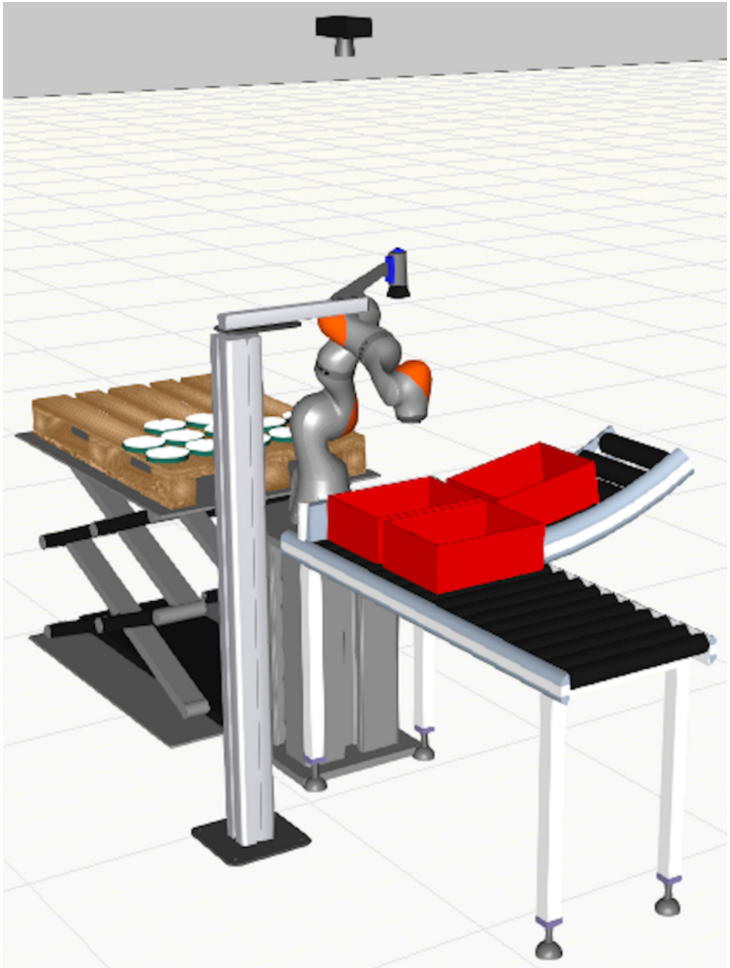
CHALMERS
UNIVERSITY OF TECHNOLOGY



Vision supported collaborative robot in pick-and-place operations

A coexistent material handling station between humans and a collaborative robot supported by vision systems

Master's thesis in Production Engineering

JOHAN HALLERSBO
NATHALIE JOSEFSSON

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Master's thesis 2018

Vision supported collaborative robot in pick-and-place operations

A coexistent material handling station between humans and a collaborative robot supported by vision systems

JOHAN HALLERSBO

NATHALIE JOSEFSSON

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Material Science
Division of Production Systems
Chalmers University of Technology
Gothenburg, Sweden 2018

Vision supported collaborative robot in pick-and-place operations

A coexistent material handling station between humans and a collaborative robot supported by vision systems

JOHAN HALLERSBO
NATHALIE JOSEFSSON

Supervisor: Jakob Krozer, Virtual Manufacturing
Ilker Erdem, Chalmers
Examiner: Åsa Fasth Berglund, Chalmers

Master's Thesis 2018
Department of Industrial and Material Science
Division of Production Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Visualization of the pick-and-place station constructed in VisualComponents.

Typeset in LaTeX
Gothenburg, Sweden 2018

Vision supported collaborative robot in pick-and-place operations
A coexistent material handling station between humans and a collaborative robot supported by vision systems
JOHAN HALLERSBO and NATHALIE JOSEFSSON
Department of Industrial and Material Science
Chalmers University of Technology

Abstract

Companies strive to streamline the material handling activities within the factory, aiming for a more sophisticated and safe interaction between machines, operators and components. The introduction of collaborative robots, as a promising solution to secure this interaction, is greatly researched. Monotonous work tasks are typically associated with high-level automation, but implementing an industrial robot requires rigorous safety routines and often space-demanding zone restrictions that can prove to be an obstacle. By utilizing a collaborative robot, these issues have potential to be diminished. This thesis aims to present the investigation of different approaches for the implementation of collaborative robots in coexistence with human workers in material handling operations. Moreover, the paper aims to present a novel concept station supported by vision systems in the realization of human robot collaboration for material handling operations. Finally, experiments involving a pick-and-place application for downsizing of assembly kits using a collaborative robot will be presented in order to demonstrate the applicability of the aforementioned system.

Keywords: collaborative robot, collision avoidance, robot vision, downsizing, object recognition, obstacle detection, safety, coexisting station

Acknowledgements

This thesis constitutes as basis for a master's degree examination in Production Engineering at Chalmers University of Technology. It has been performed and administrated at the department of Industrial and Materials Science.

First and foremost, we would like to thank our supervisors, Ilker Erdem at Chalmers University of Technology and Jakob Krozer at Virtual Manufacturing AB, for your help and advice during this thesis. Your guidance have been invaluable to this project. We would also like to thank our examiner, Associate Professor Åsa Fasth Berglund for your insightful comments contributing to an improved final report.

We would like to thank Virtual Manufacturing AB for hosting us and providing us with the opportunity to realize this thesis. We are truly grateful for the warm reception and all the help we've received along the way. We would also like to take the opportunity to thank Solme AB for your assistance with the programming and Tomas Pettersson at IFM for all the help surrounding the vision systems.

Last but not least, we would like to thank all of you who has supported us along the way, with encouragement and inputs improving this thesis.

Johan Hallersbo and Nathalie Josefsson, Gothenburg, May 2018

Contents

1 Introduction

This chapter presents the problem definition followed by a background description of the problem formulation regarding downsizing in the industry today. This part is then summarized as an aim which this report intend at fulfilling within the specified limitations. To further break down the aim, two research questions are specified to simplify and clarify the work process.

1.1 Background

A tedious issue shared by manufacturing companies is the need of downsizing their packages [1]. Downsizing encapsulate making something smaller in amount, volume or extent [2]. The components are typically supplied in containers adapted to optimally utilize all the capacity during transport for economic purposes, and less environmental impact [3]. Consequently, the container might not fit next to the production line, and often has to be repackaged into smaller storage units [1].

Most downsizing constitutes of manual labour performed by human workers which is a repetitive and non- ergonomic task [4]. A worker has to pick a large set of articles and put them into smaller bins suitable for the shop floor. Since this task fails to bring any direct value for the customers while occupying labour for a time-consuming task, there exists an increasing demand from producing companies to find an automated solution for this problem. This is the reason why an automated downsizing station will be developed using a robot.

According to [5], the automotive industry is going through a widespread transition towards electrical drive trains. With such a major shift, it is anticipated that the demand for solutions optimizing the use of the valuable factory space will increase. Consequently, investigating the capabilities of utilizing a collaborative robot for a streamlined downsizing with a future vision of mobile and flexible stations for the task is interesting. The collaborative approach will enable an open work environment without ungainly fences [6]. Furthermore, vision systems could be utilized to avoid obstacles and in the same time accommodate uncertainties in angles and positions which is desirable in an automated downsizing station [7].

1.2 Aim

Develop an automated downsizing station with a collaborative robot while providing a safe work environment for operators.

1.3 Delimitation

The collaboration between robot and humans is focusing on that humans will be able to, in a safe way, move around the robot without safety barriers or zone restrictions. This will not include that humans will be able to work in collaboration with the robot. The collaborative robot is predetermined and further investigations regarding if there is another robot more suitable for the task is ignored. Nor will a comparison regarding efficiency with other robots be performed.

The products used for testing the automated station are predetermined and limited to two different products. The two product types are delivered separately in batches on pallets to the robot and are sorted with the same side up before the downsizing procedure. The orientation of the product may vary and needs to be taken into consideration. There might also be a slight modification due to potential movements during transportation to the station causing the product to move that the robot needs to be able to handle. How the pallets and bins are supplied to the station and removed after downsizing is outside the scope of this project.

The relation in distance between the robot and the pallet is fixed, with minor variations depending on how precise the pallet is placed in the specified area. This variation can be estimated to be a few centimetres. The placement of the bin is however more precise due to specified placement. The relation in distance between the robot and the vision systems is assumed to be fixed.

Vision systems will be utilized together with its corresponding software. No efforts to design and implement a new algorithm in a vision system will be performed. Neither altering of an existing system by building an own application on another companies platform.

1.4 Research question formulation

To break down the purpose of this report further, two research questions have been established. These questions are formulated to guide and verify that the final solution will fulfill the aim.

Research question 1: What features are required at the downsizing station to enable a safe work environment for operators?

The manufacturing industry is regulated by safety standards surrounding working conditions to prevent human injuries. To enable an open work environment for both the robot and operators, restrictions on the station needs to be researched and defined.

Research question 2: How will the station ensure its process robustness?

To ensure a solution that provides value in the industry, a holistic view must be applied, linking theory with reality. Moreover, how will the the features of each area incorporated in the station work in symbiosis as a whole system. A delivery rate of 98 % is set together with industrial supervisor for reference and to quantify the result.

2
Frame of reference

This chapter aims at contextualizing Human-Robot-Collaboration (HRC) by conveying theory about where it has great potential to be utilized and boost productivity. Furthermore, different levels of collaboration are defined and components included in a typical collaborative station specified, together with safety regulations. Theory about computer vision is also conveyed in this chapter as a complement for a safe work environment and design simplifications of a material handling station.

2.1 Material handling

The mass-customization of today is taking its toll on manufacturers providing a big challenge in how to streamline and achieve an efficient handling of material within the compound [8]. How the material is gathered and where it is stored needs to be planned in detail, whereas shop floor space is costly. Ideally, the components should arrive to the assembly line in bins optimized to be kept next to the assembly station [9]. However, from a supply chain point of view, it may be more cost efficient to transport components consolidated in a container more suitable for transport [3]. A trade-off situation arises where transport costs are evaluated in relation to costs of repackaging the components in-house.

2.1.1 Bin picking

Whether it is for preparing kitting sets or downsizing of a bigger shipment, manual bin picking is greatly practiced throughout the production industry [10]. Research has shown that the layout of the component racks and the design of the container of the components impacts the entire assembly process performance in terms of efficiency, volume, product mix and flexibility [9]. A deep component rack of small width containing bins adapted for the layout, offers more capabilities of housing a wider variety of components within a closer proximity to the station than a more traditional approach with stacks of standardized European pallets. Furthermore, according to [11], studies have shown that the right tilt and size of the component container has been proven to reduce the picking time and strain on the operator. Naturally, this requires that the components are supplied in these bins or repackaged.

Warehouse picking (order picking) is estimated to compose up to 55 percent of all warehouse expenses [12]. A lot of the costs may be derived back to the fact that the task mainly is performed by human operators and that it is time-consuming [13]. Due to the high costs, the area is well researched in regards to optimizing human performance. A lot of effort is put into reducing the travel distances with new algorithms for designing smart order picking routes surfacing constantly.

In Lean manufacturing, widely acknowledged to be the optimal manufacturing system, value is defined as something the customer is willing to pay for [14]. Furthermore, the ultimate goal for an organization striving towards lean is an efficient process with minimal waste. Activities that fails to bring value, especially activities linked with people, elapsed time, methods, processes and motions, should be removed. According to [15], the output of tasks in production may be classified into value-adding, waste and something in between, auxiliary. The output of value adding tasks may be traced directly to the end product, or end user, while auxiliary tasks supports the value adding work and tasks resulting in no contribution to the end product, directly or indirectly, are considered as waste. Bin picking, in the context of kitting or downsizing, is a delicate matter since it fails to bring any value to the end customer but is still a necessity. Whether it's waste or auxiliary, it is safe to say that it is a task that should be performed as efficiently as possible nonetheless, which is in line with the lean doctrine.

2.1.2 Ergonomics in material handling

According to a study of work-related disorders during the time period 2014-2016 by the Swedish Work Environment Authority, nearly ten percent of the disorders constituted from heavy material handling [16]. The exposure of loads in repetitive cycles gradually causes the musculoskeletal system to deteriorate causing what is called musculoskeletal disorder (MSD) [13]. Furthermore, MSD is a common work-related injury amounting to financial costs for companies up to two percent of the entire gross national product of the European Union. Even so, research concerning order picking seldom take ergonomic factors into account when picking routes and activities are designed.

The risk with repetitive work lies in its cyclic nature and not that the loads on the body necessarily must be of high force but over time, without sufficient recovery, it is very strenuous on joints, ligaments and muscles [17]. Measures to address these issues exist through methodologies developed for evaluating postures and reducing health hazards, but they may be more or less difficult to use in practice. [12].

Many strenuous operations in material handling are suitable for automation, yet many companies chooses to avoid taking on such an investment, especially small and medium enterprises (SMEs) [13]. Apart from the potentially high investment, the companies are keen on not jeopardizing or compromising the flexibility in any way. Whether or not such an approach is optimal from an economic standpoint is highly situational to the best of the authors knowledge.

2.2 Human-Robot Collaboration

Traditionally, robots and humans have been kept separated from each other but a new trend is on the rise according to [18]. The trend encapsulate the characteristic strengths of humans and robots respectively in a combination.

Along with the globalization, producing companies needs to sustain the ever-increasing demand of customized products and at the same time keep competitive prices compared to mass produced ones [19]. Human workers have been associated with flexibility but constrained in productivity, whilst high levels of automation have been associated with great speed and accuracy but rigid and only suitable for monotonous tasks [18]. Many manufacturing companies sees HRC as a solution to maintain the efficiency of automated solutions without comprehending the flexibility of human operators [19].

The remaining difficulties related to HRC systems is the complexity related to safety standards and regulations when implementing these systems in industries [19]. Mainly due to the potential harm that a traditional industrial robot easily may inflict on a human [20]. However, rapid progress in information and computational technologies together with a new type of robot have led to new possibilities of revisiting the idea of HRC. Today, the regulations concerning collaboration is questionable which have resulted in a constraining condition to why it only exists a small amount of HRC stations within production and actual collaboration have not yet been achieved [6].

