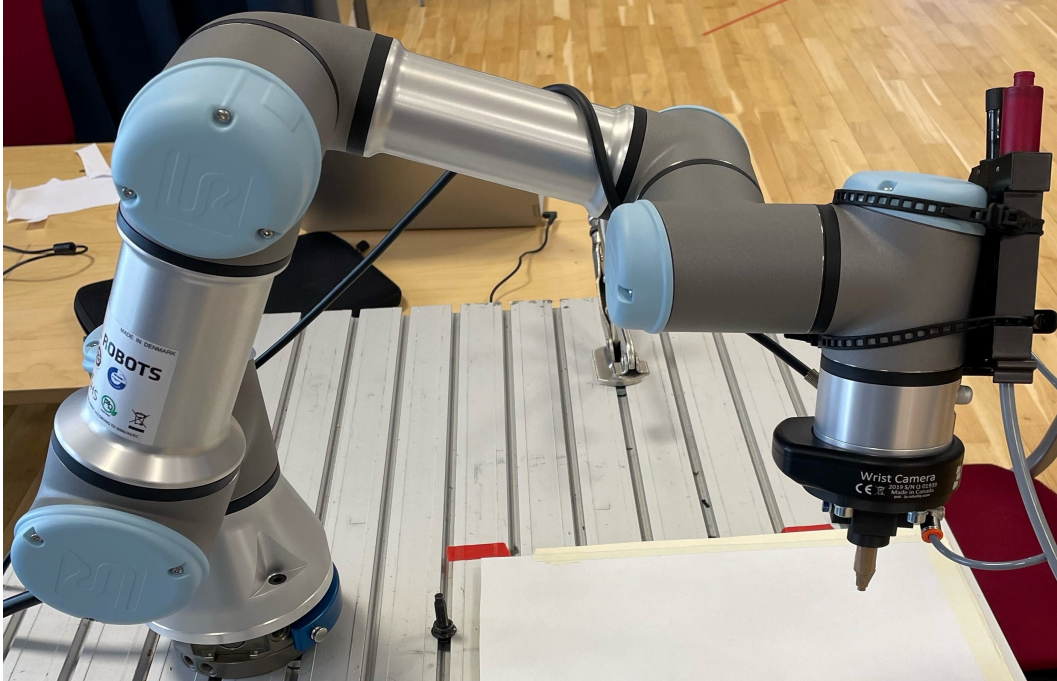




CHALMERS
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Improving Ergonomics and Quality Assurance in Actuator Production

An Enhanced Component Supply Approach for Pick & Place Robots

Master's thesis in Production Engineering

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS 2023

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Abstract

Over the past few decades, there has been a substantial increase in the automation of manual jobs. Automation gives the possibility of increasing productivity and reducing labor costs. Despite these benefits, some industries struggle to automate their processes. One of the big obstacles for automated systems is the orientation of small, irregularly shaped components. The purpose of this thesis is to specify an improved solution for supplying a pick & place robot with incoming components during the assembly process. To study this, automated palletizing solutions were developed and tested using a UR3e robot along with a Robotiq wrist camera. Some manual processes were also developed for components that had trouble being identified by the camera during testing.

The tests showed that it is in fact very hard to automate processes where small and irregularly shaped components are involved. Implementing automated solutions can create lengthy setup and cycle times, compared to manual work, and increase costs. It was also shown that the camera used is not strong enough for identifying the small and complex requirements of the components. In the case of Cochlear, a completely new vision system is needed in order to automate the material feeding of components to the assembly.

Keywords: Material Handling, Automation, Small Components.

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Marcus Alverstrand & Edward Trogen, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

FAS	Flexible Assembly System
F-FAS	Fully Flexible Assembly System
PCB	Printed Circuit Board
PTH	Pin Through Hole
SMD	Surface Mounted Devices
TCP	Tool Center Point
THT	Through Hole Technology

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1

Introduction

In this chapter, the background and purpose of the thesis are presented to provide a clear understanding of the aim and relevance of this thesis. Furthermore, this chapter will define the scope and research questions of the thesis.

1.1 Background

In recent decades, the automation of manual jobs has increased significantly, and the trend is not slowing down. During the years 1993 to 2017, the proportion of the working-age population in the US manufacturing industry decreased from 10.3% to 6.1% [1]. During the same period, the proportion of robot stocks per thousand workers increased from 0.95 to 9.8 [1]. With new technological progress in robots and AI this trend is likely to increase as it has the possibility of influencing other industries. Today, AI and machine learning can handle customer service inquiries and X-ray scanning, jobs that previously were not possible to automate [2]. Automation gives the possibility of increasing productivity and reducing labor costs, where the trend has been greater in countries with high wages [2]. Chobanov & Hardalov [3] mention cheap energy as one of the reasons for increased automation, as labor costs are higher than the energy cost to run machines or robots.

Despite the benefits that come with automation, some industries struggle to automate their processes. In the consumer electronics industry, small parts sizes and tight tolerances result in high costs for fixtures and high time consumption in setup and expansion of traditional automation [4]. In material feeding, the biggest obstacle for automated systems is the orientation of small, irregularly shaped components [5]. According to Swanson, problems with parts feeding in manufacturing can be split into three different smaller problems: separation, orientation, and presentation [6]. Separation represents the problem of separating individual parts or components from large masses. Orientation is the process that includes the steps to get a particular component in the desired direction, usually from a large lump of randomly placed parts. Presentation is the process of moving the separated and oriented components to a desired location.

Cochlear BAS, a corporation in the medical device industry, produces bone-anchored

hearing aids. Bone conduction has been around for many decades, and the technology matured in the early days at Chalmers. Today, this technology helps hundreds of thousands of people to hear better every day. The actuator which is the "motor" in Cochlear's bone-anchored hearing aid is assembled at their premises in Gothenburg. The actuator consists of several small components that are placed manually on pallets before being placed in a pick & place machine for automatic assembly. Next, the partially finished actuator is placed in a robotic cell for final assembly and balancing. Due to the small sizes of the components, odd shapes, and the requirement of being correctly oriented, the material handling process is tricky and time-consuming to perform. Awkward positions for long periods of time also imply a risk for operators from an ergonomic point of view.

1.2 Purpose

The purpose of this master thesis is to specify an improved solution for supplying the pick & place robot with incoming components during the assembly process. The expected outcome is to improve ergonomics for operators as well as to ensure the quality of actuator production.

1.3 Scope and Delimitations

This master's thesis is conducted in the spring of 2023 at Chalmers University of Technology and Cochlear BAS. The time frame is estimated to be 20 weeks. This master thesis will be limited to improving the supplying process to Cochlear's assembly robot and will not specify any improvement of the assembly process itself. The thesis will also be limited to the current design of Cochlear's product. Therefore, there will be no attempt to improve the design of the components to better suit the material handling. According to Berlin & Adams [7], the mental workload is hard to measure objectively without evaluating the before-and-after effects of an improvement. The solutions developed in this thesis are not possible to be tested by operators in Cochlear's production, thus no after-effects could be measured. In this thesis, it was therefore decided not to assess cognitive ergonomics.

1.4 Actors and Stakeholders

The project will be carried out in cooperation between Chalmers and Cochlear BAS. The actors in this project are representatives from both Chalmers and Cochlear taking part in the work. The stakeholders in this project are Cochlear and its employees, specifically employees working with or in the production unit, and representatives from Chalmers taking part in the project.

1.5 Research Questions

In order for the research to fulfill the purpose of the thesis, two research questions were formulated. These will be answered throughout the thesis by following the methodology presented. The two research questions are as follows:

1. *What are the challenges associated with the material handling of components for medical devices?*
2. *How can material handling of components for medical devices be improved to achieve higher quality and better ergonomics for operators?*

2

Theory

In this chapter, the theory and knowledge connected to the thesis are presented. This chapter provides a theoretical framework for understanding key concepts in robotics, assembly systems, and ergonomics. It covers collaborative robots, material feeding methods, ergonomics in assembly, robotic assembly, manual assembly systems, and flexible assembly systems.

2.1 Collaborative Robots

In comparison to traditional industrial robots, collaborative robots, or cobots, are usually designed with soft materials with rounded edges for safer interactions [8]. These robots make it possible to solve problems in continually developing manufacturing where operators can interact with the robot on a shared workspace [9].

Matheson et al. [9] mention that collaboration between cobots and humans is viewed positively as it can help increase productivity while costs can be reduced as non-experts are able to plan and react to changes in the easily reprogrammable robot. Cobots are widely used today in production, changing the way operators work, especially in simple operations such as pick and place. It is also possible to more easily move the cobots around in factories to do different tasks, thus increasing flexibility [10].

2.2 Material feeding

Material feeding can be defined as the goal of feeding processes such as assembly systems with components in the correct quantity and time [11]. Handling these parts is usually time-consuming, which affects workflow and, in the worst case, can increase production costs [12].

There are several names for different types of material feeding processes. Three are often used, continuous supply, batch supply, and kitting [13]. Kitting requires extra work as it all depends on materials needed in a certain process being prepared in "kits", which can be for example, in boxes or on pallets. Once these kits are ready, they are fed into their process for use [14]. Batch supply is a type of material feeding

that is based on the number of components or parts needed to achieve a batch of end products [13]. With continuous supply, all parts or components are available at the assembly stations and the stock of these parts is continuously replenished [14].

2.3 Ergonomics in Assembly

Ergonomics, a pervasive concept, encompasses a broad spectrum of factors ranging from the physical aspects of human activities, such as body alignment during work tasks (referred to as physical ergonomics), to the cognitive dimensions involving the comprehension of instructions by the mind (known as cognitive ergonomics) [7]. When conducting an inquiry into the impacts of ergonomics within a workplace, it is important to take into account both the physical and cognitive burdens that individuals experience [7].

2.3.1 Physical Ergonomics

Physical ergonomics encompasses several integral components, namely posture, force, and time, as expounded by [7]. Posture refers to the alignment of the body during various activities, and a favorable posture entails a symmetrical distribution of forces across different body regions [7]. The interplay between posture, force, and time significantly influences the overall physical load experienced. Optimal posture mitigates the occurrence of excessive physical load, yet prolonged maintenance of a specific posture can still induce critical physical strain [7]. Similarly, assuming a suboptimal posture that subjects certain body areas to substantial forces may not be consequential if sustained only briefly [7]. Thus, the consideration of all three factors is pivotal when striving to achieve favorable ergonomics within a production system [7].

2.3.2 Cognitive Ergonomics

Cognitive fatigue can contribute to errors, particularly when individuals are engaged in monotonous tasks that can undergo sudden changes [7]. Consequently, tasks lacking adequate cognitive support can lead to mental overload, ultimately intensifying chronic fatigue [7]. This, in turn, can result in reduced motivation, compromised well-being, and increased likelihood of mistakes [7].

Cognitive ergonomics comprises various essential components, including the senses, with hearing, vision, and touch is the most relevant [7]. Vision assumes a paramount role in information assimilation, as our visual sense is intricately connected to perception, which seeks meaningful patterns recognizable by the brain [7]. Visual acuity tends to decline after the age of 40, affecting the ability to discern small symbols with low contrast, for instance, [7]. Therefore, incorporating clear visual cues is crucial when devising instructions applicable to the entire workforce.

