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Investigating an Immersive Virtual Mock-Up Approach for Workstation Design

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Preface

This Masters's thesis is the Masterwork that constitutes the Master of Science degree in Mechanical Engineering at the Department of Mechanical and Industrial Engineering at NTNU. The degree is a specialisation in Operations management and was carried out during the spring semester of 2019. The thesis was carried out in relation to the Logistics 4.0 laboratory at Valgrinda, NTNU. The assumed background of the readers of the thesis is an academic background in Engineering.

Trondheim, 10 June 2019

Ivan Sjøberg

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I would like to thank the following persons for their great help during this project. I would like to thank Johanne Aadde, Mirco Peron and Andreas Alvaro and the rest of the participants for their support in wearing the suit during testing. The always inspiring Swapnil Bhalla for mental sparring of ideas. Professor Jan Ola Strandhagen and the rest of the staff at MTP for setting high standards. I would like to thank my supervisors Professor Fabio Sgarbossa and Guiseppe Fragapane for allowing me to work with state of the art technology and letting me do my own thing in the laboratory.

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I.S.

Abstract

Emerging trends in manufacturing are changing products; the consumer wants new products, more customization possibilities and more variety. With automation of manufacturing the manufacturing company gain precision, speed and competitive business models, but a fully-automated factory loses responsiveness and flexibility and achieving a high level of flexibility in what to produce is very expensive. This means that the continued use of human workers can be a cost-effective alternative to expensive automation in some stages of production. Human workers perform their tasks at a workstation. This workstation has to be designed before it can be constructed. When designing for humans, there is a link between designing the workstation for humans and increased productivity. Virtual reality and motion capture technology has matured and is now available for exploitation in workstation design. The interaction capabilities in virtual reality by combining the two technologies makes it possible to create intuitive virtual workstations.

The research of this thesis is structured around three research questions; 1) What is the state-of-art with the use of comparable systems capabilities and different virtual mock-ups related to workstation design in literature? 2) When can an immersive virtual mock-up replace a physical mock-up in the workstations design process? 3) What are the benefits, challenges and limitations of using immersive virtual mock-up approach vis a vis a physical mock-up approach?

The research uses a operations management perspective, with a focus on the application of the technology and not the technology itself. The scope is limited to workstation design which as a subcategory of facility planning. The goal of this thesis is to investigate the applications of a virtual interactive representation of a workstation in the workstation design process. The technology is considered as black-boxes, meaning that only the input and output is of interest. There will be no development of technology during this thesis.

Qualitative research methods have been applied, including a literature study and an exploratory laboratory study. Participant observations from the laboratory work are used for collecting empirical data.

Through the literature study, an academic gap was identified and used for the scoping of the thesis. The academic gap is the applications of a purely virtual mock-up with no physical objects mixed into the experience. The literature study is a thorough presentation of related work using comparable systems within the topic of workstations design and the use of immersive technology in the industry. The literature study also provided knowledge of the topics needed to be introduced in the theoretical background.

The empirical results were achieved by creating a virtual model in the laboratory and using advanced motion capture technology to produce interaction capabilities. The task selected for the virtual workstation was an assembly task consisting of a water pump.

Through the relevant theoretical topics presented, the experience gained and observations done through the creation of the virtual environment answers about; 1) when a fully-virtual approach could replace the traditional design approach of building a physical mock-up in some light-weight material. This was done by estimating the time and effort used in the different approaches. 2) An overview of the benefits, challenges and limitations of an immersive virtual approach compared to a physical approach is also given.

Sammendrag

Innen vareproduksjon er skiftende produkter en fremvoksende trend. Forbrukeren ønsker nye produkter, flere tilpasningsmuligheter og mer variasjon. Det fører med seg at bedriftene må tilpasse seg og opprettholde konkurransedyktigheten. Ved å implementere automatisert produksjon oppnår produksjonsfirmaer økt presisjon, høyere produksjonshastighet og en mer konkurransedyktig forretningsmodell. Likevel kan for mye automatisert produksjon føre med seg at en fullautomatisert fabrikk får nedsatt evne til å respondere på endringer får lavere fleksibilitet når det gjelder produkter. Det å oppnå et høyt nivå i fleksibiliteten via automatisering er svært kostbart, dette fører med seg at det vil være et kostnadseffektivt alternativ ved å bruke menneskelige arbeidstakere til automatisering i enkelte stadier i produksjonen.

Menneskelige arbeidstakere utfører jobben sin ved en arbeidsstasjon og i forkant av dette arbeidet må arbeidsstasjonen planlegges og bygges. Når arbeidsstasjonen designes er det en viktig kobling mellom kvaliteten, fokuset på designet, samt nivået på produktiviteten. Virtual reality og motion capture-teknologi er nå i enda større grad tilgjengelig for utnyttelse for design av arbeidsstasjoner i industrien.

Forskningen i denne studien er strukturert rundt tre forskningsspørsmål. 1) Hva er state-of-art ved bruk av sammenlignbare systemegenskaper og forskjellige former for virtuelle mock-ups relatert til arbeidsstasjondesign i litteraturen? 2) Når kan en fullstendig virtuell mock-up erstatte en fysisk mock-up innenfor arbeidsstasjondesignprosessen? 3) Hva er fordelene, utfordringene og begrensningene ved å bruke en virtuell design tilnærming sammenlignet med en tradisjonell tilnærming?

Forskningen er gjennomført med fokus på produksjonsledelse. Gjennom anvendelse av teknologien og ikke på selve teknologien i seg selv. Omfanget av oppgaven er begrenset til arbeidsstasjondesign som er en underkategori av fasilitetsplanlegging. Målet med denne oppgaven er å undersøke bruken av en virtuell interaktiv representasjon av en arbeidsstasjon innefor arbeidsstasjonsdesignprosessen. Denne kvalitative studien har ansett teknologien som svarte bokser, det betyr at det er bare informasjonen som går inn og ut av teknologien er av interesse. Studien har dermed ikke fokus på utvikling av selve teknologien. For å belyse omfanget omfavner studien tidligere forskning og en utforskende laboratorieundersøkelse, hvor empiriske data ble samlet ved bruk observasjoner av deltaker i laboratoriearbeidet.

I litteraturstudiet ble det identifisert et akademisk hull i tidligere forskning, som ga rom for konkretisering av studien. Det akademiske hullet omhandler bruk av en rent virtuell interaktiv modell uten noen fysiske gjenstander blandet inn i opplevelsen. Litteraturstudien er en grundig presentasjon av relatert arbeid. Litteraturstudien ser på sammenlignbare systemer innenfor temaet arbeidsstasjondesign og bruk av interaktiv virtuell teknologi i bransjen. Litteraturstudiet ga også kunnskap om emnene til teorikapittlet. De empiriske resultatene ble oppnådd ved å skape en virtuell modell i laboratoriet og ved hjelp av avansert bevegelsesteknologi skape interaksjonsfunksjoner. Oppgaven som ble valgt for den virtuelle arbeidsstasjonen var en monteringsoppgave av en vannpumpe. Gjennom forskningsprosessen har vi fått svarene på, 1) Når en helt virtuell tilnærming kan erstatte den tradisjonelle designtilnærming til å bygge en fysisk mock-up i lette forbruksmaterialer. Dette ble gjort ved å anslå tiden og innsatsen som ble brukt i de ulike tilnærmingene. 2) En oversikt over fordelene, utfordringene og begrensningene til en fullstendig virtuell tilnærming i forhold til en fysisk tilnærming er også gitt.

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Chapter 1

Introduction

1.1 Background

The emerging trend for manufacturing is changing products. Innovative products, demand for increased variety and customization and shorter product life cycles drive the need to achieve flexible production capabilities (Gorecky et al., 2017). With industry focusing on automation, which is known to increase the throughput rate, there is an associated reduction in responsiveness and flexibility (Gorecky et al., 2017). Human Factor oriented production, meaning increasing the productivity of humans and keeping a human presence within manufacturing, can function as a cost-effective alternative to expensive automated solutions to achieve increased flexibility (Boenzi et al., 2015). As a by-product, the need for increased flexibility also increases the frequency of design of new and redesign of existing workstations.

Ergonomics and Human Factors are increasingly crucial within manufacturing. The average age of the workforce in industrial nations continues to rise and focusing on ergonomics, and Human Factor elements can keep workers in positions longer before retirement. According to Eurostat's population projections within the time interval of the years 2014 and 2050, the number of people in the European Union under 16 years of age will decrease 0.8% during that period, compared with current numbers in 2019, and at the same time the number of persons aged 65 years or older will increase by 10.4% making up almost 30% of the total population (Kluge et al., 2019). The skewing of the average age will create a need for people to work longer before retiring, because of the substantial costs of welfare state systems (Kluge et al., 2019). As a consequence, the number of workers on the factory floor over 50 years of age will increase. With an older workforce more prone work-related musculoskeletal disorders and other work-related injuries focusing on human factors trough ergonomics studies will help to mitigate these unwanted side effects (Gonzalez and Morer, 2016).