2.2.1 Robot cell definition

HRC encapsulates any industrial situation where humans work alongside robots without disuniting safety barriers [6]. The same article is defining HRC in a range of different levels of cooperation between the human and the robot. To specify this statement, five levels of collaborative interaction between the two parties work spaces are defined in *figure 2.1* with increasing interaction from left to right.

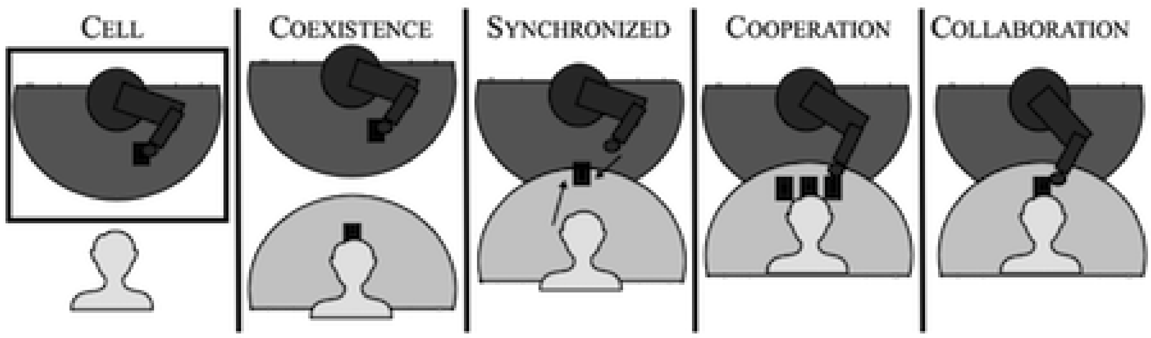


Figure 2.1: Robot cell definition, illustration adapted from [6]

Cell level is when the robot is operating inside a traditional cage where no existing HRC is present. *Coexistance* corresponds to separate work areas and tasks but a human may freely enter the robots work space. *Synchronized* is the level when human and robot share work space but work independently in the area. In *Cooperation*, robot and human work together in a shared area but on different products. Lastly, *Collaboration* is when robot and human are working simultaneously on the same workpiece, corresponding to the highest level of HRC [6].

2.2.2 Collaborative robots

Future production sites will demand a high degree of flexibility, while the speed and precision from automation still is required [21]. Within the segment of, for instance, material handling where these features are required, collaborative robots are expected to have a significant accumulation [22]. These robots may also be a solution for SMEs where small batches are produced and fast changeovers between products are essential which is not sustainable with industrial robots [23]. Furthermore, the features of collaborative robots used in packaging stations aims to decrease hazards for human workers which is not achievable with industrial robots today [22]. The possibilities to have robots assisting human operators to a reasonable price were inaccessible before the development of lightweight robots (LWR). LWR is an expression to define collaborative robots with low weight [6].

The definition of the term, collaborative robot, is today a bit unclear but [23] includes two main approaches - robots that in a safe manner collaborates with or assists human operators without a safety fence. Common attributes for collaborative robots are the soft design and that advanced technologies are applied, including torque sensing in joints and elastic actuators [22].

Figure 2.2: A typical design of a collaborative robot

Similarly to an ordinary industrial robot, a collaborative robot requires calibration [23]. The basics in a position based industrial station is the calibration to the base coordinate frame [24]. The base calibration is performed to assure that all cooperative systems in a robot cell are aligned in the same coordinate system [25]. It is essential to calibrate e.g. the tool-centre-point (TCP) of the end-effector, fixtures at the station and vision guiding systems, providing the robot with target information [24]. The relationship between the coordinate system of the robot and the peripherals is estimated by translating and rotating the coordinate systems through solving a homogeneous transformation system [26]. Calibration for a cell is traditionally done manually by jogging the robot tip to specified points, the accuracy is dependent on the operator and is time consuming concerning the effort in robot cell setup, recovery, and duplication [24].

However, this manual calibration do not need any additional equipment which other calibration methods do [27].

Collaborative robots are designed to easily be of assistance to human operators by incorporating features built on the strengths of the human body, such as reachability [28]. To minimize hazards in collisions between robot and human, the collaborative robot is designed with soft edges which allocates the force over a large area [6, 29]. A typical design of an collaborative robot is illustrated in *figure 2.2*. Moreover, the end-effector needs to be carefully selected, assessing collaborative aspects, to reduce the risk of pinch injuries [30].

The features that are added for collaborative robots are characteristic for maintaining a safe work environment for human operators, this distinguishes them from other industrial robots [6]. A substantial feature that has been complemented to the original industrial robots are the elastic torque sensing joints that controls the robot internally as can be seen in *figure 2.3* [32]. Furthermore, the sensors are also constructed to estimate any external torques for collision or failure detection [31]. Each joint is individually driven by a series of elastic elements that have sensors, these are connecting the motor and harmonic gear reducer to rigid links. Moreover, the motor position in all joints is sensed and additional torque sensors are built in to estimate externally applied torques, automatically excluding impact from gravity. An important feature is to get the required information fast from all the joints, this is done by deterministic bus communication to be able to implement control algorithms on a steering computer [32]. Furthermore, the high number of sensors such as joint torque, redundant position and wrist force-torque, demands a design that reduces the number of wires within the robot arm.

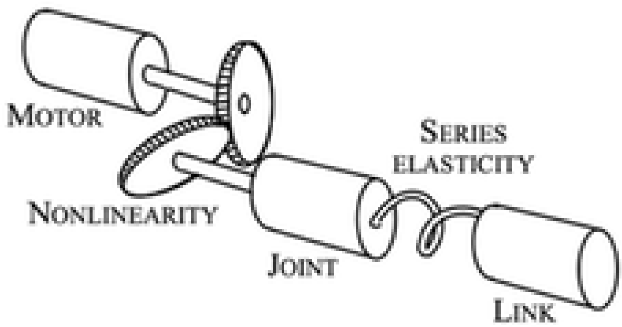


Figure 2.3: Elastic torque sensing joint, illustration adapted from [31]

A commonly occurring problem for both collaborative robots and industrial robots, is the compensation for elasticity which affects the position control [32]. To compensate for this the collaborative robot's torque sensors measures the vibrations behind the gear-box and are therefore actively damping the vibration. This is used to ensure velocity, position and is also essential when feedback control laws are used for e.g. detecting collision with a specified force or torque.

2.2.3 End-effector

An end-effector is the object that is mounted on the flange of the robot and determines what the robot is able to do [33]. Furthermore, to ensure a coexistent work station with a collaborative robot, the end-effector must be assessed in terms of safety for the operators [30]. Sharp edges, unlimited gripping force and exposed mechanical linkage are commonly existing in industry but is a problem in a HRC setting [34]. There are many suppliers of different solutions where the tool may be covered with a skin which makes the structure of the robot softer, however this reduces gripping capacity [30]. Moreover, solutions with adaptive force sensing and pre-collision detection are existing but are both expensive and inflexible.

There exists many end-effectors with different capabilities, it is however essential to consider both the application and product handled when choosing [34]. In pick and place applications, vacuum suction cups are preferable due to the flexibility and capacity of lifting a wide range of products with the same end-effector [33]. Pneumatic and vacuum technique is beneficial when manipulating smooth, light-weighing parts ranging from a few grams to several kilograms, made of plastic, metal or composites due to the soft grasp [35, 36]. The tool may be constructed accordingly, compressed air is connected to a pneumatic or electric generator with a filter, resulting in a negative pressure which generates vacuum [36, 37]. To achieve different features, check valve, vacuum and pressure switches, measuring and control devices are connected in different ways with mounting elements, hoses and connections [36].

After the vacuum is generated according to requirements from the application, the end-effector needs to be designed as the link between the vacuum generator and the products being transported [37]. The end-effector can be constructed in different ways with different materials and serves the purpose to keep the suction cups in the right position [33]. A commonly used method to construct customized end-effectors in robot applications today is additive manufacturing, referred to as three-dimensional(3D)-printing through material extrusion, which enables a fast and cheap production process [38, 39, 40]. The method requires polymer filaments to melt before extruding it through a nozzle onto a flat bed [40]. The polymer filament typically used is polyactic acid(PLA) or acrylonitrile butadiene styrene (ABS) due to excess availability and diversity in their physical characteristics [39, 40].

Furthermore, it exists a wide range of different suction cups, varying in shape, material and size depending on the structure of the products [35, 41]. To decide the shape of the cups, the material of the product (shapeless, compact, porous) needs to be defined [37]. Moreover, the surfaces are equally important to ensure easy handling, cost-efficiently. The material of the suction cups depends on parameters such as resistance to wear, intensity of stress, type of industry, workpiece quality and the surrounding environment. Information regarding which suction cups to use is provided by [37]. However, the research area within lifting capacity in relation to suction cups is yet unexplored and entails uncertainties regarding if objects will be dropped during transportation [35].

There are many factors within vacuum technology like grasp stability, amount of suction cups and path planning, that will affect the quality of the pick-and-place operation [41]. To prevent pinching, vacuum technique may be used which is harmless when working with low pressures [34].

2.3 Computer vision

Developed and enhanced by millions of years, evolution has made human vision into what it is today where visual impressions are interpreted unconsciously and effortlessly [42]. As an effort to increase the capabilities of automation, vision systems are implemented in various applications but what comes easily and naturally to humans requires tremendous computing resources.

2.3.1 Object recognition - template matching

Vision systems operate by image acquisition, image processing and finally interpretation of the scene [43]. The typical two dimensional (2D) machine vision applications found throughout manufacturing as of today utilizes a principle called template matching [44]. An area is scanned for objects with features matching models that the computer have previously been taught, see *figure 2.4*. To a large extent, human vision is about matching what is seen with similar models or concepts stored in memory [45]. These observations are then further analyzed and potential differences registered. This is the working principle mimicked in what's called model-based vision (MBV) in machine vision.

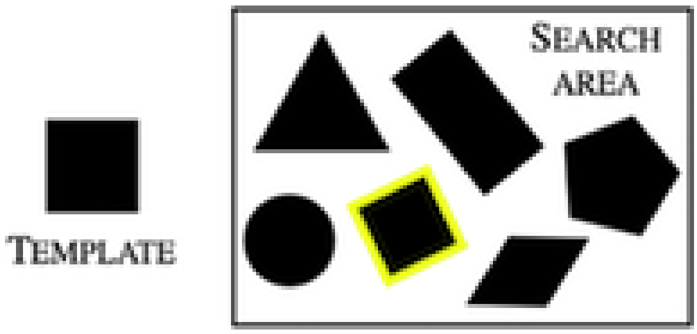


Figure 2.4: Principle of template matching

The idea of template matching sounds simple enough but contemporary machine vision systems are unable to generalize when facing an object that has not previously been taught [44]. Furthermore, MBV is not intelligent enough to detect more complex objects and shapes, consequently, elementary geometries are to prefer, such as circles, edges and curves [45]. Such geometries are well suited for transforms used in image processing, such as the Hough transform [46]. The popularity of the Hough transform in image processing stems from its capabilities of identifying shapes while being robust enough to handle measurement noise [43]. More advanced techniques for object registration exist but the algorithms are typically not robust enough in combination with requirements of very heavy computational loads [44].

Typical machine vision applications in contemporary manufacturing constitutes of quality inspection, image registration and target classification amongst others [47, 48]. The areas are suitable for the machine vision of today since it is possible to control the degrees of freedom of the object to a great extent, which simplifies the process of designing a suitable robot application [49]. Naturally, there exists circumstances which diminish the usability of MBV, such as that the system requires sufficient lightning and is vulnerable to surfaces prone to reflect light [44]. Furthermore, that it is incapable of handling scale differences which makes it practically impossible of picking parts stacked on top of each other since the object must represent the model that has been taught.

2.3.2 Computer vision in safety applications

Utilizing cameras and depth sensors for automating work tasks that requires vision has been established throughout manufacturing industry in many areas such as aforementioned quality inspection [47]. One area, to the best of the authors knowledge, where cameras and depth sensors have yet to become conventional and safety classified is within manufacturing.

One of the most actively researched areas within computer vision is object tracking due to the tremendous amount of applications which could benefit from such a feature [50, 51]. Motion based recognition and human-computer interaction are both fields where efforts have been diverted to apply motion based recognition but it is still difficult to achieve a satisfactory accuracy and speed [51]. Similarly to the aforementioned template matching, object tracking deals with occlusions, illumination, pose and scale change but it gets even more difficult since a moving object adds another layer of difficulties [50]. A moving object is prone to have slight changes in appearance as well as constantly changing its background, circumstances a vision system must be able to adapt to [51]. Not least if it is to be used for monitoring in safety applications.

Another vision principle rising in popularity is a method called Time-of-Flight (ToF), that essentially provides information about the distance to objects - the depth - captured by a sensor or camera [52]. The ToF principle is described accordingly, the sensor is transmitting a light pulse that hits an object where the time for the pulse to hit the object and return to the light source is measured [53]. The emitted light is typically modulated infrared light which, upon returning to the source causes a phase shift that is evaluated with the help of photonic mixing devices (PMD) [52]. Each point of the scanned area generates a point for an image [53]. After processing has been done, this amounts to a infrared image containing information about depth and amplitude.[52]. The method is capable of performing measurements up to 50 metres under optimized conditions. *Figure 2.5* illustrates the principle of ToF.