2.4 Robotic assembly

Robotic assembly is the use of robotic systems to automate the process of assembling parts into finished products [15]. It has become a critical part of many industries, including the automotive, electronics, and consumer goods sectors, among others. In a typical robotic assembly system, a robot (or multiple robots) is programmed to perform specific tasks such as picking up parts, positioning them accurately, and then fastening them together using various methods such as welding, screwing, or gluing [15].

Today, these robotic systems often use vision systems to perform their tasks. Vision-based systems connected to robots can perform many basic tasks in industry, such as those mentioned above [16]. A functioning robotic vision system should first capture an image or video of the target area, recognize features or objects in the captured data, and then take into account different conditions or limitations before performing its actions [17].

There are several different robot grippers that are used for various tasks. To name a few, there are robotic grippers with 2 fingers, 3 fingers, flexible fingers, vacuum, and hydraulics [18]. Developing a well-functioning robot gripper is of great importance, as it can help increase the output of a work cell, reduce the risk of errors in robot operations, and increase its precision [19]. Designing a gripper that has the capability of picking multiple components without the need for a tool change can also help increase effectivity and flexibility, especially in simple pick and place operations where multiple components are present [19].

2.5 Manual Assembly Systems

A manual assembly system is a manufacturing system in which workers assemble products using hand tools and equipment, without the assistance of advanced automation technologies. In a manual assembly system, the assembly process is typically organized around a series of workstations, each with a specific set of tools and tasks [20]. In manual assembly work, the components to be used are usually close at hand. The worker then performs the assembly using previously determined instructions on how the task should be performed [20]. The potential problems that exist with such mounting systems are, for example, human errors, and ergonomic problems for the operator, and depending on the product, the output of manual systems is usually very low [20].

2.6 Flexible Assembly Systems

A flexible assembly system (FAS) is a manufacturing system that can rapidly adapt to changes in production requirements. It can handle a variety of products and production volumes [21] and can automatically reconfigure its equipment and workflow to accommodate new product designs or variations. FAS uses different material feed-

ers to sort, orient and move components to the assembly station [20]. These feeders can only process one type of component, which means that a feeder is needed for each component that needs to be fed to the assembly station [20] [22]. These types of systems are also in need of a setup time in order to refill the feeders [20] [22].

3

Methodology

This chapter outlines the methods used in the literature search and to study production processes in the context of this research. The goal is to understand the current production system, including robotic assembly, manual palletizing, component information, and ergonomic risks. By investigating these areas, opportunities for improvement can be identified and system design solutions proposed. The findings will contribute to enhancing the production system and addressing specific challenges.

3.1 Literature Search

To gain a better understanding of the challenges and solutions to handling small components, a structured literature review was conducted. The search aimed to find English-written research papers, conference papers, and academic textbooks. Literature searches were conducted in Scopus due to both its vast database within the technical area and its high publishing requirements. The selection process will be carried out by reviewing the relevance in relation to the research questions. The structure of the literature search can be seen in Figure 3.1.

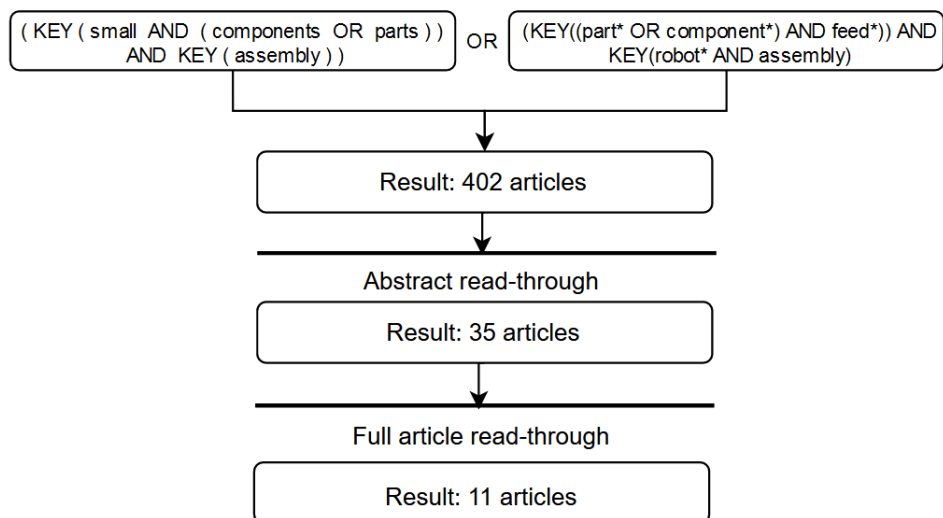


Figure 3.1: Literature search structure.

First, the abstract of each literature was read through in order to do an initial filtering of irrelevant literature. In this stage, all literature with an abstract not related to small parts, material feeding, or robot assembly were discarded. This resulted in 35 articles. A second screening was done with a full-text read-through of the remaining articles. In this stage the same criteria used in abstract read-through were utilized; this resulted in 11 articles.

3.2 Study of Production

In order to gain a better understanding of how the current production system works, the processes needed to be investigated and studied. More specifically, robot assembly, manual palletizing process, and component information had to be studied. As manual work is necessary for many parts of the process, the ergonomics of the operators were also analyzed to understand the ergonomic risks associated with the process.

3.2.1 Robotic Assembly

In order to comprehend the functioning of the assembly robot and the various steps involved in assembling the product, multiple robot cycles were observed and the steps were recorded manually. In addition to the observations made, relevant questions were discussed with both operators and engineers. These were mainly related to the possibilities and limitations of the robot for improvements, as well as its current functions.

3.2.2 Manual Palletizing Process

The palletizing process was studied by observing operators performing multiple cycles. During observations, operators could explain each step in detail, and clarifying questions could be asked. The process was also studied by performing certain process steps themselves. In this way, the understanding of the tasks and operators was deepened.

3.2.3 Components

Information about the components which the product consists of was also important, as future improvements may require very small tolerances to fit the current assembly. The procedure to collect this information began by creating a table where all the names of the components were written down. Then for each component, the number per product, packaging, specific requirements, weight, and shape were noted.

3.2.4 Ergonomic Assessment

One of the identified issues with the current manual handling of material was the ergonomic risks. Preparing material for one batch takes approximately one hour, and this process is repeated three times a day. Therefore, physical ergonomic issues

were decided to study. As suggested by Berlin & Adams [7], the observed operators were informed of the study and its purpose in advance.

For physical ergonomic risks, it was decided to use the KIM-MHO and the HARM. The KIM-MHO is suitable for evaluating manual work processes where loads are less important [23]. The HARM is developed to specifically assess the risks of musculoskeletal disorders in the hand and arm [7].

4

Results

This chapter presents the results obtained from experiments evaluating assembly and automation solutions for small components in manufacturing. It discusses the effectiveness of modified vibratory bowl feeders and cobots for PCB assembly. It also explores a dual-arm robot assembly system and examines challenges related to material feeding and component handling. The chapter concludes with a study on flexible assembly systems and robotic assembly of small components, along with ergonomic assessments and the current manual palletizing process. These results provide insights into the performance and suitability of automation solutions for small component assembly.

4.1 Literature Search

In this section, the result of the literature search is presented. The result of the literature search is divided into four different areas: Assembly of small components, Material Feeding of Small Components, Flexible Assembly Systems, and Robotic Assembly of Small Components.

4.1.1 Assembly of Small Components

In printed circuit board (PCB) manufacturing, most of the components are surface-mounted devices (SMD), hence the assembly can be done automatically. However, many PCBs also consist of components that to a high extent still require a manual assembly, so-called Pin Through Hole (PTH) components [24], or Through Hole Technology (THT) [25]. Due to its small sizes and tight tolerances in assembly, traditional robotic automation is not suitable. The reason for this is mainly the high cost of fixtures and high time consumption in setup and ramp-up [4].

According to [25] the so-called 'Odd-form' machines can be used for automatic assembly of PTH components, but due to the high cost, this is only utilized for high-volume production. Another issue with odd-form machines is that they are not capable of handling unstructured bulk-fed components unless dedicated feeding solutions are developed [25]. To cope with the rapid changes in production in the consumer electronics market, [4] suggests the use of flexible part feeding supported

by machine vision instead of hard automated part feeding systems. This is also suggested by [26] who states that humans are inefficient and error-prone when it comes to feeding in small-part assembly.

This is tested in [25] which in addition to the flexible feeding system also uses two 6-DOF serial robot manipulators and two vision systems. One robot assembles components onto the PCB, while the other robot services the flexible feeding system and kits the parts up to be ready for assembly. One vision system supervises the vibratory bowl feeder and identifies which components can be moved to the chute by the robot. The other vision system is used for identifying possible grasp corrections before the component is assembled onto the PCB. The flexible feeding system consists of a modified vibratory bowl feeder which circulates the components until the overhead vision system identifies graspable components. The robot then grasps the component and drops it into a chute which reorientates the component to be ready for assembly. The experiment showed that the system successfully could assemble the PCB with zero insertion fails. According to [25], the flexible feeder can keep up with the placement robot in the experiment but would have a hard time keeping up with the required average placement time in the industry.

The author in [24] tests the possibility of using cobots to assemble PTH components to make the process fully automated. The system consists of a cobot, a vision system, and a PLC subsystem. In addition to moving the component, the cobot also uses its internal vision system to read the PCB barcode to know which component to insert and to reference itself with respect to the assembly board before inserting the first component [24]. The function of the external vision system is to analyze whether the component is in sufficient condition to be mounted. The PLC subsystem works as a connection between the other two subsystems and is responsible for controlling and monitoring the work cell. The experiment shows that the system manages to assemble the PTH components in 30 seconds, which can be compared to the manual assembly of around 15 seconds. However, according to [24], the performance of a manual assembler tends to decrease with tiredness.

[26] instead suggests using an assembly system containing a dual-arm robot, two smart cameras, and a PLC. The benefit of using a dual-arm robot is that the arms can cooperate thus creating simpler solutions and thereby saving both space and fixture [26].

4.1.2 Material Feeding of Small Components

A problem for automated assembly systems and production, in general, is the handling and orientation of small irregularly shaped components [5]. As mentioned, problems can be divided into separation, orientation, and presentation [6]. Many have solved these feeding problems with manual work, industrial robots, and other vision systems using sensors, cameras, or lasers. Usually, these systems increase production and investment costs [5]. However, no automated process is created for an universal component or product. All different types of components need their

own designed system for separation, orientation, and presentation to work. These systems usually require a trial-and-error strategy, where many errors are not noticed until production is ready to start [6].

Swanson [6] investigated a passive juggling approach to part orientation, where the various components are laid out pre-separated on a flat table level with the robot. This table has a pre-programmed setting where it can move in translational periodic motion, during a time of motion the components lying on the table will be forced to turn and be in a desired state if the table is programmed properly. In another research, drop test experiments were performed in order to find possible positions and orientations as well as the most favorable orientation for a component when feeding material [5]. The drop test was performed by dropping a component from heights between 10 and 500 mm during several repetitions. The test resulted in the component being able to end up in eight different orientations, and from the recorded results it was also possible to see that one of these orientations was the most favorable orientation.