Increased production cannot be achieved solely with economic incentives (Rauch et al., 2019), but anthropometric facilitation, meaning designing specifically for human factors, must be included in the workstation design. The increase in productivity gained by including human factors into the work-space are well documented and contribute to mental well-being, increase job satisfaction, reduction of absenteeism and prevention of work-related musculoskeletal disorders related to workstation design (Peruzzini et al., 2017a) (Das and Sengupta, 1996)(Cavatorta and DiPardo, 2009).

As with product prototypes, development and design of industrial workstations have traditionally involved the creation of a full-scale physical model prototype of the intended workstation (Jayaram et al., 2007). This physical model, also called a mock-up, is then used to identify unwanted and inefficient characteristics, such as movements performed by the operator, material flow and tool placement, and facilitates the testing of improvements to these inefficiencies. A mock-up is produced with all the tools, furniture, mechanical levers, consoles and devices intended for the functioning workstation. The physical mock-up is usually built in either at a 1:1 scale, a dollhouse 1:16 scale (Bligård et al., 2018) or as a virtual mock-up as in this thesis. Mock-ups allows engineers to perform task analysis of the prototype design, evaluation of ergonomics and movement-time demands by observing an operator performing the intended tasks associated with that workstation on the mock-up. Editing the design of a digital Mock-up of the workstation is more cost-effective than changing something on a real-version (Pontonnier et al., 2014), adding motivation for this thesis. New technologies can help reduce the costs associated with the workstation design activity by eliminating the need for a physical prototype and a full-scale physical mock-up (Cavatorta and DiPardo, 2009; Battini et al., 2018).

1.2 Motivation and Problem Formulation

This thesis will test and examine a set of technologies, that in combination, can be used to enhance workstation design by eliminating or reducing the need for creating physical mock-ups. The thesis will illuminate the capabilities, challenges and limitation for the use within workstation design and to evaluate if the workstation design process can be altered positively with the use of immersive technology.

This thesis will utilize a similar inertial system to the one proposed in Battini et al. (2018). Recommending directions for future research, Battini et al. call for validation of the technology system. Their recommendation contributes to the motivation for this thesis; however, the system in this thesis excludes heart-rate monitoring (HRM) for choleric expenditure during use. The HRM was excluded to reduce the complexity during the master thesis. According to Battini et al., by using their system, an operator “can virtually perform all the activities he normally does during his job, but without needing a physical prototype of the workstation”. However, they did not explicitly list or describe the activities or tasks that were performed, or procedures for performing those tasks, or how the system contributes to achieving the capabilities to perform those tasks. Therefore, insights into the systems use for immersive approaches to workstation design is of great interest considering the potential of such a system.

The system that will be tested is used to evaluate tasks and design of a workstation within a purely virtual environment. The evaluations can be done in real time, without the need to produce a physical mock-up. Such validation of this technology will provide insights on the potential applicability, both in terms of productivity and human factor evaluations.

Industrial workstations are complex systems where productivity is strictly related to tool and floor layout, the dimensions of the objects processes and operation method.(Cimino et al., 2009). Traditionally, observation is the most common tool for ergonomics evaluations of workstations. A worker carries out the tasks associated with that workstation, and an ergonomics engineer measures the amount of time the worker spends in certain positions and identifies the types of movements involved (Peruzzini et al., 2019). Real-time capture of ergonomics data will have a significant impact on task analysis since it is not unusual for an ergonomics analysis of products and systems to take several months (Wickens et al., 2014). It also reduces the need to construct, and might potentially, replace the current strategy of constructing a 1:1 Mock-up of the workstation with a 1:1 fully immersive digital-mock up. Physical mock-up creation and all the activities involved implies costs connected to the development process such as staff-hours, procurement, spatial, and other interconnected expenses(Battini et al., 2018). The use of immersive reality technology reduces the number of physical mock-ups and prototypes required (Jayaram et al., 2007) (Grajewski et al., 2015). Designing, re-designing, configuration and analysis of workstations immersively have great potential in reducing the design lead time, reducing time to workstation implementation and reduction of time needed for ergonomic, layout, material flow, and motion-time analysis. The effectively potential of use in re-design of workstations are immense since most of the time used in evaluating existing designs using 2D software is the collection of task movement data and programming of movements for animation into established ergonomics evaluation software (Cimino et al., 2009), such as Jack 9.0, because of the precision of the sensor-suit and ease of use by the worker. The combination of technologies used in this thesis also provides a level of compactness without sacrificing mobility compared to other more established forms of spatially immersive systems.

1.3 Related work

Concerning related work that treat similar problems to what is covered by this thesis is presented in a literature study in the theory chapter. Here, similar technology , workstation design oriented and different immersive approaches is presented and a gap in theory is presented.

1.4 Research Questions

The goal of the thesis is to investigate if a immersive workstation can function as a realistic substitution to a physical mock-up using this combination of technologies, and to determine where this combination would add value to workstation design. The research questions chosen reflect the scope of this thesis and are presented below.

- **RQ1: What is the state of art with the use of comparable systems capabilities and different virtual mock-ups related for workstation design in literature?**

This research question helps to scope the thesis by providing a solid understanding of the related work. fore. The question will be answered through a literature study and a classification table as a summary of the study. The result can be read under the Literature study section of the theory chapter (chapter 3)

- **RQ2: When can a immersive virtual mock-up replace a physical mock-up in the workstations design process?**

This research question is interesting from an academic point of view because it can illuminate the potential benefits of using immersive technology in workstation design. Asking this question can also place the virtual mock-up more explicit within workstation design, and as a side effect illuminate the technologies potential to displace other established technologies such as two-dimensional simulation.

This question also provides answers to practical questions such as what implications the approach using purely virtual mock-ups has on the workstation design process.There will be a clarification of where in the process it might be more useful compared to a physical approach. It might be more suited for preliminary study, concept design, re-design, evaluation stage,fully replace a mock-up or be not viable compared to the traditional physical mock-up. This question will be answered using a time and effort estimation that is compared with a traditional workstation design. The basis for this estimation was discovered during the laboratory study described in chapter 3.

- **RQ3:What are the benefits, challenges and limitations of using immersive virtual mock-up approach vis a vis a physical mock-up approach?**

The reason for this question is to uncover the challenges and limitations of the system to gain increased knowledge and understanding of the existing capabilities. Insight into the aspects that answer this question provides a foundation for evaluating the two approaches. The focus will be on the virtual approach with comparisons with the physical approach.

This research question shall be answered by identifying prerequisite skills of potential users of the system and evaluation of the empirical study, using the observations and the time effort study.

Summary of Research Questions and Objectives

Research Questions	**Objectives**
RQ1: What is the state of art with the use of comparable systems capabilities and different virtual mock-ups related for workstation design in literature? **RQ2:** When can a immersive virtual mock-up replace a physical mock-up in the workstations design process? **RQ2:** RQ3: What are the benefits, challenges and limitations of using immersive virtual mock-up approach vis a vis a physical mock-up approach??	• Conduct a literature study on relevant topics and the related work • Gain insight into what skills and effort needed to set-up, use and maintain an immersive environment. • Produce a workstation environment and perform a task to gain insight into the capabilities of the immersive virtual mock-up approach by using a workstation environment.

Table 1.1: Summary of Research questions and objectives

1.5 Contributions

The main contributions in this masterwork are the evaluation of the technology application and the potential of a virtual mock-up of a workstation in the workstation design process. The creation of a virtual workstation using immersive environment. A time-effort study about the estimated time of the workstation design process using immersive technologies compared with building physical mock-ups, which puts the virtual mock-up inside the design process. A literature study about prior work on similar issues was conducted. Identification of prerequisite for the technicians using the technology that enables the use of an immersive mock-up approach is also created.

1.6 Limitations

There are some limitations that need to be mentioned in regards to this thesis. Since the field of virtual reality and motion capture technology has become more available and rapid technological advancement, there is a chance that at submission of the thesis it is already outdated. Therefore some of the older articles used in this paper might be obsolete or describing old technology. Older research addressing topics like virtual assembly, workstations of the future are more then 10 years old, and can be disregarded because of the obsoletes of the technology used in the papers.