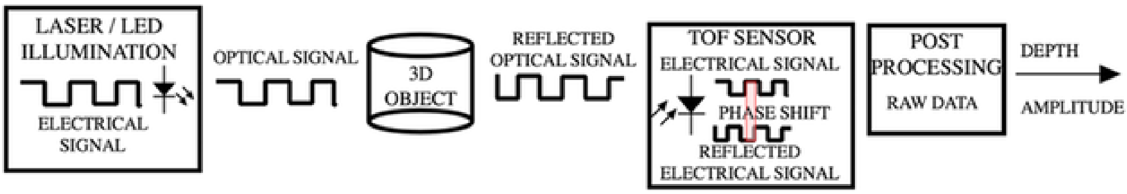


Figure 2.5: Principle of TOF, illustration adapted from [52]

Advancement in semiconductor and optical component technology increases the capabilities to implement depth sensors, which is reflected in its increase in popularity [52]. The usability correlates to the intended application resulting in algorithms and products specifically targeting a certain function. Examples of applications incorporating ToF for safety functionality exist in literature, for instance attempts on using it for pedestrian safety systems in cars [53, 54]. Algorithms are developed for people detection with ToF as well, for instance, [55] proposed a people detection technique by using depth sensor and ToF.

2.4 Remarks on Frame of reference

Companies have started to reconsider the stance regarding industrial robots and seeks to combine the strengths from both humans and automation through collaborative robots [19]. Whether it is through assisting the human operator or coexistence as explained by [6], opportunities arise with the removal of the disuniting safety bars and zone restrictions.

Material handling is an area with tasks suitable for increased automation but where companies often avoid automating to prevent risking a compromised flexibility [13]. Utilizing collaborative robots may be a beneficial substitute in these situations, like for instance in bin picking. Furthermore, by taking care of particularly strenuous tasks and utilizing the human workforce for more flexibility demanding work would reduce the risk of MSDs and sick leave.

Industrial robots are surrounded by a myriad of tough safety regulations, something that currently befalls collaborative robots as well to a great extent, which have hampered their entry into manufacturing [6]. To the best of the authors knowledge, no general methodology for implementation of collaborative robots have been established and it is more of a case study today to achieve a safety classification of a collaborative station. This is further explained in *Appendix A*.

It is safe to say that an intelligent vision system offers capabilities in terms of flexibility and versatility. It is essentially the brain-to-hand coordination that makes the human operator superior to robots in terms of adaptability [44]. Techniques for providing machines with more or less intelligent vision exists, but they typically excel at different areas according to [45], and are not as general as the human vision system. The research area of computer vision, however, is progressing constantly.

3
Research methodology

This chapter includes the working procedures throughout the project and describes in general the steps that were performed. The methodology is structured according to the outlined questions and is aiming to describe how they will be answered. *Figure 3.1* also illustrates the structure of the methodology that will be described further.

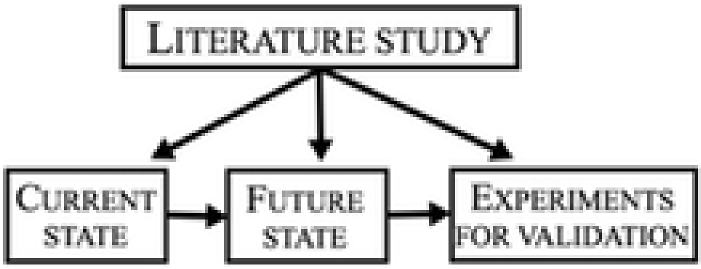


Figure 3.1: Comprehensive literature studies have formed the basis for the methodology throughout the thesis

3.1 Literature study

The databases Scopus and ScienceDirect were used to find scientific references and deeper knowledge in relevant fields. In terms of equipment, pages related to- and manuals provided by the suppliers were used.

The first phase of the literature study was targeting the existing manual downsizing procedure, possible solutions that were available today and important factors to be aware of i.e. ergonomics. Since the robot already had been specified as the LBR iiwa 14 R820 from Kuka, a general literature study regarding collaborative robot features was performed and compared with requirements that industrial robots fail to achieve today. Parts of the studies were addressed to dissolve programming issues concerning the Java programming for the LBR iiwa robot. This literature study was excluded from the report but serves its aim in the result. Further investigations about HRC, in terms of definition was performed and investigations regarding end-effector design for the robot to be able to construct a concept station.

Literature study concerning information and requirements on vision systems was also performed. Suitability of the system was including facts regarding the properties of the systems together with literature studies on the features required for the station. As specified by the company providing the project, Virtual Manufacturing, the system needed to be able to detect objects and act as a safety system detecting operators or humans surrounding the robot. Regarding the compatibility between different systems and communication, literature was studied in order to transform data.

Lastly, literature study addressing the issues concerning regulations for a robot workstation to be compatible with humans, without having to be in a restricted zone i.e. safety barriers was executed. This laid the foundation for documentation regarding requirements and recommendations for CE marking of the concept station. Furthermore, experiments was performed to validate the station regarding robustness and safety, the experiment was constructed based on funding's in literature.

3.2 Equipment

Several supporting functions were needed for the downsizing station to work as intended. Consequently, the realization process started with specifying requirements of the supporting equipment and testing out the subsystems. Moreover, how the different systems would interact with each other during testing of the final station.

3.2.1 Vision set-up and installation

First of all, the capabilities of the selected vision systems were investigated. Selection of an additional vision system was depending on available resources and IFM was used as supplier. Two vision systems were investigated, the first being a 2D camera with infrared light, O2D220 for object recognition and detection [56]. The camera provided an included software for setting up the application. The two products that were going to be used for the concept station were taught to the camera following the set-up of a new application. The camera operated on the template matching method to recognize objects and locate them in the cameras coordinate system. The output received from the camera when detecting and matching can be seen in *figure 3.2*.

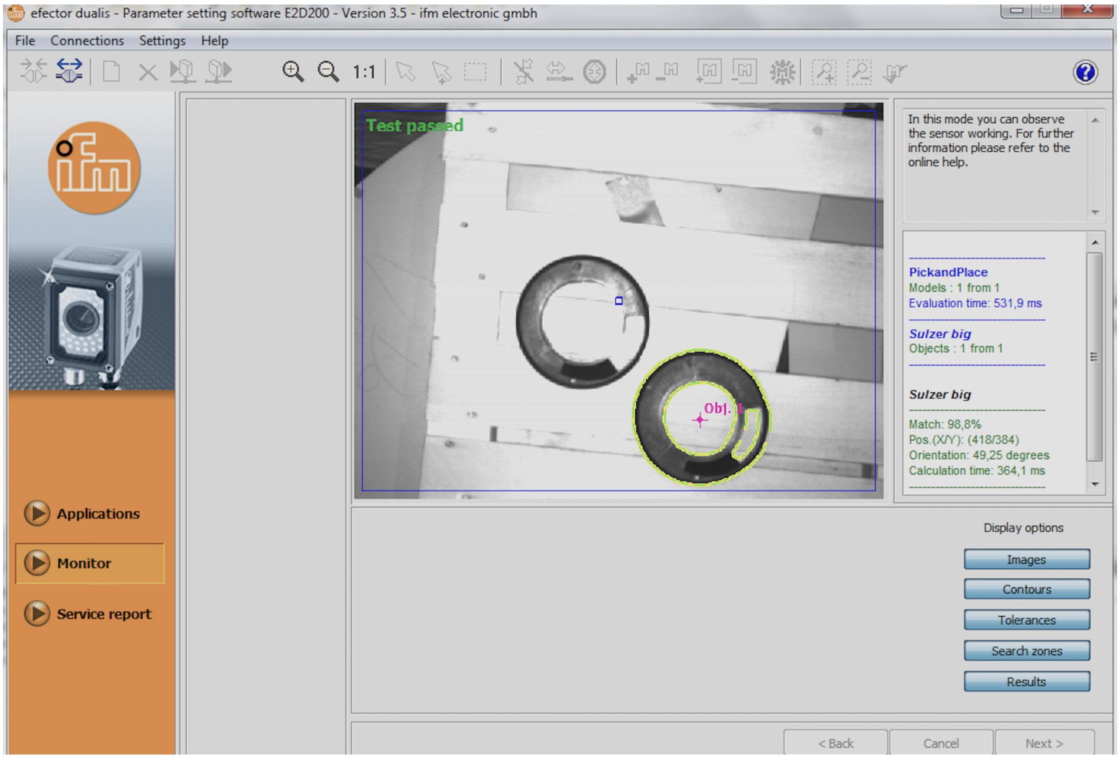


Figure 3.2: IFM software using template matching

The second vision system constituted of a 3D-sensor, O3D302 that was used for observing the station and its surroundings [57]. The sensor includes a PDM 3D ToF-chip to generate a picture of the scene with depth and amplitude data. The 3D-sensor generates a picture with worse resolution than the 2D-camera but the extra dimension is useful in applications like level and volume determination, and regulation. The software provided with the sensor is developed for these types of applications together with object recognition and detection on moving grounds i.e. conveyor belts. The level function provided by IFM was utilized to observe the station and detect when someone entered the robot station by the corresponding level increase. For this system to ensure applicability as a safety system, the process needed to be fast, which ToF technology should support. The sensor was compatible with PC and applications were easily created through following the introduction in the software. The set-up was initialized through specifying the region-of-interest (ROI) together with the allowed levels in the areas. It was also capable of setting regions-of-disinterest (ROD) in the field of view, which the camera should not react upon when the reference level was breached.

A rig for testing out the system's capabilities was set up according to *figure 3.3*, with the purpose of trying out the recognition and get an impression of suitable mounting solutions for the physical station. Both the 2D-camera and the 3D-sensor were connected through socket connection over TCP/IP, where information later was provided to the robot cabinet. The 2D-camera provided a string with the information regarding product type, the location and orientation of one object. The 3D-sensor was also sending information through a string, the information could be modified depending on the application. The information that the system could provide is e.g. if an area is over- or under-filled but also location and orientation of an object. The possibilities to export this valuable data to the robot was further investigated when the systems was installed to the robot cabinet. Depending on the requirements of the vision system, languages and programs were selected to create a harmonized robot cell that was supporting the included equipment.

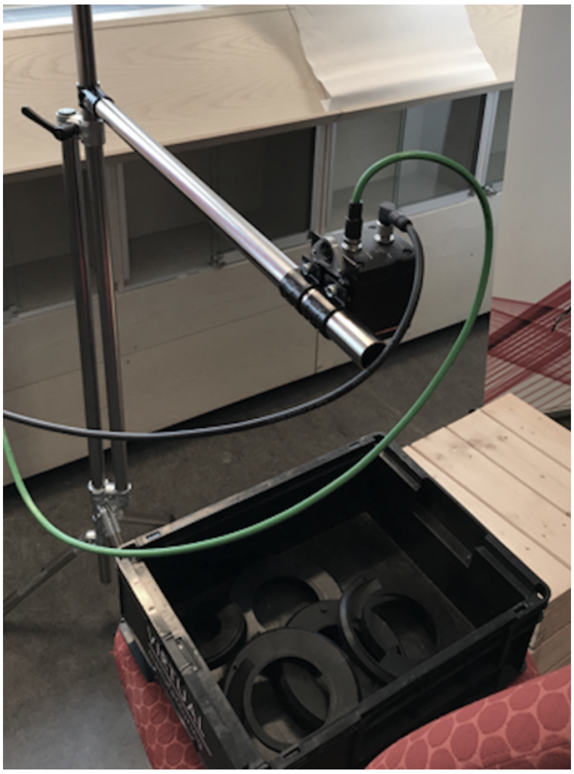


Figure 3.3: The rig constructed to test the vision systems

3.2.2 Station set-up

The next phase of the realization process was to have a more holistic perspective about the robot cell, incorporating environmental requirements of equipment and the robot cell. Furthermore, to be compatible with human workers without having to be in a restricted zone, a draft manual of a CE marking was created, see *Appendix A*. The guide was established through a comprehensive literature study regarding regulations of collaborative stations and the station was designed accordingly. The design solution was first visualized in a simulation and visualization software called VisualComponents to get a comprehensive picture of the solution, see *figure 3.4*, before building the physical station, see *figure 3.5*.

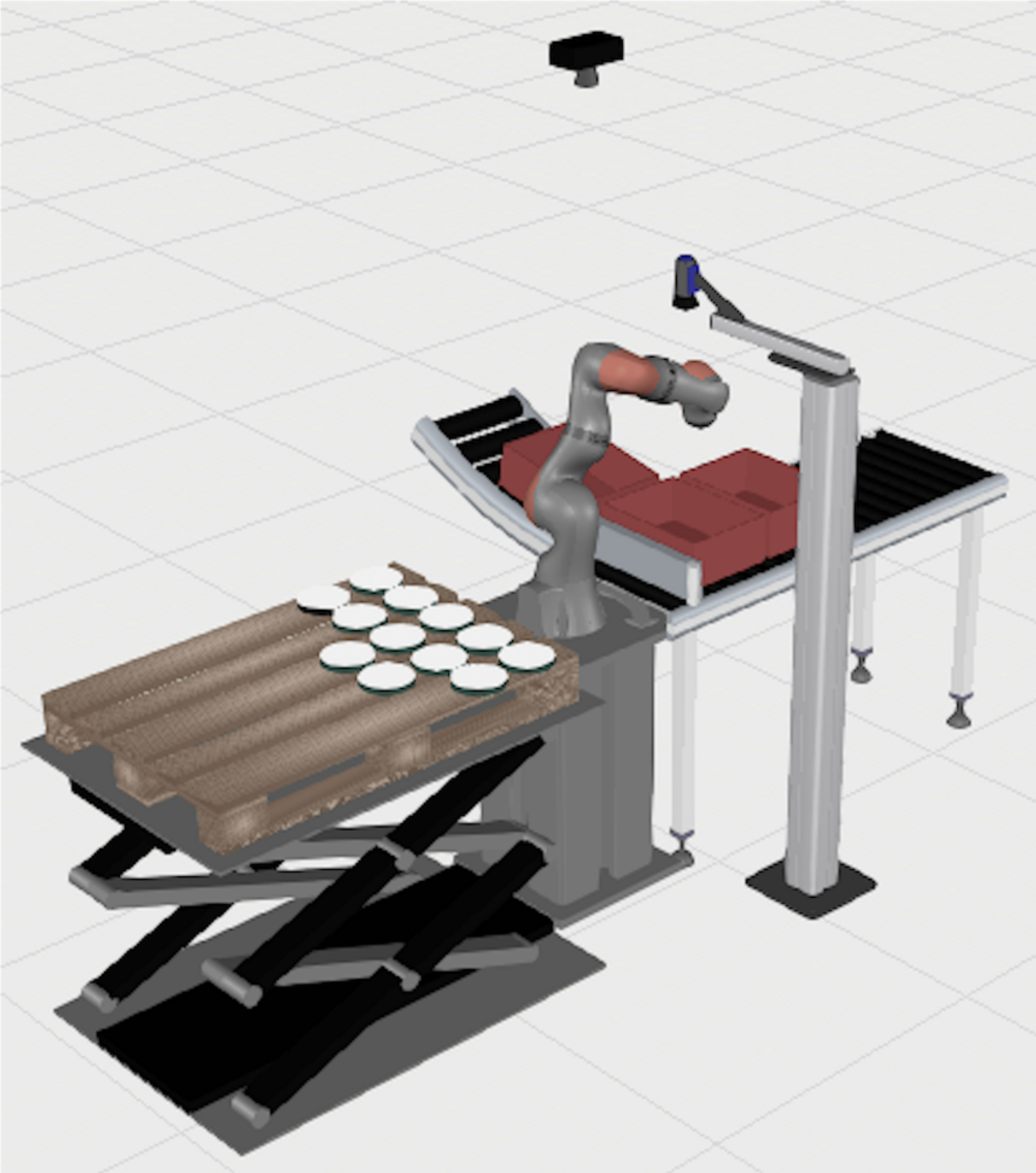


Figure 3.4: The station created in VisualComponents with robot mounted on a base, surrounded by pallet and bin

