic mode, 1. the robot should be at the hand-over position, 2. the monitored area is safe, 3. the three-button switch should be engaged, and then 4. the mode-change button (fig: 5.5d) is engaged. When the mode-change button is engaged, the lamp turns from green to red and the system starts the next production cycle.

Figure 5.5: (a) Operator enters the collaborative workspace after the lamp turns green. (b) Enabling switches integrated with the hand-guiding tool. (c) Three-button switch initiated by operator. (d) Mode-change button to initiate automatic mode.

DEMONSTRATOR 2 CM is initiated when: 1. The robot is synchronized with the moving line, 2. Laser scanner is muted and 3. Lamp turns red to green. The operator can now enter the collaborative workspace (fig: 5.5a) and begin collaborative tasks.

To reset CM back to automatic mode, 1. the mode-change button is engaged. 2. the monitored area is safe. When the mode-change button is engaged, the lamp turns from green to red and the system starts the next production cycle.

Figure 5.6: (a) Robot initiates collaborate mode (CM). (b) Operator exits collaborative workspace after completing tasks. (c) Mode-change button initiated by operator. (d) Laser scanner monitors the collaborative workspace.

The above discussion (*Demonstrator 1 & 2*) pertains to interfaces for initiating and resetting collaborative mode. In practice, the interfaces are design features to

support awareness of the system-status and function as a bi-directional channel for information exchange. That is, the operator can easily understand the status of the current cycle whereas the system understands that the collaborative task is complete and the operator is in a safe position.

5.3.2 *Interfaces and Safety*

As noted in Paper VII, interfaces are critical in maintaining awareness of the system state. The concept of awareness was discussed in terms of situational and mode awareness indicating that a loss in awareness can lead to an accident or production delays. The following observations explain the influence of awareness in maintaining a safe working environment (Paper VII):

- When the operator is carrying out tasks, attention is devoted to this activity. It is difficult to maintain awareness of the system/surrounding while occupied with this task. E. g. While preparing for upcoming tasks, the operator might find it difficult to judge the initiation of collaborative mode.
- The final-assembly plant is a populated environment where workers have relatively easy access to workstations. It is therefore a foreseeable hazard that personnel might enter (accidentally/intentionally) a hazardous zone or engage with operators working at a workstation.

5.4 SUMMARY

This chapter attempted to describe a collaborative workstation in terms of *workspaces, tasks & interaction*. These three constituents can be considered by system designers when planning and designing a collaborative workstation with large industrial robots. As discussed in section: 5.1, a logical set of workspaces can guide designers to allocate tasks to the two resources, i. e. the operator & the robot.

The immediate challenge is to define the tasks (sec: 5.2) in a manner that takes into account the essential characteristics of the two resources where the tasks (*operator, robot & collaborative*) are organized to achieve the goals of the workstation. In order for the operator to synchronize with the robotic system, the phenomenon of *interaction* (sec: 5.3) was exemplified. Feedback devices enable communication between the two resources and are essential in workstations where an operator is expected to collaborate with a robotic system.

Therefore, the three constituents that make up the model can guide system designers' effort in activities such as 1. Identification of design requirements for a workstation, 2. Hazards identification during risk assessment (sec: 3.2.4) and 3. Specify safeguarding measures to mitigate associated risks.

DISCUSSION & CONCLUSION

This chapter discusses the results with reflections on safety in automation and research. The final section attempts to answer the research questions with concluding remarks, followed by suggestions for future work.

6.1 AUTOMATION AND SAFETY

In order to introduce automation, workstation designers should agree on the characteristics of the system prior to defining the tasks and corresponding safety solutions. This section discusses characteristics of collaborative systems and the challenges in safe operations.

Figure 6.1: Illustration of *applied research* where a current situation is examined to realize a desired situation through research operations.

The presented research can be characterized as being applied (sec: 2.1) as illustrated in figure: 6.1. The demonstrators were developed by examining the current situation (robotic & assembly workstations) in order to simulate useful safety solutions (desired situation) in a laboratory environment.

6.1.1 Characteristics of Collaborative Systems

A collaborative workstation can be presented in terms of various taxonomies such as levels of automation (table: 3.1) and types of collaborative operation (sec: 3.2.3), depending upon the granularity of the discussion. For example, a robotic system executes the programmed path without human intervention and is the traditional form of robotic automation. In this respect, the demonstrators (presented in chapter: 4) exhibit a high level of automation, but the *type of collaborative operation* exhibited by them is different. In the assembly of FWC (sec: 4.1), *hand-guided* operation characteristics dominate, whereas *speed & separation monitoring* best describes assembly of UBP (sec: 4.2).

Emphasis on Static Automation

The physical demonstrators exhibit behavior that can be characterized as static automation (sec: 3.1) because the tasks (robot, operator & collaborative tasks) are pre-determined and designed not to deviate from this behavior. Any deviation should be detected and result in a protective/emergency stop. The justification for static automation is based on the characteristic of currently operational workstations that were documented as requirements for the desired situations.

Some of these requirements are: 1. Repetition, 2. Time-constrained assembly cycle and 3. Synchronization with the assembly line. That is, the assembly task is repeated and remains relatively unchanged between cycles. Also, the duration of each cycle is short (1 min – 4 min), where the start and end states of the assembled part are determined by that of adjacent workstations on the assembly line.

Complex Automation

The possibility for non-critical functions to be adaptable in behavior can be advantageous in certain situations such as increasing the level of control for the operator. The situations and corresponding conditions where the system can exhibit complex behavior should be pre-determined and judged to be safe and necessary.

For example, consider the assembly of UBP (sec: 4.2). An enabling device, either installed on the nut-runner [see fig: 4.14 bottom-right] or located in the vicinity, can be used to temporarily mute the laser scanner. This can allow personnel to temporarily occupy the collaborative workspace in order to carry out maintenance or corrective tasks. The robot is inside the monitored workspace – a precondition for muting the safety sensor – ensuring that the collaborative mode will not be initiated.

Well-defined Workspaces

The emphasis on predictable behavior motivate structured and well-defined workspaces as presented in chapter 5. A well-defined workspace is a necessity to form a suitable mental model of the workstation and encourages awareness of the system with respect to the tasks that have to be performed by the operator.

That is, usability and trust in the system can be improved if the operator can, with minimum effort, be aware of the *state* of the system & pertinent *actions* associated with the state. Therefore, defining the *robot, operator & collaborative tasks* that aggregate to a simple and coherent path to assemble a component is a necessary characteristic of a collaborative workstation.