4.1.3 Flexible Assembly Systems

Rosati et al. [22] introduce a new type of flexible assembly system, called a Fully flexible assembly system (F-FAS). Compared to FAS, F-FAS utilizes one feeder for all component types [22]. F-FAS utilizes a vibratory bulk that casually sheds the parts onto a vibratory plane. The function of the vibratory plane is to move parts back and forth and to reorient them [22]. The F-FAS then uses a machine vision system to identify and locate parts to be picked by the manipulator, the manipulator picks the required part and puts it on the assembly station [22].

In [20] the author analyzed and compared manual assembly, flexible assembly systems (FAS), and fully flexible assembly systems (F-FAS). According to [20] and [22] the potential problems that exist with manual assembly systems are, for example, human errors and ergonomic problems for the operator. Additionally, depending on the product, the output of manual systems is usually very low [20].

For a system with a high number of component types, F-FAS is beneficial [22]. Since the F-FAS only uses one feeder for all types of components, it requires less direct costs compared to the FAS [22]. This difference in direct costs for feeders increases for systems with a high number of components [22]. Another advantage of F-FAS is that it does not require any set-up times for batch changes. This is not the case for the FAS as each of its feeders must be adjusted to suit one type of component [20] [22]. For small batch production, throughput time can therefore differ significantly between FAS and F-FAS [22]. The disadvantage of F-FAS is that the working cycle is also affected by the orientation and feeding of the components. For the traditional FAS, this is not the case as the orientation and feeding of components are done in hidden time [22]. One major limitation of F-FAS is that not all types of components can be oriented in a vibrating plane [22].

4.1.4 Robotic Assembly of Small Components

Precision assembly is to manipulate millimeter-sized components with micron accuracy [27]. Usually in precision assembly, the system consists of several independent manipulators, which makes efficiency low [27]. [27] instead only uses one manipulator. The experiment is to assemble two millimeter-sized components. The assembly system consists of an industrial robot with 6-DOF, a hand camera to guide search and grasping, and two microscopic cameras with a function to capture pictures used for the alignment of the poses of the components [27]. The gripper is a cylindrical vacuum absorptive mechanism that is designed as a bell mouth to allow for small orientations of components [27]. The result of the experiment showed that this approach improved flexibility and efficiency compared to having multiple manipulators [27].

4.2 Study of Production

In this section, the results from the study of the current production system are presented. The information aims to give the reader a better understanding of current processes, components, and ergonomic assessment.

4.2.1 Robotic Assembly

In the robot assembly cell, there is a set of different tools that are used to grip the components. These tools are picked up and dropped off by the robot itself, depending on which component is to be picked up. There is a camera located next to the gripper that is used to set up the starting position where the first component is picked up. During each pick-and-place action, the robot moves to a second camera that is used to adjust the robot arm so that all components are placed correctly.

4.2.2 Manual Palletizing Process

The material is fed to the robot in different batches, where each batch contains the number of components required to assemble 40 products. All components, except the actuator rivet, are placed on pallets through a palletizing process that is done manually. In the process, operators move components with the help of tweezers and vacuum tools. It is required that the components are oriented correctly in order for the robot to be able to pick properly. To orient the disc springs in the right way a special plate, seen in Figure 4.1, and a brush are used to separate discs laying upside down and discs laying in the right way. When the pallets are fully kitted, they are fed into the robot by hand when the current batch is fully assembled.

In Table 4.1 the manual palletizing time for each component can be seen. Note that the table shows the time it takes to fill a complete pallet. The Disc spring pallet has space for 240 components, whereas the rest of the pallets has room for 40 components.

Table 4.1: Recorded times for the manual palletizing process.

Component	Magnet assembly	Disc spring	Body rivet	Counter weight	Coil	Spring	Flange
Time	4min	15min	1min 35s	2min 10s	1min	3min 30s	2min

**Figure 4.1:** Special plate to separate Disc Springs.

4.2.3 Components

There are a total of 8 different components used during assembly, one of which is fed automatically to the robot using a bowl feeder. In Table 4.2 the compiled information about the components can be seen.

Table 4.2: Compiled information of components.

	No. components per product	Packaging	Placement requirements	Kitted	Treatment before kitting	Weight	Shape
Magnet assembly	1	Three different packages	Yes	Yes	Yes (assembly)	0,89g	Cylindrical
Disc spring	6	Boxes of 5000 pcs	Yes	Yes	No	0,008g	Disc
Body rivet	1	Bag of 500 pcs	Yes	Yes	No	0,35g	Circular+cylindrical
Counter Weight	1	Palette of 85 pcs	Yes	Yes	Yes	6,54g	Rectangular
Coil	1	Palette of 200 pcs	Yes	Yes	No	0,33g	Oblong asymmetrical
Spring	2	Box of 1000 pcs	Yes	Yes	No	0,1g	Rectangular
Flange	1	Palette of 100 pcs	Yes	Yes	No	0,19g	Circular
Actuator rivet	2	Bag of 500 pcs	No	No	No	0,086g	Cylindrical

Note that the magnet assembly is a sub-assembly containing three components that are not on the list. The final product from this sub-assembly (magnet assembly) is seen as a component of the actuator. Before the magnet assembly is palletized it must be adjusted to be centered by the operator. This is necessary to assure good quality in the assembly process as the component is to be attached to the product with tight tolerances.

The counter weight needs to be treated before it can be used in the assembly. All components, apart from the actuator rivet which is fed and reoriented automatically, need to be oriented in a special way for the robot to be able to pick them up and for the assembly to take place correctly.

For each actuator product, two spring components are needed, one lower spring and one upper spring. The lower and upper spring is the same component, but as the component is not homogeneous it is decided by how the spring is flipped.

4.2.4 Ergonomic Assessment

The physical ergonomic assessment gave a mixed result. As can be seen in Appendix A the KIM-MHO assessment received a score of 60, while the HARM received a score of 9. The result from the KIM-MHO indicates that the physical load is substantially increased, and that physical overload is possible for a normally resilient person. On the contrary, the HARM in Appendix B indicates that there is no increased risk for load-related injuries in arms, neck, or shoulders for most workers. The reason why the HARM assessment received a better score than the KIM-MHO assessment is that it is more sensitive toward the duration of the task. Since the time for the manual palletizing method is only around three hours per day this affects the score for the HARM assessment.

4.3 System Design Development

From the production study, it is determined that the material handling method could be improved in three ways. The first way is to automate the palletization method. The second and third way is to improve the manual palletization method and to find methods to feed the assembly robot with components without having to palletize them first.

The third method is considered the most beneficial, as it would completely avoid the palletizing process. The first method is considered better than the second from an ergonomic point of view because it would eliminate the need for manual palletization.

4.3.1 Automated Palletizing Solutions

During the development of different solutions to automate the palletizing of components, a UR3e robot is used to test the possibilities, see Figure 4.2. It is a smaller collaborative robot that is designed for lighter workbench tasks. With quick setup and simpler programming, it is possible to quickly start the robot and experiment with its functions [28].



Figure 4.2: UR3e Robot.

The Robotiq wrist camera, seen in Figure 4.3, can be used to locate components in both structured and unstructured environments. It is made for Universal Robots and is therefore easily attached to the robot arm. During the experiments, it was found that to locate components, it is possible to use three object-teaching functions:

- CAD-file import teaching
- Automatic part teaching
- Parametric part teaching



Figure 4.3: Robotiq Wrist Camera.

It is also found that components that have more complex shapes and are difficult to scan can benefit from importing a CAD file that represents them. The parametric method is based on various parameters of common shapes, such as rings, circles, squares, and rectangles. The automatic method is also useful for complex and irregular shapes. It builds a model based on photographs and scans of the component.

To improve the camera's ability to identify the components, different camera settings were tested and used for each component. The camera settings have five different parameters that can be adjusted, these are:

- LED: Can be set to OFF, automatic, or manually scaled.
- Exposure: Scaled between -7 EV or 7 EV.

- Focus: Automatic or manual.
- White balance: Automatic or manual adjustment of the camera's balance in red, green, and blue colors.
- Threshold: Determines how similar a component must be in order to be classified as the searched component, scaled in percentage.

In addition to the camera settings, it is also noticed that the identification of components is also affected by the background and scan height. The background is important from two perspectives. The first is to act as a contrast to the component, improving the camera's ability to identify where the components are located. The second is to adjust the reflection of light from the work plane. The scan height affects how small components the camera can identify. The closer the camera is to the work plane, the smaller components it can identify. However, the scanning height also affects the camera's field of view, where a lower height also results in a smaller field of view, hence fewer components are within view.

A 2-finger gripper was used in the early stages of this project to test the robot's picking abilities. But, due to the small sizes of the components, it was decided that to pick the components a vacuum gripper was needed. The same nozzles used in the assembly robot could be utilized in the experiment. However, to obtain a vacuum in the nozzle, a nozzle holder had to be designed; see Figure 4.4.

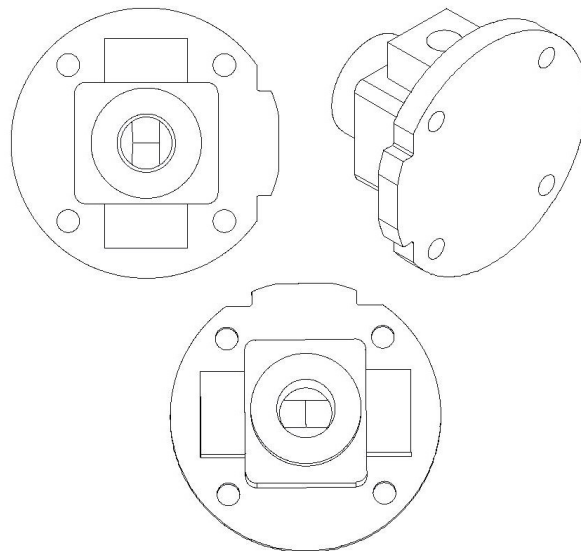


Figure 4.4: Nozzle holder.

To avoid having to replace the nozzles when switching between components to pick up, a second nozzle holder was designed, with the capacity of three nozzles at the same time, as seen in Figure 4.5.

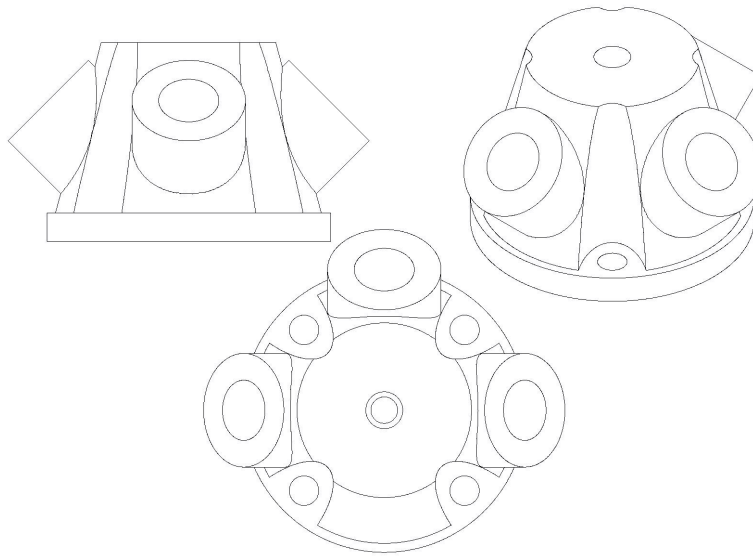


Figure 4.5: Multiple nozzle holder, with the capacity of carrying three nozzles simultaneously.

