Tampere University

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# DEFINING REFURBISHED SMART PHONE HANDLING IN A MODULAR TEST CELL

## Preliminary mechanical design

Master's thesis
Faculty of Engineering and Natural Sciences
Examiners: Prof. Kari Koskinen
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# ABSTRACT

Jyri Raninen: Defining refurbished smart phone handling in a modular test cell
Master's thesis
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This thesis concentrates on defining ways to handle smart phones in certain problematic situations. Objective is to validate the sales concept, find sensible solutions how to integrate three independent systems in one modular test cell. In this case, integration contains three phases that interact with each other in the final system. The first one is to modify one of the test systems to function in different orientation than originally intended and change manual adjustment to automatic. The second part is to design a additional feeding system because the existing gripper is not compatible with the testing system. The third part is to improve existing gripper in order to work with additional feeding system.

Interface design and validating sales concept are handled with the help of modularity theory. Brief introduction to Brownfield process helps to understand the sales concept. By investigating interfaces and their classifications it easier to divide available area in different sections and have enough room for everything. Before designing the additional feeding system, different options and control types to produce linear motion are introduced and compared. Improvements of the gripper are done after comparing different types of gripper and finding good listing of actions how to make existing grippers more flexible.

As result, all design choices were validated with real system after the detail design, manufacturing and assembly. Modules and interfaces were found to work without any required changes. The additional feeder required few minor tweaks and improvements during the validation phase. The gripper improvements succeeded on the second try.

Keywords: mechanical design, machine design, gripper, interface, modularity

# TIIVISTELMÄ

Jyri Raninen: Käytettyjen älypuhelinten käsittelyn kehittäminen modulaarisessa testisolussa
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Tämä diplomityö keskittyy määrittelemään tavat käsitellä älypuhelimia modulaarisessa testisolussa muutamassa ennalta tunnistetussa tilanteessa. Tavoitteena on vahvistaa myyntikonseptin periaate ja löytää järkevät ratkaisut kolmen itsenäisen testijärjestelmän integrointiin yhdeksi modulaariseksi testisoluksi. Tässä tapauksessa integrointi sisältää kolme vaihetta, jotka ovat tiiviisti yhteydessä lopullisessa järjestelmässä. Ensimmäisenä täytyy muokata yksi itsenäisistä järjestelmistä toimimaan eri asennossa kuin alunperin. Lisäksi käsisäätö muutetaan automaattiseksi. Toisena vaiheena suunnitellaan lisäsyöttöjärjestelmä, koska jo olemassa oleva robotin tarttuja ei ole yhteensopiva testijärjestelmän kanssa. Lisäksi kolmantena vaiheena parannetaan robotin tarttujaa.

Rajapintojen suunnittelu ja myyntikonseptin vahvistaminen käsitellään käyttäen apuna modulaarisuuden teoriaa. Brownfield-prosessin pääpiirteet käsitellään lyhyesti, koska se helpottaa ymmärtämään alkuperäistä myyntikonseptia. Tutkimalla rajapintoja ja niiden luokittelua saadaan helpommin jaettua käytettävissä oleva moduulien välinen alue eri rajapintoihin ja muihin järjestelmän vaatimiin alueisiin. Ennen lisäsyöttöjärjestelmän suunnittelua tutkitaan erilaisia tapoja tuottaa lineaarista liikettä ja ohjaustapoja. Tarttujan parannukset tehdään erilaisten tarttujien vertailun ja tarttujien joustavuuden parantamisen teorian avulla.

Tuloksina tämän työn vaiheiden sekä yksityiskohtaisen suunnittelun, valmistamisen ja kokoonpanon jälkeen kaikki suunnittelun valinnat vahvistettiin ja testattiin täysikokoisella järjestelmällä . Moduulit ja rajapinnat todettiin toimiviksi ilman tarvetta muutoksille. Lisäsyöttöjärjestelmä vaati muutamia pieniä muutoksia ja parannuksia testaamisen aikana. Tarttujan parannukset onnistuivat toisella yrityksellä.

Avainsanat: mekaaninen suunnittelu, koneensuunnittelu, tarttuja, rajapinta, modulaarisuus

# PREFACE

First, I would like to thank my examiners Kari and Jussi for providing good advice during the process. From company side, I would like to thank OptoFidelity, my supervisor Ari, the whole project team and others, who made this possible, for good spirit and teamwork. This was quite long process like the project itself.

The biggest support has came from my family, all close ones and friends. Äiti, now there is no more need for asking "When it is ready?". Thanks Kuha and MÖHINÄ, surviving throughout the years would have been so much harder (and maybe faster?) without you. I have so many important memories with all of you, like Skellari 50, Pellinki, Jullampas segelbåt, KotiXQ and many more to come also. Wouldn’t change anything.

Tampere, 18th August 2022

Jyri Raninen

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AC | Air conditioning |
| BBB | Big building block |
| BCE | Big common element |
| BfP | Brownfield Process |
| BoM | Bill of materials |
| CAD | Computer Aided Design |
| CTO | Configure To Order |
| DoF | Degree(s) of Freedom |
| DSM | Design Structure Matrix |
| DUT | Device Under Testing |
| ECF | Engineering Change Forecast |
| ETO | Engineer To Order |
| FBE | Frame-like base element |
| FE | Function-based element |
| I/O | Input/Output |
| MCE | Multifunctioncal core element |
| NTP | Normal temperature and pressure |
| RnD | Research and Development |
| SBB | Small building block |
| SC | Smart Cell |
| TPU | Thermoplastic polyurethane |
| UI | User interface |
| UPH | Units Per Hour |
| XR | Extended Reality |

# 1. INTRODUCTION

In recent years reducing emissions, increasing recycling, implementing circular economy and thinking about the full life-cycle of items have been seemingly popular and hot topics. Availability of natural resources has been significant reason for these changes and therefore industries have started seeking for alternative materials, solutions and recycling old products.

In this case study focus is on refurbished smartphones. Companies buy used smartphones in bulk. In order to sell them on market as second-hand phones, they need to be refurbished and then graded. After grading, they can be listed for sale with price that corresponds to the achieved grade. This grading needs to be repeatable and comparable to results of other phones. Manual grading done by humans can have large variance which could for example end to situation where two phones with same grades are on market. However, the other phone could be significantly in better shape than the other. Refurbished market makes sense as some customers can be satisfied more easily with a phone that serves its purpose as a communication tool. For others visual condition can be the most important attribute. Customer can save money while receiving expected features. In the smartphone industry, refurbishment business has been growing continuously. In 2018 it was the fourth largest segment. (OptoFidelity Oy) During past year or two, many new companies have noticeably increased their marketing on these refurbished smartphones.

## 1.1 Case company introduction

OptoFidelity is a company that was founded in Tampere, Finland, in 2005. It provides a variety of different high technology products to its customers. Company expertise is focused on test automation and robotics. Most of the test systems base on strong machine vision competence. The company has a core product range containing standard devices, systems configured to order (CTO) for different customer needs and is also making lots of customer specific systems engineered to order (ETO).

Most of the devices are used to grade and test different smart devices or their semi-finished parts, like smart phones and watches, extended reality (XR) devices, generally any touch screens by their functionality, accuracy and almost any other meter which might have an impact on user experience. These testing devices are used in all steps of products life cycle from first prototypes in research and development (RnD) phase to quality assurance during manufacturing process.

In order to strengthen offering on devices this market, company decided to combine its existing testing systems into one configurable testing cell to achieve complete grading for smartphone fully automatized. This thesis is about preliminary mechanical design of this case project.

## 1.2 Research questions

This case study thesis has three major research questions that are going to be studied:

1. What kind of modules to design so that they are interchangeable?
2. How to automate feeding of the devices to the test chamber?
3. How to upgrade an existing gripper design so that it is compatible automatic feeding add on?

A literature review for all three questions will be done with differentiating scope. In addition to the core of question number one, it also contains validating the original sales concept. Validating includes adjusting main dimensions to fit the system within robot reach. After validation, also critical components and their space reservations will be done to make sure that all required components will fit in the system. The literature review concentrates on modularity and interfaces. For the sub-tasks, only results are presented as they were done along standard workflow. Literature information can be used as a base to start design work for the interfaces.

The second research question also contained a literature review in the beginning. The literature review concentrates on common machine building actuators, basic control schemes and sensors. According to that information, in design phase feasible options are taken into further comparison. Feasible options are compared and evaluated while also keeping in mind the final environment and available resources. After the comparison, final solution is chosen and validated.

In early phase, part of the results of second research question were noticed to turn an existing custom gripper design become incompatible with the new system. A literature review for state of art gripper technologies was applied. Upgrading gripper to again be compatible was done according to findings in research phase. Upgraded gripper was also validated to perform as expected after the changes.

## 1.3 Thesis structure

Content of this thesis in divided into multiple chapters and subsections. In following sections, case company, research questions and methodologies are introduced. After research questions are familiar, chapter 2 goes through theory for all three research questions separately. The beginning concentrates on modularity, Brownfield Process and interfaces. After that, automated operations, actuators and control components are went through. Lastly, different types of grasping devices and theory for their design are introduced. After the theory is processed, the case project and involved products are introduced in chapter 3. Preliminary design phase and detailed information about matters answering to research questions are presented in chapter 4. In the end, conclusions, improvement ideas and other comments from the case are presented.

# 2. THEORETICAL BACKGROUND

## 2.1 Modular product design

Before dealing with modularity deeper and defining the word "modularity", first the word "module" needs to be defined somehow. Below is one definition for module.

> A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connection, thus there are gradations of modularity. (Baldwin and Clark 2000, p. 63)

It is very similar for example to how Lehtonen defines a modular system (Lehtonen 2007, p. 88). Modularity has been a way to make design and manufacturing business more effective for few decades now. It is considered that Borowski (1961) has established fundamentals of current type of modularity. He defined *Das Baukastensystem* (A constructional element system) which is a tree shaped system that is built to have different levels of constructional elements which consist of smaller elements. These smaller elements can also form their own element systems. (Lehtonen 2007, p. 32) According to Miller and Pedersen, Droste (1991) wrote that even before Borowski introduced the Baukastensystem, there was Bauhaus era which was combining standardization and industrial production by using building blocks. These building blocks could be for example functional units or rooms like kitchen or sleeping room in buildings. Baukasten evolved from Bauhaus during the years in between when also industry evolved. However Miller and Pedersen stated that functionality was not directly part of the module, instead of that mostly the geometry of the interface defined a module. Pahl and Beitz (1996) were the first to link also functionality to modules. At the same time different types of modules were defined. (Miller and Pedersen 1998)

Customer requirements have increased in recent years (Forza and Salvador 2006, p. 6). For many companies, modularity has been a key to satisfy increased customer needs, retain market shares and stay competitive (Arnheiter and Harren 2006, pp. 87-88). But always reason for designing modular systems is not due to customer needs or requirements. Other reasons for using modular systems can relate to the life cycle of the products. Those reasons can be based on manufacturing, maintenance or even logistical reasons (Lehtonen 2007, p. 89). Below in figure 2.1 different types are shown. Bright colors on the figure indicate different modules. The top row is based on manufacturing reasons. For example the final product can utilize so high technology that the modules need to be manufactured in different locations before final assembly. This type of modularity will also help on CTO deliveries and maintaining stock levels reasonable for the modules. The middle row is quite self explanatory. Full life time of working modules can be utilized fully by recycling them in multiple systems. The last row represents logistic modularity where the final product can be so enormous that it needs to be assembled on site.

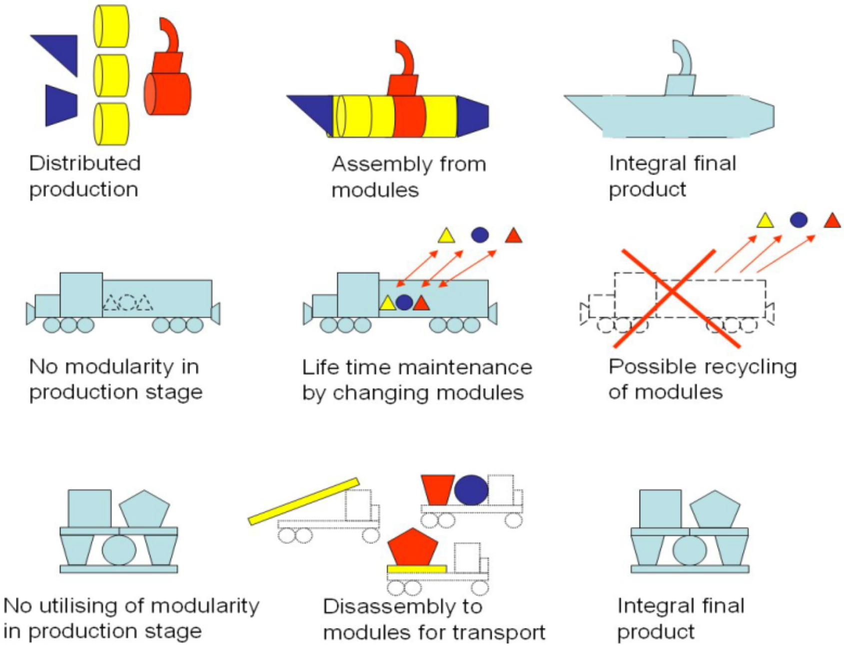

***Figure 2.1.*** *Types of lice-cycle-based modularity (Lehtonen 2007)*

Modules can vary from simple and small to complex and large containing multiple subassemblies. A complex system is usually split into multiple different modules. That way the system can be understood and solved more easily. (Arnheiter and Harren 2006, p. 86-87) A subassembly is not always a module but usually module is subassembly of some sort. According to Baldwin and Clark (1997, p. 84) and Baldwin and Clark (2000, p. 70, 91) modularity will help design process of a complex system because subsystems, or in this case modules, can be designed independently. Of course design is not fully independent from each other because interfaces need to be defined and designed in co-operation between modules. Modules will have interdependencies and during the design process all of them may not be known. To find those interdependencies as well as possible, designers must have a integration and testing phase at the end of design process (Baldwin and Clark 2000, p. 87, 89).