Warning lamps and floor marking can support the operator in this endeavour. These tools aid the operator when there is an apparent loss of awareness, whereas the arrangement of tasks and the task-frequency might have a bigger influence on the operator's perception of the system.

6.1.2 Safety & Risk Assessment

Risk Assessment (RA) methodology can support the development of a safe collaborative workstation as it includes a set of procedures and provides guidelines on analyzing and evaluating the identified hazards. The discussion and documentation of the risks, which is an integral part of a safety program, is aided by the standardized procedure.

Risk Assessment & Demonstrator Development

As noted by Björnsson [18] (sec: 2.3), demonstrators can be developed to various levels of fidelity. The type of demonstrator can reflect current understanding of the problem. During initial studies, demonstrators are conceptual models or prototypes that are developed to visualize relevant aspects under investigation.

RA can strengthen the evaluation of the generated concepts as it directs attention of the risk assessors towards personnel and process safety. Demonstrators function as a focal point for discussion that allows the safety team to predict risks and suggest solutions (changes in design/function) to mitigate them.

These suggestions, coupled with feedback from stakeholders, can lead to improvements in the design and development of higher fidelity demonstrators. Therefore, insights into the hazards specific to collaborative operations can be developed in parallel with the development of the demonstrators.

Figure: 6.2 summarizes the sequence of demonstrators that were developed during the research phase. The physical demonstrators are the final results of a series of research activities marked by demonstrators, whose development represents a distinct phase in the research process.

Figure 6.2: A summary of the two demonstrators that were developed separately by the working groups (WG1 & WG2) during the research phase (Paper VIII).

Challenges in Safe Operations

Risk assessment (sec: 3.2.4), as specified in ISO 12100 [76], is applicable to industrial machinery including robotic systems and is meant to support all phases of machine life cycle. The scope is broad and the procedure reflects this detail in its guidance for risk analysis and evaluation (fig: 3.9).

In practice, this entails ambiguity in its interpretation and the cause of the ambiguity can be attributed to the experience of the personnel as well as local safety culture. Referring to figure: 3.10, the reasoning for selecting a particular value in the decision-matrix is based upon prior understanding of the potential hazard and its ability to cause harm. To address this shortcoming, the suggested approach is to carry out risk assessment in a team consisting of members with varied expertise.

A multi-disciplinary team can be valuable in addressing the challenge of hazard identification. Some of the challenges are: 1. The ability to foresee relevant hazards and formulate a description and 2. Present risk reduction measures to eliminate/mitigate risks without introducing additional hazards. Risk assessors can rely on their prior experience in describing hazards that may seem trivial but can progress into a serious accident.

ISO 10218-1/2 (Table A.1 [22, 23]) tabulates a list of hazards particular to robot and robotic systems and can be considered as a knowledge base that can guide discussions during risk assessment. However, these are stated as *examples* in the standards. Therefore, the relevance of the suggested examples or additional potential hazards pertinent to the machine under investigation requires additional effort from the risk assessors. This challenge becomes critical when multiple valid options in the design or function can be implemented.

MULTIPLE OPTIONS FOR SAFE OPERATIONS Table 6.1 tabulates alternative procedures for the process of initiating non-collaborative mode, which exemplifies a mental exercise designers of collaborative systems should undertake while searching for an optimal task-sequence. For example, No. 2 in table 6.1 describes the procedure presented in section: 4.1, whereas No.3 describes a procedure where neither of these interfaces are used.

When multiple alternatives are presented, the challenge is to evaluate 1. the solution (risk) that suits the assembly cycle, and 2. the acceptability of the solution to the operator. It may be noted that a solution that requires operator involvement (manually initiate CM) will be prescribed as an operator task. The implication – due to the static nature of automation – is that operators will be required to keep track of pressing a button 100 times (4 – 5 min/cycle) during an eight hour working day. However, an automation of this solution (No.3) might be perceived as *over-automation* (sec: 3.1).

Situational and mode awareness were identified as the underlying principle that can result in a hazardous situation (Paper VII). These conditions can affect safety as humans can trigger protective/emergency stops due to loss of awareness of the system state or its boundary.

Table 6.1: Alternative procedures for initiating non-collaborative mode using three-button switch (3T) and/or mode-change button (MD).

No.	3T/MD	Initiating Non-collaborative mode
1.	No 3T, with MD	Operator exits collaborative workspace (CW), engages MD which activates light curtain.
2.	With 3T, with MD	Operator engages 3T, exits CW and engages MD which activates light curtain.
3.	No 3T, No MD	Operator exits CW. When system detects empty workspace & robot at the hand-over position, activates light curtain.
4.	With 3T, No MD	Operator engages 3T, exits CW. When system detects an empty workspace & robot at the hand-over position, activates light curtain.

Regardless of the chosen procedure, risk assessors/system designers are challenged with prescribing safety solutions for foreseeable hazards that include tampering, loss of awareness, misuse of equipment etc. The result of a safety program is an operationally safe workstation along with documentation of procedures for operating the machine.

6.2 RESEARCH METHODOLOGY & VALIDITY

This section discusses Interactive Research in relation to demonstrator development, where participants carry out research with researchers to gain insights into issues faced by their organization.

6.2.1 Research, Practice & Learning Systems

Interactive Research (IR) is seen as an orientation for collaborative research that highlights the roles of the members in the research team and the reasoning for their participation. The efficiency gains has been attributed to division of labor delegated between researchers and practitioners (sec: 2.2). Ellström [61] describes a collaborative research environment in terms of research and practice systems that interacts to create new knowledge (fig: 2.2).

The goal of a *research system* is to discover insights to recognized problems through systematic application of scientific methods. Research activities include development of methods & related tools, and function as a mechanism for knowledge production [59].

A *practice system* is characterized by expert knowledge derived from research, education as well as experience of practitioners. The goals for practitioners are generally directed towards development of useful and marketable techniques such as products and services.

Learning System

A general criticism of Interactive Research has been the unanticipated increase in resources necessary for practitioners to carry out research activities [63, 129]. It has also been noted by Nielsen & Svensson [57] and Johansson & Säfsten [63] that researchers act as a mediator for the participating organization.

These issues could be attributed to the interpretation of the *change process* (primary responsibility of the practitioner) to mean daily practical activities being carried out by them. The underlying principle that supports this interpretation is the definition of research and practice systems with strictly separate goals but mutually beneficial outcomes.

In this thesis, these challenges have been indirectly addressed by organizing the activities within the research-university framework. That is, in addition to the research and practice systems, a *learning system* is proposed whose purpose is to support the goals of a research university.