Many of the articles cited in this thesis are conference articles and not peer-reviewed journal articles. When presenting a conference article at a convention or conference often the article is about what is currently being researched, what results the authors' have available at the time of the conference and what the author's believe they might achieve with the research they present.

The research has been conducted inside the LOG4.0 laboratory at NTNU in Trondheim and has not had any real world industrial testing. The users of the system has also been the researcher.

Only three operators have completed the assembly task inside the virtual environment. To be able to apply statistical analysis on the usability of the system a greater number of operators, with different backgrounds and age should try to use the system.
There is a possibility that the technology used does not yet have capabilities to simulate movement correctly when just using virtual models.

The time available to conduct the thesis was limiting because of an absence of a specialization project. The temporal constraints had an impact because of the amount of time dedicated to learn how to use the technology. Commonly at NTNU, the master students produce a specialization project during the fall of the final year of their degree, and the master thesis is commonly a continuation of this project produced the following spring semester. The author of this thesis did not conduct a specialization project on the topics or the system presented in this thesis, thus limiting the potential quality and work of the final iteration of this thesis.

1.7 Outline of Thesis

The remaining part of the thesis is organised in the following way: In chapter 2, the methodology of the thesis is presented. In that chapter an explanation of the scientific methods used, how the laboratory work was conducted and how each part of the thesis is related to each other to answer the research questions presented in chapter 1.
Chapter 3 presents theoretical background and topics that were identified as central to the thesis development. The chapter ends with the literature study.
Chapter 4 presents the technology system that was used during the laboratory work, followed by how the immersive environment is created and how it functions. The assembly operation is also presented here.
In Chapter 5, the observations made during the laboratory work is presented, followed by the time-effort estimation study. The results are then discussed by answering the research questions presented in Chapter 1.
The last Chapter6 contains the conclusion of this thesis and some recommendations for fu-

ture research. The appendix A contains a description of file formats mentioned in this report.

Chapter 2

Research Methodology

The article Battini et al. (2018)'s recommendations to future research inspired this master thesis. The thesis uses the same system to create an immersive environment in the laboratory where the solution is tested to gain insight into the capabilities, prerequisites and limitations of using an immersive mock-up approach to workstation design. To be able to complete the research objectives, it was first necessary to attain information about the topics of theory, the related work of similar technology and their use in workstation design to make sure that there was an actual gap in the theory and to avoid reinventing the wheel. After this, an immersive environment was created containing a virtual mock-up of a workstation with an associated assembly task that was used to provide the results necessary to answer the research questions. The result was divided into different categories. A time-effort estimation about the use of an immersive mock-up approach compared to a physical mock-up approach within workstation design was produced. These estimations were based on the experience gained with immersive mock-ups through the environment creation.

A research methodology is defined by Kothari (2004) as "a way to solve the research problem". Meaning that the methodology should provide a clear explanation of the methods and techniques that are used to solve the problem. The three words are tiers of each other such that a methodology is composed of methods and methods are conducted using techniques Kothari (2004). Techniques can also be a method in some circumstances.

There is a divide in definition for research approaches, qualitative versus quantitative. Quantitative research is associated with the generation of numerical data which can be quantitatively analysed with formal mathematical tools like statistics Kothari (2004). Qualitative approaches differ in the way that it uses subjective assessment and the approach is ,as Kothari writes ,"...is a function of researcher's insights and impressions". A qualitative approach generates results that are non-quantitative and generated on observations.

The thesis is comprised of a theory chapter where relevant topics are introduced and a literature study about related work is included. Then the thesis has a empirical part consisting of the creation of an immersive environment with a workstation test with results, an time-effort estimation comparing a physical design approach with an immerise approach, followed by a discussion of the research questions. The research approach is defined as qualitative.

The rest of this chapter will describe the methods and techniques used to conduct this thesis.

2.1 Literature Methodology

This section describes the methods and teqniues used to search for and evaluate theory for the use in this thesis.

Literature Search

Literature searches were done with cross-references and searches. Read methodology papers from specialisation paper. The articles was found using google scholar, engineering village and Scopus.

Snowball sampling

Snowball sampling functioned as a natural teqnuice to find relevant literature. It was considered the logical starting point for literature gathering since the thesis is based on recommendations for future research stated in Battini et al. (2018). References chosen from Battini et al. (2018) was considered by relevance to the research questions of the thesis. The same was done for the selected papers subsequent references as well, contributing to the characteristics of a growing snowball rolling down a hill increasing in size as it goes. Hence the name, Snowball.

Quality check

The articles used as references in this thesis was quality vetted through different actions. The first action was to check the number of citations of the article by using either Scopus or Google Scholar. If the number was low < 10 citations, the second action is to evaluate the impact number of the publishing journal. If the journal has an impact factor above 1.0 to 1.5, it is considered a good journal. This number is also subject to the age of the journal if it is new 1.0 to 1.5 can mean that it is still sound research, but with a well-established journal expect a higher impact factor for higher quality research.

2.1.1 Literature study and theory chapter

The literature was selected on relevance to this study to make sure that the scope of the research was novel. a summary with a classification table was used to illustrate the literature gap. The theory literature used to present topics are many of the most known books and articles on the topics. Though some of the sources are old the knowledge is still valid today and can therefore be used as a solid base for the theory topics needed to understand the research problem.

2.2 Empirical study

As a part of the empirical study of this thesis an immersive virtual environment was created in the lab with a workstation and a assembly task. This was done to through observations and experience gain insight into the capabilities and factors that affect a immersive virtual mock-up approach to workstation design. The system used and description of the environment and assembly task can be found in chapter 4. The information extracted from this study is presented in chapter 5 where a time effort estimation study where produced together with the rest of the observations.

2.2.1 Time-effort estimation study

After the laboratory study of the immersive environment was completed. A time-effort estimation study was provided. The layout of the study is a experience based comparison with a physical mock-up approach and a immersive virtual mock-up approach. The estimation uses the human-centred workstation design process presented in Das and Sengupta. The study is used to answer research question 2 and parts of research question 3.

2.2.2 Results gathering during the laboratory work

The information presented in the results are produced from participant observations. Participants being either the author him self or the suit-operators. The information was produced over time and was a iterative process. All participants made comments about their experience which was added in under a separate section in the results. Most of the other results are subject to the constraints of the technology and observations done by the technician while conducting the laboratory work.

2.2.3 Black-box

It is important to clarify that there is no focus on developing new technology during this thesis and if the impression is that new technology has been developed it has no relation to the research questions of this thesis. The technology is considered as black-box technology.

☞ **Black-Box Technology:** In engineering the definition of a black box is a device, system or object where the engineer disregards all internal functions and focuses only in the transfer characteristics, in other words, input and output.

2.3 Relations in the thesis

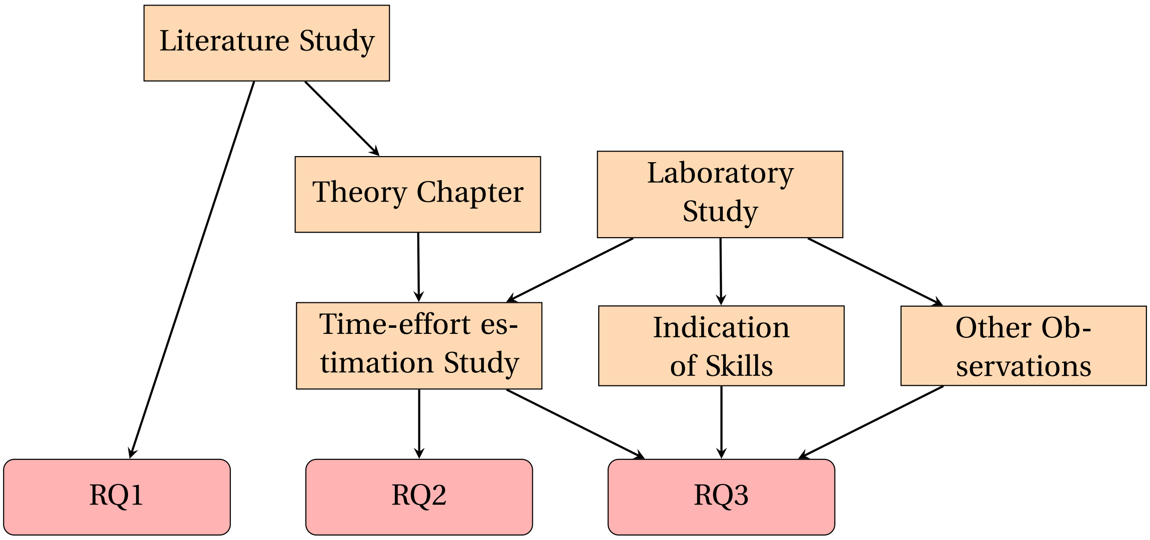

Figure 2.1: Overview scheme of which parts of the thesis supports the different elements

To better explain why the different elements have been included in the thesis, the author refers to the flow chart in figure 2.1. The literature study created the scope of the thesis and is the basis for answering research question 1. The literature study also defined the topics needing introducing in the theory chapter.
When answering research question 2, the time-effort estimation study has used the bases for creating that study was the experience gained through the Laboratory work and the theory presented in the theory chapter. Research question 3 had to be answered using the results generated through the laboratory work. The benefits, challenges and limitations that made up the research question were answered using the time-effort estimation study, the identification of prerequisite skills, and the observations made by the participants of the laboratory work.