Due to the different sizes, it was not possible to have both the nozzle holder and the wrist camera mounted on the UR3e robot simultaneously. To solve this problem, a middle plate had to be designed. The middle plate, seen in Figure 4.6, had to be mounted on the wrist camera at one end, and at the same time enable the nozzle holder to be attached at the other end.

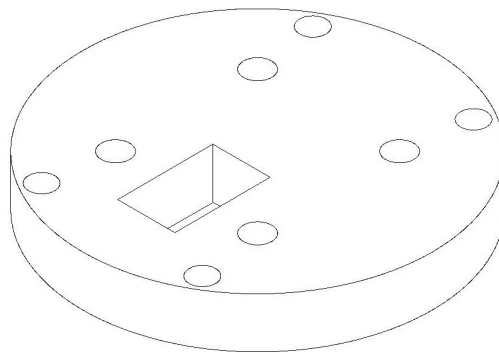


Figure 4.6: Middle plate connecting nozzle holder to wrist camera.

To pick the body rivet component with a vacuum tool, it had to be in an approximately 30° position to the work plane. With current tools, this was not possible without the risk to hit the work table with the camera. To facilitate the picking process, a seven-centimeter-long extended tool was designed and printed, see Figure 4.7.



Figure 4.7: Extended nozzle to enable picking of body rivet.

The extended tool was able to be mounted on both the single nozzle holder and the multi-nozzle holder. Since the multi-nozzle holder already has a 45° angle to the work plane, it required fewer rotations to reach the grasping position, hence the extension was mounted on it, see Figure 4.8.



Figure 4.8: Extended nozzle mounted on the multi-nozzle holder.

In Figures 4.9 and 4.10 the setup of the experiments can be seen. When the setup was ready, the next step was to investigate the robot picking precision and the

4. Results

performance of the wrist camera's vision system. The main aim was to gain an understanding of which components were possible to identify with the wrist camera and if these could be successfully palletized with the robot. The workflow progressed mostly through trial and error, where many different parameters of the wrist camera and movements were used to pick the components. Each component required specific camera settings and scanning height in order to be successfully identified. A lot of time was also spent analyzing and investigating how the robot behaved when it identified the components and picked them up. This step was especially important because incorrect picking of components would have a direct negative effect on the performance of the palletizing. In the end, a list was created with the various preferred parameters for the particular set-up used during the course of the work. This meant that it became possible to edit or redo the programs quickly as all the parameters already existed and only the code needed to be changed.

For each component that was possible to identify with the vision system, a separate sub-program was created in the teach pendant. This was necessary as all components looked different and therefore needed their own unique program with various positions, TCPs, and tool movements. In each program, the robot palletized a quantity of ten to sixteen components.

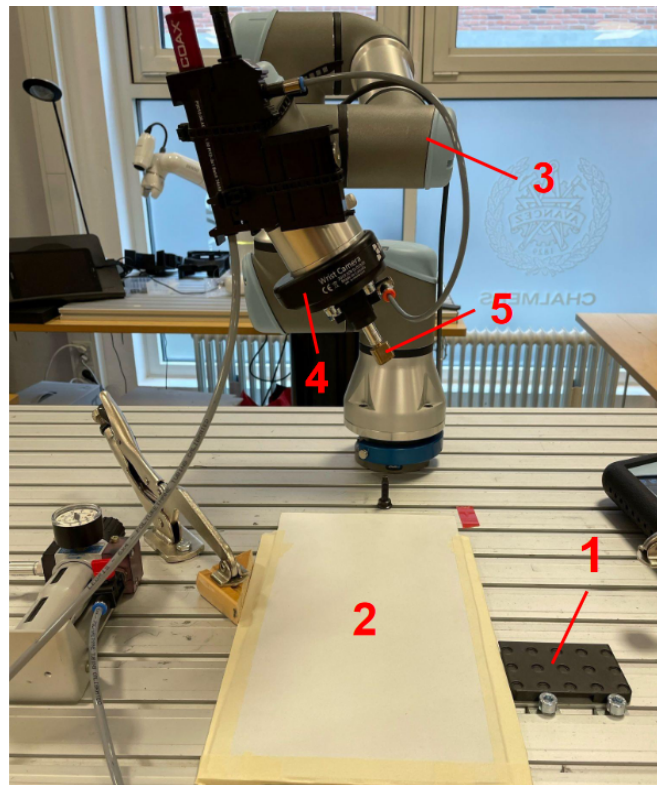


Figure 4.9: Setup of the experiment. 1: Pallet, 2: Work plane, 3: UR3e Robot, 4: Robotiq Wrist camera, 5: Nozzle.



Figure 4.10: Setup of the experiment. 1: Robotiq Wrist camera, 2: Middle plate, 3: Nozzle holder, 4: Vacuum inlet, 5: Nozzle.

To confirm that the camera could distinguish between the different components and not just be able to find them individually, an additional test was constructed. Tests were carried out in which several different components were placed on the work surface at the same time. These tests were built into a complete program consisting of all different subprograms of the components. Running this program made it possible to see how the camera and the robot behaved and whether they could be distinguished.

4.3.2 Manual Palletizing and Feeding solutions

The method for generating ideas for the continuous feeding of the assembly robot was identical to the method of developing ideas for improving the manual palletizing process.

Ideas were generated internally through brainstorming sessions and from discussions with employees at Cochlear and externally by looking at already developed material feeding systems. In the next step, all the ideas generated were analyzed, and those that did not meet the requirements were discarded. After the screening process, the next step was to develop conceptual models. The ideas were sketched in CATIA V5 and then 3D printed. In order not to waste time and resources more than necessary, small prototypes of ideas were initially printed. In this way, it was possible to discard or modify the models before full-size printing.

4.4 System Design Solutions

This section provides a comprehensive analysis of the results obtained from the automated palletizing and feeding solutions implemented in the assembly process. The focus is on evaluating the performance of the robotic system in terms of component identification, handling, and cycle time. In addition, the results of manual palletizing improvements are presented and evaluated. The findings presented herein offer significant insights into the effectiveness and feasibility of the proposed system design solutions.

4.4.1 Automated Palletizing Solution

The wrist camera was able to identify the flange and the magnet assembly completely correctly, regardless of the orientation of these components. The differences in how the components looked depending on the orientation they had were large enough compared to the correct position that the component had to have in order to be picked up by the robot. The flange can be oriented in two ways where one side has a slight elevation shaped like a circle, if this side is directed upwards, the component is in the correct position and will therefore be picked by the robot. The magnet assembly has three different orientations it can end up in, two of these are correct as it lies flat and can be picked. The third happens if the component is on its side, in this case, the robot will ignore the component.

During counter weight tests, the camera was able to identify the component. The camera was also, with high probability, able to identify how the counter weight was turned and pick it up sufficiently. However, it was necessary to manually ensure that the component was placed with the right side facing upward. The counter weight can be oriented in three different directions. If it was on its high side, the robot ignored the component, but regardless of which flat side it was facing up, the robot identified it as usual and continued in the program.

Similarly to the counter weight, the camera was also able to identify and locate the disc spring component. The disc spring is shaped like a disc, hence the name, where the convex side must be directed upward on the pallet. For the disc spring component, the differences between the convex and concave sides were far too small for the camera in this setup to be able to tell the difference. To separate between components lying with the convex or concave side upwards, the special plate in Figure 4.1 was used. Disc springs were brushed over the plate and, when finished, the plate could be placed under the robot. Although the background changed when picking from the plate, instead of the work plane, the camera and robot were able to identify and pick components with high precision. One problem identified during testing with the disc spring component was that if disc springs lay too close to one another, the vacuum could suck up several components simultaneously. Therefore, it was necessary to separate the disc springs lying too close before starting the palletizing process.

It was not possible for the camera to identify if the spring was oriented to be an upper or lower spring, apart from this, the wrist camera could detect if the component was on the work plane. When the body rivet was randomly placed on the work surface, the camera was able to distinguish its orientations and ignore any undesirable placements. However, with the setup used during the tests, it was very difficult to turn the robot around its axes to pick up the component in all orientations. This was mainly because the robot arm was too short.

The palletization of the different components had results that correlated with the degree to which the wrist camera could identify them. If a component was not recognized correctly, picking was performed poorly and consequently palletizing could not take place in a consistent manner. The components that had a successful palletization were therefore those that could be successfully identified by the camera, more specifically the counterweight, flange, disc spring, and magnet assembly.

The tests with multiple different components at the work plane simultaneously confirmed that the intended component was always identified and picked. This proved that the camera was able to intercept differences in the various components and place them in the right pallet.

4.4.2 Verification Tests of Automated Palletizing

In order to assess the accuracy and consistency of the robot's palletizing ability multiple pick and place repetitions were conducted from the work surface to the pallet. Tests were performed on the four components that could be correctly identified by the Robotiq wrist camera and successfully picked up by the robot. More specifically Counter Weight, Disc Spring, Magnet assembly, and Flange. During the tests, four different requirements were measured:

- Identification
- Picking
- Placement
- Cycle time

If the identification of the component is correct, the robot gets a precise position of where it is located, then the component is picked up centered in the nozzle which results in a good placement in the pallet. A total of 100 repetitions were made, the result of how many correct identifications and pick and place actions out of these 100 can be seen in Table 4.3.

It can be seen that the counter weight had the most problems with being identified by the camera, but that it could be picked up by the robot regardless. The reason for this occurrence in those instances was that the camera detected the component

Table 4.3: Results from the test with 100 cycles.

	Identification	Picking	Placement	Time [s/cycle]
Counter Weight	92/100	100/100	92/100	11s
Flange	97/100	90/100	90/100	8s
magnet Assembly	100/100	100/100	81/100	9s
Disc Spring	99/100	94/100	99/100	8s

as a mirrored image, causing the robotic arm to move in the incorrect direction while attempting to pick it up. Although the component was picked up, it was placed on the pallet 180 degrees wrong.

The flange had three identification errors where the camera simply did not see the component, this may have been due to changes around the work surface such as poor light in the room or reflections from the light outside. It could also be seen that the further away from the center of the camera a component was placed, the robot picked the component less centered in the nozzle. However, this was only noticeably bad for the flange in the measured 10 cases including when the camera could not identify the component. When the robot picked it up poorly centered in the nozzle, the palletizing in these cases was also poorly executed.

The magnet assembly had no problems being either identified by the camera or picked up by the robot, but during palletizing there were some problems. As mentioned in section 4.2.3, this component needs to be centered before it can be used in assembly. Today, there is also manual centering before it is placed on the pallet by the operator, who can also carefully pry the component into its place on the pallet. This cannot be done by the robot, so in cases where the lower part of the magnet assembly is skewed, the component is not placed correctly in the pallet.

Out of the hundred cases, the camera made one mistake in identifying the disc spring. In this case, the camera identified a non-existing disc spring, hence no disc springs were picked in the cycle. As the disc springs are very small and light, there was a risk of two components being sucked into the nozzle at the same time if the camera identified the component incorrectly and the robot went to an incorrect location. However, incorrect picks could be corrected directly in the nozzle due to the light weight of the disc spring. In cases where the robot picked the component incorrectly, it was always sucked in and became centered in the nozzle. Therefore, the result for placement was better compared to picking.