The term university refers to an institution whose primary goal is education and pedagogical development, whereas a research university is characterized by an additional goal to create knowledge. The ambitions for a learning system are: 1. Students knowledgeable in current research trends and practices, and 2. Knowledge dissemination of research results organised in public events.

These ambitions are inline with the goals of research universities tasked with dissemination of scientific knowledge and practices. These goals are intended to enhance the competence of current and future researchers & practitioners. In this thesis, the *learning system* has been operationalized to support research objectives by prescribing student-led projects (sec: 2.5). By participating in research projects, students benefit with insights on current research issues as well as challenges faced by an industrial organization.

6.2.2 *Integrating Task*

Ellström [61] notes that an integrating task can serve to produce a common understanding of the research object. An integrating task is a set of research activities that are organized to be performed interactively. In this thesis, *development of demonstrators* acted as an integrating task (fig: 6.3) to enhance understanding of the research object.

It can be stated that the intention to develop demonstrators encourages efficiency in activities by directing efforts in discussion and action. The activities include: 1. Understanding the problem; 2. Identifying appropriate tools and techniques (design support) and 3. Identifying resources to address lack in expertise.

Understanding the research object is an evolving process that can be supported by development of demonstrators – the integrating task – at appropriate fidelity levels. As noted in section: 6.1.2, the fidelity of the demonstrators can reflect the state of understanding of the research object. To illustrate this point, during initial

Figure 6.3: A model to describe Interactive Research orientation in Demonstrator-based Research Methodology. Development of demonstrators function as an integrating task to gain insight into the research object.

phases, the pragmatic approach was to develop demonstrators (virtual simulations or prototypes) that can enable cognitive understanding of the research object (fig: 6.2).

Development of demonstrators is aided by multiple tools, requirements for which are tentative on the current understanding of the research object. The selection of these tools to carry out the integrating task is predicated on research members reaching a consensus on issues such as 1. the immediate goals and 2. the challenges that need to be addressed to realize the objectives. The application of tools requires practical skills and knowledge, and therefore demands effort.

As discussed in the previous section, student-led projects can complement immediate research objectives. Students can facilitate these activities by conceptualizing solutions, identifying and selecting appropriate tools and applying these tools to demonstrate a design.

The activities related to *development of demonstrators* provide an opportunity for practitioners to learn about practical techniques that are useful for their organization (fig: 6.3). Practitioners can gauge the usefulness of the demonstrator through demonstration activity where (probable) users can be surveyed through appropriate methods. These activities are learning events for research participants and users.

User-feedback is valuable in evaluating the usefulness of the demonstrator where the nature of data can be described as qualitative (Paper V). However, it can enable recognition of deficiencies in understanding of the research object, which permits design iteration.

6.2.3 *Research Validity*

In a collaborative research environment, it is difficult to plan activities over a lengthy period of time as information and the ability to collect information are opportunistic. Over the time-frame pertinent to this thesis (fig:2.5), there has been an immense interest in HRC for both academic researchers and practitioners. Additionally, there has been an increase in equipment specifically designed for HRC along with developments in safety standards. This represents an increase in knowledge available to the research community.

In order to explain the functioning of an assembly station (current situation), established methods such as observation, semi-structured interviews, literature studies etc., were employed. The integrity of the data is attributed to the approach and can be discussed in two ways.

First, the interactive research orientation in selecting and applying methods can ensure internal validity – validity in selection and application of research methods – as the emphasis on consensus can discourage biased views. Second, the parameters to explain the current situation were established and developed during two separate occasions (WG1 & WG2 in fig: 6.2). According to Yin [73], replicative case studies can diminish threats to internal validity.

As noted by Nielsen & Svensson [57], the interactive research orientation can also support external validity – generalizability/acceptance of research results. One of the delimitations of the presented research is the approximation of the assembly task. However, feedback from participants who attended the industrial workshops indicates interest in collaborative operations and their acceptance of the general layout (see chapter 4.) and safety strategy.

6.2.4 *Final Remarks*

The demonstrator development was marked by a progressive understanding of the user in terms of the tasks and the environment within which they are expected to operate. In the context of a workstation, the term *user* is stated to address a multi-disciplinary perspective required in the design. To develop demonstrators that represent solutions that might be feasible in practice, design can be driven through user-evaluation, where a demonstrator can aid in these activities.

Feedback from *users* has broad and distinct lines of arguments that can be distilled down to statements highlighting usefulness for their organization. These are generally subjective arguments and their implications for the demonstrators are at the discretion of the research team. Robustness in feedback, referring to consistency in information from multiple sources is valuable and can be prioritized, though it is not a guarantee of factuality. Examples of sources of information are practitioners, documentation, standards as well as own observation.

Iteration is an observable feature of the methodology presented in this thesis, where each loop reflects better understanding of the research object. The broad scope of the problem faced by practitioners relates to the introduction of large

industrial robots in assembly operations. The question tackled in this thesis revolves around safety and its influence on the tasks and specification of working environment.

An iterative approach can be considered a requirement in a collaborative research environment as it allows for a natural progression in collecting, interpreting and validating data. A collaborative research environment is characterized by evolving requirements for the desired situation during the research phase. That is, new insights and information (such as the publication of ISO/YS 15066 [100] in 2016) are introduced during the research, affecting the desired situation.

As noted earlier, fidelity of the demonstrators reflects current understanding of the research object where demonstrators acts as a platform for discussion and learning. Demonstrators have proved their usefulness during various activities such as risk assessment discussions, user-feedback, research dissemination etc. Therefore, demonstrators function as an experimentation platform for technology research.

6.3 CONCLUSION

This section details thesis contributions followed by concluding remarks and future work.

6.3.1 Contributions

Methodological and research contributions of this thesis will be presented briefly.

Methodological Contribution

Demonstrator-based Research (DBR) methodology is presented with an Interactive Research (IR) orientation. In this environment: 1. Joint-learning that goes on between researchers and participants is emphasized and 2. Research operations are delegated between researchers and participants.

Researchers and participants collaborate through the development of demonstrators in order to gain insight into industrial challenges. It has been shown that the *development of demonstrators* can function as an *integrating task* that directs action and resources to achieve this aim.

In addition to research and practice systems (fig: 2.2), a learning system has been proposed to support the systematic design of demonstrators and learning objectives in an interactive research environment (fig: 6.3). A learning system can exist within a research university framework and functions to develop and disseminate research and practice-oriented knowledge.