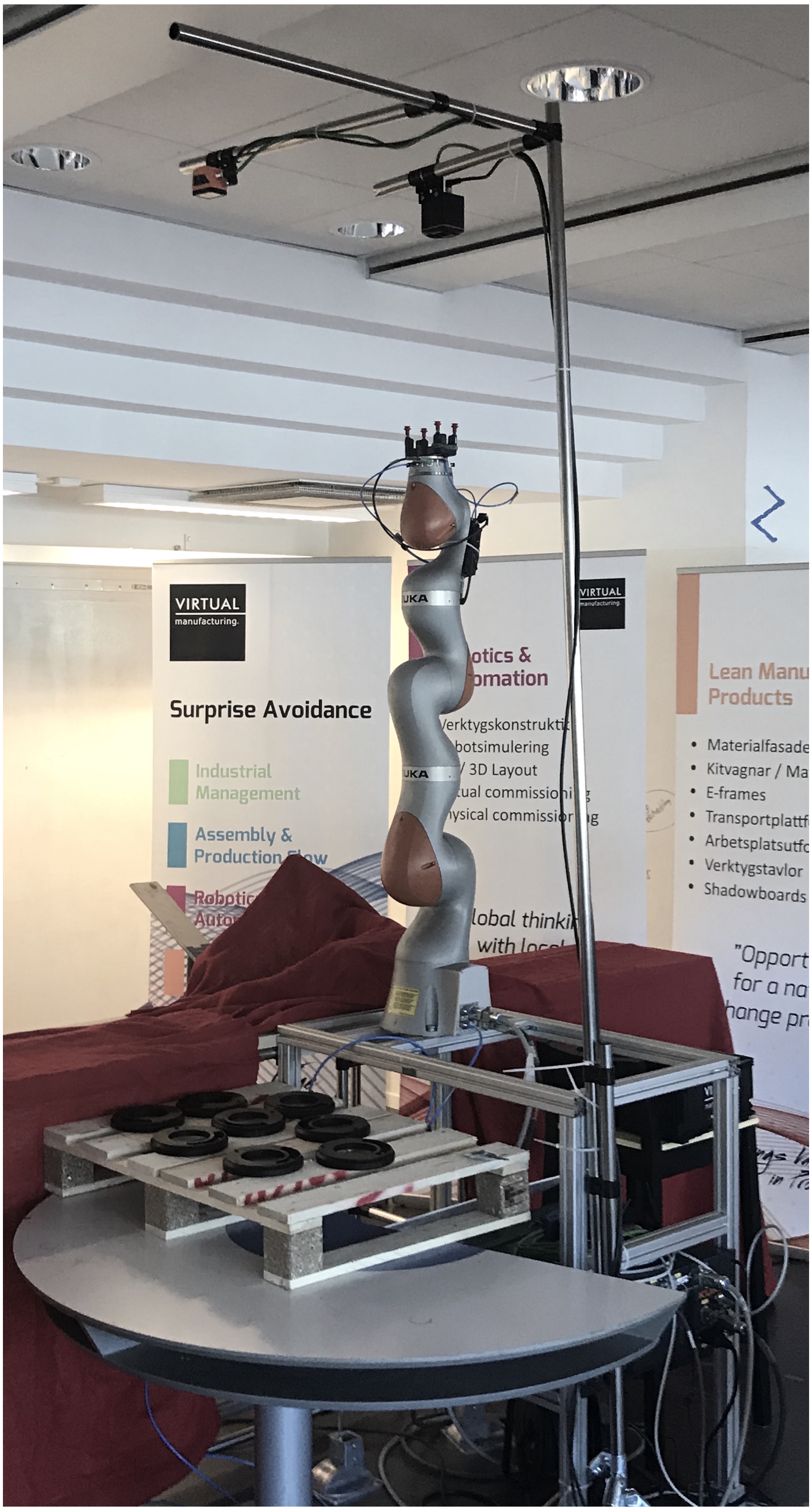
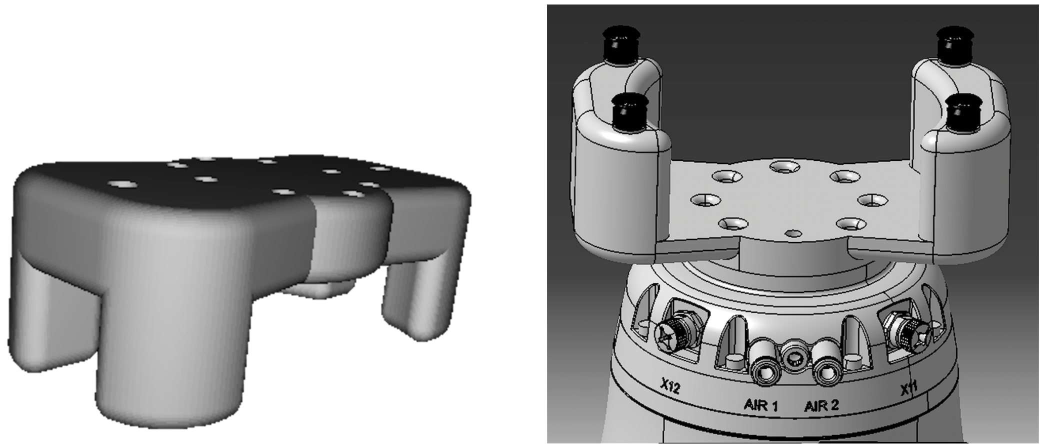


Figure 3.5: The physical station with robot mounted on a base with gripper, surrounded by pallet and bin

3.2.3 Construction of End-effector

The end-effector was constructed based on regulations, literature studies and with the restrictions that it had to be able to pick and place the components. Vacuum was chosen as the best alternative for the application. The gripper holding the vacuum cups was designed for 3D-printing in a Computer-aided design program called CatiaV5, as can be seen in *figure 3.6(a)*, and printed at Chalmers University of Technology. The gripper was also assembled together with the rest of the equipment to see the applicability, illustrated in *figure 3.6(b)*.

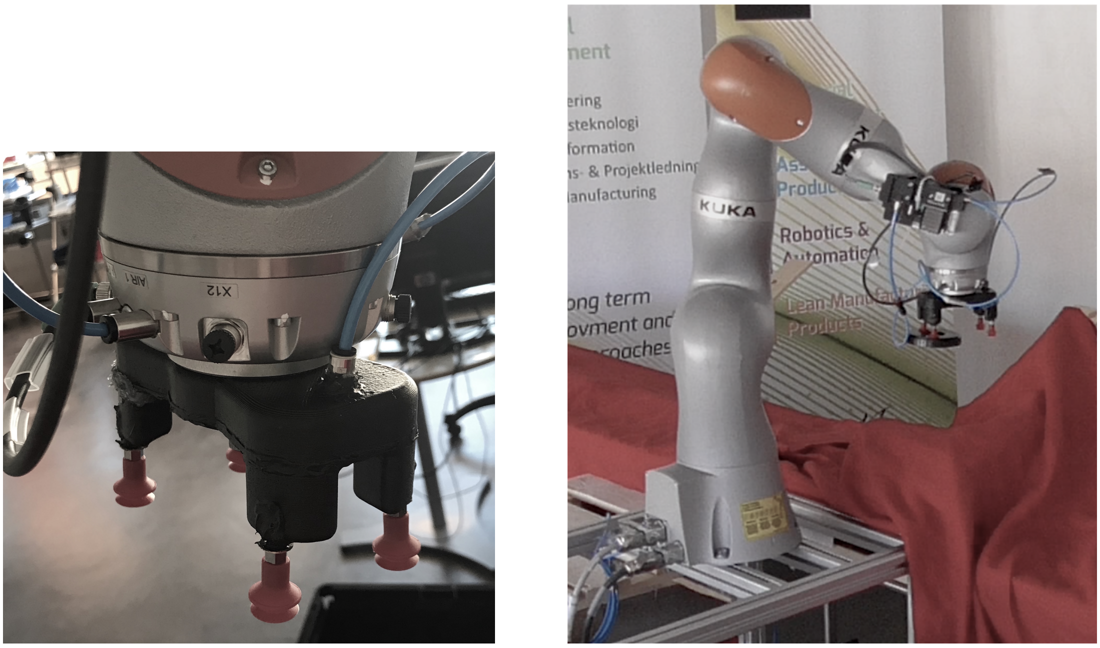


(a) Vacuum gripper

(b) Gripper with suction cups assembled on the robot

Figure 3.6: The gripper designed in Catia V5

The material used for printing was ABS which gave a solid base. The gripper was, however, not guaranteed to be gas proof which was solved by adding liquid gum through spray (Auto-K) [58]. Thread inserts were inserted in the holes in the gripper and sealed with silicone. Four suction cups were used of round bellow cups, 15 mm diameter in silicone, as seen in *figure 3.7 (a)* [59]. This was sufficient for handling both components.



(a) The physical end-effector with bellow suction cups mounted on the robot

(b) Robot equipped with vacuum end-effector connected to air and I/O supply

Figure 3.7: The end-effector mounted on the iiwa robot

To get vacuum from the generator of compressed air, a vacuum generator including a vacuum ejector with high vacuum performance, vacuum sensing, non-returning valve, electrical control of vacuum and automatic blow-off was used. All features were included in one package provided by Piab, the product was called PiCompact10 [60]. For the application to work, two channels were used to be able to steer the two sides of the gripper separately. The gripper was connected to the robot media flange through I/O connections operating by Boolean conditions. The output was set to true to activate the vacuum and false to turn it off. When switching off, blow-off was automatically activated. *Figure 3.7 (b)* presents the robot with gripper and vacuum supply unit connected to both I/O outlets on the robot and the compressed air supply.

3.3 Programming

When the station was physically constructed with robot, vision, pallet and bin, the programming of the tasks was carried out in Java. To show the fundamental steps in the program *figure 3.8* has been drawn. The program's purpose was to find products on the pallet through the 2D-camera, pick the products up and move them to the bin. Meanwhile, a background program handled the surveillance of the restricted regions (ROI). The collaborative part, meaning stop if someone touched the robot, was also incorporated.

Calibration was accomplished manually by transforming the coordinate systems of the vision system to match the robots world coordinate system. This transformation was both a rotation 180 degrees around the y-axis, 90 degrees around the z-axis and translations along both the x- and y-axis. The information needed from the vision systems was the location of the product expressed in the cameras coordinate system which then were transformed according to the description above. The transformation was performed automatically in the robot program.

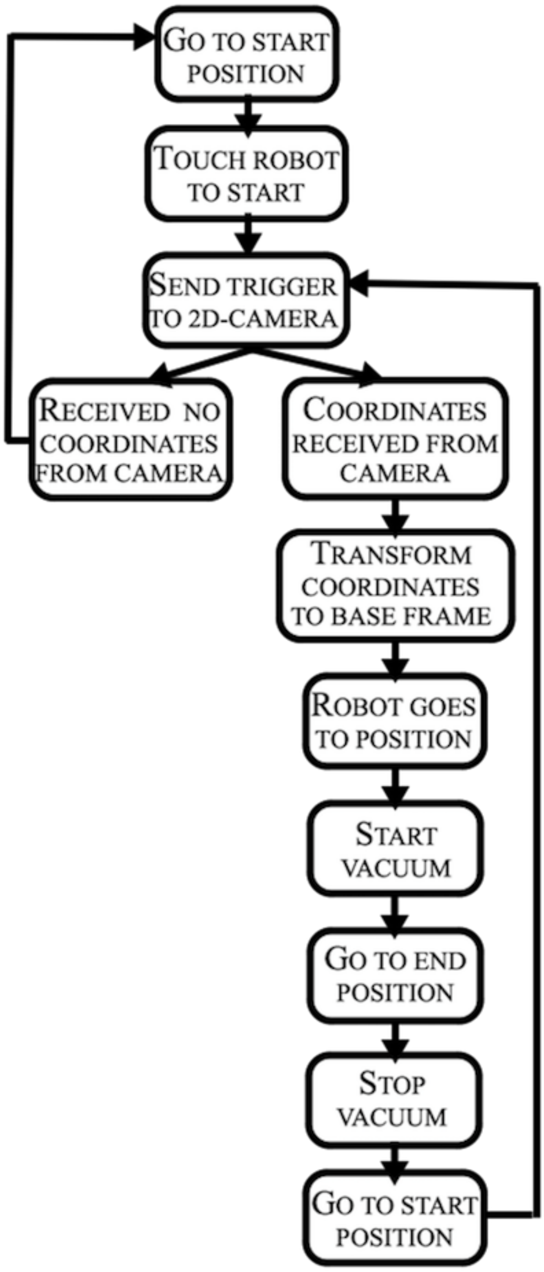


Figure 3.8: Configuration of structure for the robot program

The height, where the pallet was placed was pre-determined which limited the vision system to deliver the position on the xy-plane. The orientation of the object was also interesting to be able to place the object in an organized pattern, in the bin. This detection part of the object was carried out by the 2D-camera. The camera took a picture when the robot sent a trigger, which was included in the main program. The set-up of hardware and software connections between the 2D-camera and the robot are illustrated in *figure 3.9*.