In Table 4.3 it can be seen that the flange and the disc spring had the quickest palletizing process with eight seconds per cycle. The magnet assembly instead required nine seconds, mainly because the scanning height is higher than for the rest of the components, which means the distance to pick components from the work plane is larger. The counter weight had the highest time per cycle with eleven seconds. For the counter Weight component, the scanning height is similar to Flange and Disc spring. However, as the counter weight has a shape similar to a rectangular

it requires that the tool is rotated correctly before it can pick up the component. In contrast, as the flange, disc spring, and magnet assembly have a circular shape, their tools do not require any specific rotation in order to pick components correctly.

4.4.3 Continuous Feeding Solutions

One feeding solution can be seen in figure 4.11. The idea of the solution is to enable continuous feeding of body rivets to the assembly robot. The chute of the fixture aims to utilize gravitation to feed the components to the grasping point. The groove in the end of the chute is small enough to stop the head of the body rivet to fall down, but wide enough for the shank to fall down. The idea is to drop body rivet components onto the chute and use the groove in the chute to orient the component with the head upwards, and the shank downwards into the groove. Gravity will then transport components along the groove and stack them where the groove ends.

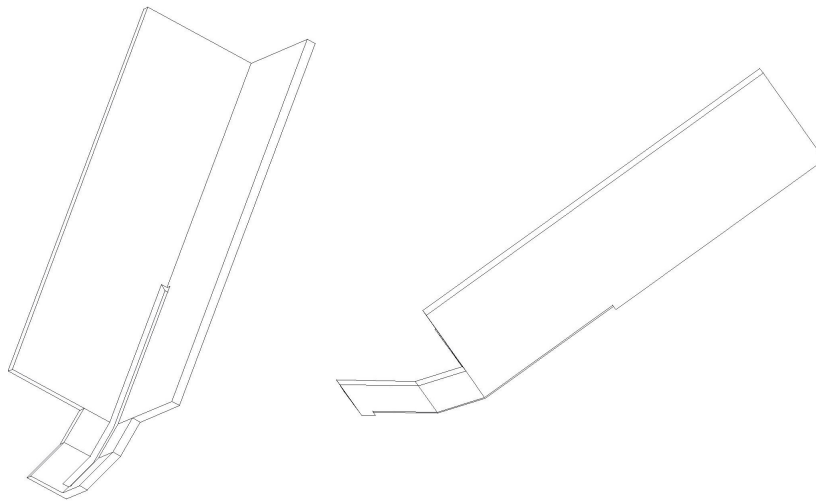


Figure 4.11: Body rivet chute.

The chute was 3D printed and tested by dropping components from varying heights. It was held at different angles to see how the orientation of the component was affected and if gravity could transport the component effectively. The result showed that the chute was insufficient in orientating the component correctly. When dropped over the chute, the components were orientated in two different ways, either with the shank pointed downwards in the groove, or with the head pointed downwards, laying on top of the groove. The outcome of the orientation was random. Regarding the transport function, the result showed that if orientation were correct, gravity could effectively transport the component towards the end of the groove and fix it in position. However, when dropping more components onto the chute, these were not always stacked correctly in a queue. In addition, gravity was insufficient in transporting queued components whenever the component first in the queue was removed. It would therefore be hard for the chute to continuously feed components to the assembly robot.

Another feeding solution can be seen in Figures 4.12 and 4.13. The idea is to feed disc springs into a cylinder that is threaded on the inside. The screw-shaped part, seen in figure 4.13, acts as a stop to prevent the components from sliding out of the cylinder. The idea was that when components are fed into the cylinder, it is shaken and then stacked in the same direction on top of each other. The screwlike part is then screwed in to allow one single component to be taken at a time. If this idea were to be used in the assembly instead of the palette with disc springs, some kind of motor would have to be used to continuously screw up components from the cylinder.

The tests of this idea showed that the components were stacked on top of each other and with a large majority going in the same direction. However, they were stacked with the concave side up, an explanation for this could be that during shaking, they turn with the center of gravity. Therefore, the solution would be insufficient to continuously feed the assembly robot with Disc springs.

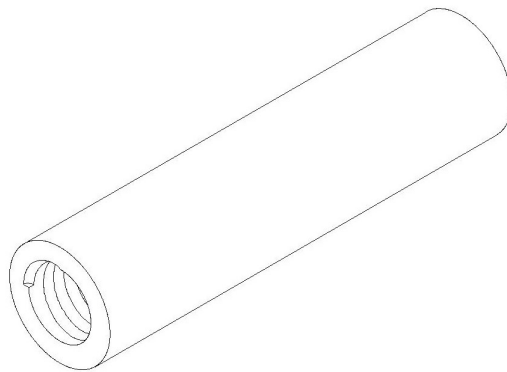


Figure 4.12: Cylindrical holder for disc springs

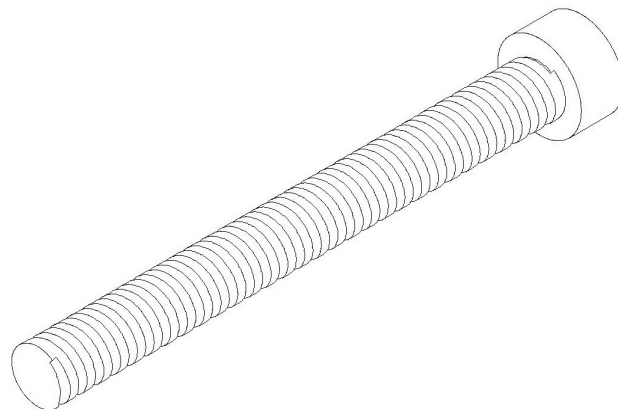


Figure 4.13: Screw used to feed disc springs

4.4.4 Manual palletizing solutions

The manual handling of components was mostly focused on disc springs, as this component is very difficult to handle in the current method due to its small dimensions and assembly requirements. A possible solution to this can be seen in Figures 4.14-4.16. The first plate, seen in figure 4.14 is a further development of an already existing fixture with the function to separate right-faced disc springs and wrong-faced disc springs.

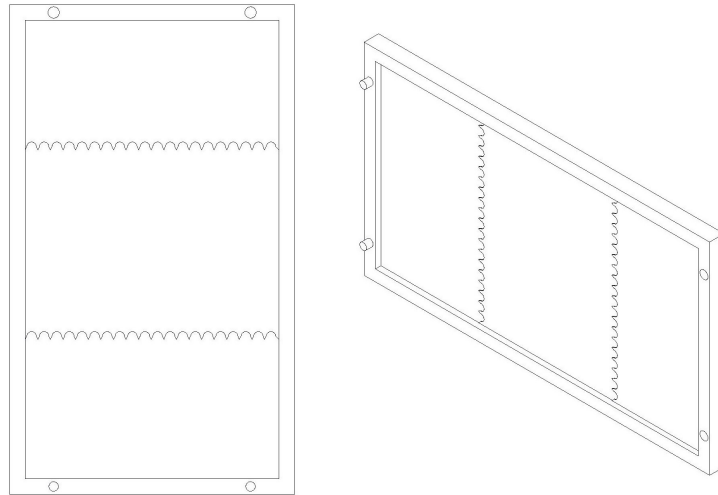


Figure 4.14: Disc spring plate 1.

The idea is to brush disc springs on the plate where the right-faced will stop in the small cleft, while disc springs laying upside down will slide over. In the original process, components that were right-facing were placed on the pallet one by one using a vacuum tool. In the newly developed solution, a second plate is instead used for this process. The plate, which can be seen in Figure 4.15, has small pegs with the same distance between them as in plate 1.

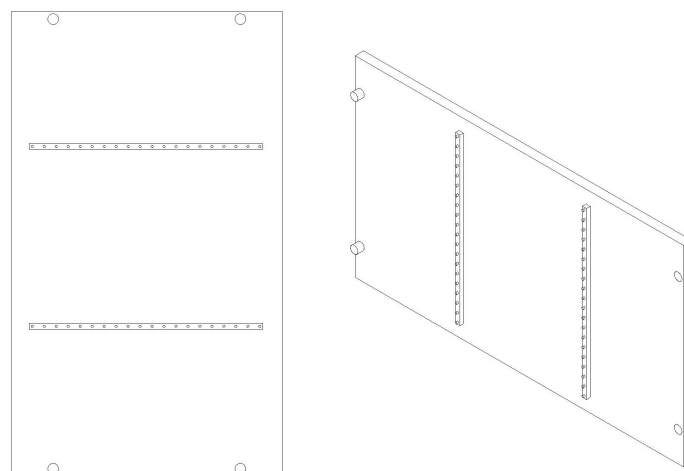


Figure 4.15: Disc spring plate 2.

The plate is mounted onto the first plate placing the pegs inside the disc springs. When flipping the plates upside down, the disc springs get fixed around the pegs in plate 2, laying upside down. Plate 3, seen in Figure 4.16, is then mounted on plate 2. Flipping the plates once again orientates the Disc springs correctly, and places them in a fixed position. Plate 3 can then be placed in the assembly robot, similar to the currently used pallet.

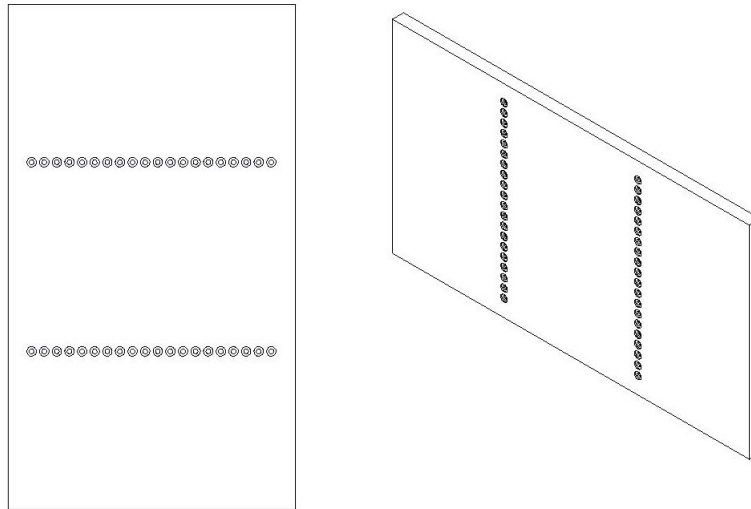


Figure 4.16: Disc spring plate 3.

The idea was tested with one smaller prototype seen in figure 4.17 and with one larger prototype seen in figure 4.18. The smaller prototype aimed at testing the flipping function. This test showed that the plates effectively could transport the disc springs from the clefts in plate 1 to a fixed position on the pegs in plate 2. Likewise, it successfully transported the disc springs from the pegs in plate 2 to a fixed position on plate 3.

The larger prototype aimed at testing how the flipping function was affected by having several disc springs scattered on the plate. When tested, disc springs were brushed on plate 1, disc springs laying with the convex side upwards got stuck in the cleft, while disc springs laying with the concave side up were collected in a pile at the end of the plate. The tests showed that having Disc springs scattered on the plate did not affect the flipping function negatively. Those disc springs laying in the correct position in the cleft on plate 1 were fixed on the pegs on plate 2 when flipping the plates. The rest of the disc springs, not laying on the pegs, could then easily be brushed off plate 2 before flipping it to a fixed position on plate 3. The tests also showed that many of the pegs on plate 2 were in bad shape when 3D printed, resulting in not being able to fix disc springs around them. Some pegs melted during the printing process, making them shorter. Some were fragile which made them snap during tests. This had the consequence that during tests with the larger prototype, all disc springs were not fixed on the pegs.