Research contributions

Two laboratory demonstrators that showcase safety solutions for collaborative operations with large robots have been presented in chapter: 4. They facilitated dissemination of research results to manufacturing organization through industrial workshops as well as the academic community (Appended Papers I–VIII). The demonstrators are:

1. A demonstrator that showcases hand-guided assembly of a flywheel housing cover. The design of the end-effector that includes a hand-guiding tool mounted on a force-torque sensor is also presented (sec: 4.1).
2. A demonstrator that showcases collaborative assembly on a continuously-moving line. The design of a safe gripper and the use of a safety-control system have been detailed (sec: 4.2).

6.3.2 Research Questions

RQ.I: What constitutes a collaborative assembly workstation?

Ω A collaborative workstation with a large industrial robot can be described in terms of *workspaces*, *tasks* and *interaction* between operator and robot. A model for a collaborative workstation is presented in chapter 5.

The robot, operator and collaborative workspaces together form the layout and correspond to the physical location allocated to the robot and the operator to carry out tasks. The collaborative workspace permits the robot and the operator to carry out assembly tasks either together or independently.

Interaction is required for collaboration when an operator needs to synchronize with the robotic system to complete an assembly cycle. Therefore, defining the robot, operator and collaborative tasks at the corresponding workspaces supported by interfaces can allow an operator to safely assemble components during an assembly cycle.

RQ.II: What are the relevant safety issues for collaborative operations in automotive assembly plants?

✱ RQ.II.A – What are the hazards when industrial robots are operated collaboratively? ✱ RQ.II.B – What are the safety solutions to mitigate risks associated with these hazards?

Ω The hazards associated with an automated robotic system have been documented in safety standards and the solutions to mitigate the associated risks are widely practiced. However, a collaborative workstation implies close proximity of humans and robots, which is in contrast to robotic systems that are designed to be operated within an isolated environment.

An automotive plant is a populated environment and is designed for humans. In this environment, the probability of occurrence for collisions is high due to

the proximity necessary for collaboration. Additionally, the probability of hazards such a crushing, pinching etc. also increases with collaborative operations.

The standard safety practice of installing physical fences can mitigate the risk of collision by forming a physical barrier between the hazard zone and the operator. Collaborative workspace, which represents a hazard zone can be monitored using safety sensors (e. g. Laser scanner, light curtain) in order to bring the system to a safe state if an intrusion is detected.

Safe-design of the end-effector can be emphasized as it is most likely to come into contact with an operator. Controlling the speed and spatial location of the robot arm during collaborative mode can mitigate the effect of a collision. The effect of a collision or risks of crushing/pinching can be mitigated by designing the end-effector with passive or active measures. A desirable solution is elimination of the contact risk.

Strategies for safety should also consider human factors as a cause of a hazardous situation. In this thesis, a loss of situational or mode awareness (sec: 5.3) has been shown to result in operators entering a hazardous zone or causing unintended stops.

The demonstrators have exemplified solutions to mitigate risks associated with loss of awareness (sec: 4.1 & sec: 4.2) using interfaces such as enabling devices, warning lamps, buttons etc. Additionally, the possibility of automating the start and end of collaborative mode (sec: 5.3), which represents a significant hazard in collaborative operations has been discussed in detail.

6.3.3 Concluding Remarks

In order to better understand the nature of collaborative operations with large industrial robots, the approach was to develop demonstrators that simulates assembly workstations. The research activities that led to the demonstrators were planned and organized with participants from the manufacturing industry.

Development of demonstrators is the essential *research tool* that engage the research team to discuss and reflect upon challenges that should be recognized and addressed. This thesis motivates an interactive research orientation to achieve validity in research where *research validity* refers to useful & acceptable insights that is mutually beneficial for both industrial participants and academic researchers.

Two physical demonstrators that were developed in a laboratory environment during the research phase was presented in this thesis. The physical demonstrators performed two additional research functions: 1. It enabled the research team to demonstrate usefulness of industrial robots operated collaboratively, 2. It also permitted the team to gather feedback from probable users that can benefit from this form of automation.

An analysis of the physical demonstrators shows that there are three aspects that describes a collaborative workstation. In this thesis, a model was developed

that articulates the qualities of these aspects namely: 1. well-defined workspaces; 2. synchronised tasks & 3. intuitive interaction.

Safety in collaborative operations is critical and may determine its usefulness. Therefore, operational risks needs to be methodological identified and evaluated. Risk Assessment, a standardized safety focussed methodology, can be employed in conjunction with the development of collaborative systems. The presented model can support risk assessors in detailing overall system layout, safeguarding strategies as well as specifying tasks to be performed by the robot and the operator.

Future Work

In order to introduce collaborative robots, the function that can be automated should be identified as it directly affects efficiency and productivity. The question is related to the development of methods for task-delegation between an operator and the industrial robot, as well as identification of current manual workstations that benefit from robot-assisted automation.

Academic literature discusses intuitive programming of robots with an emphasis on methods such as hand-guiding and interfaces where the goal is to reduce the cost of development and maintenance. However, these developments should consider parameters that affects safe operations while allowing for flexibility in the system. Therefore, there is a need to develop methods that considers safety during development of industrial systems.

REFERENCES

- [1] Klaus Schwab. *The Fourth Industrial Revolution*. Crown Publishing Group, ISBN: 1524758868, New York, NY, USA, 2017.
- [2] Joseph Tidd, Keith Pavitt, and John Bessant. *Managing innovation*, volume 5. John Wiley and Sons Inc, 2013.
- [3] Fulvio Castellacci. Technological paradigms, regimes and trajectories: Manufacturing and service industries in a new taxonomy of sectoral patterns of innovation. *Research Policy*, 37(6-7):978–994, 2008.
- [4] Waldemar Karwowski, Mansour Rahimi, and Tina Mihaly. Effects of computerized automation and robotics on safety performance of a manufacturing plant. *Journal of Occupational Accidents*, 10(3):217 – 233, 1988.
- [5] Gavriel Salvendy and Waldemar Karwowski. *Design of Work and Development of Personnel in Advanced Manufacturing*. Wiley-Interscience publication. Wiley, 1994.
- [6] Yash P. Gupta and Sameer Goyal. Flexibility of manufacturing systems: Concepts and measurements. *European Journal of Operational Research*, 43:119–135, 1989.
- [7] David M Upton. The management of manufacturing flexibility. *California management review*, 36:72–89, 1994.
- [8] R Beach, a P Muhlemann, D H R Price, A. Paterson, and J.A. Sharp. A review of manufacturing Flexibility: Theory and Methodology. *European Journal of Operational*, 122:41–57, 2000.
- [9] Andrea Krasa Sethi and Suresh Pal Sethi. Flexibility in Manufacturing : A Survey. *The international journal of Flexible Manufacturing System*, 2:289–328, 1990.
- [10] Donald Gerwin. Manufacturing Flexibility: A Strategic Perspective. *Managememnt Science*, 39(4):395–410, 1993.
- [11] A. De Toni and S. Tonchia. Manufacturing flexibility: A literature review. 36(6):1587–1617, 1998.
- [12] IFR. *Positioning Paper – Robots and the Workplace of the Future*. International Federation of Robotics, Frankfurt, German, 2018.
- [13] International Federation of Robotics. <https://ifr.org/>. site accessed – March 2019.