There are reports from successful deployment of modularity from various industries. In automotive industry for example truck manufacturers MAN (Forg et al. 2014), Mercedes

Benz (Zürn et al. 2012) and Scania (Piller and Kumar 2006) have used modular approach on satisfying different customer needs by offering loads of different configurations of trucks achieved by modular design.

Products and systems are never fully ready and the require improvements to fulfill needs. Not always products are designed for modularity from scratch. (Koh et al. 2015) Changing systems require additional work and thinking to ensure support capabilities for delivered versions, compatibility to rest of the system for the updated version. Generally engineering changes have been studied widely, but Koh et al. introduced a Design Structure Matrix (DSM) for comparing change requirements to product components. As a result from this DSM, the Engineering Change Forecast (ECF) index for each component is extracted. Higher the ECF index is, higher priority is for making it more modular. The study concluded that method produced sensible results and pointed out new, previously unrecognized, areas that needed better modularity. (Koh et al. 2015)

### 2.1.1 Brownfield Process

Brownfield Process (BfP) is a process to turning varying existing products into modular and configurable product families. Lehtonen et al. introduced the Brownfield Process the first time in 2011. It was complemented in 2016 with small changes in authors. It suits to companies that are executing customer projects which are mostly tailored and engineered to customer needs. (Juuti et al. 2016, p. 216) If company has varying existing products and is aiming to increase revenue significantly, starting to use modularity and BfP might be one key towards the set business goals. In for example automotive industry modularity has been a great way to move away from centralized design system and switch to modular design. Modules can be outsourced and by module supplier competition, manufacturer can look for the best quality, lower module costs or something in between. (Baldwin and Clark 1997, p. 87) BfP is divided into five main topics which are:

- Partitioning logic
- Set of modules
- Interfaces
- Architecture
- Configuration knowledge

These main topics contain different things and should answer the example supporting questions made by Juuti et al. (2019, p. 13) regarding modular system's existence or lack of information and challenges.

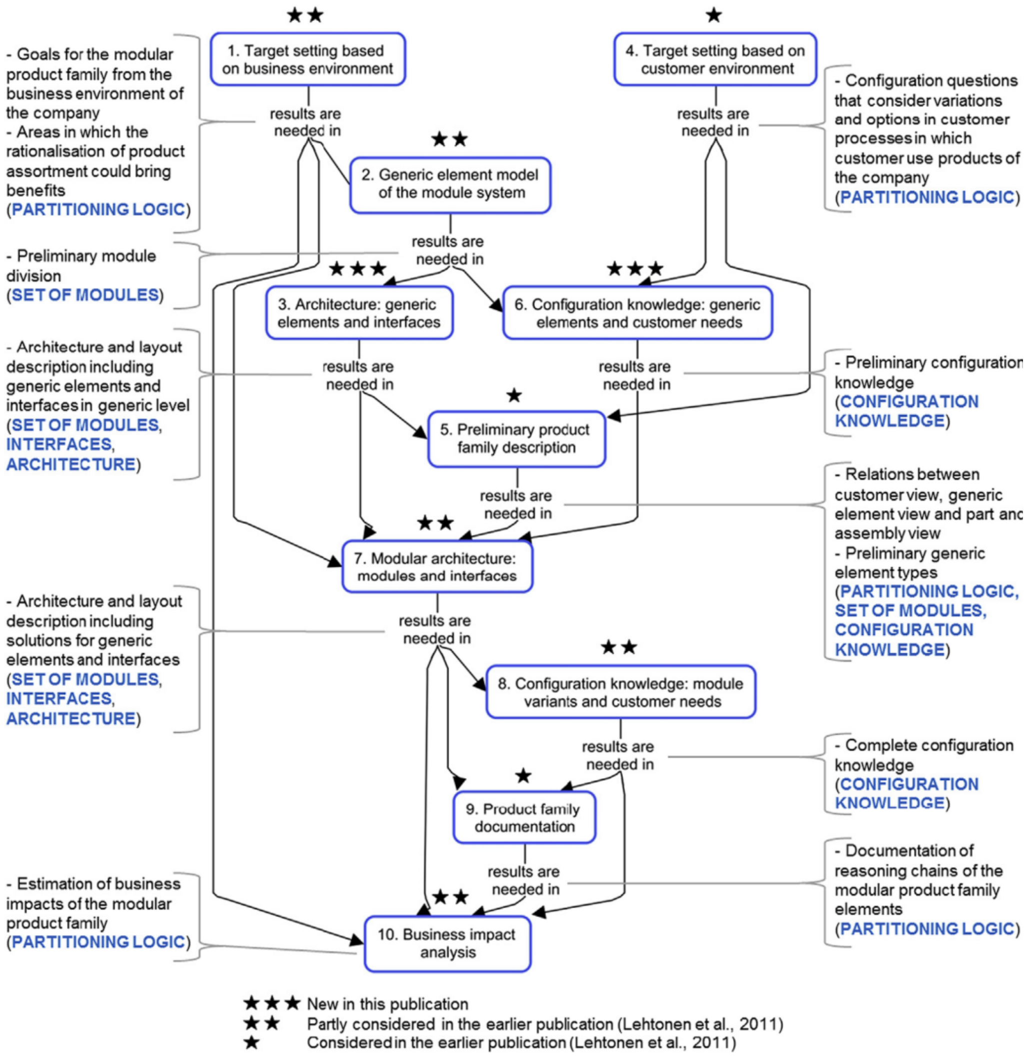

***Figure 2.2.*** *Brownfield Process chart (Juuti et al. 2016, p. 217)*

Above in figure 2.2 is the full Brownfield Process chart. The first driving topics in partitioning logic are business environment requirements and main customer questions and goals along with beneficial product structure rationalisation possibilities. After those are defined, can generic elements and reasonings of the specific module system be drafted. Partitioning logic is again involved in the middle of the process where preliminary product family and descriptions are ready. Before defining the final architecture design, relations between the targets and needs to be evaluated. (Juuti et al. 2016, p. 217–218) Partition logic is also considered in the latter parts of process when doing business impact analysis. (Pakkanen 2015) There are multiple different approaches to partitioning logic and types. Juuti et al. (2020) introduced six of different partitioning types. They organized an university course about modularity over multiple years and conducted a modularity challenge where students modified a standard LEGO wheel loader kit to be modular and documented the whole process.

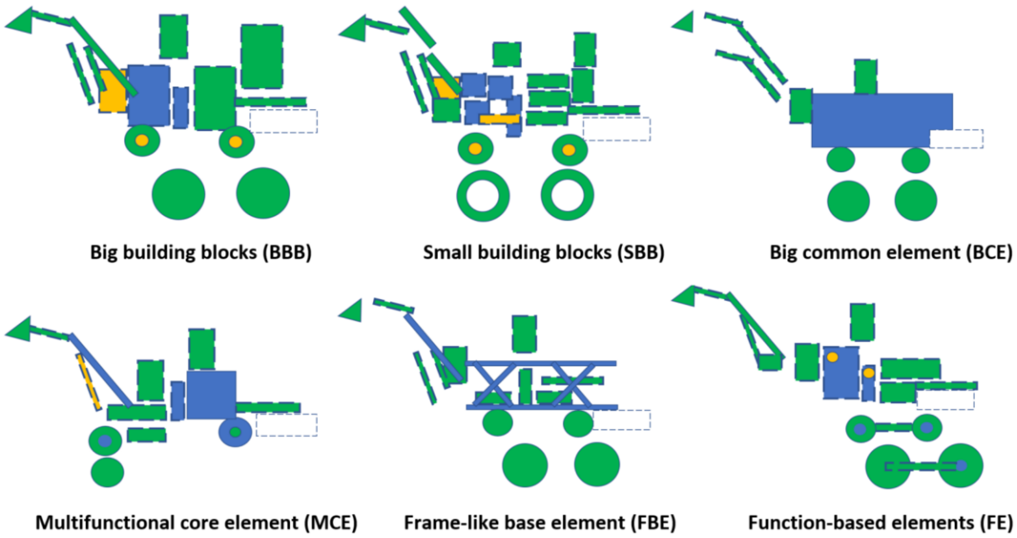

***Figure 2.3.*** *Different partition types (Juuti et al. 2020, p. 2330)*

In above figure 2.3 are shown the six partitioning types found during the course implementations. Results showed that when modifying non-modular design to be modular, most of the groups resulted in designs based on Big common element (BCE) or Multifunctional core elements (MCE) even if groups started big (BBB) or small building blocks (SBB) in mind. Frame-like base element (FBE) and Function-based elements (FE) were unpopular options due to needed work for major redesign and estimated assembly difficulty. During the four years of the course, FBE was chosen by only one group. FE was not chosen by any of the 30 groups but it was stated that there are markings in the literature that FE has been used in other products. (Juuti et al. 2020; Juuti et al. 2021)

Set of modules is simply just all different modules that can be used to building the system. It also contains architecture during the process from preliminary module division to final layout descriptions and generic solutions. Main customer questions can also be part of the module map which is also describing the partitioning logic (Juuti et al. 2019, p. 17–18). Set of modules is considered alongside architecture definition, to get at least preliminary modules defined. A bit later down the process, standardisation possibilities related to these preliminary modules should be discussed. (Pakkanen 2015) Set of modules and interfaces are tightly tied together because interfaces are the way to connect modules together physically or functionally (Parslov and Mortensen 2015, p. 183). According to Parslov and Mortensen (2015, p. 186–187) Bettig and Gershenson (2010) have stated that most research about interfaces nowadays regard the interface as part of the module or component, not as an external entity between the modules.

### 2.1.2 Interface design

Interfaces can be designed in different ways. For example Zheng et al. (2016, p. 27) states that there are four different types of interface: geometric interface, energy interface, control interface and data interface. That is a clear division by the functionality of an interface. Zheng et al. defines the different categories as follows, a geometric interface defines a physical connection between modules, an energy interface defines ways to transfer energy (e.g. mechanical, electrical, fluid power) between modules. Control interfaces can indicate how different elements can be controlled by others and data interfaces define ways to transfer communication between components and modules. One module can have from just one type to all of the different interface types represented. Very similarly to Zheng et al., Miller and Pedersen divide interfaces into three groups: functional, mechanical and electrical (Miller and Pedersen 1998, p. 14).

Zheng et al. also classifies interfaces by their configuration. This configuration describes what kind of elements are connected to each other. Three different elements are component, environment and interface. Usually the first configuration that comes to mind, is interface between two components (C_I_C). It indicates how those components are connected and can interact with each other. The second configuration is interface between component and environment (C_I_E). It indicates how component behaves in certain environment. The third type is interface between component and interface (C_I_I). It means that there are effects like heat and vibration generated by components and interfaces. These effects need to be taken into account on both sides. The fourth type is interface between two interfaces (I_I_I). It just indicates how two interfaces are interacted by each other. The fifth and last is interface between environment and interface (I_I_E). Similarly to C_I_E it indicates how an interface is behaving in certain environment conditions. (Zheng et al. 2016, p. 27)

Parslov and Mortensen refers to Grady (1994) and Kapurch (2007) that they have stated that one of the biggest reasons for poor perceived product quality are either unidentified or poorly defined interfaces. Integrating complex and big systems is challenging and should encourage to spend time and resources in identifying and defining the interfaces well. That is why interfaces need to be effective to succeed in product development and achieve desirable quality. In these cases, risk for communication between different engineering fields is high. This can be for example due to different specialty and understanding fields. (Parslov and Mortensen 2015, p. 183–184, p. 196–197)

Parslov and Mortensen also divide interfaces of a modular product into two types. A-type–interface is strategically important and require to be well defined and characterized. They have high likelihood for variance due to different possible factors. These factors can for example be future upgradeability, serviceability and maintainability. B-type–interfaces are the work horses providing physical contact points and for example transfer of work, current and heat. They are not strategically important but require good reliability or robustness. It is possible to have a ratio of even 1:50 in quantity between A-type and B-type interfaces. (Parslov and Mortensen 2015, p. 194)

In Brownfield process and modular architecture, interfaces are important part of the design. Describing preliminary architecture, generic elements, their practical realisations and interfaces together is vital to get the desirable level of interchangeability and modularity achieved. Multiple ways can be used to present the architecture, generic elements and interfaces. Before rushing to open CAD software, rough lines are easier to present with simple figures made with generic visual tools or for example a DSM. (Pakkanen 2015)

Kreimeyer et al. introduced Architectural Standards as part of a modular kit. Modular kit is a part of MAN's basic documentation, where different modules and variants are introduced and can be selected. These standards are divided into four different categories. It is shown below in figure 2.4 how they can vary. Functional standards can limit quantity, volume or another attribute of the component or module. In the example fuel tank volumes is used, but it could also be for example stroke of a cylinder. Secondly is listed technological standards and variance of those. As an example is mentioned changing fuel tank material between steel and aluminium. In some environment one can be better and even required over the other. The third standard and variance is related to geometry. Using the same fuel tank as an example, geometrical variance can vary for example cross-sectional profile, installation space, or both. The last one that is not present in the figure below is interface standard. It can be a mix of all previously mentioned standards. That is to ensure and maintain compatibility and usage of multiple components. (Kreimeyer et al. 2014) These commercial trucks have tons and tons of different possible configurations and it is crucial to be aware of interfaces to be able to execute exact product configurations. Functional standardization reminds of design process where modules are designed concurrently. Making a space reservation in the beginning and at least drafting or mutually agreeing type of interface between those modules.