2.4 Laboratory work and Procedure

As mentioned the testing of a virtual mock-up approach was conducted during this master thesis using the logistics lab 4.0 at NTNU. This involved several stages including training period, creation and assembly run. In the rest of this chapter the way the author achieved proficiency in the use of immersive technology and the creation of the environment is covered. The procedure for the laboratory study is presented in figure 2.2.

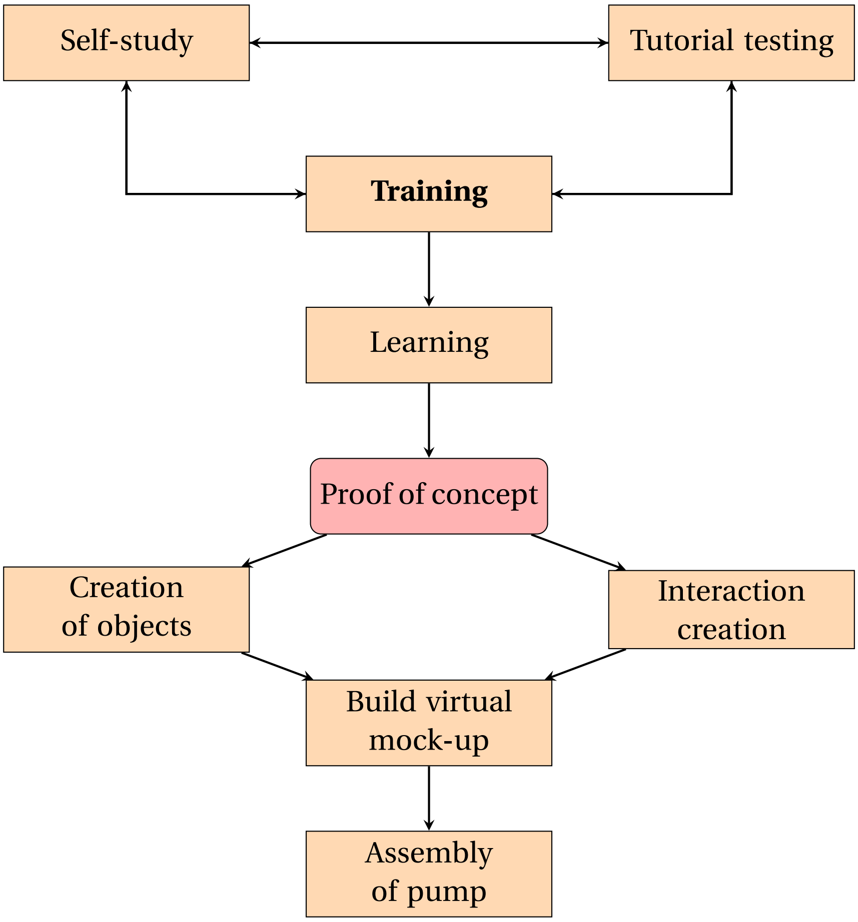

Figure 2.2: Flow chart of the laboratory work procedure. Comment: The learning tab represents the bare minimum of skill needed to be able to conduct the proof of concept, but the learning process continued throughout the lab work

2.4.1 Learning to use the System

Learning how to use the MoCap Technology

Inital and Online training by Synertial

Initial instruction on the use of the Synertial™ motion capture suit, Syndash-PRO, Syndash, Siemens Jack 9.0 and other programs that ended up not being used in this thesis, was carried out during a 20-hour seminar held over two days at NTNU. A representative from Synertial™ flew in from the United Kingdom to provide the instruction. The seminar was to provide the technician adequate knowledge and experience with the motion capture technology, such that further instruction over the internet was possible. Three instances of training over video-conferencing and email correspondence was the extent of the online training.

Learning by using

After the seminar provided by Synertial, the author of this thesis tried to recreate the seminar. Many hours were used gaining proficiency of all elements of the suit, including troubleshoot-ing and maintenance work.

2.4.2 Learning how to use HTC Vive

The time to get proficient with the HTC Vive system was minimal. The set-up has a very intuitive tutorial to follow.

2.4.3 Learning how to use Tecnomatix Jack 9.0

Jack 9.0

Proficiency in the program was achieved through reading the usermanual and completing the tutorials available with the software package. The process was time consuming needing several days to complete.

MoCap-interaction plug-in

Learning how to use the plugin took about the same amount of time it took to learn how to use jack 9.0. There was a user manual and a few examples available on potential use. It was written by a third party company and written to be used with different hardware.

2.4.4 Proof of concept

The system was first tested on an example scenario provided with the plug-in. The POC was decided to assemble one object to another in the example scene in the plugin. This was achieved with an operator on 4 april 2019, and that started the creation of the environment.

2.5 Creating the Immersive environment

2.5.1 Deciding on assembly task

En assembly task is a good representation of a workstation. The pump was chosen because the laboratory had acquired 3 pumps of Grundfos JP-6 and JP-5 models. These pumps were purchased because of the availability of replaceable components if parts where broken. The pump is simple to disassemble and require no special skills, as long as you refrain from disassembling the electrical components and the mechanical power-transmission. These characteristics made it readily available for use in the immersive environment.

2.5.2 Creating the 3D models

CAD models used in this thesis was created in Dassault Solidworks$^{\text{TM}}$ 2018 student edition. The producer of the assembly workstation bench provided partial and incomplete CAD models, and the needed to be completed using Solidworks$^{\text{TM}}$. The pump and the workstation bench was re-created in full scale. The available real-life components were hand-measured and than modelled digitally. The CAD modelling demanded a significant amount of time; over 30 hours.

2.5.3 Importing from CAD to Immersive reality platform

The parts to the 3D CAD models used in this thesis was created in Solidworks$^{\text{TM}}$ 2018 and ported to Siemens NX as .STEP files (Appendix A) for assembly. The reason for the use of two programs in the 3D-modelling stage was two reasons. The first reason was because of the difference in the author's prior experience with the programs. The modeling speed of the author is significantly faster in Solidworks$^{\text{TM}}$ over NX. The assemblies were created in Siemens NX because of a restriction in the import format of files for use with the MoCap-interaction plug-in in Jack 9.0. The Files has to be exported as a Siemens specific .jt files(Appendix A), which Solidworks$^{\text{TM}}$ at this time is not able to do without additional third-party software. So to assure smooth importation and translation between the software, this was the fastest solution.

2.5.4 Creating the scenes

When creating an environment using the software, there is a need for two scenes. The initial scene, functioning as the start point, and the final scene is acting as the endpoint. Counter-intuitively, creating the endpoint is the first scene to set-up. The scene is created by importing all the objects. In order for objects to be interactive, assemblies have to be imported as individual parts and assembled in their desired end locations. Manipulation of objects is done by click-and-drag. When finalised, the position and orientation of all the objects of the final scene are saved in files. When creating the Initial scene, the final scene is loaded, and by the same click-and-drag manipulation, the components are relocated to the desired starting positions. The initial scene is saved, and a configuration is done to the positional data file such that the system recognises that the final positions are the same as in the final scene.

Chapter 3

Theoretical Background and Literature Study

This chapter contains the theoretical background of the topics discussed in this thesis. It starts by presenting the topic of workstation design. The section starts by explaining human-centred design what it is and what it is used for. The section then continues to explain how a workstation design process is staged and gives a detailed explanation of the respective steps of the process. The theory chapter then continues to present the topic of Human Factors and ergonomics and gives an introduction into the different elements of that field, which is used within workstation design. After this, there is a section on motion-time studies and movement. The last parts that are introduced is an overview of motion capture technology to give the reader an understanding of the technology, followed by a section on immersive reality. The chapter ends with the literature study identifying a research gap by assessing literature of related work.