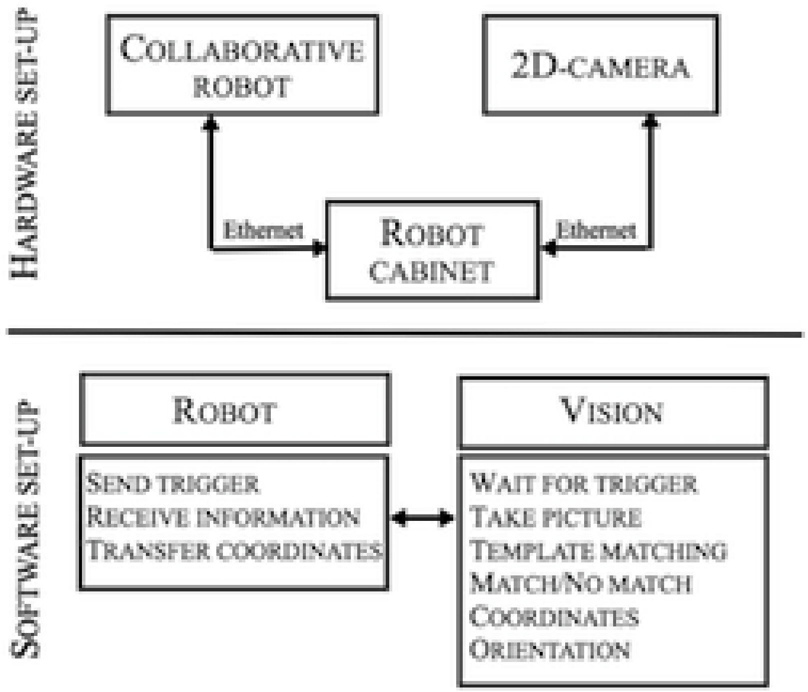


Figure 3.9: Hardware and software set-up for the 2D-camera

Moreover, information regarding where potential humans were in the station needed to be sent to the robot. This communication had to be instantaneous for the robot to act immediately on human motions. To solve this a background task was created to cyclically run and search for a specific variation in the string sent from the 3D-sensor. If a variation was detected, caused by someone or something entering the workstation the background program should stop the robot by utilizing a provided safety feature on the robot called Event-Driven Safety Monitoring (ESM). If a certain condition was met - an event - the superior safety system was going to kick in to stop the robot. The robot was going to be unable to move until the ESM stopped being violated. The logic concerning the background program and the hardware set-up is presented in *figure 3.10*. When bouncing into the robot with a torque larger then a specified value, another safety feature was utilized called Collision Detection, which was a Permanent Safety Monitoring (PSM) function. The safety function was going to prevent the robot from further movements in the same fashion as the aforementioned ESM.

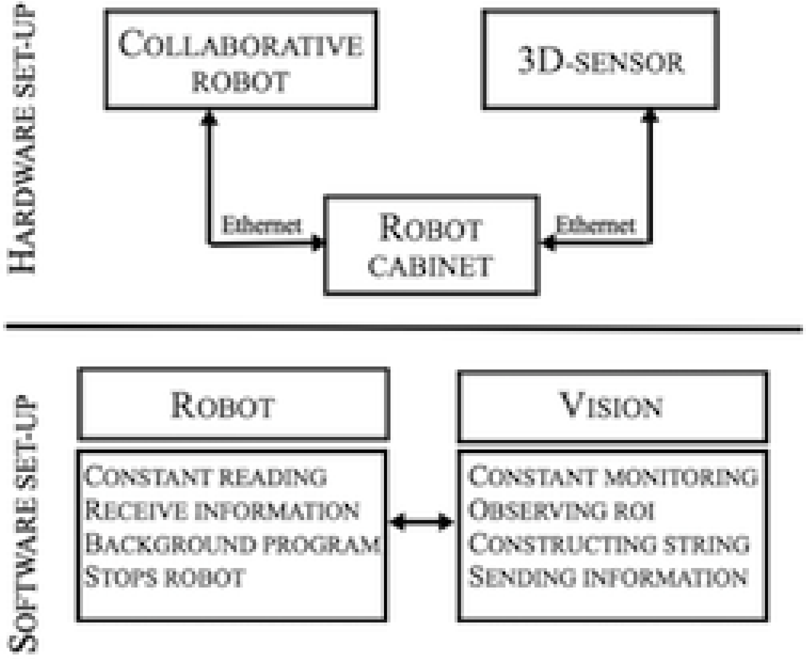


Figure 3.10: Hardware and software set-up for the 3D-sensor

3.4 Experimentation

The finalized solution was then exposed to a set of experiments to validate that it achieved the overall aim. The tests were constructed to answer the research question formulation of this report. The experiments were divided into three main areas which served to test out different features of the solution.

The first experiment category tested that the robot could locate the right position for components on a pallet, pick them up and place them in a bin. To test this, the two components in *figure 3.11* were used, one at a time, on the pallet. The large product is from here on referred to as component 1 and the small product, component 2. The experiment was successfully performed if 98 % of all products were moved from the pallet to the bin and sorted into separate stacks as a quantification of the result received from the industrial supervisor at Virtual Manufacturing.

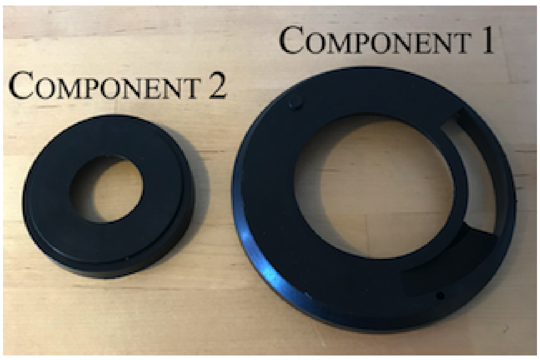


Figure 3.11: Components used for experimentation

This category of experimentation was testing the robustness of the station. Moreover, provided data for if the robot, with help from the vision system, could find and deliver all parts on the pallet. The material on the pallet were refilled ten times with five products for each of the two components, without stopping the task. The amount of tests was set to ten to get an indication of how the station would perform. The variable in these tests was the arbitrary positioning of the components on the pallet. The products that the vision found but robot failed to pick up due to any circumstance, were removed manually. The result was presented in a table including result for recognition by the camera and right orientation for component 1, due to the design with a hole. The result also included if the product was picked up by the robot and if it was delivered to the right position. This was performed to be able to get a reasonable result for a concept station for both products and to easily locate problems.

The second experiment category tested the collaborative aspect of the station concerning when humans surrounding the station stepped into the working area. When this situation occurred, the robot should stop immediately and start the task from the stopped position as soon as the area was clear. The experiment was performed accordingly, a human approached the working area from the front side as can be seen in *figure 3.12* and reached to touch the robot. This was done during different places in the robot program to get an approximation of the function. The backside of the station is representing a wall and the workstation can therefore not be entered from that side.

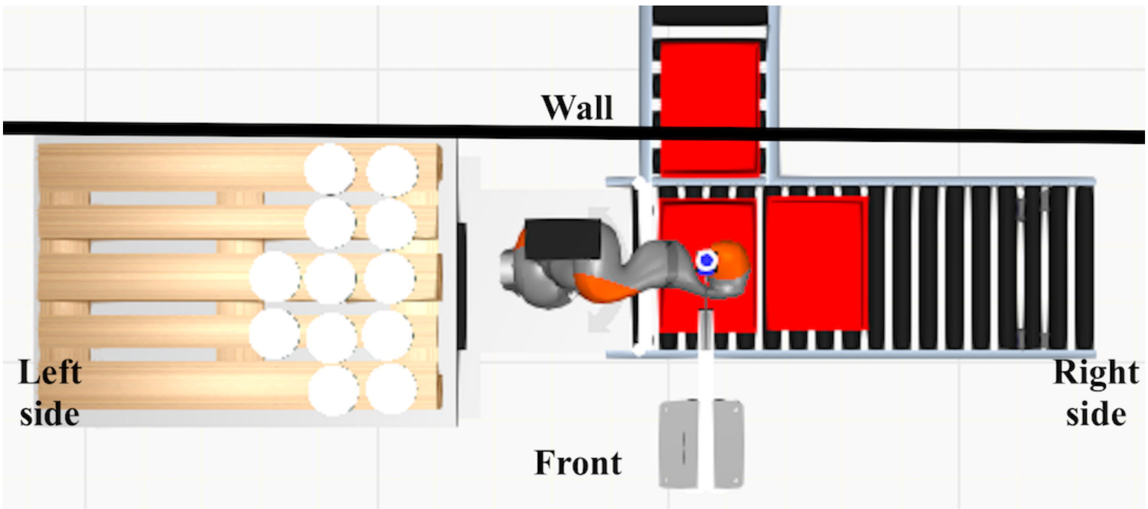


Figure 3.12: Layout of the downsizing station from VisualComponents with specifications

The aim was to estimate a safety distance so that the robot would stop before the human was able to touch the robot to secure that nobody got hurt. The human was reaching for the robot since this situation was rated to have the shortest reaction time for the vision system to stop the robot due to the decreasing distance between the robot and human. The estimations were done with help from *Appendix A* to get a result for the safety distance needed and reaction time for the system, from that the human entered the restricted area until the robot stopped.

The last experiment category tested that the robot was safe to work beside, even if the safety trigger that stopped the robot was not released. In this experiment the torque sensing feature in every joint of the robot was utilized to stop the robot when the torque exceeded a certain limit. To test this function, a human arm was put in the path of the robot to test if the robot stopped and if the sensitivity varied in different regions on the robot arm. To set an optimal value of the external torque, experimentation with different limits was performed with the purpose that the robot would stop when something was in the way. The torque was first set to a level of 20 Nm and then lowered in steps of 2 Nm. The levels were set according to *Appendix A* where specific forces are specified on the human body in relation to pain. After preventing the robot from pursuing the planned path the robot should resume the program from where it was stopped. This test was performed to secure that the hit from the robot would not hurt the human, meanwhile the robot had to be able to continue with the task to downsize.

4

Results

In this chapter the results from the experiments, described in the *Methodology*, are presented. The result is aiming to be the base for a discussion that narrows down into a conclusion. This sections purpose is therefore to present enough data to answer the research questions for this report.

4.1 Test of Process robustness

The first component to pick-and-place in the downsizing station was component 1 and the result is presented in *table 4.1.* 22 % of the products were successfully picked and moved to the bin. This resulted in no drop of products during transportation. Almost all products were recognized by the camera and coordinates were delivered to the robot 98 % of the time. The orientation was identified and successfully transferred to the robot at all times but resulted in a orientation rate of 98 %, since the orientation was dependent on the recognition. These two steps of the process are therefore above the required delivery rate.

Component 1				
	Recognition	Orientation	Picked	Delivered
Test 1 (pcs.)	4	4	0	0
Test 2 (pcs.)	5	5	2	2
Test 3 (pcs.)	5	5	2	2
Test 4 (pcs.)	5	5	1	1
Test 5 (pcs.)	5	5	1	1
Test 6 (pcs.)	5	5	1	1
Test 7 (pcs.)	5	5	1	1
Test 8 (pcs.)	5	5	0	0
Test 9 (pcs.)	5	5	1	1
Test 10 (pcs.)	5	5	2	2
Total (pcs.)	49	49	11	11
Percentage	98 %	98 %	22 %	22 %

Table 4.1: Test result for the process robustness of component 1

The robot achieved the highest degree of parts picked in the corner marked with green corresponding to 100 % of the times, see *figure 4.1*. Furthermore, the products situated in the opposite corner, marked with red, had the biggest offset error. At least one time in every test, the tool was situated with minor millimetre offset errors, resulting in that the robot could not pick it up.

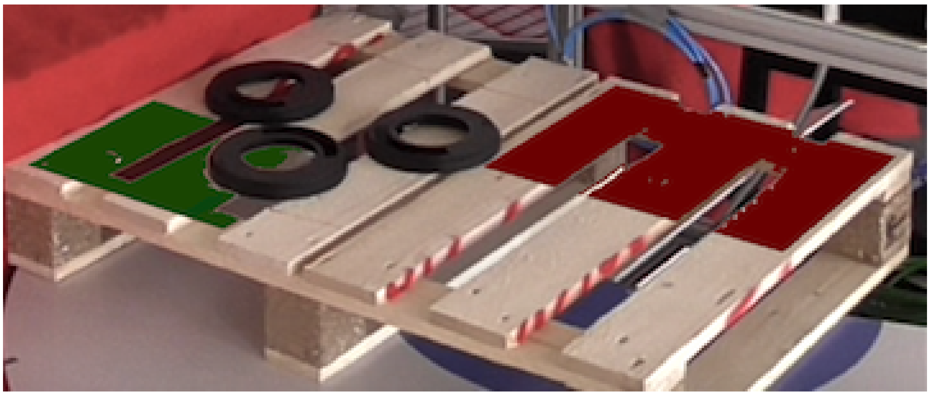


Figure 4.1: Component 1 on the pallet with marks concerning offset errors

The result of successfully delivered products from the pick-and-place application of component 2 was 40 %. The same amount of components were picked up and delivered in a successful way. All 50 components placed on the pallet for testing were recognized by the camera and coordinates were delivered to the robot as can be seen in *table 4.2*.