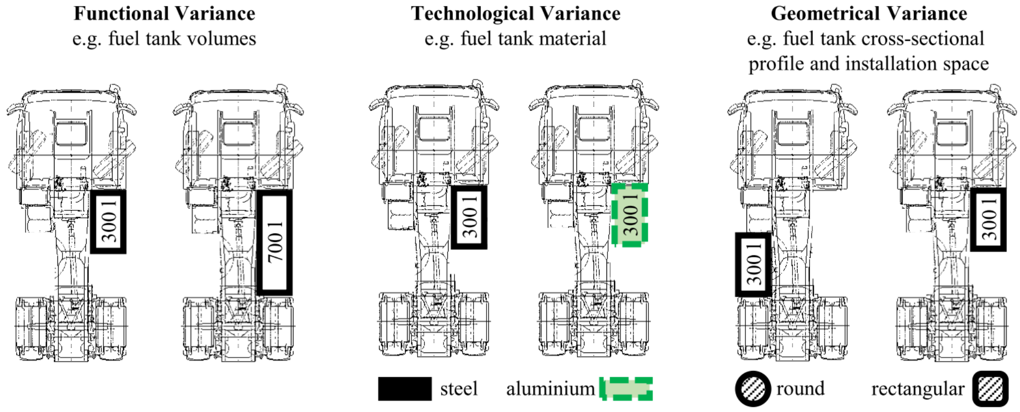

**Figure 2.4.** *Variance of Architectural Standards (Kreimeyer et al. 2014, p. 7)*

Earlier was briefly mentioned about few companies in automotive industry which have successfully been utilizing modularity. Also Cabigiosu et al. introduced a study which analyzed two different cases in automotive industry. The study compares interface definitions between two air conditioning (AC) units in cars. These units use same components in the AC itself, but interfaces between components have been defined differently between manufacturers. The study found that this level of modularization may require significant amount of component specific knowledge and even investments to maintain that knowledge. Case A relied on stable and well defined interfaces, however many of them were non-standard. Meanwhile case B used mostly open or closed standard interfaces but their stability, was lower than in case A. Unstable interfaces come at a cost when there is higher complexity and continuous design changes required. On the other hand it gives more flexibility to suppliers who actually deliver the AC systems. Case A had better control over the performance and supplier substitutability but at the same time, it restricted supplier's ability for contribution. (Cabigiosu et al. 2013)

## 2.2 Automating manual operations

Though section 4.3 is about feeding devices into the testing device, it follows many similar principles that assembly machines. Thus theory on this section is primarily based on design of similar functions or systems and how to control them. Linear motion is the core function, but also rotary motion is briefly dealt with because it can be quite easily translated to linear motion.

There can be multiple reasons for upgrading manual operations to automatic. Vijayaragavan et al. mentions couple of them: fatigue of human operators and increased speed of the process. In their study, significantly increased cycle time between multiple operators was found when time for the same process was measured 15 times in a row. (Vijayaragavan et al. 2020) In addition to fatigue, high productivity, sick leaves, lacking force and precision and breaks during shifts are reasons why processes have been automated. However, there are also downsides. It can be time consuming to program the system when handling complex tasks. (Krüger et al. 2009) Adaptation to variating tasks or parts can also be difficult. On a different source, García et al. mentions that usually in the most tedious, hard and dangerous tasks humans are replaced by robots or other machines. Exceptionally, the new wave of automating is not seeking to replace humans, but seeking to use best of both. That can be reached through co-operation and collaboration. Also one additional reason can be quality assurance and control. (García et al. 2020) Krüger et al. also wrote about hybrid assembly work stations and workplace sharing systems and workplace and time sharing systems.

In assembly processes usage of robots is well studied. Some of them are already mentioned earlier, but Boothroyd mentions five advantages of using robot assembly:

- stability of the product design,
- production volume,
- style variations,
- part defects and
- part size. (Boothroyd 2005)

Stability and production volume are already mostly covered. Style variations mean that robot can have multiple different work cycles, for example pick only specific parts to be assembled depending on the final product. According to the text, a feeder system can jam and cause create bigger loss than a robot system that has longer cycle times compared to the high-speed assembly line. The last advantage mentioned, is that parts can be laid on pallets or trays. Those can have a repeated patterns or arrays of parts. (Boothroyd 2005, p.172) On the contrary, manual assembly is often used when production quantities are low, there are high number of product variants, product is a one-off or lead time is short. Then tooling and equipment costs can be kept low but labour costs will rise. (Swift and Booker 2013, p. 282)

### 2.2.1 Actuator types

Usually basic actuators have one degree of freedom (DoF), so they will move along one axis or rotate around it. Actuator, in this context, is a device that transforms a given input into some kind of action or motion (Childs 2004, p. 291). In addition to one DoF actuators, combined actuators also exist, for example Makino et al. and many others have combined linear movement along one axis and also rotation around the same axis into one actuator. Generally this kind of actuator is called a $\theta$-$Z$ actuator. By doing this, it is possible to make both movements at higher precision. (Makino et al. 2016) Systems with multiple degrees of freedom are often made by stacking multiple actuators. Movements with all six degrees of freedom can be also done with commercial systems. Six axis robot arms provide a wide range of sizes, reach, possibilities and flexibility. All movements are usually produced by rotary joints and arms between those. On the other side of movements in 6 DoFs, a hexapod provides extreme precision to specific applications because movement ranges are usually very limited already at origin. Changing the pivot point or doing movements along multiple degrees of freedom will reduce already limited movement possibilities on other movements. Hexapods differ from robot arms, because movements are produced by linear actuators instead of rotary. Childs introduce multiple categories for different actuators by their type and source of power:

- pneumatics
- hydraulics
- magnets

- electromagnets and solenoids
- electric motors
- piezoelectric devices (Childs 2004)

Motion can be executed by several different ways and different types of actuators. Often true linear motion from actuators is used as it is, but may be stiffened by for example linear guides. Often for example servo and stepper motors produce rotary motion which can be used as it is or easily translated to linear movements depending on the application. Rotary motion can also be produced by hydraulic and pneumatic actuators. Popular true linear movement actuators can be for example, linear motors, voice coils and hydraulic or pneumatic cylinders. Rotary to rotary applications can use direct drive, gearing and belt drives. Rotary to linear movements can be achieved through belt, chain and rope drives, roll feed, rack and pinion and ball or lead screw drives. (Moritz 2014; Mott 2018) In order to complete these movements, also bearings, seals, motor couplings, clutches, brakes and other components are used. Shafts are also important part of the system design.

### 2.2.2 Control and sensors

Actuators can be controlled in many ways, depending on the actuator. Open loop and closed loop control can be linked to different actuator types differently. Below figure 2.5 shows control diagram of a closed loop DC motor. Desired reference signal, whether it is speed, position or something else, is modified before drive controller according to the actual measured parameter. Therefore drive controller will receive signal that is regulated according to the feedback signal. Open loop system is otherwise identical but is completely missing the feedback signal and thus is only actuated by the assumptions of operator controls and drive controller.

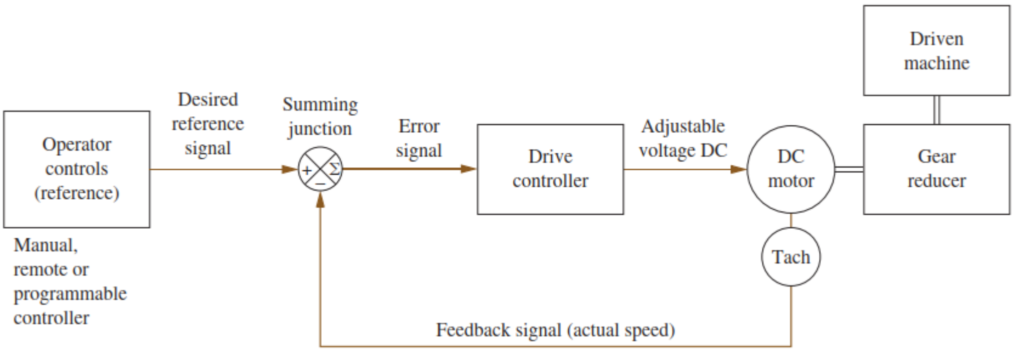

***Figure 2.5.*** *Example of a closed loop DC motor control diagram (Mott 2018, p. 745)*

One downside of open loop control is possibility to have a permanent error in the actual position. One example is with stepper motors, an excitation to move the motor is made too quickly that the motor can't respond to that. Therefore controller will expect motor to be in different position than it is really. (Acarnley 2002, p. 90) Also, either insufficient power delivery, too high load or both can lead in similar errors. That is why open loop motors are rarely used on their full torque (Acarnley 2002, p. 130). Depending on the application, these position errors can cause damage to the hardware or the application itself, whether it is a testing, assembly or any other kind of application. Acarnley states that similar problems are avoidable by using closed loop control. The motion control system will always get feedback from the motor, how previous command was executed. There is no possibility even in the worst load situation to lose position of the load. One statement also was that is the most appealing feature of closed loop system. After thorough comparison, the author noted closed loop as more reliable and eliminating many of the problems that relate to open loop control. (Acarnley 2002, p. 112, 130) Open loop control also has its own use cases, for example garage door openers, clutch/brake systems, packaging, sorting, indexing, conveying because many of them are only running continuously. Only either timers, position sensors or both are controlling the run and stop actions. (Moritz 2014, p. 16)

These actuators may have integrated or external sensors that can measure wide variety of things but the most common measured parameters are position, speed, force, torque, pressure and fluid flow. Determining true position of an actuator is very popular and important in precision movements and executing closed loop control. (Childs 2004) Therefore all of these sensors, position sensors will be processed bit deeper. Like actuators perform linear or rotary movements, position sensors also exist for both movement types. Linear application sensors use mainly four different working principles: resistive, inductive, magnetic and optical. In industrial applications, optical sensors are the most frequently used as they provide very high resolution and accuracy without physical contact compared to other technologies. Commercial optical encoders typically have a resolution from 0,1 nm to 5 µm. They consist usually of a steel or glass scale tape with alternating grating which is read by the readhead. Steel scales are usually easier to use as they can be cut to suitable length but glass tapes are for extreme precision because of lower thermal expansion coefficient. Readhead will either measure the transmitted light through scale tape or measure reflected light from it. In incremental encoders, readhead also reads reference mark and starts measuring accurately from that. (Gieras 2012) That means, after a power cycle incremental position encoder doesn’t know its true position until a homing sequence to the reference mark is performed. Gieras states that therefore also absolute encoders are utilized. Other reasons to use them is long inactive periods or low speed applications. Absolute encoders provide safe and failure-free operation. Because scale tape grating for absolute encoders needs to be unique, maximum scale length can limit the system in some use cases. One absolute position is a ’word’ which contains the position information in binary code. More accurate grating and longer travel distances require longer words and more tracks to be read from scale. That of course increases complexity and cost of the system. (Gieras 2012) Rotary encoders can work with same principles but the scale is a ring instead of tape. Encoders can also utilize multiple different types of signals for controllers that can read the signal properly.

## 2.3 Grasping devices

During the past decades, industry has leant towards automating processes and started using more robotics to run processes more efficiently and even fully automated. Smaller lot sizes and customized products demand abilities to adapt to different versatile tasks. (Krüger et al. 2009) Many of the publications about grasping devices deal with assembly processes. Section 4.4 in this thesis will deal with similar tasks but not on an assembly line, but these principles can be utilized there. Robots have become cheaper, more accurate, universal and easier to approach. However a robot is nothing without its end effector, which often is some kind of gripper. The gripper is the mechanical interface between the robot and its environment (Pham and Yeo 1991, p. 303). Design of the gripper can be the most important part when designing a robot system. It is easy to decrease efficiency of the system by failing in gripper selection or design.