3.1 Workstation Design

3.1.1 Human-Centered Design

There are three dominant design paradigms adopted by large numbers of designers and professionals; Technology driven design, sustainability design, and Human-centred design. These three approaches emphasise characteristics and their priority within the design, based on the specific values and discourse adopted by the designers (Giacomin, 2014). Given the task of designing a transport vehicle, the three approaches mentioned would produce very different solutions, all emphasising different characteristics. Technology-driven-design focuses on the technologies abilities and nothing else they would maximise for technological performance. Sustainable-design focuses on the environmental impact of the product during the life cycle. Human-centred design traditionally focuses on ergonomics and Human factors but has also incorporated mental well-being and should lead to physically and cognitively intuitive designs (Giacomin, 2014). Projects including virtual reality, the leading measures of progress is always the user experience, making it essential to have a human centred design Jerald (2015). A Human-Centred Design approach needs to have a representative of an end user testing the design as early as possible to retain the focus on human elements and keep this focus present during the entire design process, and not just add "fixes" and workarounds at the end of a design process when its to late (Jerald, 2015; Wickens et al., 2014; Giacomin, 2014; Greig et al., 2018).

3.1.2 The Workstation Design Process

Many factors go into the creation of a workstation from facilities planning. The theory identifies many of the factors governing workstation design. When designing an industrial workstation, it is essential to include the abilities and functions of the operator contributing to task requirements, and not only focus on improving the workstation's equipment performance. Lost productivity and avoidable injuries are products of poor workstation design (Das and Sengupta, 1996). The organisation of the workstation minimises material handling, reduces worker fatigue and increases efficiency. Therefore, the time used for searching for and selecting tools should be minimised, such that the most frequently used tools are close to the worker. Working in awkward positions increases the risk of injury and quickly leads to fatigue, and should also be avoided (Muhundhan, 2013). Usually, as shown in figure 3.1, the process of designing a workstation can be divided into three steps. Visualisation, mock-up testing and prototype creation.

Figure 3.1: Three stages of a workstation design process.Visualisation, physical mock-up, CAD prototype and finished product.(*Photo: https://www.cardboardengineering.de/, access date: 06 june 2019*)

Das and Sengupta presents a systematic approach on how to incorporate ergonomic factors into the design process and to define the design parameters. The process is divided into ten steps, shown in figure 3.2. The steps suggested by Das and Sengupta, introduced in figure 3.2 needs some embellishment to descriptive.

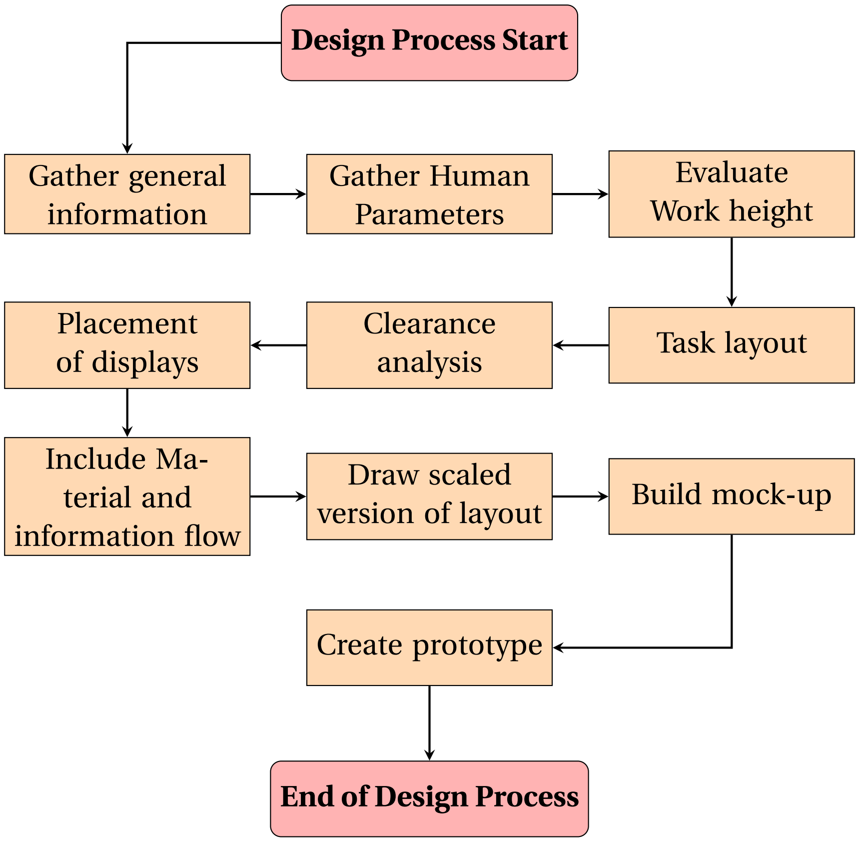

Figure 3.2: The workstation design process. Inspired from Das and Sengupta (1996)

Gather General Information

Gathering relevant information is the natural starting point of any design endeavour, some factors influence and dictated what elements are necessary to perform the tasks of the workstation efficiently, and they need to be identified. There are several layers of information needed, including information on how to perform the task, the equipment needed, the work posture of similar activities and the environment the WS will be placed. All this information brings constraints into the design, which is important to produce a productive end product.

Gather Human Parameters

Knowing the demographics of the workforce is important such that scaling can be done to fit the workers' physical measurements. This scaling can be done either by acquiring measurements from inside the company or use statistical data from surveys.

Evaluate Work Height

Locating the height range of the tasks that are going to be performed at the station. Are the tasks done seated or standing? Does the bench or the chair need to be adjustable? Do the tasks include lifting of objects, maybe a lifting mechanism should be added? Questions like this need to be known since posture has a massive impact on the development of work-related ergonomic injuries (Cavatorta and DiPardo, 2009).

Task Layout

At this stage, all tools, levers, controls and the different bins needed to perform the workstation tasks should be laid out inside the Working Area, figure 3.5. There should be a clear idea of which objects are used with the highest frequency at this stage if the design process. Start by placing the most frequently used objects and tools inside the Normal Work area, continue this until there is no more space, then place the remaining objects within the maximum work area. Some objects may have constraints connected to size and weight, which make this impractical or impossible, and choices about what type of technology versions of the tools, (e.g. battery drill versus cable drill), but this process is more about getting an idea of the space requirements, and to gain understanding about the tools needed.

Clearance Analysis

There needs to be a consideration of where the worker needs to have clearance, such that there is adequate room for the worker with the tools and equipment. One example is that if the worker needs to wear headgear, this needs to be included in the clearance analysis.

Placement Of Displays

If the workstation has digital displays or other analogue versions of displays, such as paper clipboards, there should be careful consideration on the potential placement. The displays should be placed within the normal field of vision to avoid discomfort in the neck. The dependence on the display should also be taken into account when suggesting placement.

Include Material Flow And Information Flow

Considerations of which direction the material and information flows can influence the design. Several elements can contribute to poorly designed workstations, including but not limited to the orientation of workstation compared to the material flow direction, demands for ease of access in specific directions and the overall layout of the workstation. Das and Sengupta recommends seeking out already existing functional models and experienced personnel for information about essential requirements that will influence the design.

Draw Scaled Version Of Layout

This part of the design process is the accumulation of all the previous steps in the process. This stage is where the engineers try to draw a scaled version of the workstation with all elements present. In figure 3.1, the first step is an example of a visual drawing. In the figure, they made small drawings of all the elements that will make up the layout place them in logical positions and within reach of the worker as explained earlier. The smaller drawings are then used to facilitate the creation of the preliminary two-dimensional model of the workstation. This preliminary model will be the basis for the light-material mock-up.

Build Mock-up

The next step in the design process is building a light-material mock-up of the workstation. In figure 3.3, engineers are building a physical mock-up of the future design in cardboard. The mock-ups are used to get a better understanding and feel for the design compared to the two-dimensional version created in the previous stage. Building a light-material mock-up is both time-consuming and labour intensive, making it costly, such that thorough work should be dedicated to the visualisation of the future workstation. There are several areas of expertise included in the building a mock-up. When testing the mock-up, using workers from the proper end-user population, or people with an anthropometric profile comparable to the end-user population is of great importance the workstation gets optimised for the end-user in mind. Ergonomic evaluation of posture, reach, and clearance must be conducted to illuminate unwanted design limitations. The layout is also set up using the mock-up. Several candidates of possible layouts are proposed and tested for ergonomics, motion-time studies and practicality to achieve the best possible configuration of the workstation. This process requires multiple iterations and the rebuilding of the mock-up for each layout suggestion, making the process very expensive.