Component 2			
	Recognition	Picked	Delivered
Test 1 (pcs.)	5	1	1
Test 2 (pcs.)	5	2	2
Test 3 (pcs.)	5	2	2
Test 4 (pcs.)	5	2	2
Test 5 (pcs.)	5	3	3
Test 6 (pcs.)	5	2	2
Test 7 (pcs.)	5	2	2
Test 8 (pcs.)	5	3	3
Test 9 (pcs.)	5	1	1
Test 10 (pcs.)	5	2	2
Total (pcs.)	50	20	20
Percentage	100 %	40 %	40 %

Table 4.2: Test result for the process robustness of component 2

Likewise for component 2, products in the corner marked with green in *figure 4.2* were more often successfully picked then products in other corners. The components situated in the green corner were picked and delivered 100 % of the times. The red marked corner in the same figure had the worst offset and products situated there were never picked.

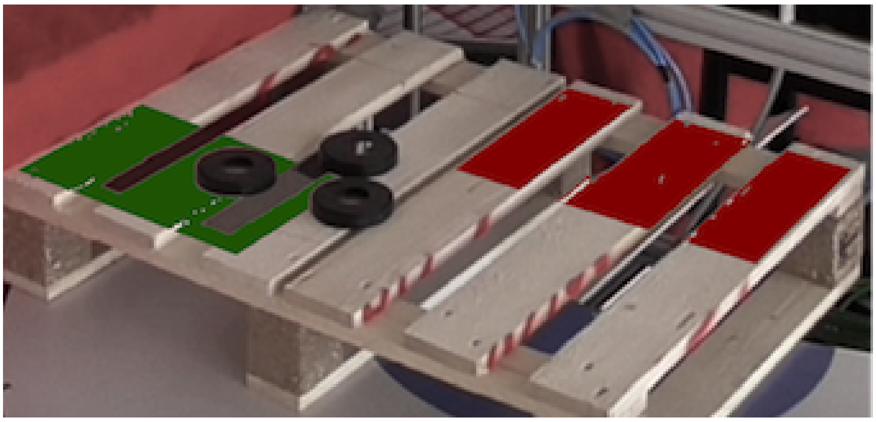


Figure 4.2: Component 2 on the pallet with marks concerning offset errors

The placement of the component in the bin were in all cases successfully performed for both components like *figure 4.3* is illustrating. The time to pick up five components and deliver them in the bin took 2 minutes and 40 seconds for both components.

Figure 4.3: The bin where the components are sorted in stacks

Due to the offset error, further experimentation was performed to determine the source. The point in the upper left corner, see the calibration point in *figure 4.4*, was marked on the pallet. The point was registered by the camera which was generating coordinates on the xy-plane. The robot was calibrated to this point by the manual calibration method to receive the transformation.

A program was then constructed by triggering the camera to receive the coordinates for a point on the pallet. The coordinates were expressed in the world coordinate frame and the robots TCP moved to this position.

Four points were marked on the pallet including the calibration point, i.e. black points in *figure 4.4*. The program was then executed, registering one point at the time and the offset errors of the robots TCP were measured, i.e. grey points in *figure 4.4*. This was performed five times to evaluate if there were any variation in positioning of the robots TCP between the tests. The experimentation resulted in the same offsets for all tests.

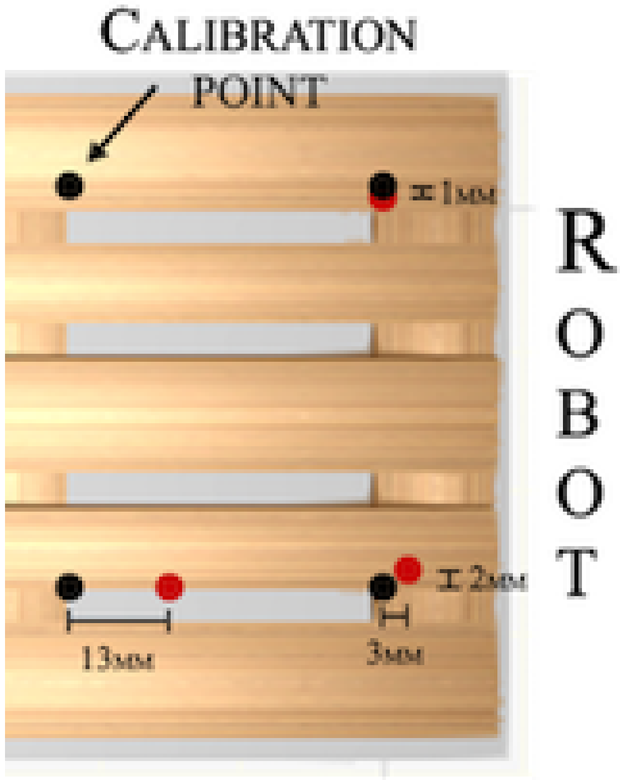


Figure 4.4: Illustration of the offset error at the downsizing station

4.2 Test of Safety restriction zone

The robot stops when the operator is entering the station from the front. *Figure 4.5* and *figure 4.6* shows how reality and sensor software correlates. With the knowledge of where the restricted area is, the operator tries to reach for the robot in different places of the program. The ROI is set to 400 mm from the pallet and the robot base, this is right outside the reach and working area of the robot. The robot is not reached by the operator in any case before the program stops. This distance is for that reason estimated to be enough.

Figure 4.5: Operator entering downsizing station and violating the ROI

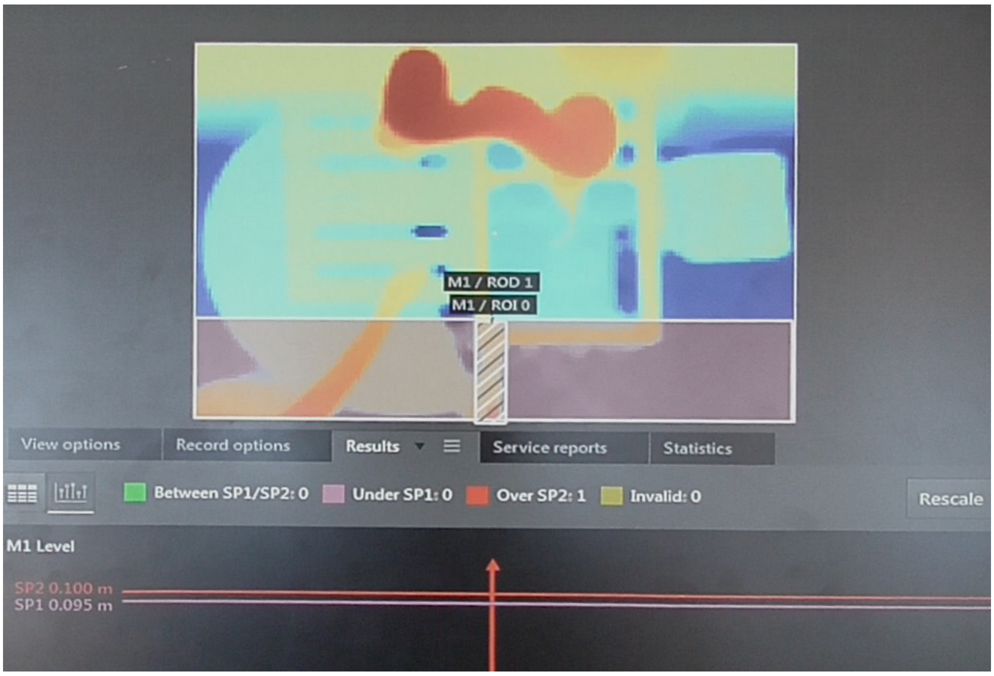
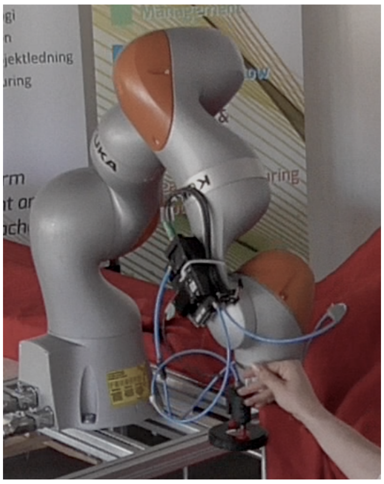


Figure 4.6: Operator entering downsizing station and violating the ROI (*figure 4.5*), seen in the IFM software

The time it takes, from that an operator enters the area until the robots stops is clocked from a recording of the station in action. Since this process is fast, an estimation had to be done based on the clocked time including reaction times and other margin of errors. The time received from ten different tests was always less then one second, a reaction time including stopping time of one second was therefore set. With the safety distance of 200 mm and the reaction time including stopping time of one second, according to *Appendix A*, the speed can not exceed 400 mm/s if the operator was standing still. It was calculated for that the operator was moving in a speed of less then 200 mm/s which allows the robot to move with a speed of 200 mm/s as well. In the method to calculate the safety distance, there is also calculated for intrusion distance and uncertainty factors, this extra safety distance have been included in the reaction and stopping time. The set time of 200 mm/s in the tests is therefore corresponding well to the theory.

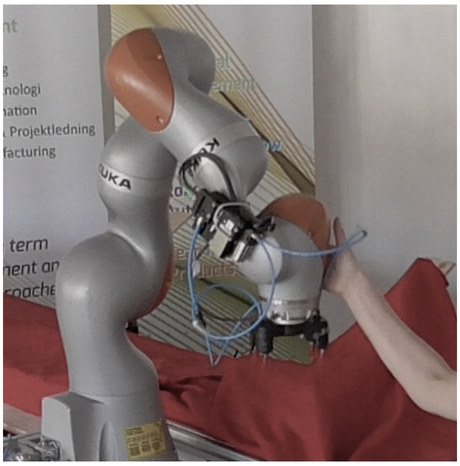
4.3 Test of Joint torque sensing

The experimentation with collision detection resulted in a torque of 9 Nm. The torque was first set to a level of 20 Nm and then lowered in steps down to 8 Nm. At the final step of 8 Nm, the robot was too sensitive since a minor hit from a hose on the end-effector was capable of stopping the robot a few times. Another issue that arose was that the collision detection system interfered with the collaborative touch-start function. The system had to be sensible enough to detect a collision quickly but the touch function operated in close proximity to that torque region.
The torque limit was for this reasons increased to 9 Nm where the robot was able to perform all tasks and stopped with a little touch. Independently of the placement on the robot the program stopped immediately and continued on the same path again, this is illustrated in *figure 4.7*. The value of 9 Nm is bellow the limits of the observed pain thresholds that are described in *Appendix A*.



(a) Positive y-direction

(b) Positive x-direction



(c) Negative x-direction

(d) Positive z-direction

Figure 4.7: Collision in different directions amounting to a violation of the PSM stopping the robot

5

Discussion

This chapter intends to discuss the outcome from the different experiments. Underlying reasons behind the results are explored and analyzed with the ambition to relate back to the research questions. Moreover, prepositions of further studies are suggested as well.

5.1 Discussing Process robustness

The overall result from the process robustness test indicates that the percentage of delivered parts from the station is unequalled with the delivery rate of 98 %. The result, presented in *table 4.1* and *4.2*, of 22 % delivered parts for component 1 and 40 % for component 2 is unsatisfying and indicates that the station haven't achieved an acceptable degree of process robustness. *Table 4.1* and *4.2*, indicates that the recognition of components works well and almost all parts were detected, a problem connected to the performance of the camera is therefore unlikely. Also the delivery correlates one-to-one with parts picked which implies that the transportation of parts with the vacuum gripper works well. However, something goes awry when the robot is about to pick up parts since the recognition rate of above 98 % is not reflected in parts picked. A series of underlying reasons behind the robot's incapability to pick is hereby to be discussed.

What is believed to be the biggest reason behind the result is the calibration between the robot and the 2D camera used for parts detection. The mounting was assumed to be parallel, corresponding to aligned x- and y-axes of robot and camera, but completely accomplishing this in practice was never expected. The small margin of error was however assumed to have minor effects on the result. After the rotations, the distances between the two coordinate systems were carefully adjusted by the manual method to one point on the pallet. In practice, an impossibility to achieve completely flawless but believed to be a good enough solution to accomplish a satisfactory degree.

Another factor pointing towards a calibration error was that even though the components were disposed arbitrarily on the pallet, it became evident that it was just components within a close perimeter to the point used for calibration which were picked as intended. This indicates that the world coordinate frame and the camera frame were not parallel to each other. An additional experiment was performed to exclude hardware and software errors of the robot and camera to ensure that promised tolerances were kept. As can be seen in *figure 4.4*, there is an exact repetitiveness of all five tests indicating that the displacement of the end-effectors TCP is not affected by tolerances from the camera or robot. The only offset error remaining and moreover due to no offset error on the calibration point indicating that there is a slightly off calibration. Furthermore, even if *table 4.1* and *4.2*, expresses a result with a picking rate that does not deviate from the mean value over the course of this test, it is believed that efforts to re-calibrate the camera also has to take place over time as slight displacement is probable. A longer test may have indicated such an interval but it was out of the scope for this project.

It became evident that the margins to be able to pick the components, especially component 1, was very small with the current end-effector design. A slight displacement, even within a tolerable range, impeded the gripper. If larger tolerances were accepted by the gripper, a higher degree of picked parts could have been achieved. Even with a better calibration, the end-effector would benefit from a revised design more capable of handling slight offsets.

In terms of parts detection, the vision system performed to a satisfactory degree implying flexibility since the system was able to adapt to the component it was exposed to. Only one failure was registered which is promising given the fact that no efforts to enhance lightning conditions and reduce reflections were performed. The station is deemed robust in regards to occlusion since the only relevant obstacle with potential of occluding the 2D camera was the robot. This was handled by having the robot to wait outside of the pallet when triggering the 2D camera.

The depth sensor supported a function capable of detecting objects solely on their elevation from the configured reference level indicating that the technology comes with possibilities of parts detection. However, since the components used were flat and the resolution of the sensor low, it was difficult to separate them from measurement noise in the point cloud. Thus, ToF was deemed unsuitable for the task and inferior to the template matching of the 2D camera regarding parts detection.