In the history grippers usually have had for example only one specific item to pick and place. After moving more and more to modular manufacturing, need for universal grippers and throughput has increased. Using machine vision in gripping systems has also increased. (Causey and Quinn 1998) Nowadays a gripper might have multiple different tasks or end effectors to either or both, increase flexibility and throughput. Pham and Yeo introduced five different ways to increase flexibility of a gripper:

- notching of gripper fingers,
- changing of gripper fingers,
- changing of grippers,
- use of multiple gripper units, and
- use of universal grippers. (Pham and Yeo 1991, p. 304–307)

All of the five options have different impacts on the system as a whole and for usual grippers they seem to be mostly in order from the least complex and increasing after that. Notching is something that is done already in the design phase of the gripper. It will differently shaped and sized objects to be grasped. On contrary, changing gripper fingers or grippers between actions to support different objects is also possible. Time consumed during the change is of course unproductive and change should happen as quickly and seldom as possible. When using multiple gripper units, they can be mounted for example on a rotating or on a slider system. That is faster operation than changing between different grippers but can consume the robots payload or conflict with physical size limitations. Universal grippers can still be divided into two groups, active and passive. Active grippers are usually imitating human hands with articulated three to five fingers. Passive grippers use different techniques to conform themselves to the objects shape. Ensuring precise positioning with passive grippers is difficult. (Pham and Yeo 1991, p. 304–307)

According to Causey and Quinn grasping devices in robotics can be divided into two different major categories. The first category improves system throughput and the second improves system reliability. However, those are not the only benefits of a well designed gripper. They can also compensate for robot inaccuracies and add value for example in assembly in human-robot collaboration. (Causey and Quinn 1998, p. 1453)

| Component | Task | Environment | Robot | Gripper |
|---|---|---|---|---|
| • Geometry<br>• Weight<br>• Material<br>• Surface quality<br>• Temperature | • Type<br>• No. Different components<br>• Positional accuracy<br>• Cycle time | • Contamination<br>• Interference<br>• Temperature<br>• Humidity | • Repeatability<br>• Accuracy<br>• Speed/acceleration<br>• Lifting capacity<br>• Power source<br>• Mechanical connection | • Weight<br>• Gripping force<br>• Actuation<br>• Operating temperature<br>• Jaw opening/contact area<br>• Host robot<br>• Cost |

***Figure 2.6.*** *Different factors in the gripper selection process (Pham and Yeo 1991, p. 309)*

Selecting a gripper can be done through knowledge. Figure 2.6 above shows different factors that should be considered when selecting a gripper. Pham and Yeo describe a knowledge-based gripper selection method where important factors are listed, scored and weighted to reach a final score. In addition to factors listed in figure 2.6, also more specific parameters for scoring can be established if required. Those can be for example "area of intersection", "moment arm" or "twisting distance". (Pham and Yeo 1991, p.309–313) If the gripper selection process is bit simpler and has some numerical requirements or limitations, Gomis-Bellmunt and Campanile introduce multiple graphs to compare gripper performance, design parameters and geometrical factors between different types of grippers. Considering all the requirements and results, the designer should have guidelines to choose a suitable gripper type for the application. After that the actuator size should be matched with the requirements. Lastly, the designer should perform design work for geometry and interface(s) simultaneously. (Gomis-Bellmunt and Campanile 2010, p. 29–39) Of course, the design process will often need some iterations to be optimal and validated, maybe even a change of actuator type.

After selection of the gripper, it needs to be validated for the specified task. It can be done in several ways. Gomis-Bellmunt and Campanile refer to few different possibilities for gripper validation which are prototype construction, industrial actuators and simulation. Prototype construction is traditional way to get testing results. (Gomis-Bellmunt and Campanile 2010, p. 61) In the best case scenario, the prototype can already be ready on the first go and work as designed and expected. Lead time and costs can be downsides at least if the gripper needs many iterations during the process. The second validation method Gomis-Bellmunt and Campanile refer, is comparing to similar industrial actuator or gripper. This of course requires that suitable gripper is available on the market. Designer can compare performance between their own design and industrial version. There might be intentional differences on performance, cost, weight or required volume. Simulations can test the actuators or grippers virtually, without building a prototype. (Gomis-Bellmunt and Campanile 2010, p. 61–62) Simulation work often requires expert knowledge, software licenses and much computational power. Depending on the designer experience, knowledge and available software, it might be possible to do small and simpler simulations.

Upcoming sections 2.3.1 and 2.3.2 are about different gripper types that are either popular, significant for this thesis or somehow different to other types and worth mentioning. In addition to different fluid and electrically powered grippers there are variations like needle, electrostatic, Van der Waals, ice, acoustic, laser and adhesive grippers (Fantoni et al. 2014, p. 680-681). Fantoni et al. also has a wider research about the topic and different types. Despite of that, the theory on upcoming sections is gathered from different authors. For example theses from Azim and Aparisi i Escriva handle the complete design process. (Aparisi i Escriva 2016; Azim 2019)

### 2.3.1 Fluidic, hydraulic and pneumatic grippers

One of the most commonly used grippers are fluidic grippers. At first one might think of hydraulic and pneumatic grippers. However, there is more to them. Vacuum is also widely used for grasping, often to planar surfaces.

Hydraulics and pneumatics share the same working principle and they are widely used in industry also elsewhere than in grippers. It is easy to perform linear or rotating movements with these power sources. Movement speeds, forces and torques are easily and continuously adjustable. Hydraulic power can provide significantly more force as it is using non-compressible fluid to transmit the energy. Therefore hydraulic systems are easier to control than pneumatic systems. Downside of these is relatively low efficiency and properties of the fluid itself. Like said air, that is often used as fluid in pneumatic systems, is compressible and may make controlling complicated. On the other hand, hydraulic liquids are usually oil and their viscosity can be highly dependent on the temperature, they are very mildly compressible compared to air and they easily stain if fluid spills on non intended place. (Kauranne et al. 2008) In variating temperatures hydraulic systems may require running freely for some time to heat up the oil to operating temperature.

***Figure 2.7.*** *Pneumatic parallel jaw gripper (Festo 2022)*

Above in figure 2.7 is shown one of the possible gripper types. It is pneumatic gripper but similar constructions can be found using hydraulic power. The jaws move linearly in opposite directions on this type of gripper. Different types of jaw grippers seem to be very popular. Other types of jaw grippers can have mechanisms or linkages in order to change properties of gripper. For example jaw movement path, force or some other attribute can be controlled by modifying these mechanisms.

Vacuum applications are also considered as fluid power. Unlike in hydraulic and pneumatic overpressurize the medium, vacuum is underpressurizing or sucking the medium out of the system to create an attraction force. Zero pressure level is considered at NTP conditions. Vacuum grippers are often used because they can be used to grasp even hefty and large objects softly (Mantriota 2007). Vacuum generates a contact pressure between the suction cup or gripper and the object is being grasped. This contact pressure and static friction together hold object in place. Downsides and dangers of vacuum suction are slipping and falling of the object (Mantriota 2007). Unwanted slipping can happen due to too small friction between the surfaces in contact, too low contact pressure, or both. Falling of object is strictly due to too low vacuum level at contact, which can be caused for example by too big leaks or poor vacuum flow through the system.

***Figure 2.8.*** *Vacuum gripper (OnRobot 2022)*

Above in figure 2.8 is shown one type of vacuum gripper. In shown configuration it is 100 mm squared in size and can hold up to 6 kilograms of payload. With extended arms and bigger suction cups payload can be grown up to 15 kg. In addition to flat suction cups, they can have even more bellows than in the figure above to increase compatibility with different objects.

Speciality grippers in pneumatics are for example Bernoulli and vortex grippers. Instead of fingers or jaws, they try to minimize the contact area. These kind of grippers are often used on planar workpieces which can also be delicate to touching, have very low stiffness or both. Bernoulli grippers blast air through a nozzle or series of nozzles. Air will flow with high speed along surface through a small gap between the gripper and workpiece to be grasped. Underpressure is generated by the flow in the gap between gripper and workpiece. (Dini et al. 2009) One example of Bernoulli gripper can be seen on next page in figure 2.9 Small silicon pads for achieving minimal contact can be seen on the edges of gripper. Vortex grippers vary a bit from Bernoulli grippers. On vortex grippers, compressed air is pushed tangentially in to a hollow cylinder to create a rotating vortex of air inside. Air does not exit between the workpiece and gripper like in Bernoulli, instead of that it exits through a gasket that is above workpiece. (Li et al. 2015) Working principle of a vortex gripper is presented also on next page in figure 2.10 As a downside, both of these gripper consume vast amounts of compressed air. Total energy consumption between Bernoulli and vortex gripper on different surfaces was for example studied by Li et al.

***Figure 2.9.*** *Bernoulli gripper (Schmalz 2022)*

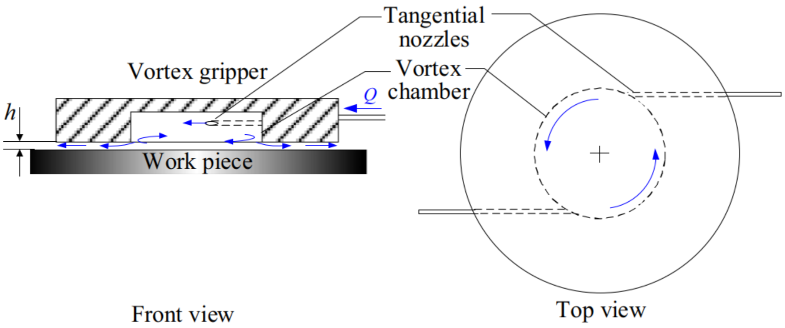

***Figure 2.10.*** *Vortex gripper working principle (Zhao and Li 2016)*

A universal gripper can be also considered as vacuum application. In this case the universal gripper is based on jamming of granular granular material inside. Brown et al. introduced multiple authors that had presented grippers with inflatable pockets filled with loose grain, small pellets or spheres. None of those had researched the real gripper performance. Maybe because of those did not gain any popularity, until Brown et al. researched the achieved holding force as of few different functions. Universal grippers can be useful for largely variating objects. Due to their unpredictability or lack of accuracy, they are mostly used for pick and place applications. On the other hand it can also be used as a strength because robot position does not need to be accurate. It is enough to cover a fraction of the object. (Brown et al. 2010)

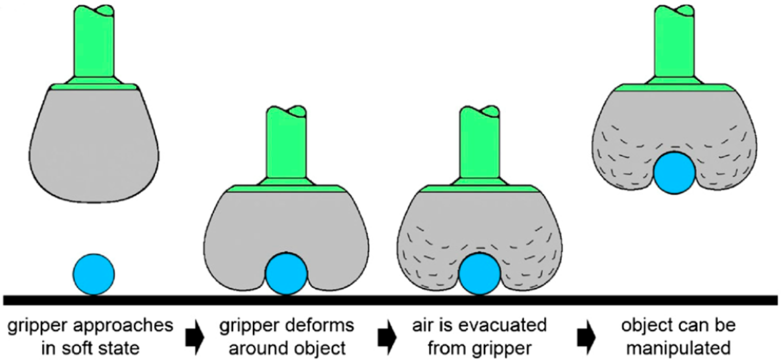

***Figure 2.11.*** *Universal gripper working principle (Brown et al. 2010)*

Working principle of this kind of universal gripper is shown above on figure 2.11. For the gripper to work, it needs to be able to reach sides of the object. Round, spherical or tubular, objects are good for this. Brown et al. mentioned for example small light bulbs, LEDs, bottle caps, plastic tubing and variety of other things. On the other side, difficult or even impossible items can be a hemisphere that is larger than about half of the gripper, thin disks laying flat or very soft objects. (Brown et al. 2010, p. 18810)

### 2.3.2 Electrically driven grippers

Electrically driven grippers can perform many similar tasks as hydraulic or pneumatic grippers as the movement is often linear or rotating. Electrical motors usually produce rotating movement which needs to be altered to linear movements for typical jaw grippers. Linear motors also exist but are not typically used in grippers. In addition to Lorenz et al., only few Chinese patents were found to use linear motors in different types of grippers. One reason for not using linear motors on gripper could be that on power loss without external brakes, linear motors do not keep their force in grasping situation. On the other hand a ball or lead screw driven linear motion will require usually significant force to start back driving. Worm gears are also famous of their self-locking features.

***Figure 2.12.*** *Servo driven parallel jaw gripper (ServoCity 2022)*

Like mentioned, functionality of electrically driven parallel jaw gripper can be similar than hydraulic or pneumatic version. The power train behind the jaw movement still can be different. Like can be seen from figure 2.12 above, rotating movement of a servo motor is altered to synchronized clamping movement of jaws through linkages and gears.

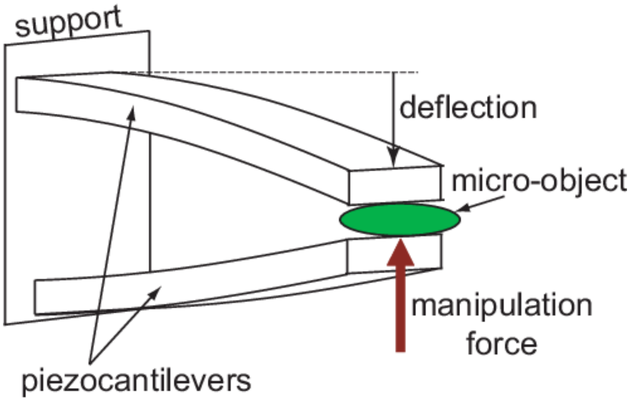

***Figure 2.13.*** *Piezoelectric micro gripper made of cantilevers (Rakotondrabe and Lutz 2009)*

In microactuators and grippers piezoelectric devices are also used. A simple representation and working principle of one type piezoelectric gripper is shown above in figure 2.13. Eletrical current is applied to the piezo actuators, or in this case cantilevers, to make them bend and grasp on the object.

Magnetic grippers also exist. Instead of gripper fingers or jaws it relies to pulling magnetic force and friction between the surfaces in contact. Naturally objects need to be ferromagnetic in order to use magnetic gripper. Rough or uneven surfaces can significantly decrease magnetic force. This is because magnetic force decreases very quickly as a function of distance (Amrani 2015).