- [14] ABB AB. <https://new.abb.com/>, site accessed – 11 December 2018.
- [15] Torgny Brogårdh. Present and future robot control development – An industrial perspective. *Annual Reviews in Control*, 31(1):69–79, January 2007.
- [16] Bruno Siciliano and Oussama Khatib. *Springer Handbook of Robotics*. Springer-Verlag New York, Inc., Secaucus, NJ, USA, 2007.
- [17] Marie Jonsson. *On Manufacturing Technology as an Enabler of Flexibility : Affordable Reconfigurable Tooling and Force-Controlled Robotics*. Linköping Studies in Science and Technology. Dissertations: 1501. 2013.
- [18] Andreas Björnsson. *Automated layup and forming of prepreg laminates*. Linköping Studies in Science and Technology. Dissertations 1858. 2017.
- [19] Mathias Haage. *On the Programming and System Integration of Robots in Flexible Manufacturing*. PhD thesis, Lund University, 2010.
- [20] Maj Stenmark. *Intuitive Instruction of Industrial Robots : A Knowledge-Based Approach*. PhD thesis, Lund University, 2017.
- [21] Lee M. Sanderson, James W. Collins, and James D. McGlothlin. Robot-related fatality involving a U.S. manufacturing plant employee: Case report and recommendations. *Journal of Occupational Accidents*, 8(1-2):13–23, 1986.
- [22] Swedish Standards Institute, Stockholm, Sweden. *SS-ISO 10218-1:2011 – Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robot*. 2011.
- [23] Swedish Standards Institute, Stockholm, Sweden. *SS-ISO 10218-2:2011 – Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration*. 2011.
- [24] Robotic Industrial Association. *RIA TR R15.406-2014: Safeguarding*. 2014.
- [25] B.S. Dhillon. *Robot Reliability and Safety*. Springer-Verlag New York, 1991.
- [26] A. Albu-Schäffer, S. Haddadin, Ch. Ott, A. Stemmer, T. Wimböck, and G. Hirzinger. The DLR lightweight robot: design and control concepts for robots in human environments. *Industrial Robot: An International Journal*, 34(5):376–385, 2007.
- [27] Åsa Fasth-Berglund and Johan Stahre. Cognitive automation strategy for reconfigurable and sustainable assembly systems. *Assembly Automation*, 33:294–303, 2013.
- [28] Shozo Takata and Takeo Hirano. Human and robot allocation method for hybrid assembly systems. *CIRP Annals - Manufacturing Technology*, 60(1):9–12, January 2011.

- [29] Panagiota Tsarouchi, Alexandros-stereos Matthaiakis, and Sotiris Makris. On a human-robot collaboration in an assembly cell. *International Journal of Computer Integrated Manufacturing*, 00(00):1–10, 2016.
- [30] Björn Diffner. *Combining Flexibility and Efficiency in Automotive Assembly : Preparing for New Powertrain Vehicles*. Linköping : Department of Management and Engineering, Linköping University, 2011.
- [31] J. Krüger, T.K. Lien, and A. Verl. Cooperation of human and machines in assembly lines. *CIRP Annals - Manufacturing Technology*, 58(2):628–646, January 2009.
- [32] J Edward Colgate, Michael Peshkin, and Witaya Wannasuphoprasit. Cobots: Robots for collaboration with human operators. pages Vol. 58, 433–440, 1996.
- [33] J. Krüger, R Bernhardt, and D Surdilovic. Intelligent Assist Systems for Flexible Assembly. *CIRP Annals - Manufacturing Technology*, 55(1):29–32, 2006.
- [34] Carlos Morato, Krishnanand N. Kaipa, Boxuan Zhao, and Satyandra K. Gupta. Toward Safe Human Robot Collaboration by Using Multiple Kinects Based Real-time Human Tracking. *Journal of Computing and Information Science in Engineering*, 14(1):011006, January 2014.
- [35] Valeria Villani, Fabio Pini, Francesco Leali, and Cristian Secchi. Survey on human-robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics*, (June 2017):1–19, 2018.
- [36] Hongyi Liu, Tianyu Zhou, Yuquan Wang, and Lihui Wang. Deep Learning-based Control Multimodal Interface for Human-Robot Collaboration. *Procedia CIRP*, 72:3–8, 2018.
- [37] Rethink_Robotics. <http://www.rethinkrobotics.com/>. site accessed – May 2014.
- [38] Chung-Hao Chen, Chang Cheng, David Page, Andreas Koschan, and Mongi Abidi. Tracking a moving object with real-time obstacle avoidance. *Industrial Robot: An International Journal*, 33(6):460–468, 2006.
- [39] Kuka AG. <https://www.kuka.com/>. site accessed – 11 December 2018.
- [40] Przemyslaw a. Lasota, Gregory F. Rossano, and Julie a. Shah. Toward safe close-proximity human-robot interaction with standard industrial robots. 2014 *IEEE International Conference on Automation Science and Engineering (CASE)*, pages 339–344, aug 2014.
- [41] Sten Grahns, Varun Gopinath, Xi Vincent, and Kerstin Johansen. Exploring a Model for Production System Design to Utilize Large Robots in Human-Robot Collaborative Assembly Cells. *Procedia Manufacturing*, 25(May):612–619, 2018.