Figure 3.3: Engineers are creating a cellular workstation mock-up out of cardboard. (*Photo: Staufen AG, URL: https://www.heise.de/select/ct/2019/8/1555071151816291, Access date: 06 June 2019*

Create Prototype

After solving for the optimum layout and the mock-up is redesigned to be a physical representation of the end-product, its time to produce a CAD model from the final mock-up design. Changes can still be done to the design in the digital prototype, but this is more subject to economic and physical constraints. After producing the CAD model, the design process can be considered complete.

3.2 Human Factors And Ergonomics

Often Human-factors is defined by using the goals of the field. Wickens et al. (2014) defines it as

> *The goal of human factors is to reduce human error, increase productivity, enhance safety and comfort with a specific focus on the interaction between the human and the thing of interest.*

So in other words, Human-factors is the science that concerns human interaction with systems, and thus is an integral part of human-centred design. Since we cannot change the format of the human body, except for in scale by substituting one human for another if alternative workers of the required skill level are available, we have to facilitate that the environment, equipment and tasks are designed with Human factors in-mind.

Equipment design with regards to Human factors is the design and change of equipment to increase usability through increased interaction ability (Wickens et al., 2014). A good example is a hand-held drill. For drilling holes, the only components needed is a drill-bit and a drill motor. To make it more suited to a human, increase productivity and increase precision, we add shape and accessories to the design. The ergonomic handle increases grip and disperses and balances the weight of the drill-motor during operation. The planning of button placement increases usability by, when pressed, the drill can change directions of rotation without the operator needing to move the tool or change position. Some drills even have a little flashlight illuminating the area around the drill-bit to increase precision when working in dark hard to reach places.

Environmental design takes into account human factors by changing the environment to fit a human(Wickens et al., 2014). e.g. adding rubber mats to floors to hinder falling, optimum lighting, access to basic-need facilities, countermeasures to noise and dust pollution, management strategies, among others. Designing for improved environmental conditions have significant positive effects on job performance (Cavatorta and DiPardo, 2009)(Wickens et al., 2014).

Task Design is concerned with the *way* a task is carried out. Optimisation of tasks can be centred around a specific goal (e.g. throughput rate, quality, waste reduction, human-factors), but in reality, a balance between many factors happens during the decision process. Human factors that should be evaluated include, but limited to, heavy lifting, unnecessary and dangerous movement, tool placement(Wickens et al., 2014).

3.2.1 Anthropometry - Human Parameters

Human parameters such as body size, dimensions, physical strength, mobility and the capacity for work as the primary measurements that make up Anthropometry; *the measurements of the human body* (Pheasant, 2003). Humans have a certain amount of diversity that varies with gender and demographics such that this has to be taken into account when designing workstations and workspaces (Pheasant, 2003; Wickens et al., 2014; Cavatorta and DiPardo, 2009). These differences can as many phenomena in nature, be described using The Normal distribution (Walpole, 2016). The normal distribution can model the diversity of the human body. The interesting values can be presented in percentiles

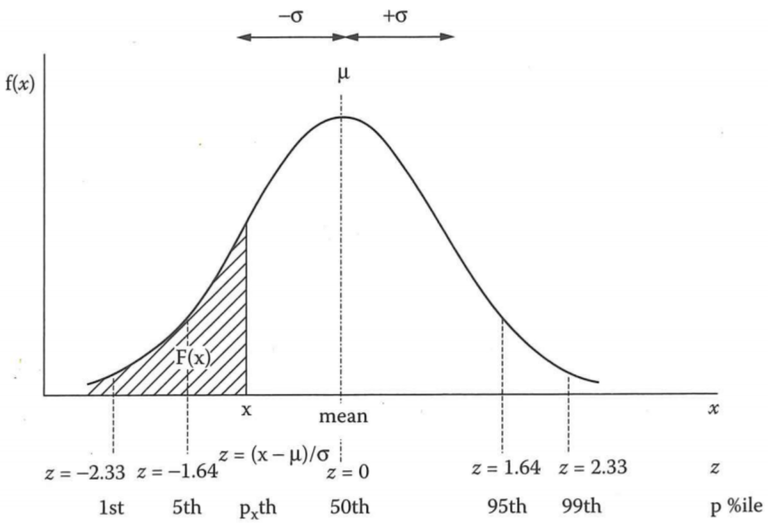

Figure 3.4: The Normal distribution with percentiles (from Pheasant (2003))

The normal distribution of human anthropometrics is divided into the 5th, 50th, and 95th percentile where the 5th percentile is the extreme small people and the 95th percentile describes the extreme spectrum of giant humans. Such that when referring to 95% of the workers, the value corresponds to the 50th percentile of humans.

3.2.2 Clearence

In workstation design, it is essential to make sure that the workstation has enough clearance for the most significant users or 95% of the workers (Wickens et al., 2014). Issues with clearance are one of the ergonomic problems that are most frequently encountered in workstations (Wickens et al., 2014), creating a loss in productivity and can potentially produce discomfort in the worker.

3.2.3 Reach

Another factor that needs addressing when designing workstations is the reach of the smallest person. Defining it as the smallest users maximum reach that can be reached without impractical stretching of the body. Pheasant (2003) describes the reach as ’The Workspace envelope’ which is the total three-dimensional volume of space a human can reach with their arms using dynamic movement. When standing, this volume is subjected to the balance of the worker, and when seated, the volume reduces because of the legs takes up space.

3.2.4 The Working Area

Work study experts define the area of a human’s convenient reach as *the maximum working area* (Barnes, 1958), illustrated by the dotted outer arches. The definition is constrained to horizontal movement since the vertical working area is different because of anatomy. When observing figure 3.5, The outer perimeter of the convenient reach of the worker in the illustration is the already mentioned maximum working area, but there is another area that is defined as the Normal working area (Pheasant, 2003). The definition provided by Pheasant of the Normal working area is "A comfortable sweeping movement of the upper limb, about the shoulder with the elbow flexed at 90° or a little less". The area is the area inside the solid lines.

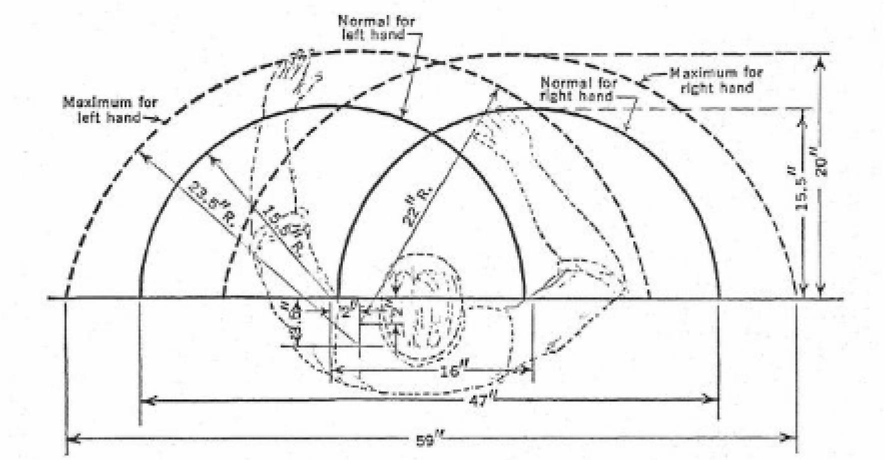

Figure 3.5: The maximum and normal work area. Dimensions are in inches, but the specific numerical values are not important for the focus of this thesis. (From Barnes (1958),*Motion and time study,4th edition, Wiley, USA*)

3.2.5 Ergonomic Evaluation Methods

There are several evaluation methods developed for use on workers. In Battini et al. (2014) a classification of the methods and their characteristics are done, and motion data, from the same data the motion capture suit used in this thesis exports, are used to calculate ergonomic values directly and can be used in design evaluations. Interested readers are encouraged to read Battini et al. (2014).

3.2.6 Ergonomics And Human factors: Performance Indicators

Proper ergonomics is essential to avoid the development of muscular skeletal disorders. Many of the cumulative trauma disorders, (CTD), are associated with bad posture while working. (Das and Sengupta, 1996) The combination of awkward positions and the repeated movements that generate with enough force generation to strain the body contribute and are strictly related to these disorders (Armstrong et al., 1986). When introducing ergonomics and the other human factors in the workplace, several performance indicators have been reported. The performance indicators are divided into Economic Indicators and social goals, Table 3.1, which give measurable results and proved the benefits of Human Factors. Cavatorta and DiPardo writes that to achieve the combination of benefits, from the economic to the social, can best be achieved by applying the human factor and ergonomics mentality broadly, providing not only technological innovations but also organisational improvements.