# 3. CASE PROJECT INTRODUCTION

This thesis concentrates on preliminary mechanical design and requirement listing to help detail design of project named "Smart Cell" (SC) in the case company. Smart Cell is about combining company's three different second hand smart phone testing devices into a cell with automated handling using a 6-axis robot arm and a customer supplied buffer-feeder system. The devices under test are called DUTs. The testing devices, FUSION, RATA and SCORE are introduced in the following sections. The challenge, in addition to space limitations, was in this particular project due to that these devices are originally mostly designed to work independently and with manual feeding. FUSION has been fully ready for automated feeding and RATA with some limitations. SCORE has originally been designed to be fully manually fed (Haara 2020, p. 8).

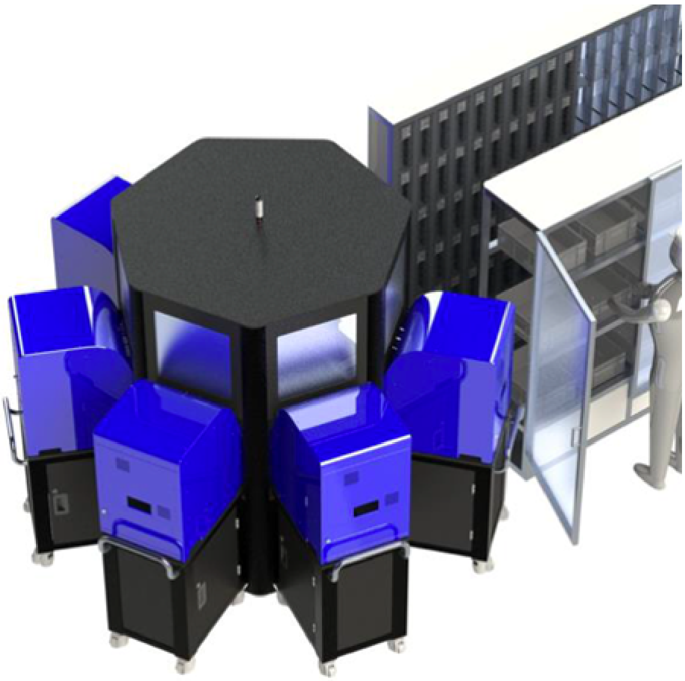

***Figure 3.1.*** *SmartCell concept*

Figure 3.1 shows how SC was seen during concept phase. Because it was only for illustration purposes it contains only FUSIONs. Also feeding system was unknown at that time. The purpose of this preliminary design phase, which is processed more in deep in section 4, was to verify all concept plans, scale system dimensions to be sensible, check feeding robot's reach to each device and identify all the required main components and fit those in the model.

During the project, system was designed for specific project needs. Despite of that, straight from the beginning, modularity and future projects were taken into consideration during the design process. Therefore the system can be quite easily configured differently also for different project and customer needs. Also, there was left free capacity to add testing modules later if customer decided so.

## 3.1 All-in-one functional tester

FUSION is the flagship functional test system for refurbished smartphones in the case company's offering. FUSION does not need phone model specific mounting hardware and is capable of manual and automated feeding. Time has shown that with full test coverage of FUSION can easily sustain 20 units per hour (UPH) and 95 % utilization. Only limitation for some modern phones are the maximum outer dimensions of 158,2 x 77,9 (mm). That will result in maximum screen size of 5,7 inches.

***Figure 3.2.*** *FUSION with its testing chamber doors open (OptoFidelity Oy 2020a)*

Above in figure 3.2 FUSION is shown. The test chamber doors will close when phone is inserted and testing begins. It is due to reach as dark conditions as possible for the display, camera and flash testing. Also audio testing requires sound isolation. FUSION has a wide range of different test cases:

- Audio (speaker, microphone, headset)
- Display
- Camera & flash

- Touch & force
- Fingerprint & heart rate monitor
- Side buttons (physical and capacitive)
- Vibration
- Connectors (micro-USB, USB-C)
- Wireless (Bluetooth, WiFi, GPS, NFC, GSM)
- Sensors (compass, accelerometer, gyroscope, IR, ALS, barometer, proximity)
- SIM-card & memory card

Test cases can be selected according to needs and of course all phones don't even have all of features mentioned above. According to the brochure, 30 % increase in result reliability can be achieved with the system. (OptoFidelity Oy 2020a)

## 3.2 Preparation system

RATA is a system that simulates human interaction with phones. Human interaction in this case is taps and swipes on the touch screen and possibility to operate the side buttons. It is a low-cost machine, because functional use doesn't require big accuracy, and it is intended to prepare phones for testing in FUSION and SCORE. Preparing usually means powering up the phone, connecting to a wireless hotspot, installing and launching a test app. Doing these steps would consume too much of the real testing capacity in FUSION. After the tests phones can be reset to factory defaults or just powered off, depending case by case.

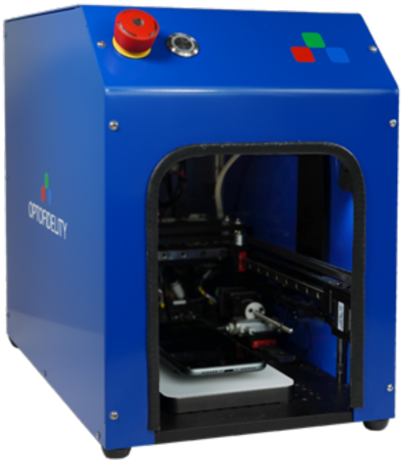

***Figure 3.3.*** *Functional testing and initialization device RATA*

The system is shown above in figure 3.3. In this case the system will be doing only the usual steps. Idea of the system is that the user can make a custom script that can go through any kind of sequences on the phone.

## 3.3 Cosmetic grading system

SCORE is a system for second-hand smart phone grading. Its main focus is grading second-hand smart phones for cosmetic defects and display quality, but it has also some other test technologies leveraged from FUSION. Cosmetic defect and display quality grading are based on strong machine vision competence of OptoFidelity. Manual grading done by humans would have a lot more variance in grades. SCORE benefits from few different features. It does not need phone model specific hardware and is compatible with almost all smart phones made during last few years. Also it is designed to be transportable and fit in standard flight baggage restrictions. (Haara 2020)

***Figure 3.4.*** *Cosmetic grading device SCORE (OptoFidelity Oy 2020b)*

Above in figure 3.4 is shown SCORE in its normal form. For the SC project SCORE needed some modifications. Normal version of SCORE lies on a table but in this project it was required to turn the device on its side. Also, it has all the functional parts mounted on a aluminium frame that can be easily removed from the enclosure. This was necessary to do because of physical space limitations. These modifications are processed more in deep in section 4.3.

Full list of possible SCORE test cases contains following tests:

- Cosmetic quality
- Display quality
- Backlight

- Flash
- IR transmitter
- Vibration motor
- Loudspeaker
- Receiver speaker
- LED Indicator (OptoFidelity Oy 2020b)

These versatile test cases in addition to the main test cases, cosmetic and display quality, made it possible to transfer test cases between SCORE and FUSION enhance throughput and cycle times.

## 3.4 Smart Cell

Smart Cell is a system that combines all three previously introduced devices together in a testing cell. SC was first designed for a specific project needs. From the beginning of project it was clear target to design a system that can be later configured for different needs and start making productization of SC. Alongside project delivery, almost identical system was also built to be able to market and offer similar systems in exhibitions and marketing material to different customers. SC can later be configured to use any combination of these three devices or just one device type alone, fully depending on the customer needs. Previously figure 3.1 showed the sales concept of SC, but below in figure 3.5 is shown the finished preliminary design of SC from two different sides in order to show everything.

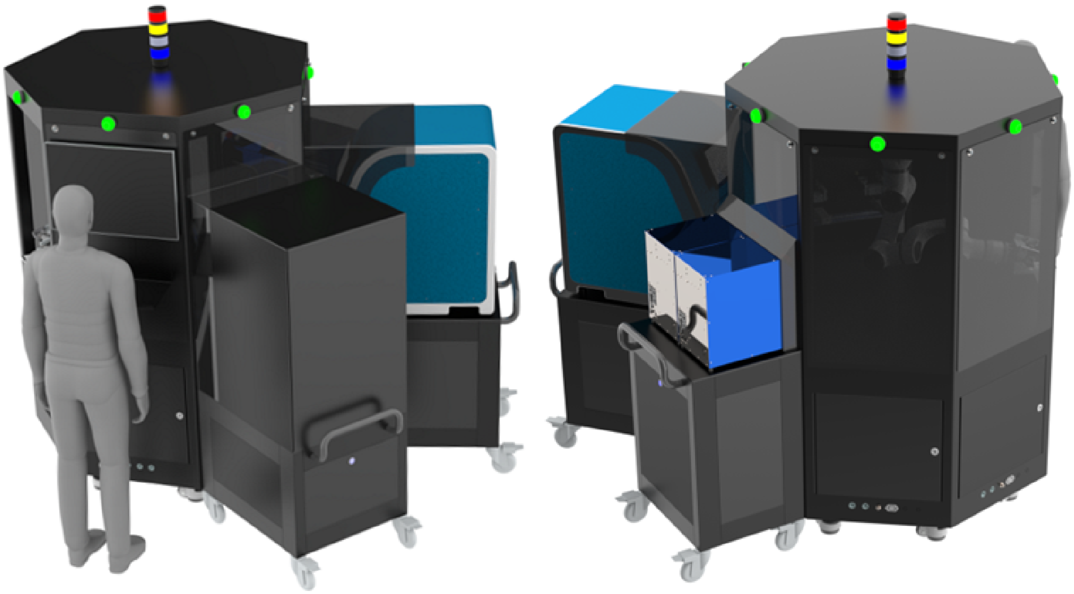

***Figure 3.5.*** *SmartCell preliminary design ready*

During the project preliminary mechanical design was done alongside electrical design. Required outputs from preliminary phase were examples and concepts as well as gathered a list of requirements to be passed to detail designers. Also, design reviews during the detail design were held together, and support during detail design and manufacturing phases was given. Quite much manufacturing support was needed during the project because of truly weak component availability, too long lead times and few discontinued products from existing device's bill of materials' (BoM).

This thesis concentrates on the project delivery configuration which contains two RATAs, two SCOREs and one FUSION. These are capable of testing almost all features of a smart phone. Some of testing capabilities of these devices overlap, so therefore it is possible to move test cases between devices to optimize cycle times. SC consists of a center frame and detachable modules. There are three different kind of modules to be connected to the center frame:

- 2 x RATA
- 2 x SCORE
- 1 x FUSION

Later it is possible to fit four RATAs in one module if needed, but it will require some additional design work and modifications to basic RATA model. SC was deviant from normal BfP process because at first partitioning logic or partly even set of modules were noted, and those reasons drove to think about modular design. The center frame was designed and built to serve and connect all different devices together. To reduce amount of required work, plan from the beginning of project was to use devices as they were used independently, with their own enclosures by just mounting required protection around them. This realized with RATA and FUSION, but SCORE needed further work and upgrades before it could be used in the SC. These upgrades are processed more in deep in section 4.3. Building the complete system into one package would have been too large to fit through doors and transportation costs would have been big. This could be referred to figure 2.1 about different types of lice-cycle-based modularity and more specifically logistic modularity.

# 4. PRELIMINARY DESIGN PHASE

Preliminary design of the system started from investigating project content and layout using concept design as base. This thesis concentrates on the preliminary mechanical design, requirement and design information gathering for detail designers. Focus is not on the detail design itself. Proof of concept had been done earlier with RATA and FUSION side by side on a table. A six-axis robot arm was a clear choice for moving phones between devices.

Preliminary design contained layout design of the cell, modules, electrical cabinet and robot working area. In addition to this, some of the electrical components needed to be fit inside preliminary model to be notified during the detail design. Most of these tasks were done simultaneously. All of these mentioned above and in addition to that, SCORE and gripper upgrades will be processed in the following sections.

## 4.1 Test cell layout

Like from figures 3.1 and 3.5 can be seen, preliminary design turned out to be much like original concept. Even if it can not be seen from the concept figure, original plan was to use all devices as they were, one device per slot on the center frame. After noticing that at least two RATAs and SCOREs could be fit in one slot and they were included in the project scope, it was decided to do so because of increased capacity and reduced need of material and footprint of the whole system. Despite of unusually good concept design, finishing the preliminary design required couple of weeks work to verify movement area and fitment of all devices. Some of the used time was spent on learning to use RoboDK software, which was used in designing the robot reach, frame sizes and locations of modules.