- [42] Jeremy A. Marvel. Performance metrics of speed and separation monitoring in shared workspaces. *IEEE Transactions on Automation Science and Engineering*, 10(2):405–414, 2013.
- [43] Jeremy A Marvel and Rick Norcross. Implementing speed and separation monitoring in collaborative robot workcells. *Robotics and Computer Integrated Manufacturing*, 44:144–155, 2017.
- [44] M. Morioka and S. Sakakibara. A new cell production assembly system with human–robot cooperation. *CIRP Annals - Manufacturing Technology*, 59(1):9–12, January 2010.
- [45] Robot Operating System. <http://www.ros.org/>, site accessed – June 2019.
- [46] George C Devol Jr. Programmed article transfer, 1961.
- [47] Brian Spear. Robots and patents. *World Patent Information*, 23:333–338, 2001.
- [48] Michael Peshkin. "cobots" work with people, site accessed – March 2019.
- [49] William T.Townsend. *The Effect of Transmission Design on Force-Controlled Manipulator Performance*. 1988.
- [50] B.S. Dhillon, A.R.M. Fashandi, and K.L. Liu. Robot systems reliability and safety: a review. *Journal of Quality in Maintenance Engineering*, 8(3):170–212, 2002.
- [51] C.R. Kothari. *Research Methodology: Methods and Techniques*. New Age International (P) Limited, 2004.
- [52] Paul D. Leedy and Jeanne Ellis Ormrod. *Practical Research: Planning and Design*. Pearson Education Limited, 2013.
- [53] Mathew B Miles, A. Michael, and Johnny Saldana. *Qualitative Data Analysis: A Methods Sourcebook*. SAGE Publications, 3 edition, 2013.
- [54] Ingemar Nordin. *Using Knowledge : On the Rationality of Science, Technology, and Medicine*. Lexington Books, 2017.
- [55] TEC-SHS. *Technology Readiness Levels Handbook For Space Applications*. European Space Agency, 2008.
- [56] George Charalambous, Sarah R. Fletcher, and Philip Webb. The development of a Human Factors Readiness Level tool for implementing industrial human-robot collaboration. *International Journal of Advanced Manufacturing Technology*, pages 1–11, 2017.
- [57] Kurt Aagaard Nielsen and Lennart Svensson, editors. *Action research and interactive research: beyond practice and theory*. Shaker Publishing, 2006.
- [58] P. Reason and H. Bradbury. *Handbook of Action Research: Participative Inquiry and Practice*. SAGE Publications, 2001.

- [59] Lennart Svensson, Per-Erik Ellström, and Göran Brulin. Introduction - on Interactive Research. *International Journal of Action Research*, 3(3):233–249, 2007.
- [60] Pernilla Lindskog. Organizational Change through Interactive Research or a Consultant’s Intervention: Reflections about pros and cons. In *The Nordic Academy of Management conference, NFF, Stockholm*, number 20-24 August, 2011.
- [61] Per-Erik Ellström. Knowledge Creation Through Interactive Research: A Learning Perspective. *The European Conference on Educational Research (ECER), Gothenburg, September 10-12,,* pages 1–12, 2008.
- [62] Per-Erik Ellström, Jörgen Eklund, Henrik Kock, Liselott Lindström, and Ulf Melin. Knowledge Creation Through Collaborative Research: An Emerging Model. In *1st HSS conference, Dalarna Högskola, Falun*, pages 1–22, 1999.
- [63] Glenn Johansson and Kristina Säfsten. Results Produced by Interactive Research: Examples and Discussion. *Participatory Innovation Conference*, pages 386–393, 2018.
- [64] Julie Hermans and Annick Castiaux. Knowledge creation through university-industry collaborative research projects. *The Electronic Journal of Knowledge Management*, 5(1):43–54, 2006.
- [65] Lucienne T. M. Blessing and Amaresh Chakrabarti. *DRM, a Design Research Methodology*. Springer Publishing Company, Incorporated, 1st edition, 2009.
- [66] Colin Potts. Software-Engineering Research Revisited. *IEEE Software*, 10(5):19–28, 1993.
- [67] Jay Nunamaker Jr. F. and Minder Chen. Systems Development in Information Systems Research. *Journal of Management Information Systems*, 7(3):59–106, 1991.
- [68] ToMM – Collaborative Team of Man and Machine, 2012-03685. <https://www.vinnova.se/p/tomm/>, site accessed – December 2017.
- [69] ToMM2 – Future Collaborative Assembly Team of Man and Machine, 2015-03722. <https://www.vinnova.se/>, site accessed – June 2017.
- [70] FFI – Fordonsstrategisk forskning och innovation. <https://www.vinnova.se/en/m/strategic-vehicle-research-and-innovation/>, site accessed – May 2019.
- [71] A Safety Model for Collaborative Robots (SCOR), 2016-03313. <https://www.vinnova.se/>, site accessed – May 2019.
- [72] Det Strategiska Innovations-programmet för flyg, 2015-06057. <https://innovair.org/>, site accessed – June 2019.

- [73] R.K. Yin. *Case Study Research: Design and Methods*. Applied Social Research Methods. SAGE Publications, 2014.
- [74] Björn Backman and Carl S:T Clair Renard. Simulating human-robot collaboration : - an example from cab assembly. Master's thesis, KTH, Production Engineering, 2015.
- [75] Mats Alvesson and Jörgen. Generating research questions through problematization. *Academy of Management Review*, 36(2):247–271, 2011.
- [76] Swedish Standards Institute, Stockholm, Sweden. *SS-ISO 12100:2010 – Safety of Machinery – General principles of Design – Risk assessment and risk reduction (ISO 12100:2010)* . Number SS-EN ISO 12100:2010. 2010.
- [77] B.S. Dhillon and A.R.M. Fashandi. Safety and reliability assessment techniques in robotics. *Robotica*, 15(06):701–708, 1997.
- [78] Thomas B. Sheridan and William L. Verplanck. Human and computer control of undersea teleoperators, 1978.
- [79] Thomas B. Sheridan and Raja Parasuraman. Human-Automation Interaction. *Reviews of Human Factors and Ergonomics*, 1(1):89–129, 2005.
- [80] Mica R. Endsley and D. B. Kaber. Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics*, 42(3):462–492, 1999.
- [81] R. Parasuraman, T.B. Sheridan, and C.D. Wickens. A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, 30(3):286–297, 2000.
- [82] Christopher A. Miller and Raja Parasuraman. Beyond Levels of Automation: An Architecture for More Flexible Human-Automation Collaboration. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 47(1):182–186, 2003.
- [83] Raja Parasuraman, Thomas B Sheridan, and Christopher D Wickens. Situation Awareness, Mental Workload, and Trust in Automation:Viable, Empirically Supported Cognitive Engineering Constructs. *Journal of Cognitive Engineering and Decision Making*, 2(2):140–160, 2008.
- [84] E. Hollnagel. *Cognitive Reliability and Error Analysis Method (CREAM)*. Elsevier Science, 1998.
- [85] David B. Kaber and Mica R. Endsley. *The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task*, volume 5. 2004.
- [86] Nancy G Leveson. *Engineering a Safer World: Systems Thinking Applied to Safety*. Engineering systems. MIT Press, 2011.