A robust process must also be efficient in terms of productivity. The robot was rather slow indicating that a human certainly would perform the current task quicker but the station have a lot of potential for improving this. The robot base and camera mounting was not stiff enough to enable the robot to operate in full speed as this could shake and displace the camera, implying a more rigid mounting or change in station layout. Furthermore, the robot was used in another project which affected and limited the ways that the station could be designed. The distance between bin and pallet could have been adjusted to reduce the transportation distance, and consequently the time consumed on the task, if not due to the other occupant. Moreover, by incorporating demanding conditions such as orientation and placement of products in the bin, the robot excels with its inexhaustible precision over an operator. Despite from material supply the station is completely automated which opens the opportunity for the robot to work day and night. Worth emphasizing is also how monotonous and repetitive this work task is. The task encompass the elements of small cyclic loads with little to no rest in between. An operator solely working with downsizing in this context would most definitely be exposed to MSDs over time and possibly burden the company with costly sick leave.

5.2 Discussing Safety restriction zone

The results show that the linked system managed to detect the operator and stop the robot in time during all attempts to enter the monitored zone. The result indicates that a depth sensor, indeed, would work for safety monitoring. Furthermore, the depth sensor's capabilities of dividing the monitored area into regions, ROI and ROD, offers more versatility than a conventional safeguard, such as a scanner. The 2D-camera, and the principle of template matching, would also be unsuitable for this task since it only detects specified rigid models. This implies that the system would not be able to detect an unknown object or objects changing in appearance, and a human in motion is anything but rigid.

The output string of the depth sensor could be edited to incorporate more features, such as which zone that was being violated and the distance to the obstacle. This enables possibilities to design a smarter program capable of avoiding obstacles, and not just stop the robot. In practice, these zones could be configured to either stop or slow down the robot, based on its motion pattern. With this feature of the 3D-sensor an application could have been established which do not necessarily mean that the robot stops working when someone enters the restricted area. The possibilities of this sensor together with the collaborative robot makes it adjustable for coexistent set-ups where the robot do not stop if material e.g. is changed.

Optimally adapting the monitored zone to the station requires knowledge about the intended operating speed of the robot, operator speed and the reaction time of the safety system. This experiment examined if the linked system would work as intended and an estimation of the reaction time was done indicating roughly one second from object detection to robot standstill. With the knowledge of the distance for the safety zone and also the robot speed, a speed could be calculated for the human according to the ISO/TS 15066:2016, see *Appendix A*, resulting in 200 mm/s. Since the velocity of the operator in the tests was unknown, an assumption is that the speed of the operator in the tests were 200mm/s or below. A more reasonable assumption is that the distance between the robot and the operator was more then 400mm in all tests or that the robot was moving in the same direction as the operator. Any of these assumptions will signify that the test performed corresponds to the theory. The speed of the operator, when approaching the working area, is therefore essential to be aware of to secure a safety distance for future safety classifications. Such an optimization would ensure that a robot and a human would never collide at full speed within the reaction and stopping time. It would also ensure that the safety system wasn't too sensitive, reacting unnecessarily early and thus affecting performance negatively.

The system was only set-up to work in front of the station due to 3D camera limitations. The field of view sight offered by the camera was not enough to incorporate monitoring of the left- and right side of the station. An attempt at restricting zones of the sides was performed but the robot stopped itself. The camera, however, can be provided with a wide lens which would have given a sufficient field of view search area.

How well the system works in different settings would also have to be determined to ensure that the intended safety standard is upheld. How well it would operate under variable lightning conditions, for instance, next to a window exposed to sunlight. This experimental set-up only assured that the system would work in the surrounding conditions that occurred at the test site. Further investigations and new installations with other conditions are therefore unexplored and not secured in this test. In terms of occlusion, the system is deemed very robust since the very principle it acts on is distance to objects, and not an algorithm designed for object detection that can be impeded by occlusion. Once the threshold level is breached, the system reacts.

5.3 Discussing Joint torque sensing

The capabilities of a collaborative robot was clearly expressed in this experiment. Joint torque sensing is arguably what makes it a collaborative robot. It provides new ways of working with a robot as well as adding another layer for safety. Essentially the same function but applied differently depending on the operational setting gives it a whole new purpose. In practice, this also means that a conflict may arise when using the function for the two purposes simultaneously, as was seen in this test. A low threshold for collision detection was desirable but this interfered with the collaborative touch-start function. However, emphasis in this project was on safety.

The present collision detection function incorporates all torques in the different joints and recalculates the total external torque which makes it safe to collide with in any direction and placement on the robot, as could be seen in the result. The collision detection system could also be altered in an alternative way, since it offers the possibilities to monitor and specify conditions for each joint individually. This approach could have been used to set a more sensitive interval in a direction if needed.

Collision detection might appear a bit redundant in the current setup where the depth sensor is supposed to stop the robot if a human enters the station. It can, however, be seen as an additional layer of safety. Furthermore, by using the depth sensors capabilities of separating the monitored area into different zones and speeds, the collision detection function would come into its own. In that case the robot would continue to work at a slower pace if an operator entered the station and stop at earliest upon collision.

6
Conclusion

This project has provided a concept station and proven that utilizing a collaborative robot equipped with two separate vision systems for obstacle- and parts detection may be used for downsizing in a coexistent setting in manufacturing. Furthermore, the proposed solution showcased a station capable of fulfilling the aim of its confined area.

The finalized station indicates a robust solution but the importance of a correct calibration cannot be understated as was seen from experimentation. The camera system used for parts detection managed to detect and correctly specify model and orientation. The delivery rate corresponded one-to-one with the picking rate implying a sufficient and balanced end-effector.

A surveillance system monitoring around the robot, together with joint torque sensors capable of detecting collision, ensured a safe working environment. Furthermore, the principle of time-of-flight demonstrated great capabilities since the system managed to detect obstacles and stop the robot flawlessly. By dividing the monitored area into different ROI, more capabilities of optimizing the robots behaviour were offered compared to a conventional scanner, i.e. speed reductions over stopping in certain areas, without compromising safety.

Assisted by the features of the collaborative robot, the solution is slim and flexible since ungainly fences can be removed. The compact design with cameras mounted on the robot base facilitates mobility which makes it possible to put the station in its entity on an AGV in a future application.

Bibliography

[1] J. P. v. d. Berg and W. H. M. Zijm. Models for warehouse management: Classification and examples. *International Journal of Production Economics*, (59(1)):519–528, 1999.

[2] Merriam-Webster. Downsize, 2018. Available at: https://www.merriam-webster.com/thesaurus/downsize. Accessed: 12-02-18.

[3] Teodor G. Crainic, Luca Gobbato, Guido Perboli, Walter Rei, Jean-Paul Watson, and David L. Woodruff. Bin packing problems with uncertainty on item characteristics: An application to capacity planning in logistics. *Procedia - Social and Behavioral Sciences*, 111:654–662, 2014.

[4] Chris A. Ortiz and Taylor Francis (e-book collection). *Kaizen assembly: designing, constructing, and managing a lean assembly line*. CRC Taylor Francis, Boca Raton, FL, 1 edition, 2006.

[5] X. Mosquet, H. Zablit, A. Dinger, G. Xu, M. Andersen, and K. Tominaga. The electric car tipping point. 2017. The Boston Consultant Group.

[6] Wilhelm Bauer, Manfred Bender, Martin Braun, Pete Rally, and Oliver Scholtz. Lightweight robots in manual assembly—best to start simply. *Frauenhofer-Institut für Arbeitswirtschaft und Organisation IAO, Stuttgart*, 2016.

[7] Elias N. Malamas, Euripides G. M. Petrakis, Michalis Zervakis, Laurent Petit, and Jean-Didier Legat. A survey on industrial vision systems, applications and tools. *Image and Vision Computing*, 21(2):171–188, 2003.

[8] Simon Emde and Nils Boysen. Optimally locating in-house logistics areas to facilitate jit-supply of mixed-model assembly lines. *International Journal of Production Economics*, 135(1):393 – 402, 2012.

[9] C. Wänström and L. Medbo. The impact of materials feeding design on assembly process performance. *Journal of Manufacturing Technology Management*, 20:30–51, 2009.

[10] Robin Hanson, Lars Medbo, Cecilia Berlin, and Jonas Hansson. Manual picking from flat and tilted pallet containers. *International Journal of Industrial Ergonomics*, 64:199 – 212, 2018.

[11] Martina Calzavara, Robin Hanson, Fabio Sgarbossa, Lars Medbo, and Mats I. Johansson. Picking from pallet and picking from boxes: a time and ergonomic study. *IFAC-PapersOnLine*, 50(1):6888 – 6893, 2017. 20th IFAC World Congress.

[12] Battini Daria, Calzavara Martina, Persona Alessandro, Sgarbossa Fabio, and Visentin Valentina. Fatigue and recovery: research opportunities in order picking systems. *IFAC-PapersOnLine*, 50(1):6882 – 6887, 2017. 20th IFAC World Congress.

[13] Martina Calzavara, Christoph H. Glock, Eric H. Grosse, Alessandro Persona, and Fabio Sgarbossa. Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse. *Computers Industrial Engineering*, 111:527 – 536, 2017.

[14] Applying lean in aerospace manufacturing. *Materials Today: Proceedings*, 4(8):8439 – 8446, 2017. International Conferenceon Advancements in Aeromechanical Materials for Manufacturing (ICAAMM-2016).

[15] Siri Adolph, Patrick Kübler, Joachim Metternich, and Eberhard Abele. Overall commissioning effectiveness: Systematic identification of value-added shares in material supply. *Procedia CIRP*, 41:562 – 567, 2016. Research and Innovation in Manufacturing: Key Enabling Technologies for the Factories of the Future - Proceedings of the 48th CIRP Conference on Manufacturing Systems.

[16] Work-related disorders 2016. The Swedish Work Environment Authority. Available at: https://www.av.se/globalassets/filer/statistik/arbetsorsakade-besvar-2016/arbetsmiljostatistik-arbetsorsakade-besvar-2016-rapport-2016-3.pdf. Accessed: 2018-04-01.

[17] Harold B. Maynard, Kjell B. Zandin, and AccessEngineering (e-book collection). *Maynard's industrial engineering handbook.* McGraw-Hill, New York, 5th edition, 2001. Accessed: 2018-04-01.

[18] Valeria Villani, Fabio Pini, Francesco Leali, and Cristian Secchi. Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. *Mechatronics*, 2018.

[19] Integrated risk assessment and safety consideration during design of hrc workplaces. *Emerging Technologies and Factory Automation (ETFA), 2017 22nd IEEE International Conference on*, pages 1–10.

[20] Xi Vincent Wang, Zsolt Kemény, Jósef Váncza, and Lihui Wang. Human–robot collaborative assembly in cyber-physical production: Classification framework and implementation. *CIRP annals*, 66:5–8, 2017.

[21] Mikkel Rath Pedersen, Lazaros Nalpantidis, Rasmus Skovgaard Andersen, Casper Schou, Simon Bøgh, Volker Krüger, and Ole Madsen. Robot skills for manufacturing: From concept to industrial deployment. *Robotics and Computer-Integrated Manufacturing*, 37:282 – 291, 2016.

[22] Collaborative robots market is expected to drive by growing demand from small and medium-sized enterprises till 2025: Grand view research, inc, Mar 10 2017. Copyright - (Copyright M2 Communications, 2017; Last updated - 2017-03-10.

[23] C. Schou, R.S. Andersen, D. Chrysostomou, S. Bøgh, and O. Madsen. Skill-based instruction of collaborative robots in industrial settings. *Robotics and Computer-Integrated Manufacturing*, 53:72–80, 2018.

[24] Yuye Cai, Hao Gu, Cheng Li, and Huashan Liu. Easy industrial robot cell coordinates calibration with touch panel. *Robotics and Computer-Integrated Manufacturing*, 50:276 – 285, 2018.

[25] Yahui Gan, Xianzhong Dai, and Donghui Dong. Robot calibration for cooperative process under typical installation. *Journal of Applied Mathematics*, 2014.

[26] Biao Mei, Weidong Zhu, Kangzheng Yuan, and Yinglin Ke. Robot base frame calibration with a 2d vision system for mobile robotic drilling. *The International Journal of Advanced Manufacturing Technology*, 80(9):1903–1917, 2015.

[27] Shibin Yin, Yongjie Ren, Jigui Zhu, Shourui Yang, and Shenghua Ye. A vision-based self-calibration method for robotic visual inspection systems. *Sensors (Basel, Switzerland)*, 13(12):16565–16582, 2013.

[28] Pauline Maurice, Vincent Padois, Yvan Measson, and Philippe Bidaud. Human-oriented design of collaborative robots. *International Journal of Industrial Ergonomics*, 57:88 – 102, 2017.

[29] Iñaki Maurtua, 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), 2017.

[30] Roman Weitschat, Jorn Vogel, Sophie Lantermann, and Hannes Hoppner. End-effector airbags to accelerate human-robot collaboration. pages 2279–2284. IEEE, 2017.

[31] Vinay Chawda and Gunter Niemeyer. Toward torque control of a kuka lbr iiwa for physical human-robot interaction. pages 6387–6392, 2017. 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).

[32] 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*, 34(5):376–385, 2007.

[33] Jim Camillo. What's new with end-effectors. *Assembly*, 57(13):40–43, 12 2014.

[34] Costas Charalambous. How to choose the right type of eaot for your collaborative robot? *Assembly*, pages 44–45, 04 2017.

[35] Giacomo Mantriota. Optimal grasp of vacuum grippers with multiple suction cups. *Mechanism and Machine Theory*, 42(1):18 – 33, 2007.

[36] Jim Camillo. Vacuum grippers: (suck it) up for the challenge. *Assembly*, 59(13):42–45, 12 2016.

[37] FESTO. Basic principles of vacuum technology. Available at: https://www.festo.com/net/SupportPortal/Files/286804/Basic_Vacuum_Technology_Principles.pdf. Accessed: 2018-04-05.

[38] J. Z. Gul, M. Sajid, M. M. Rehman, G. U. Siddiqui, I. Shah, K. . Kim, J. . Lee, and K. H. Choi. 3d printing for soft robotics–a review. *Science and Technology of Advanced Materials*, 19(1):243–262, 2018.