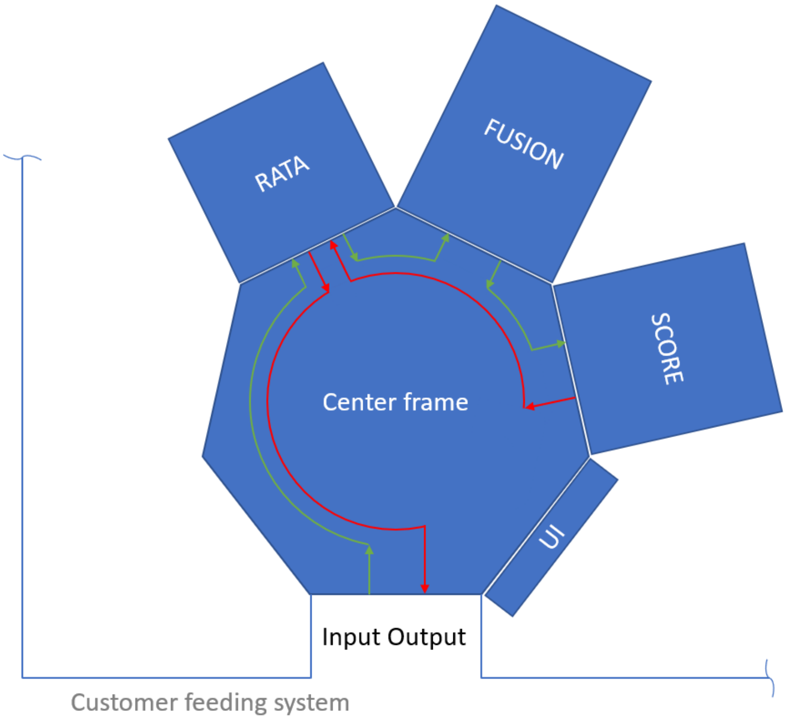

***Figure 4.1.*** *Layout and DUT flow path*

In figure 4.1 is shown the final layout of SC and flow path how DUTs flow through the cell from input slot to output slot in this specific project. The figure is not in scale, but shows relations well. One slot is taken by the user interface (UI) but with minor changes it is possible to change it to testing use as well. Then it would be required to design a roof mounted and possibly rotating arm to hold a display, keyboard and mouse. In some other project after completing these modifications, doubled testing capacity would be possible to achieve. In this case project, it is possible to fit two empty slots with more RATAs. In this case, others will not fit because before preliminary design review there was no solid information from the customer about their feeding system. In the review it was decided to continue detail design without making major changes to design because preliminary design did manage to fulfill the project scope and also serve possible future projects.

During a full test cycle a DUT will travel first from input slot to one of the RATAs. RATA will turn the DUT on, connect to a wireless access point, make few changes to settings and open a proprietary testing application. After those steps DUT will be moved to FUSION for functional testing. After functional tests DUT moves to SCORE for mostly cosmetic grading. After cosmetic grading, DUT is moved back to the second RATA to be turned off and settings reverted back to normal. A ready DUT will then move back to buffer storage through output slot.

An octagon shaped center frame would have ended in too big footprint for the chosen feeder robot arm. Narrower module slots in the other hand would have then been too narrow to fit two RATAs or SCOREs in the same slot. On the other hand a hexagon would have left some of the capacity unused. Like figure 4.1 also shows, in this specific project there is some excess movement between the feeding slot and RATAs. That was not considered as problem or threat to UPH requirement because movements are fairly quick and robot can do most of these movements while the devices are running tests.

As mentioned before, regarding part handling, this system can be treated as an assembly process. Handling DUTs can be treated like as it was intermittent transfer in the assembly process. Workheads, so to say testing devices, are stationary and work carrier, meaning the six-axis robot, will transfer DUTs between workheads after assembly operations, or in this case the testing sequences, have been finished. Intermittent transfer in a assembly process referred to Boothroyd. (Boothroyd 2005, p. 17–19)

The layout was also designed having the robot application limitations in mind. Moving close to singularities can produce high axis or joint speeds for the robots (SFS-EN ISO 10218-1:2011). Singularities can be faced when executing Cartesian space motion, where a desired final pose and path are defined. If the path kinematics calculation by the robot controller fails, singularities arise. (Bonev 2019) If there was a hazard for the operator, SFS-EN ISO 10218-1:2011 would have required a singularity protection by stopping motion and giving a warning or generating a warning signal and limiting speed. In this case, operator had access to the robot only when running in pose teaching mode. Different types of singularities can be faced usually when specific axes align parallel or normal to each other (Bonev 2019). That was noticed in design phase when RoboDK stated warning of approaching singularity. It happened usually when moving close to maximum reach.

## 4.2 Modules and interfaces

It would have been possible to make design for the specific project easier, but while the case company has been able to establish a complete set of testing devices for refurbished smart phones, it was an understandable strategic choice to start combining all of these devices together as a complete testing cell. In this project modules and modularity has been mostly considered as the different test devices. Partitioning type of SC (figure 4.1) is closest to big common element (figure 2.3) type of division. In addition to earlier references to modules as RATA, FUSION and SCORE trolleys, also the user interface (UI), input and output slots make their own interfaces with environment.

The biggest challenge on the modular design of SC was to fit all of the three modules in similar, repeatable, accurate and sturdy enough mounting scheme, or shortly geometric interface, to the center frame. Luckily required energy, control and data interfaces were similar in every module, only number of connectors needed to be matched for every possible device. Every module needed power inlet, one ethernet port per device and standard RATA and FUSION required also pressurized air. Every device needed its own control

PC. As the center frame lower compartment was for distributing electricity, air, network and other things for the modules, module trolleys can take single input through the interface and divide electricity and pressurized air in the trolley. For simpler network topology it was chosen to use one ethernet port per device, so two in total per module, instead of a single port and a networking switch inside trolley.

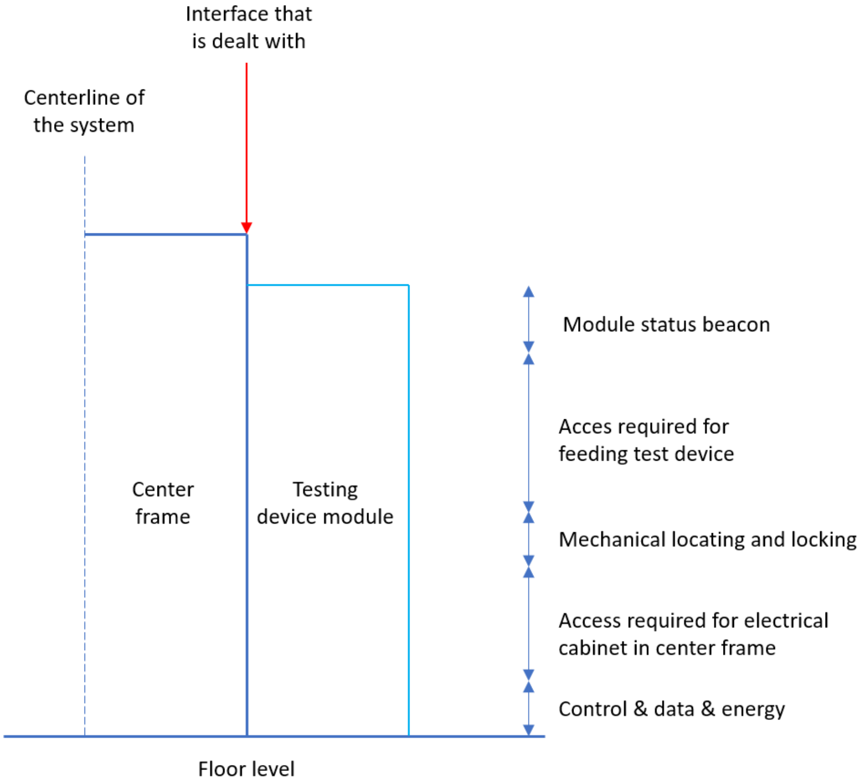

***Figure 4.2.*** *Section view of interface division (not in scale)*

Many different locations were considered for the geometric interface and locking modules to the center frame. Interface needed to be mechanically repeatable, i.e. when removing module trolley and attaching it back to center frame, they need to locate back in same position. Also, trolley was not allowed to move from light external forces. Therefore it was easy to make geometric interface right next to the testing devices, like can be seen from figure 4.2. Location of the tester was the most critical to stay same. It would have been easier for usage and maintenance to use quick locks for locking parts together but according to the standard, guards need to be fixed so they can not be opened or removed without a tool (SFS-EN ISO 14120:2015). Wedge shaped locating features were chosen. Male part is located in the module trolley and has screw slots in it. Female versions with threaded holes for locking are located on each center frame facet which is meant for module location. These lock sideways and depth-wise movements but allow slight vertical movement. Possibility for small vertical movement was allowed because it is unlikely to happen, as it could only happen due to damaged wheels. Locking screws are located inside the trolley lower compartment. One needs an electric cabinet key and a hex key to remove modules from center frame, so the solution is compliant with SFS-EN ISO 14120. Exact location of wedges was challenging to determine because of different heights of testing devices.

Control, data and energy interfaces were located in bottom of the interface region. That was reasonable choice after geometric interface was defined, since the chosen location happened to fit on same height as cabling was located on center frame. It could have been possible to use a single multifunctional connection for all of the connections. Required unobstructed access for using module also without center frame in bring up and calibration phase favored using separate connections. That led into solution where center frame has female connections for pressurized air, ethernets and power. Respectively, modules have free labeled cables and a small hatch where cables can be fed through to the connectors at the same time when module is locked to center frame. Using the multifunctional connector for all connections would have increased hardware and design costs significantly.

The testing devices could not be left on the trolley without any safeguard between them and center frame, like it was shown on figure 3.1. Protective covers had to be added to block users from getting inside the hazard zone. Covers are statically mounted to module trolleys and they have extra mounting spots to center frame when module is attached to it. Empty slots are blocked similarly with a safeguard that is not bypassable without removing it. In addition to locking with a tool, there are presence sensors in each module slot, so feeding robot can not be moved while one or more of modules are open to user. It could have been beneficial to put robot in collaborative mode with safety-rated reduced speed and forces if all modules were not closed but there was no support for that on the robot controller. The covers are easy enough to be removed for maintenance.

## 4.3 Cosmetic grading device upgrades for automated feeding

SCORE needed few upgrades to be able to work with automated DUT feeding. Due to the chosen cell layout, it was required to change orientation of SCORE. In the standard version of SCORE, top block of the mover unit relies on gravity and spring force, see figure 4.3 on next page. It also has an input adjustment lever with two different manually changeable positions for differently sized phones. Because of automated feeding and change of orientation, it was required to get more accurate control of the top block as it was no longer moving in the same direction as gravity. There was added a stepper motor linear lead screw actuator to control the top block position. Some free space was left for this motor during original design, but accessories like motor bracket, lead screw bracket and home sensor location and plate needed design work in heavily limited space. After that top block could float in between two springs to get flexibility and enough grip on the DUT.

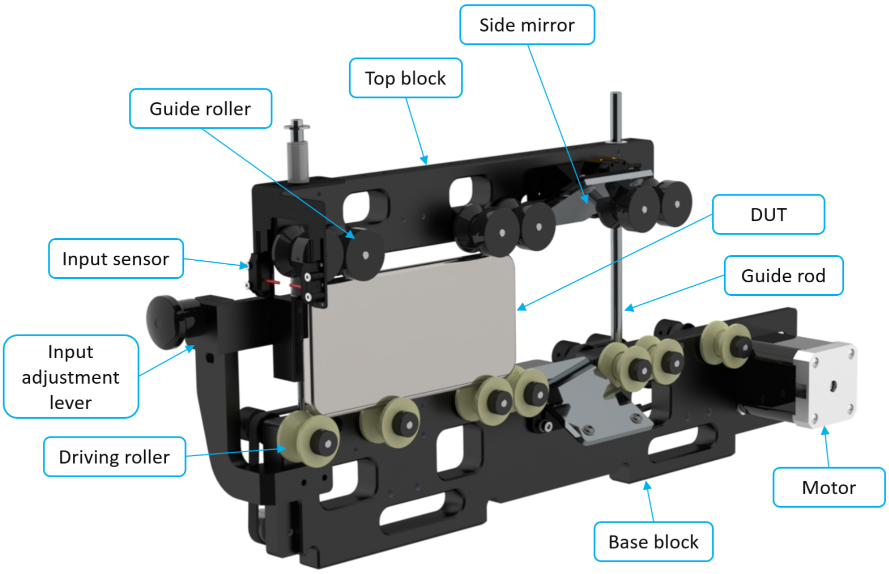

***Figure 4.3.*** *Mover assembly before modifications (naming adapted from Haara 2020)*

In addition to motor controlled top block, after initial tests, it was found that guide rollers near entry side don't provide enough support. The first roller on near entrance was moved to be in line with others, because it was offset a little bit to easen out manual feeding. One additional guide roller was added on lower side to provide more support when the phone is extracted out of the device and held barely on the other end before the other feeder grasps on phone. Below in figure 4.4 are shown the final controllable top block assembly of SCORE and the additional feeder. Unrelated components are left out to get better view on the updated system. The most important design choices of additional feeder are gone through more in deep later in this section.