Economic Indicators		Social Goals	
Increased	Decreased	Increased	Decreased
Investments	Cycle Times	Workers' Health	Physical Workload
Innovativeness	Production Costs	Safety	Mental Workload
Flexibility	Human Errors	Comfort	Pain
Product Quality	System Errors	Motivation	Complaints
	Lost work time	Work Satisfaction	Injuries
	Sick leave		
	Injury costs		
	Drop in labor turnover		

Table 3.1: Economic Indicators [EI] and Social Goals[SG] from Cavatorta and DiPardo (2009)

3.3 Motion And Time Study

In the performance of a piece of work, there are tools, equipment, materials and methods used, the analysis of these elements is what is called motion and time studies. Barnes (1958) writes that the purpose of the analysis is to provide several useful functions. The overarching theme is, of course, economic motivation. A solid motion and time study it allows for standardisation of tools, equipment and materials. A benchmark of how fast a skilled worker performs the task at hand, which can be used to measure the performance of other workers and help to indicate improvement potential. When the optimum way of performing a task has been realised, it can be put to use to improve the training of new workers and achieve benchmark results faster than without the study. The ultimate purpose is to find the most economical way to perform the task, which all the formerly mentioned purposes help in achieving.

3.3.1 Movement

To Establish effective material flow and workflow within the workstation, the importance of ergonomic and motion studies becomes invaluable. In *'Facilities Planning'*, Tompkins (2010) presents five characteristics to describe the desired factors for flow within a workstation.

Movement characteristic:
Natural
Rhythmical
Simultaneous
Habitual
Symmetrical

Table 3.2: Tompkins Movement Characteristics (Adopted from Tompkins (2010)

of increased strain and fatigue experienced on the body of the operator (Tompkins, 2010). A natural movement needs to curve along with the biomechanics that dictates joint movement and the movement has to be continuous and use naturally generated momentum. Habitual and rhythmic motion is closely connected such that automatic movement sequences develop methodically; this will reduce the experienced cognitive and physical fatigue of the operator (Tompkins, 2010). Designing for simultaneous flow, coordinated use of limbs, minimise idleness of the operator when working at a workstation. It is essential to design movement such that the operator moves symmetrically around the centre of the body, assuring correct posture. Correct posture will make sure that the strain distribution acting on the operator is absorbed optimally by the body (Tompkins, 2010).

There are several methods and variations available to conduct motion time studies and task time estimation. These methods can have a massive impact on the throughput time of a workstation if included early and during the design process, though it can still produce improvements of existing workstations, the task performance will be subject to the constraint of the design of the workstation (Morlock et al., 2017).These methods are not essential for the focus of this thesis.

3.4 Technologies for Immersion

3.4.1 Terminology

☞ **Skeleton:** When the word skeleton is used throughout the text, with the exception when written as an organic skeleton. The word skeleton represents the kinematic representation of the tracked operator used inside the software platforms. When writing about the skeleton, the word represents the entire collection of segments making up the human abstraction. The skeleton is made up of segments known as bones. See figure 3.6

☞ **Bone:** The segments that make up the lines between the joints of the skeleton is known as bones. These are modified to give the skeleton the human parameters of the operator being tracked. see figure 3.6

☞ **Manikin:** A jointed model of a human, different from a mannequin in that it can move exactly as a human would. This word is used in this thesis to represent the digital rendering of the operator within the immersive environment. see figure 4.5

3.4.2 Terminology Of Users

☞ **Operator**: All the actions conducted by the person wearing the motion capture suit and immersed within the virtual reality, will henceforth be referred to as the actions of the operator.

☞ **Technician**: All actions or functions performed by the user of the system outside of the definition of the operator will henceforth be referred to as the actions of the technician.

These definitions are there to increase the clarity of whom the text is referring to an attribute to consistency. The operator and the technician can be the same person, but the title is used to distinguish between the two functions.

3.4.3 Motion Capture

Guerra-Filho and Gutemberg (2005)'s definition of Motion capture is " the process of recording the real-life movement of a subject as sequences of Cartesian coordinated in 3D space." Motion Capture features in different areas including entertainment, sports, clinical studies, and engineering (Corazza et al., 2006). The use of the technology is divided into two categories; Synthesis and Analysis (Guerra-Filho and Gutemberg, 2005). Motion synthesis is

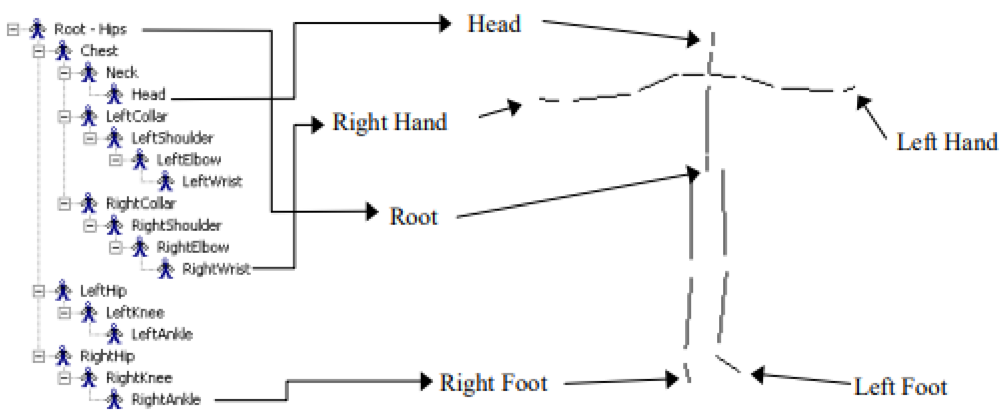

Figure 3.6: Representation of the hierarchical structure of a motion capture file. (*from Meredith and Maddock (2001)*)

the concept the average consumer thinks about when hearing about motion capture. The entertainment-industry use motion capture to create believable realism in the movement of characters, be it movies or video games. It is also used as player input to video games. Motion analysis, on the other hand, is the collection of data for scientific or medical evaluation, e.g. motion-time studies or ergonomic evaluations. In this thesis, synthesis and analysis are combined and used as input and output, respectively, of motion data to the system. This combination is the premise for the immersive capabilities of this thesis.

The input is, as explained, motion, and the output is a series of coordinates that can be saved digitally and used to calculate the position of specific points in space and time, and the angles between them (Meredith and Maddock, 2001). The technique of capture varies among the different technologies available. Motion capture can be done using colour recognition, edge recognition, point tracking and sensor transmission. There are several sets of methods and technologies on the market that allowed for real-time motion capture. They can be clumped together into two main categories, Optical and Non-optical.

3.4.4 Optical Motion Capture

Optical Motion Capture(OMC) are high-end versions of motion capture. They all consist of one or more cameras, depending on the need for angles, and reflective markers to track. When using markers, the computer software tracks the brightly coloured points on the suit and extract data (Guerra-Filho and Gutemberg, 2005). The Markerless Optical Motion Capture technology uses a technique called visual hull reconstruction to generate a motion capture model. Contrary to OMC, Markerless-OMC does not use markers, eliminating the limitations of influencing movement and the skin artefact phenomenon (Corazza et al., 2006). Skin-artefact describes the travel a measuring point moves when a sensor or marker has unwanted movement sliding atop the suit-operators skin and is not following the organic skele-

Figure 3.7: Optical motion capture session of recording for a major cinematic movie (Courtesy of Animatrix. All rights reserved)

ton of the operator consistently. The markerless-technique uses several cameras pointed at the human and uses silhouette recognition and a statistical algorithm to generate the visual hull, a 3d model of the surface of the tracked individual, from the intersecting camera planes(Corazza et al., 2006) illustrated by figure 3.8.

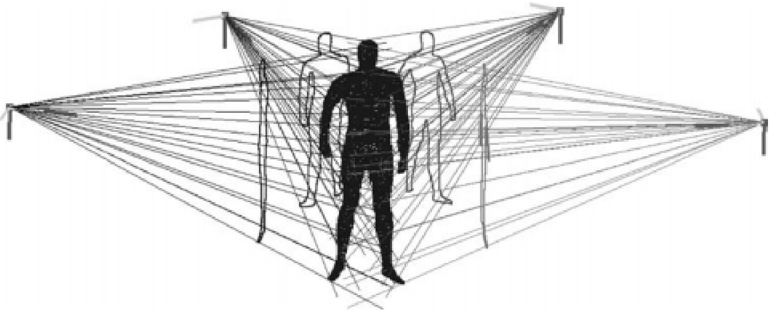

Figure 3.8: Intersection of camera planes. illustration: Corazza et al. (2006)

Markerless-OMC provides excellent freedom of movement since markers used in Marker-based-OMC can influence movement. The placing of markers can be time-consuming (Corazza et al., 2006). Both methods need large amounts of equipment. All forms of OMC also has the limitation of demanding a controlled static environment to achieve high-quality results. In order to triangulate a marker's position sufficiently, there is a need for a minimum of four cameras. The accuracy increases with numbers of cameras, valid for marker-less OMC also, but according to Meredith and Maddock, there is generally not useful to exceed 32 cameras. Cinematic motion capture exemplifies the significant amount of equipment needed for OMC in motion pictures, which demand very high-quality data. Figure 3.7 was provided to the author by the motion capture company Animatrix, which is the leader in motion capture in the entertainment industry. Animatrix has delivered motion capture for use in the newest instalments of the Star Wars saga, Avengers: Endgame, Avengers: Infinity War and great titles from the videogame industry. Figure 3.7 shows the amount of equipment needed for capturing motion at the accuracy needed. In the image 3.7, the large number of cameras are oriented in such a way to capture as many angles as possible, and the image also shows the sizeable controlled area such amounts of equipment demand.