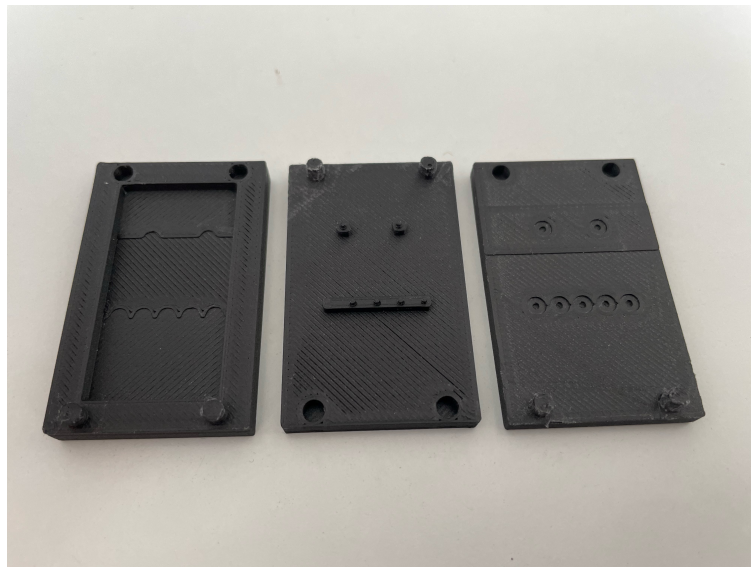


Figure 4.17: Small prototype of disc spring plates.

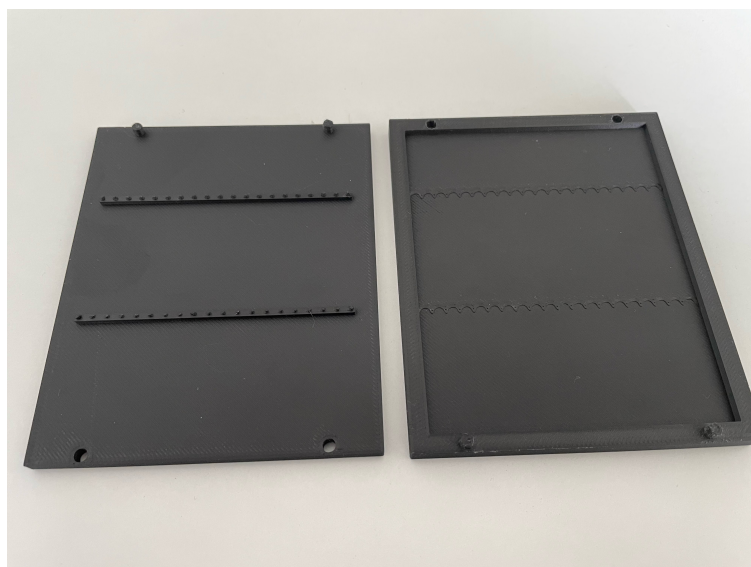


Figure 4.18: Large prototype of disc spring plates.

5

Discussion

In this chapter the results of the thesis is discussed. First, a general discussion of material handling is presented, followed by an evaluation of the presented system design solutions. Furthermore the research questions of the thesis is answered, and recommendations on future research is presented.

5.1 Material Handling

As mentioned in Section 2.2 there are several different material feeding methods. Cochlear uses batch supply for the components they palletize, and continuous supply for the actuator rivet, which is fed by the bowl feeder. Section 4.1.2 highlights that automation often encounters difficulties in the material handling of small and irregularly shaped components [5]. This challenge is particularly prevalent in the medical device industry, where products often comprise intricate and minuscule parts. In the case of Cochlear, the vast number of components of the actuator, as well as their sizes, present significant obstacles. Furthermore, none of the components conform to the standard specifications, thus impeding the implementation of existing solutions. As mentioned, currently only one of the components is accommodated by a standard bowl feeder solution, while each nozzle utilized in the assembly robot is custom-made for a specific component.

As previously mentioned in Section 2, FAS leverages distinct material feeders to sort, orient and transport the components to the assembly station [20]. In this study, various feeders that could proficiently handle small and complex components were observed during the external study phase 4.3.2. Several attempts were made to develop feeders to suit Cochlear's components, such as the chute and cylindrical holder discussed in Section 4.4.3. It is worth noting that the feeders in FAS are capable of processing only one type of component, necessitating one feeder for each component [20][22]. In systems with a high number of component types, this could lead to a considerable direct cost [22]. In such scenarios, the implementation of F-FAS would be advantageous [22]. As described in Section 4.1.3, F-FAS employs a vibratory plane, machine vision system, and manipulator to convey the components to the assembly station, thereby requiring only one feeder for all component types [22]. While not tested in this research due to practical constraints, in theory, the

UR3e robot could be employed to feed the components directly into the assembly cell instead of palletizing them first. However, an apparent disadvantage of F-FAS is that not all components can be correctly oriented with a vibratory plane [22].

5.2 Evaluation of System Design Solutions

In this section the systems design solutions is evaluated and discussed. First, the section discusses the performance of the setup used in the automated solution, followed by an evaluation of the test results from the automated and manual solutions.

5.2.1 Setup

The camera's field of view was one of the main aspects of how well the components could be identified. As mentioned in section 4.3.1, a smaller field of view will result in fewer components being visible to the camera on the workspace and vice versa, a larger field of view provides room for more components. To be able to have several components on the work surface at the same time, you could build the program or the setup of the robot in a different way. Since most components need different fields of view to be recognized by the camera, the components that need a smaller one would be placed in the center of the workspace while those that can handle a larger one would be placed at the edges. By varying the field of view above this single surface, it is possible to use the same surface to pick up the different components. However, this would reduce the number of components that fit simultaneously on the work surface. Another solution would involve a workspace per component, where each surface has a specific field of view. In this way, the robot would move around itself to the different areas and pick components for palletizing. This would result in more space for more components around the robot. Using a cobot for these types of changes can greatly facilitate the work. As mentioned in section 2.1, collaborative robots can help to solve problems in developing manufacturing workspaces, they do not require any high level of skill to use compared to a traditional industrial robot. Hence, trying different solutions, reprogramming, and changing the work area will not be as time-consuming.

There may be a few likely explanations as to why the robot picked the components less and less centered the further out to the edges of the camera's field of view they were located. A possible explanation for this could be lens distortion, where objects at the edges of an image are usually more prone to this [29]. Another reason could be environmental factors that affected the camera as mentioned in the result, reflections from the light outside and suboptimal light in the room around the setup.

The component that had difficulty being recognized by the camera was, as mentioned, the spring. This component is very thin but is also one of the larger components of the product. Due to its thinness, it lies very flush with the work surface. As it has such a large surface to reflect light from, some problems were encountered with the camera identification when the LED lamp was switched on. When the lamp is switched on, the light is reflected from it, and important details on the

component to make the identification with disappeared. However, when the lamp was turned off, it was only on a few attempts that small details distinguishing how the component was located were captured by the camera. As mentioned in section 2.4, a well-functioning vision system needs to be able to not capture an image, but also distinguish between different features, and objects and then act accordingly to them. Changes in the design of the component to more easily distinguish orientation could prevent this problem.

The multi-nozzle holder and the single-nozzle holder created some differences in how the robot was handled. The TCP for the single-nozzle holder had only one change in the Z-direction, while for the other, it had three different TCPs in the x, y, and z-direction. This changed the behavior of how the robot had to rotate to pick up the components. The multi-nozzle holder had to rotate around multiple axes and for a longer time to adjust to pick up a component, while the single holder rotated around the z-axis and therefore had a shorter rotation time. A setup using a single-nozzle holder would therefore run through conceivable programs if tool changes are disregarded. The various things needed in a multi-nozzle holder setup are more complex, for example, to be able to decide which nozzle should be activated, several inputs and outputs are needed. However, as mentioned in the theory section 2.4, a gripper or a robot end effector with the ability to pick up multiple components without the need for a tool change can help increase the effectivity and flexibility in the robot cell. Therefore, it would be advantageous to implement such a design.

During the course of the work, for the sake of flexibility, manual switching on and off of the vacuum gripper has been used. This resulted in a small variation when starting and stopping the vacuum gripper, however, this was nothing that noticeably changed the result when palletizing. In order to achieve the highest precision and accuracy, and avoid manually turning the vacuum gripper on, automatic systems should be used.

5.2.2 Automated Palletizing Solution

As mentioned in sections 2.3.1 and 2.3.2 ergonomic problems can contribute to errors and other personal issues. To avoid ergonomic problems for operators when palletizing the automated palletizing solution was tested to see if it could reach the accuracy and precision needed to replace manual work. Therefore, testing the robot palletizing process with 100 cycles for each component was important since it gave a more comprehensive picture of the result.

The tests showed that the camera had some problems in identifying the counter weight sufficiently. The counter weight is not completely homogeneous and, when incorrectly identified, was picked up by the robot 180°wrongly. In most cases, the camera was able to see this difference, but in eight cases the misidentification led to Counter weights being placed in the palette incorrectly. The tests also showed that the UR3e robot was slow in palletizing the counter weight component. Eleven seconds is significantly longer than the manual palletizing time of 2 to 3 seconds.

The processing time for palletizing the counter weight is higher than for the rest of the components. This is mainly because this component is not circular, hence the robot arm has to rotate to pick it up. As the rotation motion is slower than other motions, the time increases.

For the flange component, the camera had three cases where it struggled to identify the component. In these cases, a new component identification was performed, and hence it did not affect the palletizing process more than just slowing it down. The robot also had some problems with properly picking the flange. In these cases, the pick-ups were skewed, which also resulted in a skewed placement. Poor picking depended on where on the work plane the components were located. In each case where the picking was poor, the flanges were located in one specific area of the work plane. Although the skewness affected the placement of flanges, this did not have any negative impact on the palletizing quality. It was enough with a light touch on the palette to make all the components place correctly.

For the magnet assembly, the identification and picking were 100% but due to the component being a bit skewed, there were significant problems with placing the components on the palette. When being manually handled by operators this was solved by centering the components before placing them in the palette. With the robot, this is not possible. However, currently, the magnet assembly is also centered inside the assembly robot, which might make the first centering unnecessary. If so, the tolerances of the holes on the palette can be increased and result in better placements.

The disc spring had a good result as 99 out of 100 placements were correct. As mentioned in the result, the poor picking quality did not affect the placement quality as the components were sucked into the nozzle anyway. The problem with disc springs is the time it takes to prepare the brush plate. Since the vacuum risks also sucking in nearby disc springs, the disc springs had to be separated on the plate before being palletized, which is a time-consuming process.

5.2.3 Manual Palletizing Improvements

The result in section 4.4.3 showed that the chute was insufficient in feeding body rivet components to the assembly robot. Both the function of transporting and orienting the body rivet proved to be poor. The chute solution was inspired by a similar solution used to correctly turn screws in a robot cell. The difference between the body rivet component compared to a screw is the location of the center of gravity. The body rivet has a bigger head relative to the shank than a screw has, which places the center of gravity closer to the head. Therefore, the shank of the body rivet does not tend to pull down into the groove to the same extent that a screw shank would.