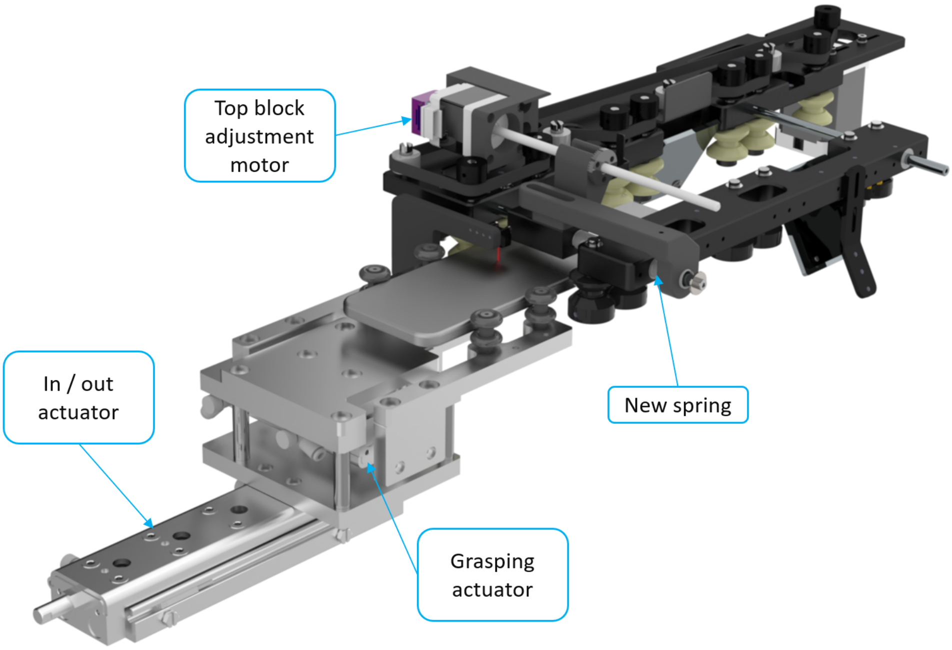

***Figure 4.4.*** *Mover assembly after modifications*

In addition to functional changes, original enclosure of SCORE was removed. There was few different reasons for that, the first reason being too big and bulky. Using custom enclosure for both of the SCOREs, module trolleys could be made narrower. The second reason was that maintenance with original enclosures would have been nearly impossible for the second unit. In the final design removable enclosure with two independent lightproof chambers was made. The first SCORE can be accessed by removing outer panel of the chamber. The second one was not so easy to get access to because all hardware is mounted on a single base plate and only bottom side of that plate could be seen if side panel was removed. A hinge was added so, the whole second system can be accessed by turning the base plate open. In order to maintain stability of the narrow trolley, there is a support leg against floor when hinge is in open position.

More challenging task was to make the existing robot gripper to be compatible with SCORE. Like referred before, this system can be compared to automatic assembly process. Boothroyd defined automatic assembly of one part to have two steps. The first step was handling and presentation of the part to the insertion device. The second one was the insertion of the part. (Boothroyd 2005, p. 173) In this case the feeder robot conducted the handling and presentation portion, DUT was the part to be inserted, but the insertion device was missing. If the existing gripper was for only one DUT, it could have worked. But because it is for two DUTs, it was not possible to insert a DUT straight to SCORE while carrying the second DUT.

For the additional feeder, different linear motion principles were investigated for the application by comparing each solution against available resources and required work amount. Requirements were to have a simple and robust stage that has two independently controllable linear actuators. The first actuator needed only to move between ends and the second one between other end (open) and variating other end with light amount of force (close). It was required to have knowledge of the achieved position at least on the movement limits in order to be able to conduct the next steps in sequence. Different actuator types and control schemes are introduced earlier in sections 2.2.1 and 2.2.2.

***Table 4.1.*** *Different solutions for the SCORE feeder*

| Requirement | Weight | Electromechanical linear actuator | Pneumatic linear actuator | Belt drive |
|---|---|---|---|---|
| Design work required | 0,8 | 0,4 | 1,0 | 0,2 |
| Amount of components | 0,5 | 0,8 | 1,0 | 0,2 |
| Price of components | 0,4 | 0,5 | 0,5 | 1,0 |
| Position information | 0,5 | 1,0 | 0,6 | 1,0 |
| Ease of control | 0,8 | 0,5 | 1,0 | 0,5 |
| Available resources (I/O, driver) | 1,0 | 0,6 | 1,0 | 0,6 |
| Component lead time | 0,5 | 0,8 | 0,5 | 0,8 |
| Total | | 2,8 | 3,9 | 2,6 |

Scores given for each solution are presented above in table 4.1. Scores were given according to subjective evaluation and consultation from others in the project team. It is good to explain some of the chosen weights for the comparison. Table contains weights for each aspect that was considered when choosing the final solution. Comparison was done mostly from mechanical and electrical design perspective, and some comments were also asked from software team. There was not much leftover design work budgeted to use, so it was quite important. Amount and price of components were not so important but considered worth comparing. System is not intended for mass production so cost reduction in every component is not required especially if slightly higher component cost can reduce amount of required design hours. The amount of components affects also to amount of required design and assembly work. Exact position information was not crucial as requirement was to have "in", "out", "open" and "close" states at least recognised, but exact information was considered beneficial. Ease of control is totally a software feature and means required amount of software work to get the system running. This was also important due to low hour budget. Available resources for the system control was one of the most important considerations because of limited work resources and existing systems wanted to be utilized as well as possible. Component lead time and especially availability were challenging due to Covid-19 pandemic. Some of the originally chosen components were replaced with alternative options due to poor availability.

Like mentioned above, design work and amount of components are related to each other. By minimizing quantity of components in best case scenario it is possible to reduce assembly work or even get rid of it completely (Boothroyd 2011). Design work and sourcing commercial components can be time consuming. The designer needs to configure components, import CAD model(s), go through catalogues and manuals for intended use and design instructions, create part number and do other things that are related to the normal design process. In manufactured parts, in addition to the design work and part number creation, also drawings are required. Miniature linear actuators with guide rails in approximately appropriate size are expensive when compared to other components. A single linear actuator without a stepper motor and a coupling was found to be similarly priced or more expensive than the pneumatic actuators. A belt drive system could have been done fairly cheaply due to widely available and cheap components and but it would have required more design effort. The pneumatic system was easy to control because it was only required to control couple of outputs and monitor inputs in correct order. Others would have required more work to get motors up and running and motor tuning in appropriate level. Both motor drivers of the system were already used for SCORE functions. It would have been possible to chain more drivers, but cost for the drivers only would have been on the same level as with the pneumatic solution. On the other hand, just barely all of the required input and outputs for the pneumatic system were available after a small firmware update with the existing setup.

Using a stepper or some other motor type equipped with an encoder to drive the feeder would have provided exact position information. Also, there would have been position and speed control over the whole movement range. Drawback would have been that without separate sensors, there would have been no information if DUT was in feeder or not. Similarly than in the six-axis robot gripper, pneumatic system does know if there is a DUT or not but can not distinguish size of it.

Pneumatic system was discovered after the first alternative. Linear movements using pneumatics are fairly simple to implement and there was already supply of pressurized air to every module slot because RATA and FUSION require it for normal operation. Using appropriate valve type and sensors on cylinders there is also information, if DUT was not caught in the gripper. Using this option, system consumed all free digital inputs and outputs from SCORE, but there is enough information from sensors to detect possible issues, for example fallen or missing DUT.

When validating the system with updated design, operation improved significantly. However, initial testing included only few different phone models. During these validation tests before shipping of the system, no problems were found. Reliability with smaller than the smallest tested phone model still left some concerns, but as system worked fine with chosen validation models, no changes were made. During the customer validations, some problems were found and improvement was required. Luckily by adding few components, this could be tackled. A roller with bearings was added between the gripper arms of the additional feeder. It was adjusted so, that in normal operation it does not even touch DUTs. Only in problematic cases it will support and guide the DUT in correct orientation so gripper robot will grasp properly. An off the shelf roller with bearings and same material as in SCORE was found available. It just required a shaft and couple of machined parts to mount it.

## 4.4 Robot gripper improvements

Rather quickly after starting design of the additional feeder, it was noticed that the existing robot gripper was not anymore compatible with design plans. The gripper fingers would have collided between additional feeder and feeder robot. Additionally, the original gripper fingers were quite large in diameter, which would have led into problems when handling smaller phones.

The original tests were ran with an eye-in-hand machine vision camera. That is a camera mounted straight to the gripper or end-effector. Other option could be eye-to-hand, where camera is staticly mounted next to robot and pointed to the robot workspace. (García et al. 2020, p. 154025) The camera was using machine vision to locate phones in input and output slots. That made operation more robust when picking up phones that were put in holders by humans. So to say, concept tests were run in hybrid station, but the end product wanted to be fully robotized without human interaction. Camera was not necessary feature to have because capturing and processing the image consumed time and placement of DUTs improved when human was left out of the process. The feeder robot was stated to achieve up to ±0,03 mm repeatability (Han's Robot 2022). In order to achieve such good accuracy and repeatability, robots usually need to be calibrated. There are many different algorithms, calibration models and ways to do it and it can improve accuracy even by order of a magnitude when compared to a non calibrated one. (Zhuang 1996) Such high accuracy was not even required in this pick and place application. Camera was removed in order to save time and some costs. Camera was mounted on a bracket which accommodated also the pneumatic valves, so the bracket was left in place.

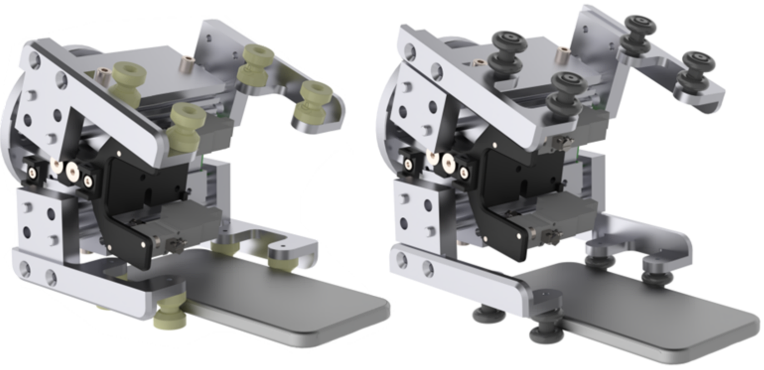

***Figure 4.5.*** *Gripper before (left) and after (right)*

Above in figure 4.5 can be seen what updates were done to the gripper. The gripper arms worked in concept testing because the phones were laid on a platform that lifted them off the table to fit the gripper fingers around phone. When adding the additional feeder that was designed in previous section, gripper needed to interact with that. L-shaped gripper arms would have collided with gripper fingers of additional feeder when transferring the grasp between each other. Also gripper fingers were too big to fit all eight fingers (four from feeder robot and four from SCORE feeder) along sides of the smallest phone models. Luckily it was possible to interchange left and right arms and move gripper fingers on other side of arm. By doing that, stiffening part of L-shaped bracket could be moved from DUT side to free side.

Section 2.3 referred to Pham and Yeo and different ways of increasing flexibility of a gripper. As minimal work was wanted and notching of gripper fingers was not enough to solve problems, the gripper fingers were changed. Changing those required few iterations until performance was reached expected level. The initial version used two O-rings with a gap in between attached to machined plastic frame. Also, another set of fingers with different geometry were available. Those were machined fully out of polyurethane. Requirements for the fingers were:

- does not leave stains or scratches,
- does not interact with side buttons,
- does not stick and
- does have some soft geometry to suit different thicknesses and shapes.

The polyurethane tips tested to be working otherwise but geometry was not perfect. They could trigger side buttons on specific phone models. It could have been possible to get the same material work with updated geometry. However, it was not possible to get machined parts in required time frame because the material was not stocked on vendors. It was required to start sourcing soft materials from 3D print suppliers. A sample set was provided by the supplier. Out of all materials available, thermoplastic polyurethane (TPU) and rubber were chosen for tests. Many of the other samples stuck to human skin and phone surface when trying to detach the surfaces. After receiving and testing the fingers tips, TPU was found to have too high hardness and rubber too soft. Also, rubber was sticking to phones, so phones could move during detachment from gripper. This material was not included in the sample set but was chosen for test. After these tests, it was decided to find O-rings with similar thickness but considerably smaller diameter than original gripper had. After a thorough search, one supplier was offering suitable O-rings. The geometry of original machined plastic frame was scaled down to fit new O-rings and made out of plastic with 3D printing to achieve shorter lead time for new tests. At the same time, cost of one gripper finger was reduced to about 40 %. Basic rule of thumb on the company's suppliers is that 3D printed parts have 50 % or more lower lead time compared to machining parts, so also spare parts can be also ordered faster than before.

# 5. CONCLUSION

The preliminary design itself was not complicated after few of the key things were resolved. The biggest challenges were faced on component availability and lead times. Reviewing and supporting the detail design process and component sourcing from different continent was challenging and consumed lot of time. Even some suboptimal components were used because of these challenges. Also, some problems were faced due to limited language skills and poor communication between teams. Poor communication and lack of division of responsibilities between teams introduced some uncertainties during the project. This could be due to changed human resources in some phase of this long project. General improvements for all of the design and delivery processes in company have been initiated already during the project. Training about modularity and some work to improve that also has been done. Once finished, these should help avoid most of similar situations in future projects.

Like mentioned in 3.4, two similar systems were built. That helped a lot because one of the two center frames was shipped to Finland. This was done because real hardware was necessary to have during integration phase as all software integration and initial debugging was done in Finland. However, the individual modules were not shipped due to high logistics costs. That introduced some difficulties with SCORE and its additional feeder, because same functionalities still had to be built in order to test the system thoroughly.

As a result for the first research question about module design, three different modules were designed. Each one of those has similar mechanical interface for positioning and locking. All of them have similar data and energy interfaces as only quantity of connectors variate between one and two. The opposite side on the center frame was accommodated with connectors that are compatible with each module. The second research question, automated feeding of devices to SCORE was implemented using two pneumatic linear actuators mated with positions sensors in each end. After a comparison between different possible methods of doing the same thing, that was found to be the most efficient. The last research question about upgrading an existing gripper was tackled by changing gripper fingers and arms. Arms did not require any design work, because swapping arms between left and right was enough to increase clearance on operation. Gripper fingers however were updated with new geometry.