- [87] Mica R Endsley. Situation awareness global assessment technique (SAGAT). In *Aerospace and Electronics Conference, 1988. NAECON 1988., Proceedings of the IEEE 1988 National*, pages 789–795, 1988.
- [88] Mica R. Endsley. Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1):32–64, 1995.
- [89] Nadine B. Sarter and David D. Woods. How in the World Did We Ever Get into That Mode? Mode Error and Awareness in Supervisory Control. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1):5–19, 1995.
- [90] Kevin Anthony Hoff and Masooda Bashir. Trust in automation: Integrating empirical evidence on factors that influence trust. *Human Factors*, 57(3):407–434, 2015.
- [91] D. A. Norman. The ‘Problem’ with Automation: Inappropriate Feedback and Interaction, not ‘Over-Automation’. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 327(1241):585–593, 1990.
- [92] Nadine B. Sarter and David D. Woods. Situation Awareness: A Critical But Ill-Defined Phenomenon. *The International Journal of Aviation Psychology*, 1(1):45–57, 1991.
- [93] Kenneth R. Laughery and Michael S. Wogalter. Designing Effective Warnings. *Reviews of Human Factors and Ergonomics*, 2(1):241–271, April 2006.
- [94] Connor Upton and Gavin Doherty. Extending Ecological Interface Design principles: A manufacturing case study. *International Journal of Human Computer Studies*, 66(4):271–286, 2008.
- [95] G. Salvendy, editor. *Handbook of Human Factors and Ergonomics*. Wiley, 2012.
- [96] Clifton A Ericson. *Hazard analysis techniques for system safety*. John Wiley & Sons, 2015.
- [97] Herbert William Heinrich. *Industrial accident prevention: A scientific approach*. New York. McGraw-Hill, 1931.
- [98] SS-ISO 8373:2012 – *Industrial Robot – Terminology*. Number SS-ISO 8373:2012. Swedish Standards Institute, Stockholm, Sweden, 2012.
- [99] The International Organization for Standardization (ISO) . <https://www.iso.org/home.html>, site accessed – June 2017.
- [100] The International Organization for Standardization. *ISO/TS 15066 – Robots and robotic devices – Collaborative robots*. 2016.
- [101] Swedish Standards Institute, Stockholm, Sweden. *ISO/TR 20218-1:2018 – Robotics — Safety design for industrial robot systems – Part 1: End-effectors*. 2018.

- [102] The International Electrotechnical Commission. *IEC TS 62046:2008 – Safety of machinery - Application of protective equipment to detect the presence of persons*. 2008.
- [103] The International Organization for Standardization. *ISO 13856-1:2013 – Safety of machinery – Pressure-sensitive protective devices – Part 1: General principles for design and testing of pressure-sensitive mats and pressure-sensitive floors*. 2013.
- [104] The International Organization for Standardization. *ISO 13856-2:2013, Safety of machinery – Pressure-sensitive protective devices – Part 2: General principles for design and testing of pressure-sensitive edges and pressure-sensitive bars*. 2013.
- [105] The International Organization for Standardization. *ISO 13856-3:2013 Safety of machinery – Pressure-sensitive protective devices – Part 3: General principles for design and testing of pressure-sensitive bumpers, plates, wires and similar devices*. 2013.
- [106] Universal Robot. <http://www.universal-robots.com/>. site accessed – March 2017.
- [107] S. Robla-Gomez, Victor M. Becerra, J. R. Llata, E. Gonzalez-Sarabia, C. Torre-Ferrero, and J. Perez-Oria. Working Together: A Review on Safe Human-Robot Collaboration in Industrial Environments. *IEEE Access*, 5:26754–26773, 2017.
- [108] Jeffrey Too Chuan Tan, Feng Duan, Ryu Kato, and Tamio Arai. Collaboration Planning by Task Analysis in Human-Robot Collaborative Manufacturing System. In Ernest Hall, editor, *Advances in Robot Manipulators*, chapter 6, pages 113–132. InTech, 2010.
- [109] John R. Ethernton. Industrial machine systems risk assessment: A critical review of concepts and methods. *Risk Analysis*, 27(1):71–82, 2007.
- [110] Robotics Industries Association. *RIA TR R15.306-2014, Technical Report, Task-Based Risk Assessment Methodology*. Number RIA TR R15.306-2014. Robotics Industries Association, 2014.
- [111] W.Min. Chow. *Assembly Line Design: Methodology and Applications*. Marcel Dekker, Inc., 1990.
- [112] Hwaiyu Geng. *Manufacturing Engineering Handbook, Second Edition*. McGraw-Hill Professional, 2016.
- [113] G. Reinhart, Jochen Werner, and F. Lange. Robot based system for the automation of flow assembly lines. *Production Engineering*, 3(1):121–126, 2009.
- [114] Neville A. Stanton. Hierarchical task analysis: Developments, applications, and extensions. *Applied Ergonomics*, 37:55–79, 2006.

- [115] International MTM Directorate. <http://mtm-international.org/>, site accessed – May 2019.
- [116] Fredrick Ore, Lars Hanson, N Delfs, and M Wiktorsson. Virtual evaluation of industrial human-robot cooperation: An automotive case study. *3rd International Digital Human Modeling Symposium (DHM2014)*, 2014.
- [117] Fredrik Ore, Lars Hanson, Niclas Delfs, and Magnus Wiktorsson. Human industrial robot collaboration – development and application of simulation software. *International Journal of Human Factors Modelling and Simulation*, 5(2):164–185, March 2016.
- [118] ATI Industrial Automation. <https://www.ati-ia.com/index.aspx>. site accessed – 14 Feb 2019, 2019.
- [119] Dag Toijer. Robot och människa samarbetar på riktigt. In *Automation Tidningen*. 19, April 2017.
- [120] Varun Gopinath. Hand guided collaborative assembly with a kuka kr-210 industrial robot, youtube video: <https://youtu.be/tfl9hghlnru>. site accessed – 20-July 2017.
- [121] piab AB. <https://www.piab.com/sv-se/>. site accessed – March 2019, 2019.
- [122] Festo AG. <https://www.festo.com/hq/en/cms/festo.htm>. site accessed – March 2019, 2019.
- [123] SICK Sensor Intelligence. <http://www.sick.com>. site accessed – December 2016, 2016.
- [124] Mikael Sönne. Så kan människor och robotar samarbeta. In *Linköping University Webb Nyheter*. 14, September 2018.
- [125] Varun Gopinath. Collaborative assembly on a continuously-moving line, online youtube video: <https://youtu.be/3yaw6gemulw/>, site accessed – 09-October 2019.
- [126] Lisanne Bainbridge. Ironies of automation. *Automatica*, 19(6):775–779, 1983.
- [127] Christopher A. Miller and Raja Parasuraman. Designing for Flexible Interaction Between Humans and Automation: Delegation Interfaces for Supervisory Control. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(1):57–75, 2007.
- [128] Jennifer Bützler, Sinem Kuz, Henning Petruck, Marco Faber, and Christopher M Schlick. Function allocation between humans and systems in self-optimizing production networks. *Procedia Manufacturing*, 3(Ahfe):371–378, 2015.
- [129] Narges Asadi. *Flexibility in assembly systems using product design*. PhD thesis, Mälardalen University, December 2017.