The result in section 4.4.4 showed that it was possible to get disc springs in a fixed position and in the correct orientation, using the flipping function. This proves

that the function of the solution works. The process of 3D printing the plates gave the advantage of low lead times and low manufacturing costs. This gave the opportunity to construct several prototypes and to get quick feedback on the model. The upgrades could then immediately be implemented in the CAD model. The drawback of constructing the prototypes with 3D printing was the quality aspect. The main quality issue concerned the pegs in Plate 2. Due to it having a diameter of only 1mm, the pegs became fragile and some of them fell off after testing the flipping function. Some pegs also melted, making them unusable. On Plate 3, the holes, where disc springs are flipped into, did not become completely circular, resulting in the disc springs not fitting in the holes. This was solved by increasing the diameter of the hole. Due to the mentioned quality issues, it was hard to evaluate the time it would take to palletize the Disc spring component with the flipping solution. Therefore, quality issues would have to be solved before the solution can be completely evaluated.

The mentioned quality issues would most certainly not exist if the plates were manufactured in metal instead of plastic. Therefore, the next step in the research would be to construct the plates in metal and evaluate the flipping function again.

When it comes to the cylindrical holder for disc springs, it is of great importance that the components are always stacked on top of each other in the same direction. In further testing of this idea, it would have been interesting to use a longer cylinder to give more room for the discs to spin around, but also to manufacture it in a different material as 3D printing is not always of the best quality.

5.3 Research Questions

What are the challenges associated with the material handling of components for medical devices?

Automating the handling of small and irregularly shaped components is challenging [5], especially in the medical device industry like Cochlear. The vast number and unique specifications of the components make it difficult to implement existing solutions. Most components require custom feeding mechanisms, resulting in a labor-intensive and time-consuming assembly process. Both Cochlear, in the medical device industry, and the consumer electronics industry face challenges in automating production due to small component sizes and tight tolerances [24] [25]. Conventional robotic automation is difficult due to setup time, fixture costs, and the need for dedicated feeding solutions [4].

Due to mentioned reasons above, numerous processes are still kept manual. Manual processes pose risks such as human error and poor ergonomics [20]. Cochlear, for example, spends approximately three hours per day on manual palletization alone. The ergonomic assessment yielded mixed results, the HARM assessment revealed no ergonomic risks, while the KIM-MHO assessment revealed a substantially higher risk.

How can material handling of components for medical devices be improved to achieve higher quality and better ergonomics for operators?

As described in Section 4.1.1 there have been various attempts to fully automate PCB production. Although both experiments in [25] [24] achieved satisfactory assembly quality, they were not as fast as a manual assembly. Despite the tendency for process time to increase with the automation of small and complex products, the benefits of reducing human error and ergonomic injuries should not be overlooked. Automation can be a good alternative for improving the material handling of medical devices in systems with lower requirements for high output.

An additional approach to enhance material handling is the implementation of FAS or F-FAS, elaborated in 4.1.3. In this study, several attempts were made to develop feeders, such as the chute and cylindrical holder, discussed in Section 4.4.3. Although these solutions proved to be inadequate, various feeders that could proficiently handle small and complex components were observed during the external study phase 4.3.2. With suitable equipment, it is not unlikely that a FAS could be effective in the material handling of medical devices.

FAS feeders can process only one component type, necessitating a feeder for each component [20][22]. This can result in high direct costs, especially in systems with numerous component types [22]. F-FAS, on the other hand, employs a vibratory plane, machine vision system, and manipulator to convey components to the assembly station, requiring only one feeder for all types. While not tested in this research, the UR3e robot could potentially directly feed components into the assembly cell instead of palletizing them first. However, a drawback of F-FAS is that not all components can be correctly oriented using a vibratory plane [22].

5.4 Recommendations for Future Research

While this thesis provides a comprehensive analysis of the material handling of medical devices, there is scope for further improvement. This section outlines the areas where additional actions or further research are recommended.

This research included a comprehensive study of the possibility of automating Cochlear's palletizing process. During the study, it became evident that the main constraint of the system was that the Robotiq Wrist Camera was not powerful enough to identify the components. Whether a more powerful vision system would be able to identify Cochlear's component or not remains uncertain before being fully tested. However, the literature is filled with experiments where vision systems are capable of identifying smaller components than Cochlear's, for example, [27], mentioned in Section 4.1.4. For future research, it would be interesting to see the effects a more powerful vision system would have on the palletizing process.

This research was limited to improving the supplying process to Cochlear's assembly robot, hence the automated solution was limited to palletizing the components. The

two main reasons for this are that the assembly process is harder to perform than the palletizing process and that the assembly process has additional requirements on achieving sufficient product quality. However, if it would be possible to use a vision system to identify components and assemble them immediately, the palletizing process could be fully neglected and time and resources can be saved.

6

Conclusion

The purpose of this Master's thesis was to investigate the challenges associated with the material handling of components for medical devices, specifically at Cochlear, and to explore ways to improve these processes for higher quality and better ergonomics for operators. The main objective was to identify the limiting factors and suggest improvements to enhance efficiency, reduce errors, and alleviate ergonomic burdens for operators.

Handling small and irregularly shaped components presents a challenging task in terms of automation, particularly in the medical device industry. The challenges of conventional robotic automation include lengthy setup times, high fixture costs, and the requirement for specialized feeding solutions. Due to challenges with automation, manual processes are still common. These processes carry risks, including the potential for human error and suboptimal ergonomics.

Previous attempts to automate the handling of small and irregularly shaped components have resulted in good assembly quality and reduced ergonomic risks, while the processing time has increased. This makes automated solutions more suitable for systems with lower requirements on high output. Implementation of FAS in Cochlear's production removes the need for palletizing but can result in high direct costs for feeders. For F-FAS the direct costs are small since only one feeder is used. The disadvantage of F-FAS is that not all components can be correctly oriented using a vibratory plane.

Due to the numerous and distinct standards of its components, Cochlear faces numerous challenges. The research showed that these components created difficulties in picking, placing, and identifying when using the current vision system. To address these difficulties and to automate the palletizing process using a robot, additional advancements in component design may be required. However, it is concluded that another vision system is in need of implementation if this process is to become fully functional.

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A

Appendix 1

KIM for assessing and designing physical workloads during Manual Handling Operations (KIM-MHO)

Workplace/sub-activity:			
Duration of the working day:		Evaluator:	
Duration of the sub-activity:		Date:	

1st step: Determination of time rating points

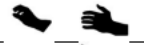


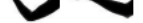
Total duration of this sub-activity per working day [up to ... hours]	up to 1	2	3	4	5	6	7	8	9	10
Time rating points:	1	2	3	4	5	6	7	8	9	10

2nd step: Determination of the rating points for other indicators

Type of force exertion in the finger/hand area within a "standard minute"	Holding ¹⁾			Moving				
	average holding time [sec. per minute]			average movement frequencies [number per minute]				
	31-60	16-30	≤ 15	< 5	5-15	16-30	31-60	61-90 ²⁾
Level	Description, typical examples							Rating points
low	Very low / low forces (up to 15% F_{maxM}) e.g. button actuation / shifting / ordering / material guidance / insertion of small parts Moderate forces (up to 30% F_{maxM}) e.g. gripping / joining small work pieces by hand or with small tools High forces (up to 50% F_{maxM}) e.g. turning / winding / packaging / grasping / holding or joining parts / pressing in / cutting / working with small powered hand tools Very high forces (up to 80% F_{maxM}) e.g. cutting involving major element of force / working with small staple guns / moving or holding parts or tools Peak forces³⁾ (more than 80% F_{maxM}) e.g. tightening, loosening bolts / separating / pressing in Powerful hitting³⁾ with ball of the thumb, palm of the hand or fist							
high	5.5	3	1.5	0.5	1	2.5	5	7
	9	4.5	2.5	0.5	2	4	7.5	11
	14	7	3.5	1	3	6	12	18
	22	11	5.5	1.5	5	10	19	
	100		35	8	30	100		
			8	30				
Rating points of force exertion:				Left hand	Right hand			
13					X			

¹⁾ The amount of time of holding work is only considered as such in the assessment if one arm is held continuously statically for at least 4 seconds!
²⁾ Please note: if one of these categories was chosen, it is recommended to evaluate this sub-activity also using the KIM-BF!
 These forces might not be exerted at all or might no longer be exerted reliably. This applies to women in particular.
³⁾ In case of even higher frequencies, the resulting risk score must be extrapolated linearly or the E version (KIM-MHO-E) must be applied.





Force transfer / gripping conditions	Rating
Optimum force transfer/application / working objects are easy to grip (e.g. bar-shaped, gripping grooves) / good ergonomic gripping design (grips, buttons, tools)	0
Restricted force transfer/application / greater holding forces required / no shaped grips	2
Force transfer/application considerably hindered / working objects hardly possible to grip (slippery, soft, sharp edges) / no or only unsuitable grips	4

Hand/arm position and movement ⁴⁾	Rating points
 Good: position or movements of joints in the middle (relaxed) range, only rare deviations / no continuous static arm posture / hand-arm rest possible as required	0
 Restricted: occasional positions or movements of the joints at the limit of the movement ranges / occasional long continuous static arm posture	1
 Unfavourable: frequent positions or movements of the joints at the limit of the movement ranges / frequent long continuous static arm posture	2
 Poor: constant positions or movements of the joints at the limit of the movement ranges / constant long continuous static arm posture	3

⁴⁾ Typical positions are to be considered. Rare deviations can be ignored.

Unfavourable working conditions (specify only where applicable)	Rating points
Good: there are no unfavourable working conditions, i.e. reliable recognition of detail / no dazzle / good climatic conditions	0
Restricted: occasionally impaired detail recognition due to dazzle or excessively small details / difficult conditions such as draught, cold, moisture and/or disturbed concentration due to noise	1
Unfavourable: frequently impaired detail recognition due to dazzle or excessively small details / frequently difficult conditions such as draught, cold, moisture and/or disturbed concentration due to noise	2

Indicators not mentioned in the table are to be taken into account accordingly.

Body posture/movement ⁶⁾	Rating points
 <ul style="list-style-type: none"> - Alternation between sitting and standing, alternation between standing and walking, dynamic sitting possible - Trunk inclined forward only very slightly - No twisting and/or lateral inclination of the trunk identifiable - Head posture: variable, head not inclined backward and/or severely inclined forward or constantly moving - No gripping above shoulder height / no gripping at a distance from the body 	0
 <ul style="list-style-type: none"> - Predominantly sitting or standing with occasional walking - Trunk with slight inclination of the body towards the work area - Occasional twisting and/or lateral inclination of the trunk identifiable - Occasional deviations from good "neutral" head posture/movement - Occasional gripping above shoulder height / occasional gripping at a distance from the body 	2
 <ul style="list-style-type: none"> - Exclusively standing or sitting without walking - Trunk clearly inclined forward and/or frequent twisting and/or lateral inclination of the trunk identifiable - Frequent deviations from good "neutral" head posture/movement - Head posture hunched forward for detail recognition / restricted freedom of movement - Frequent gripping above shoulder height / frequent gripping at a distance from the body 	4
 <ul style="list-style-type: none"> - Trunk severely inclined forward / frequent or long-lasting bending - Work being carried out in a kneeling, squatting, lying position - Constant twisting and/or lateral inclination of the trunk identifiable - Body posture strictly fixed / visual check of action through magnifying glasses or microscopes - Constant deviations from good "neutral" head posture/movement - Constant gripping above shoulder height / constant gripping at a distance from the body 	6 ⁷⁾

⁶⁾ Typical body postures are to be taken into account. Rare deviations can be ignored.