The module interfaces worked fine and as intended. Mechanical locking was found to be repeatable enough and other connections could be done fairly easily after that. After manufacturing these first units as minimum viable products, mounting of the protective covers could be improved and made more visually appealing by using for example smoke acrylic instead of sheet metal.

The additional feeder system and internal upgrades for SCORE were the most challenging to get working as required. Some of the challenges were caused by the rough testing setup that was built from components and materials that were available on hand. Many test setups or fixes were first done in hurry to get testing running due to blocking issues. Then later some of them were fixed properly and some left like that if they functioned somewhat properly.

It was proposed to improve software control of the feeding robot to comply with differently sized phones and improve reliability when transferring DUTs from feeder robot to SCORE feeder system. That was not done due lack of resources and time but should be considered in some point. Some of the challenges faced in integration phase were caused by the feeder robot. Documentation was hard to get, some of the issues required software update and remote support from manufacturer. When starting to build next systems, changing the arm manufacturer to more reputable should be strongly considered even if it requires some software work to write a new driver for it.

The existing gripper was modified to work with the system, but improvements could still be done for future projects. It should be possible to decrease physical size to help teaching robot positions with RATA. The gripper arms had some free play that was fully caused by the pneumatic actuator shafts. Shorter gripper arms or additional linear guide to reduce play should be considered. Similar actuators could not be found after a quick search from different manufacturers. Also designing teaching tools for teaching correct robot positions was discussed but left in backlog. That should help bringing up the system.

Research done in chapter 1.2 helped mostly in the gripper and SCORE feeder phases. Interface design and the module system utilized some tips and information from Brownfield Process but not much as the design work was mainly practical work how to fit every required component in limited space. Much work and improvements were left to be done in future projects but minimum amount of functions was implemented for now.

# REFERENCES

Acarnley, P. (2002). *Stepping Motors - A Guide to Theory and Practice*. 4th ed. Institution of Engineering and Technology (The IET).

Amrani, D. (Mar. 2015). A simple experiment showing the determination of the magnetic dipole moment of a permanent disc magnet. *Physics Education* 50, pp. 142–145.

Aparisi i Escriva, A. (2016). Design of a Smart Gripper for Industrial Applications. MA thesis. Tampere University of Technology.

Arnheiter, E. D. and Harren, H. (2006). Quality management in a modular world. eng. *TQM magazine* 18.1, pp. 87–96.

Azim, M. S. (2019). Designing a universal gripping solution for handling part variations in a robot application. MA thesis. Tampere University.

Baldwin, C. Y. and Clark, K. B. (1997). Managing in an age of modularity. eng. *Harvard business review* 75.5, pp. 84–93.

– (2000). *Design rules*. eng. The MIT Press. The MIT Press.

Bettig, B. and Gershenson, J. K. (2010). The representation of module interfaces. *International Journal of Product Development* 10.4, pp. 291–317.

Bonev, I. (2019). *What are Singularities in a Six-Axis Robot Arm?* Accessed: 2022-06-28. URL: `https://www.mecademic.com/en/what-are-singularities-in-a-six-axis-robot-arm`.

Boothroyd, G. (2011). *Product design for manufacture and assembly*. 3rd ed. Manufacturing engineering and materials processing. CRC Press.

Boothroyd, G. (2005). *Assembly automation and product design*. 2nd ed. Manufacturing engineering and materials processing ; 66. Taylor  Francis, p. 512.

Borowski, K.-H. (1961). *Das Baukastensystem in der Technik*. Vol. 5. Springer Berlin Heidelberg, p. 106.

Brown, E., Rodenberg, N., Amend, J., Mozeika, A., Steltz, E., Zakin, M., Lipson, H. and Jaeger, H. (Oct. 2010). Universal Robotic Gripper Based on the Jamming of Granular Material. *Proceedings of the National Academy of Sciences of the United States of America* 107, pp. 18809–18814.

Cabigiosu, A., Zirpoli, F. and Camuffo, A. (2013). Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry. *Research Policy* 42.3, pp. 662–675.

Causey, G. and Quinn, R. (1998). Gripper design guidelines for modular manufacturing. *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*. Vol. 2, 1453–1458 vol.2.

Childs, P. R. N. (2004). *Mechanical design*. 2nd ed. Butterworth-Heinemann.

Dini, G., Fantoni, G. and Failli, F. (2009). Grasping leather plies by Bernoulli grippers. *CIRP Annals* 58.1, pp. 21–24.

Droste, M. (1991). *Bauhaus 1919-1933 / Bauhaus Archiv*. Benedikt Taschen.

Fantoni, G., Santochi, M., Dini, G., Tracht, K., Scholz-Reiter, B., Fleischer, J., Kristoffer Lien, T., Seliger, G., Reinhart, G., Franke, J., Nørgaard Hansen, H. and Verl, A. (2014). Grasping devices and methods in automated production processes. *CIRP Annals* 63.2, pp. 679–701.

Festo (2022). *Parallel gripper DHPC*. Accessed: 2022-04-01. URL: `https://www.festo.com/gb/en/p/parallel-gripper-id_DHPC`.

Forg, A., Stocker, J., Kreimeyer, M., Lienkamp, M. et al. (2014). Enabling modularization potentials by standardized vehicle layouts. *DS 81: Proceedings of NordDesign 2014, Espoo, Finland 27-29th August 2014*, pp. 754–764.

Forza, C. and Salvador, F. (2006). *Product Information Management for Mass Customization*. Palgrave Macmillan UK.

García, A., Girbés-Juan, V., Solanes, J. E., Gracia, L., Perez-Vidal, C. and Tornero, J. (2020). Human-Robot Cooperation for Surface Repair Combining Automatic and Manual Modes. *IEEE Access* 8, pp. 154024–154035.

Gieras, J. F. (2012). *Linear synchronous motors: transportation and automation systems*. 2nd ed. Electric Power Engineering Series. CRC Press.

Gomis-Bellmunt, O. and Campanile, L. F. (2010). *Design Rules for Actuators in Active Mechanical Systems*, p. 205.

Grady, J. O. (1994). *System Integration*. Taylor  Francis Group.

Haara, O.-P. (2020). Mechanical Design of a Smartphone Grading Device. MA thesis. Tampere University.

Han's Robot (2022). *Elfin Brochure*. Accessed: 2022-06-28. URL: `https://elfincollaborativero`
`eu/images/brochures/HR-Elfin-Brochure-EN.pdf`.

Juuti, T., Pakkanen, J. and Lehtonen, T. (2016). Brownfield Process: A method for modular product family development aiming for product configuration. *Design Studies* 45, pp. 210–241.

– (2019). Identifying and addressing challenges in the engineering design of modular systems – case studies in the manufacturing industry. *Journal of Engineering Design* 30.1, pp. 32–61.

– (2020). Partitioning types in product modularisation. *Proceedings of the Design Society: DESIGN Conference* 1, pp. 2325–2334.

– (2021). Observations on modular product structures based on teaching product modularisation. *Procedia CIRP* 100. 31st CIRP Design Conference 2021 (CIRP Design 2021), pp. 476–481.

Kapurch, S. J. (2007). *NASA Systems Engineering Handbook*. NASA.

Kauranne, H., Kajaste, J. and Vilenius, M. (2008). *Hydraulitekniikka*. WSOY Oppimateriaalit.

Koh, E., Förg, A., Kreimeyer, M. and Lienkamp, M. (2015). Using engineering change forecast to prioritise component modularisation. *Research in Engineering Design* 26.4, pp. 337–353.

Kreimeyer, M., Förg, A. and Lienkamp, M. (2014). Fostering modular kits in an industrial brownfield environment. *Proceedings of TMCE 2014*, p. 12.

Krüger, J., Lien, T. and Verl, A. (2009). Cooperation of human and machines in assembly lines. *CIRP Annals* 58.2, pp. 628–646.

Lehtonen, T. (2007). Designing modular product architecture in the new product development. PhD thesis. Tampere University of Technology.

Lehtonen, T., Pakkanen, J., Järvenpää, J., Lanz, M. and Tuokko, R. (2011). Brownfield process for developing of product families. *ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design*. Vol. 4, pp. 248–257.

Li, X., Li, N., Tao, G., Liu, H. and Kagawa, T. (2015). Experimental comparison of Bernoulli gripper and vortex gripper. *International journal of precision engineering and manufacturing* 16.10, pp. 2081–2090.

Lorenz, R., Zik, J. and Sykora, D. (1991). A direct-drive, robot parts, and tooling gripper with high-performance force feedback control. *IEEE Transactions on Industry Applications* 27.2, pp. 275–281.

Makino, S., Shikayama, T., Murokita, I., Yahara, H. and Ohto, M. (2016). A Direct Drive -Z Motor for Rotary and Linear Motion. *Electrical Engineering in Japan* 196.1, pp. 52–60.

Mantriota, G. (2007). Theoretical model of the grasp with vacuum gripper. *Mechanism and machine theory* 42.1, pp. 2–17.

Miller, T. and Pedersen, P. (1998). *Defining Modules, Modularity and Modularization: Evolution of the Concept in a Historical Perspective*. 13th Integrated Productions Systems Research Seminar (IPS'98) ; Conference date: 01-01-1998. IKS, p. 19.

Moritz, F. G. F. (2014). *Electromechanical motion systems: design and simulation*. Wiley, p. 308.

Mott, R. L. (2018). *Machine elements in mechanical design*. 6th ed. Pearson, p. 873.

OnRobot (2022). *Vacuum gripper VGC10*. Accessed 2022-04-01. URL: `https://onrobot.com/en/products/vgc10`.

OptoFidelity Oy (2020a). *OptoFidelity FUSION Brochure*. Accessed: 2022-06-16. URL: `https://www.optofidelity.com/hubfs/202008_OptoFidelity_Fusion_broschure_english_A4.pdf?hsLang=en`.

– (2020b). *OptoFidelity SCORE Brochure*. Accessed: 2022-06-23. URL: `https://www.optofidelity.com/hubfs/202008_OptoFidelity_Score_brochure_english_A4.pdf?hsLang=en`.

OptoFidelity Oy (). *Functional Testing of Refurbished Smart Devices*. Accessed: 2022-08-10. URL: `https://www.optofidelity.com/offering/solutions/functional-testing-of-refurbished-smart-devices`.

Pahl, G. and Beitz, W. (1996). *Engineering Design: A Systematic Approach*. Springer Verlag.

Pakkanen, J. (2015). Brownfield Process: A Method for the Rationalisation of Existing Product Variety towards a Modular Product Family. PhD thesis. Tampere University of Technology.

Parslov, J. F. and Mortensen, N. H. (2015). Interface definitions in literature: A reality check. *Concurrent Engineering* 23.3, pp. 183–198.

Pham, D. and Yeo, S. (1991). Strategies for gripper design and selection in robotic assembly. *International Journal of Production Research* 29.2, p. 303.

Piller, F. and Kumar, A. (Jan. 2006). Mass customization: Providing Custom Products and Services with Mass Production Efficiency. *Journal of Financial Transformation* 18, pp. 125–131.

Rakotondrabe, M. and Lutz, P. (2009). Force estimation in a piezoelectric cantilever using the Inverse-Dynamics-Based UIO technique. *Robotics and Automation, 2009. ICRA '09*, pp. 2205–2210.

Schmalz (2022). *Floating Suction Cups SBS*. Accessed 2022-04-04. URL: `https://www.schmalz.com/en/vacuum-technology-for-automation/vacuum-components/special-grippers/floating-suction-cups/floating-suction-cups-sbs-306036/`.

ServoCity (2022). *ServoCity Parallel Gripper*. Accessed 2022-04-07. URL: `https://www.servocity.com/parallel-gripper-kit-a/`.

SFS-EN ISO 10218-1:2011 (). *Robots and robotic devices. Safety requirements for industrial robots. Part 1: Robots*. Finnish Standards Association, p. 48.

SFS-EN ISO 14120:2015 (). *Safety of machinery. Guards. General requirements for the design and construction of fixed and movable guards*. Finnish Standards Association, p. 43.

Swift, K. G. and Booker, J. D. (2013). *Manufacturing Process Selection Handbook.* 1st ed. Butterworth-Heinemann, p. 457.

Vijayaragavan, E., Amardeep, Vijay, K. and Singh, A. P. (2020). Design of an automatic sliding rack for injection moulding machine. *IOP Conference Series: Materials Science and Engineering* 988.1, p. 7.

Zhao, J. and Li, X. (2016). Effect of supply flow rate on performance of pneumatic non-contact gripper using vortex flow. *Experimental Thermal and Fluid Science* 79, pp. 91–100.

Zheng, C., Le Duigou, J., Bricogne, M. and Eynard, B. (2016). Multidisciplinary interface model for design of mechatronic systems. *Computers in industry* 76, pp. 24–37.

Zhuang, H. (1996). *Camera-aided robot calibration*. 1st ed. CRC Press.

Zürn, J., Richter, U., Mierisch, U. and Müller-Finkeldei, R. (2012). DER NEUE ACTROS VON MERCEDES-BENZ. ger. *ATZ. Automobiltechnische Zeitschrift* 114.1, pp. 36–45.