- [130] Stefan Brending, Michael Lawo, Jürgen Pannek, Tobias Sprodowski, Patrick Zeising, and Daniela Zimmermann. Certifiable software architecture for human robot collaboration in industrial production environments. *IFAC-PapersOnLine*, 50(1):1983 – 1990, 2017. 20th IFAC World Congress.
- [131] A. Sanderud, T. Thomessen, H. Osumi, and M. Niitsum. A Proactive Strategy for Safe Human-Robot Collaboration based on a Simplified Risk Analysis. *Modeling, Identification and Control*, 36(1):11–21, 2015.
- [132] Csaba Kardos, Zsolt Kemény, András Kovács, Balázs E. Pataki, and József Váncza. Context-dependent multimodal communication in human – robot collaboration. *Procedia CIRP*, 72:15–20, 2018.
- [133] Fabian Ranz, Titanilla Komenda, Gerhard Reisinger, Vera Hummel, and Wilfried Sihm. A Morphology of Human Robot Collaboration Systems for Industrial Assembly. *Procedia CIRP*, 72:99–104, 2018.
- [134] Sahar Heydaryan, Joel Suaza Bedolla, and Giovanni Belingardi. Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry. *Applied Science*, 8(3):22, 2018.
- [135] Rolf Dieter Schraft, Christian Meyer, Christopher Parlitz, and Evert Helms. PowerMate - A safe and intuitive robot assistant for handling and assembly tasks. *Proceedings - IEEE International Conference on Robotics and Automation*, 2005(April):4074–4077, 2005.
- [136] D. Macdonald. *Practical Machinery Safety*. Practical professional books from Elsevier. Elsevier Science, 2004.
- [137] Jens Rasmussen. *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*. Elsevier Science Inc., New York, NY, USA, 1986.
- [138] Iina Aaltonen, Timo Salmi, and Ilari Marstio. Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry. *Procedia CIRP*, 72:93–98, 2018.
- [139] International Electrotechnical Commission (IEC). <http://www.iec.ch/>, site accessed – June 2017.
- [140] Dorota Stadnicka and Dario Antonelli. Human-robot collaborative work cell implementation through lean thinking. *International Journal of Computer Integrated Manufacturing*, pages 1–16, 2019.
- [141] Iñaki Murtua, Aitor Ibarguren, Johan Kildal, Loreto Susperregi, and Basilio Sierra. Human-robot collaboration in industrial applications: Safety, interaction and trust. *International Journal of Advanced Robotic Systems*, 14(4):1–10, 2017.
- [142] Lars Harms-Ringdahl. *Guide to safety analysis for accident prevention*. Citeseer, 2013.

- [143] Ray Eberts and Gavriel Salvendy. The contribution of cognitive engineering to the safe design and operation of cam and robotics. *Journal of Occupational Accidents*, 8:49–67, 1986.
- [144] H. McIlvaine Parsons. Human factors in industrial robot safety. *Journal of Occupational Accidents*, 8(1-2):25–47, 1986.
- [145] WALDEMAR KARWOWSKI and MANSOUR RAHIMI. Worker selection of safe speed and idle condition in simulated monitoring of two industrial robots. *Ergonomics*, 34(5):531–546, 1991. PMID: 1884709.
- [146] Tomas Backström and Marianne Döös. Problems with machine safeguards in automated installations. *International Journal of Industrial Ergonomics*, 25(6):573–585, 2000.
- [147] J Etherton, M Taubitz, H Raafat, J Russell, and C Roudebush. Machinery risk assessment for risk reduction. *Human and Ecological Risk Assessment*, 7(7):1787–1799, 2001.
- [148] Per Runeson and Martin Höst. Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14(2):131–164, 2009.
- [149] Waldemar Karwowski, Mansour Rahimi, Hamid Parsaei, Bangalore R. Amarnath, and Nai Pongpatanasuegsa. The effect of simulated accident on worker safety behavior around industrial robots. *International Journal of Industrial Ergonomics*, 7(3):229 – 239, 1991.
- [150] Bernhard Zimolong, Shimon Y. Nof, Ray E. Eberts, and Gavriel Salvendy. On the limits of expert systems and engineering models in process control. *Behaviour & Information Technology*, 6(1):15–36, 1987.
- [151] P.C Cacciabue. Human factors impact on risk analysis of complex systems. *Journal of Hazardous Materials*, 71(1-3):101–116, 2000.
- [152] T. Arai, R. Kato, and M. Fujita. Assessment of operator stress induced by robot collaboration in assembly. *CIRP Annals - Manufacturing Technology*, 59(1):5–8, January 2010.

APPENDED

ARTICLES

- Paper I *Design Criteria for a Conceptual End-effector for Physical Human-Robot Production Cell*
- Paper II *Risk Assessment Process for Collaborative Assembly – A Job Safety Analysis Approach*
- Paper III *Safe Assembly Cell Layout through risk assessment – An Application with Hand Guided Industrial Robot*
- Paper IV *Risk Assessment for Collaborative Operation: A Case Study on Hand-Guided Industrial Robots*
- Paper V *Demonstration of Robot-Assisted Assembly on a Continuously Moving Line*
- Paper VI *Demonstrators to support research in Industrial safety – A Methodology*
- Paper VII *Understanding Situational & Mode Awareness for Safe Human-Robot Collaboration: Case Studies on Assembly Applications*
- Paper VIII *Development of Demonstrators for Industrial Safety – An Interactive Perspective*

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Department of Management and Engineering (IEI)

Linköping University
SE-581 83 Linköping, Sweden

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