⁶⁾ If the manual handling operations are not carried out in a stationary sitting, standing, kneeling, squatting, lying position, but in motion (walking, crawling), it is recommended to evaluate the sub-activity also using the KIM-BM.


⁷⁾ Please note: If this category was chosen, it is recommended to evaluate this sub-activity also using the KIM-ABP!

Work organisation / temporal distribution	Rating points
Good: frequent variation of the physical workload situation due to other activities (including other types of physical workload) / without a tight sequence of higher physical workloads within one type of physical workload during a single working day.	0
Restricted: rare variation of the physical workload situation due to other activities (including other types of physical workload) / occasional tight sequence of higher physical workloads within one type of physical workload during a single working day.	2
Unfavourable: no/hardly any variation of the physical workload situation due to other activities (including other types of physical workload) / frequent tight sequence of higher physical workloads within one type of physical workload during a single working day with concurrent high load peaks.	4

3rd step: Evaluation and assessment

		13				
Type of force exertion in the finger/hand area		13				
Force transfer / gripping conditions	+	0				
Hand/arm position and movement	+	2				
Unfavourable working conditions	+	1				
Body posture	+	4				
Work organisation / temporal distribution	+	0				
Time rating points	x	Total of indicator rating points:	20	=	Result	60

The risk score calculated and the table below can be used as the basis for a rough evaluation:

Risk	Risk range	Intensity of load ¹⁾	a) b)	Probability of physical overload Possible health consequences	Measures
	1	< 20 points	low	a) Physical overload is unlikely. b) No health risk is to be expected.	None
	2	20 - < 50 points	slightly increased	a) Physical overload is possible for less resilient persons. b) Fatigue, low-grade adaptation problems which can be compensated for during leisure time	For less resilient persons, workplace redesign and other prevention measures may be helpful.
	3	50 - < 100 points	substantially increased	a) Physical overload is also possible for normally resilient persons. b) Disorders (pain), possibly including dysfunctions, reversible in most cases, without morphological manifestation	Workplace redesign and other prevention measures should be considered.
	4	≥ 100 points	high	a) Physical overload is likely. b) More pronounced disorders and/or dysfunctions, structural damage with pathological significance	Workplace redesign measures are necessary. Other prevention measures should be considered.

¹⁾ The boundaries between the risk ranges are fluid because of the individual working techniques and performance conditions. The classification may therefore only be regarded as an orientation aid. Basically, it must be assumed that the probability of physical overload will increase as the risk scores rise.

B

Appendix 2



Assessment form Hand Arm Risk-assessment Method (HARM)

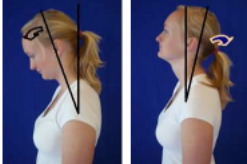






HARM 2.0

Task	Date
Department/job	Completed by

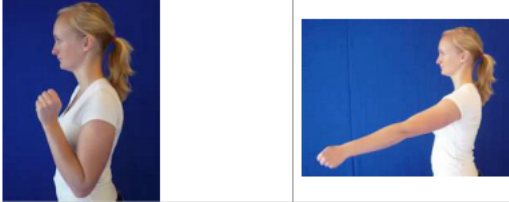
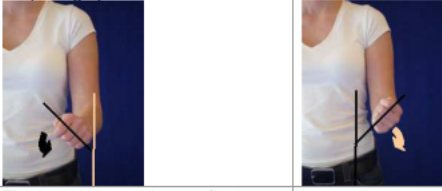
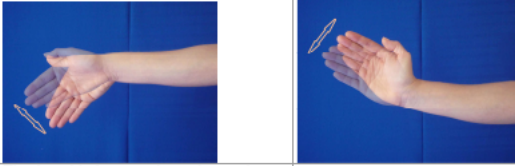
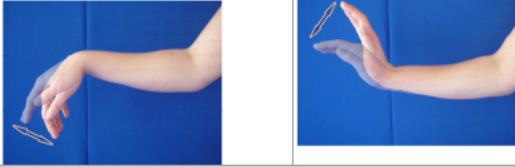
Step 1. Task duration score	
Step 1A: The total time duration of the task over the course of an 'average working day' (all time periods should be added together). Indicate the time duration only for the days that the task occurs (10 hours maximum). Step 1B: How many days per week does the task occur? - for 1 or 2 days per week: deduct 1 point from the score: - for 3 or more days, the score remains the same: Step 1C: Is a break of at least 7.5 minutes* taken every 1.5 hours? - Yes; deduct 1 point from the score - No; the score remains the same:	3 hours - 1 = ..2... -1 -0 -1 -0
* Read the annex for what is meant by a break	
Step 1D: Calculate the task duration score	If the task duration score is less than 1, then the score is 1 ..1.....

Step 2. Most active hand Circle the most active arm/hand during the task: right / left
 continue with step 3 till 8 for this hand

Step 3. Force score		Step 3B			Step 3C		
Step 3A Indicate which hand is the most active very similar forces should be assessed as one and the same force		Duration of the force exertion in seconds per minute			Number of force exertions per minute (frequency) (skip if frequency is smaller than 1x/min)		
Amount of force	Description and examples	<4	4-30	>30	1-4	4-30	≥ 30
(extremely) low to average: weight < 100 g to 1 kg force < 1 N to 10 N	Light pressure with fingers to holding/ grasping. For example: - sorting letters/objects, - pressing with the fingers, - using hand to hold small electric tools - grasping/gripping, holding or attaching parts, pressing firmly	0	2	3,5	1	2,5	4
somewhat high to high: weight: 1-6 kg force: 10-60 N	Holding firmly with hand to high force exertion by the arm. For example: - use of a knife/pliers, - using tools, - pushing heavy objects (e.g. cashier operator), - holding heavy tools, operating a stiff lever	0	4	6,5	2	4	6,5
peakforce	Striking with flat hand/fist e.g. hammer	-	-	-	3	5	8
Step 3D Force score = highest score circled = ..3.5.....							
In the event of high forces: Please note! If the force exertion is more than 6 kg, these must be assessed using a different method (e.g. lifting, or pushing/pulling risk assessment method).							

Step 4A Posture score for the HEAD/NECK and the SHOULDER/UPPER ARM		The percentage of the task duration that the posture occurs:		
		<10%	10-50%	>50%
<p>The head is tilted further forward than in the first photograph OR further back than in the second photograph</p> 	<p>The head is tilted further sideways than in the first photograph OR the head is turned, as in the second photograph</p> 	0	1,5	3
<p>The head is tilted forward and turned at the same time</p>		0	2	4
<p>The head is tilted backward and turned at the same time</p>		0	3	4
<p>Head (chin) pushed (extended) forward</p>		0	1,5	3
<p>With the arm unsupported, the upper arm is further forward OR sideways of the trunk than in the photographs OR angled behind the trunk</p>		0	2,5	3,5
<p>Shoulders raised (high)</p>		0	3	4
<p>Determine 'posture score for neck/shoulder' = highest score =</p>		<p>3</p>		

B. Appendix 2

Step 4B Posture score for the WRIST/LOWER ARM		The percentage of the task duration that the posture occurs:		
		<10%	10-50%	>50%
Elbow significantly bent or extended		0	1	2
The lower arm is rotated further (in the direction of the arrows) than in the photographs below		0	1	2
The hand is bent sideways (in the direction of the little finger and/or thumb) at the wrist so that the position of the wrist is between the positions shown in the photographs.		0	1,5	3
The hand is bent at the wrist so that the position of the wrist is between the positions shown in the photographs		0	1,5	3
Determine 'posture score for lower arm/wrist' = highest score =		1,5		

Step 5. Vibration score
Are vibrating tools used? <ul style="list-style-type: none"> No, insert '0' for the vibration score in the grey boxes below and proceed to Step 6 Yes, is the vibration intensity known? <ul style="list-style-type: none"> No, go to Step 5A: the vibration intensity is <u>unknown</u> Yes, go to Step 5B: the vibration intensity is <u>known</u>

Step 5A The vibration intensity is <u>unknown</u>		
Which of the situations applies? Circle the corresponding score and put this in the grey box at the bottom of the table.	Duration of exposure within the task	
	0-4 hours	4-8 hours
Description	Score	
Hardly any vibration, or no vibrations perceived by the user or visible to the assessor	0	0
Vibrations not visible, but perceived by the user (quivering sensation)	2	2
Vibrations just visible on the lower arm/hand, clearly perceived by the user	2	4
The hands, arms or shoulders can be clearly seen to vibrate and vibrations are clearly perceived by the user	4	4
Vibration score: use the circled score:	..... 0	.....

Step 5B The vibration intensity is known		
Which of the situations applies? Circle the corresponding score and place this in the grey box at the bottom of the table.	Score	
	Duration of exposure for the task	
Vibration intensity	0-4 hours	4-8 hours
< 2,5 m/s ²	0	0
≤ 2,5 - 5 m/s ²	2	2
≤ 5 - 10 m/s ²	2	4
≥ 10 m/s ²	4	4
Score for vibration: use the circled score:	..... 0	.....

Step 6. Other factors:	
Indicate whether the following situation apply to the task	Circle the correct answer
Breaks can only be taken at set break times (as opposed to breaks taken at the employee's discretion)	Yes <input checked="" type="radio"/> no
Work with cold or wet materials is performed without gloves	Yes <input checked="" type="radio"/> no
Disruption to concentration occurs regularly (only if work requires concentration)?	Yes <input checked="" type="radio"/> no
Hand grips are not shaped or are slippery or wet. Stretched fingers or a 2- or 3-finger pinch grip often occur because large or small materials are gripped or held	Yes <input checked="" type="radio"/> no
The work performed is a precision task. It requires precise positioning or moving of fingers or hands, such as assembly of very small pieces or surgical actions	Yes <input checked="" type="radio"/> no
Score for other factors: 0,5 for each 'yes' above:	..... 1

B. Appendix 2

Step 7. Calculate total risk score	
Use the scores from steps 1 through 6	Scores:
Force score (step 3)	..... 3.5
Posture score for the neck/shoulder (Step 4A)	..... 3
Posture score for the lower arm/wrist (Step 4B)	..... 1.5
Vibration score (Step 5)	..... 0
Other factor score (Step 6)	..... + 1
Calculate total score (A):	..... 9
Task duration score (taken from step 1) (T)	..... 1 X
Calculate risk score (task duration score (T) X total score (A))	..... 9

Step 8. Risk assessment:		
Determine the risk of experiencing complaints when performing the task by using the table below:		
Total score	Risk	Description
<30	GREEN	No risk of arm, neck or shoulder complaints for virtually the entire working population.
30-50	AMBER	Increased risk of arm, neck or shoulder complaints for some employees. In order to protect all employees, it is important to take preventative measures that lower the risk.
≥50	RED	High risk of arm, neck or shoulder complaints. It is important to take preventative measures immediately.
Health complains		If there are complaints that are suspected to be related to the task, it is ALWAYS important to identify the risk factors and take preventative measures!

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