[39] Max Haffner, Austin Quinn, Tsung yen Hsieh, E. Bradley Strong, and Toby Steele. Optimization of 3d print material for the recreation of patient-specific temporal bone models. *Annals of Otology, Rhinology & Laryngology*, 127(5):338–343, 2018.

[40] J. R. McGhee, M. Sinclair, D. J. Southee, and K. G. U. Wijayantha. Strain sensing characteristics of 3d-printed conductive plastics. *Electronics Letters*, 54(9):570–572, 2018.

[41] Yukihisa Karako, Toshihiro Moriya, Masayoshi Abe, Haruna Shimakawa, Shinichiro Shirahori, and Yumi Saitoh. A practical simulation method for pick-and-place with vacuum gripper. pages 1351–1356. The Society of Instrument and Control Engineers - SICE, 2017.

[42] E.R. Davies. *Computer and Machine Vision (Fourth Edition)*. Academic Press, Boston, fourth edition edition, 2012.

[43] Eduardo A. Murillo-Bracamontes, Miguel E. Martinez-Rosas, Manuel M. Miranda-Velasco, Horacio L. Martinez-Reyes, Jesus R. Martinez-Sandoval, and Humberto Cervantes de Avila. Implementation of hough transform for fruit image segmentation. *Procedia Engineering*, 35:230 – 239, 2012. International Meeting of Electrical Engineering Research 2012.

[44] R. Kouskouridas, A. Amanatiadis, S.A. Chatzichristofis, and A. Gasteratos. What, where and how? introducing pose manifolds for industrial object manipulation. *Expert Systems with Applications*, 42(21):8123 – 8133, 2015.

[45] Michael Magee and Steven Seida. An industrial model based computer vision system. *Journal of Manufacturing Systems*, 14(3):169 – 186, 1995.

[46] A. Oualid Djekoune, Khadidja Messaoudi, and Kahina Amara. Incremental circle hough transform: An improved method for circle detection. *Optik - International Journal for Light and Electron Optics*, 133:17 – 31, 2017.

[47] Paolo Bellandi, Giovanna Sansoni, and Angelo Vertuan. Development and characterization of a multi-camera 2d-vision system for enhanced performance of a drink serving robotic cell. *Robotics and Computer-Integrated Manufacturing*, 28(1):35 – 49, 2012.

[48] Jae-Chern Yoo and Chang Wook Ahn. Template matching of occluded object under low psnr. *Digital Signal Processing*, 23(3):870 – 878, 2013.

[49] Gordon Wells, Christophe Venaille, and Carme Torras. Vision-based robot positioning using neural networks. *Image and Vision Computing*, 14(10):715 – 732, 1996.

[50] Zhiyong Li, Song Gao, and Ke Nai. Robust object tracking based on adaptive templates matching via the fusion of multiple features. *Journal of Visual Communication and Image Representation*, 44:1 – 20, 2017.

[51] Xin Zhang, Gui-Song Xia, Qikai Lu, Weiming Shen, and Liangpei Zhang. Visual object tracking by correlation filters and online learning. *ISPRS Journal of Photogrammetry and Remote Sensing*, 140:77 – 89, 2018.

[52] Norbert Druml, Christoph Ehrenhoefer, Walter Bell, Christian Gailer, Hannes Plank, Thomas Herndl, and Gerald Holweg. A fast and flexible hw/sw coprocessing framework for time-of-flight 3d imaging. *Microelectronics Reliability*, 81:64 – 76, 2018.

[53] T. Ringbeck, T. Möller, and B. Hagebeuker. Multidimensional measurement by using 3-d pmd sensors. *Advances in Radio Science*, 5:135–146, 2007.

[54] Minjie Chen, Günter Bärwolff, and Hartmut Schwandt. Time-of-flight technology applied in pedestrian movement detection. *Transportation Research Procedia*, 2:189 – 194, 2014. The Conference on Pedestrian and Evacuation Dynamics 2014 (PED 2014), 22-24 October 2014, Delft, The Netherlands.

[55] Carlos A. Luna, Cristina Losada-Gutierrez, David Fuentes-Jimenez, Alvaro Fernandez-Rincon, Manuel Mazo, and Javier Macias-Guarasa. Robust people detection using depth information from an overhead time-of-flight camera. *Expert Systems with Applications*, 71:240 – 256, 2017.

[56] ifm electronic gmbh, 2018. Available at: https://www.ifm.com/products/ us/ds/O2D220.html. Accessed: 2018-05-04.

[57] ifm electronic gmbh, 2018. Available at: https://www.ifm.com/products/ us/ds/O3D302.htm. Accessed: 2018-05-04.

[58] Jula Sverige AB, 2018. Available at: https://www.jula.se/catalog/bygg-och-farg/farg-och-fog/sprayfarger/spraylacker/gummispray-623114/. Accessed:2018-05-11.

[59] Piab AB, 2018. Available at: https://www.piab.com/Products/suction-cups/shape/bellows/b—bellows-5-150-mm/3250037s/. Accessed: 2018-05-11.

[60] Piab AB, 2018. Available at: https://www.piab.com/Products/vacuum-pumps/compactstackable/picompact10x/. Accessed: 2018-04-28.

[61] Maskiner, 2008. The Swedish Work Environment Authority. Available at: https://www.av.se/globalassets/filer/publikationer/foreskrifter/maskiner-som-slappts-ut-pa-marknaden-efter-29-dec-2009-foreskrifter-afs2008-3.pdf. Accessed: 2018-03-12.

[62] Angelica Wingfors. Ce-certifiering av egentillverkad robotcell: tillvagagangssatt och exempel, 2003.

[63] ISO/TC 299 Robotics. Iso 10218-1:2011, 2011. Available at: https://www.iso.org/standard/51330.html. Accessed: 2018-05-20.

[64] ISO/TC 299 Robotics. Iso 10218-2:2011, 2011. Available at: https://www.iso.org/standard/41571.html. Accessed: 2018-05-20.

[65] Maria Lazarte. Robots and humans can work together with new iso guidance, 2016. Available at: https://www.iso.org/news/2016/03/Ref2057.html. Accessed: 2018-05-20.

[66] ISO/TC 299 Robotics. Iso/prf tr 20218-1, 2018. Available at: https://www.iso.org/standard/69488.html. Accessed: 2018-05-20.

[67] ISO/TC 299 Robotics. Iso/ts 15066:2016, 2016. Available at: https://www.iso.org/standard/62996.html. Accessed: 2018-05-20.

[68] Sami Haddadin, Alin Albu-Schaffer, Mirko Frommberger, Jurgen Rossmann, and Gerd Hirzinger. The "dlr crash report": Towards a standard crash-testing protocol for robot safety - part i: Results. pages 272–279, 2009.

[69] Sami Haddadin, Alin Albu-Schaffer, Mirko Frommberger, Jurgen Rossmann, and Gerd Hirzinger. The "dlr crash report": Towards a standard crash-testing protocol for robot safety - part ii: Discussions. pages 280–287, 2009.

A

CE-marking and restrictions regarding a collaborative station

A CE-marking of a collaborative robot constitutes of the entire application, i.e. workpiece, tool and work environment also needs consideration [6]. The robot by itself is according to Machinery Directive 2006/42/EC an incomplete machinery and can only be provided with a Declaration of Incorporation. ISO standards are gathered to elucidate hazards within industrial robot applications and especially stations with a collaborative approach. To CE-mark the station, a risk assessment needs to be performed to identify and evaluate risks, followed by appropriate precautions [61]. Technical information about the station is also needed to be able to approve the station according to CE regulations, for instance, drawings, instruction manual and certificates from suppliers [62].

To implement a collaborative robot and create a coexistent workstation, EN ISO 10218-1,-2 and ISO/TS 15066 needs to be followed in particular [6]. EN ISO 10218-1:2011 is mainly focusing on the hazards connected to industrial robots regarding safe design, protective measures and information for users [63]. The information provided is describing basic hazards and how they are diminished or eliminated. Furthermore, EN ISO 10218-2:2011 is describing restrictions for the whole industrial robot system with industrial robot included, defined in EN ISO 10218-1:2011 [64]. The standard EN ISO 10218-2:2011 is defining hazards concerning design, manufacturing, installation, operation, maintenance and decommissioning of the system. Moreover, specifying how to eliminate or adequately reduce the risks associated with these factors are explained.

Both standards are focusing on industrial robots and stations where humans and robots can not share or interact in each others work space [63, 64]. However, since the arrival of new robots with collaborative features, a new ISO standard ISO/TS 15066:2016 has been developed to enable an open work space [65]. The focus of the standard is to evaluate situations where humans and robots are incidentally interacting with each other with the aim to prevent painful outcomes and injuries. The standard are based on data provided by studies to give a specific guidance regarding safety to enable evaluation and control of risks. ISO/TS 15066:2016 are dependent on that the requirements are met in both EN ISO 10218-1 and -2.

There are also other guidelines to consider excluded from the standard for collaboration, such as equipment and humans surrounding the station[6]. E.g. requirements regarding operation certification for humans working in industrial environment, ISO/IEC 17024:2012. The end-effector is also excluded, for this occasion the standard ISO/PRF TR 20218-1 is used [66]. This standard is however under development and not finished. Meanwhile, the specifications for the robot are transferred to the end-effector to secure a safe work station.

There are some main chapters in the standard ISO/TS 15066:2016 that will be summarized and mentioned with accordance to [67]. The characteristics of the control system regarding safety is one. To assure that the safety features work and cooperate with each other is essential. Some built-in systems that are safety-related in collaborative robots are safety-rated monitored stop, speed monitoring and force limiting. The last mentioned is explained in *5.5.5 Power and force limiting*, where data from studies related to pain thresholds are included, see [68, 69]. Specification regarding design of the robot is also included to minimize risk of injuries.

Chapter *4 Collaborative industrial robot system design* is describing factors that needs to be considered regarding the layout of a collaborative robot system [67]. However, even collaborative robot systems with provided safety systems needs protective measures. In *5.5.4 Speed and separation monitoring*, the speed in relation to distance between human and robot is defined according to *figure A.1.*

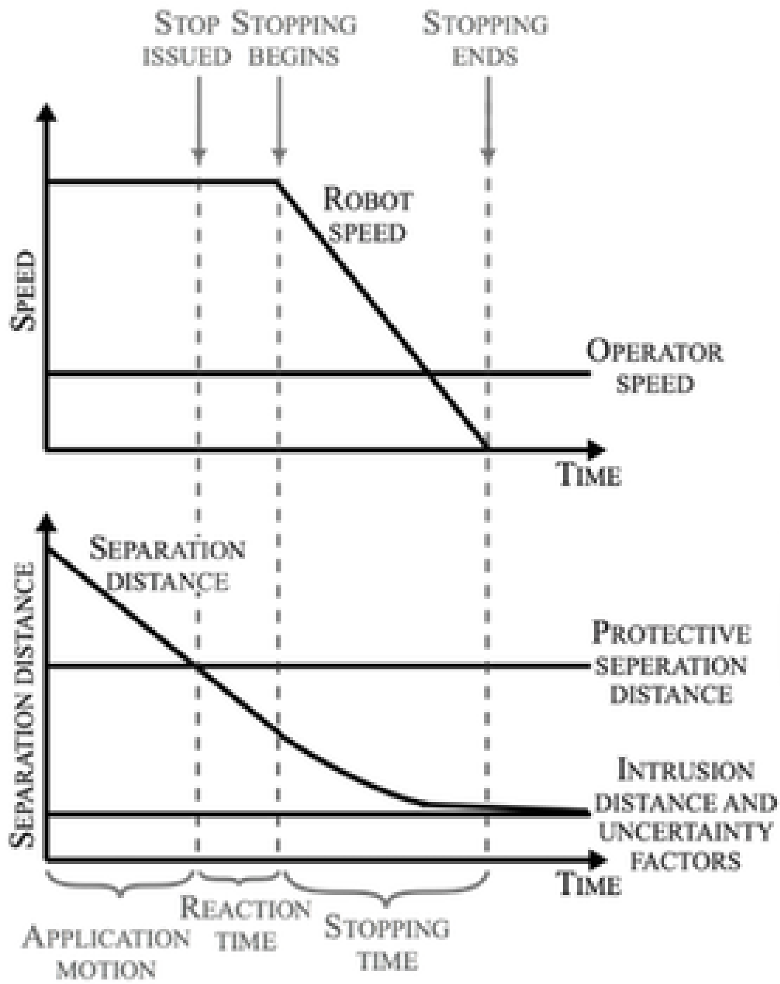


Figure A.1: Definition of protective separation distance for a robot and an operator including contributing representation, illustration adapted from [67]

Figure A.1 is illustrating the robot and operator speed (top graph) and separation distance (bottom graph) in correlation to time. The contributing factors to robot speed losses are due to that the protective separation distance is violated by an operator. This results in that the stop is issued, but the robot will not stop directly. First, the system has a reaction time resulting in that the speed of the robot is lowered until the robot is standing still, which ends the stopping procedure. During this time the operator is constantly moving towards the robot. Preferably, the stopping time should be less then the time it takes for the operator to reach the robot to maintain a safe work environment. To secure that the robot stops before the operator reaches the robot, an intrusion distance and uncertainty factors are included in the graph. How to calculate the allowed speed of the robot and operator in relation to protective separation distance are further explained in ISO/TS 15066:2016 [67].

In order to CE-mark a collaborative robot station, a risk assessment based on the information provided above needs to be performed [61]. The main purpose with the risk assessment is to highlight risks at the station to be able to improve them, resulting in safety optimization of the station. The risk assessment concerns the station in operating, stoppage and maintenance mode. There are four main steps in a risk assessment that follows;

1. Risk identification
2. Evaluation of risks
3. Adjust identified risks
4. Monitor the effect of the adjustment

It is important to eliminate risks if possible, otherwise reducing the occasions or severeness of the outcomes [61]. It is also important that substantial protective measures for injuries are taken into action. If risks remain that has no protective measure, operators needs to be informed and educated to prevent hazards. For examples and more detailed information regarding CE-marking of robot stations, see [62].