3.4.5 Non-Optical Motion Capture

The use of Inertial measurement units(IMU) is another way to conduct motion capture. A full body suit has several IMUs grafted into the fabric of the suit and placed close to the skin of the suit-operator and specific locations. The IMU data is processed through extended Kalman filtering and transmitted through telecommunication signals, e.g. wifi, Bluetooth.(Caputo et al., 2019) The function of the entire system is the use of sensors, and a linearised estimation of the non-linear relationship between the sensors (Welch and Bishop, 1997)to compute orientation and positional data, from multi-axial accelerometers, gyroscopes and magnetometers (Szczęsna et al., 2017).

Figure 3.9: Operator wearing an IMU-MoCap suit while connected to HTC Vive.

Since there are no cameras involved in the motion capture, it removes the need for a controlled environment and total freedom of movement within the range of the receiver. Just as marker-based OMC the suit is subject to possible skin artefact since the sensors are not attached to the bones of the human but worn on the outside of the skin.

Other systems are based on receivers measuring the flux of low-frequency magnetic fields induced by dipole markers placed on body joints (Yabukami et al., 2000).

3.4.6 Immersive Virtual Reality

Berg and Vance (2017) describes VR as "a set of technologies that enable people to immersively experience a world beyond reality." The technology makes use of the human sensory system to produce a virtual experience. Computers generate the environment and translate it into sensory input for human consumption, such as visual and audible representation with or without interaction capabilities. In creating a platform that is capable of producing a virtual reality environment, both input and output devices are essential. Input-devices sends commands to the program, and output-devices lets the operator experience the response. Projection based systems (Powerwall, CAVE) (Cruz-Neira et al., 2002) and Head-mounted-displays (HMDs), such as the HTC Vive HMD (HTC, 2019), outputs a graphical representation of the digital environment displayed through googles to the operator or projected on screens. Some devices have haptic-capabilities in which the hand-controllers generate a physical response when fulfilling certain program conditions (Anthes et al., 2016)(Berg and Vance, 2016). The controllers are often the primary input device with buttons and analogue-joysticks movement for interaction commands. Newer iterations of HMDs and controllers also have tracking capabilities which input movement and position of the devices, such that when the operator moves his head, the environment responds realistically(Anthes et al., 2016). This feature can also be used to navigate within 3d-space. This thesis heavily exploits this feature. The last type of input device that creates a significant degree of immersion to a virtual representation is when VR couples with body tracking technology, or motion capture under which it is more commonly known. In this thesis, the technology is represented by the Synertial Motion-Capture suit.

3.5 Literature study

3.5.1 Related research on workstation design using digital mock-ups, immersive capabilities and motion capture:

Application of Immersive reality in industrial settings is not a new idea. The potential of Virtual reality technology has not gone unnoticed but has been limited in application because of price and lack of maturity. With technology evolving ever faster, driven by gaming and video entertainment industries (Anthes et al., 2016) and the increased ease of use means that the technology is available to more companies than ever before. In Chagué and Charbonnier (2016), the authors present a fully immersive system using optical motion tracking. The proposed system comprises of HMD, hand-held controllers and outfits the operator with an integrated backpack, covered with motion-tracking-markers, containing a power source for the HMD and a WIFI transmitter. The pack enables cable-free movement for the operator within the confined area covered by the Mocap-cameras. The system combines the inertial-tracking of the HMD with the optical capture of the camera system to reduce latency and better eliminate positional drift in the virtual environment. Haptic interaction with the environment is simulated using the placement of markers on physical objects which renders to their desired appearance in the virtual setting. The operator can, therefore, pick up a physical thing in real life while experiencing different colour characteristics in the virtual environment. i.e. a stick with markers can become a burning torch. The paper only suggests recreational use of the system.

Podkosova et al. (2016) has developed a system for use in large areas in sizes up to 200m^2. The system enables multiple users to experience the same instance concurrently. Each user is outfitted with an HMD for visual capability, a mobile-phone for small-object recognition and an inertial motion capture suit for body tracking. A laptop is strapped to the user's back for local-rendering to reduce latency before transmitting over WIFI to a VR-gaming software. The system focuses on simultaneous multiple user immersive experience. The interactive in-game objects are real physical objects with markers for optical tracking. These objects provide haptic feedback and are rendered in-game to different visual representations. The article mentions the applicability to entertainment centres. With technology driving change in the manufacturing industry, under the umbrella term of Industry 4.0, immersive reality can no longer be considered ((Caputo et al., 2018)) to have only entertainment value, or considered as niece technology that is only available to corporate giants like Lockheed Martin and BMW.

Berg and Vance (2017)'s survey concludes that virtual reality technology is readily available and industrial exploitation has become prevalent. The survey includes 18 companies in 7 different industries. Of the Thirty-seven identified facilities, 40% are classified as Spatially immersive devices (SID) and projection based systems, but the presence of professional motion capture technology was non-existent. One example of an industrial application described by Berg and Vance (2017) is Ford Motor Co's use of HMD, physical props and force sensors to support ergonomics engineers in ergonomics evaluations of product design criteria.
Design evaluation and clearance studies are applications that Virtual reality is well suited. Gaining insight into the design of products without producing expensive mock-ups have the potential of saving manufacturers money.

Berg and Vance (2016) conducted a case study on the use of immersive virtual reality as a general design tool for product design. The focus of the paper is what can be done from a technological standpoint and how the use of immersive virtual reality influences the decisions done during the design process. The technology used in the experiment is a three-walled projection of the environment, and a Nintendo Wii Remote controller is used as an input device. After three design reviews, two resulted in significant design changes.

Guo et al. (2018) proposes an immersive maintainability verification and evaluation system based on virtual reality. The system is supposed to be used in early design stages to help make good design decisions by evaluating a digital mock-up of the end product. They argue that designing for good maintainability is paramount in complex products and that desktop simulations are inferior compared to their type of immersive system. Guo et al.'s system is based on the CAVE-design (Cruz-Neira et al., 2002) with tracking by HMD internal sensors, optical motion capture with six cameras and joystick controllers for interaction purposes. The use of virtual representation for use in workstation design is well established, and software on the market has different features to assist in the design process. The academic research into workstation design usually has the topics of comparisons of real-life mock-ups of the station and digital virtual mock-ups.

Bligård et al. (2018) experimented comparing different scale and versions of mock-ups to examine the feedback each of the three models tested generated under a workstation evaluation. The comparison consisted of creating mock-ups of a ship bridge workstation in 1:1 scale physical version, a 1:16 dollhouse version and a CAD version. The study found that CAD models were the best of the three on real design evaluation. For the evaluation of validity, Bligård et al. perceived the 1:1 model to be the best. The CAD model was evaluated on a screen using a mouse for interaction, hence no immersion.

In a real case study, Cimino et al. (2009) created a 3D-CAD evaluation model of two different workstations. The redesigning uses CAD models to simulate changes to the layout based on removing the ergonomic issues. Cimino et al. shows a connection between improved ergonomics relation to improved productivity. The movement was programmed to simulate worker-movement of a skinning workstation and an assembly workstation. The authors performed ergonomics evaluations and measured the changes made in the redesign proposal using MTM-analysis and MOST-studies and changes in caloric expenditure performing the tasks. Relative to the initial workstation design, they showed in some operations caloric reduction of 28%, process task time reduction of 53% and a total productivity increase of 55%.

Jayaram et al. (2007) tried to determine if industrial assembly situations could be modelled and realistically studied using immersive virtual interaction capabilities. The paper presents two detailed industrial case studies and concluded that the technologies were mature enough for continued research and that the technologies have great potential. Most of the limitations that were identified by the case studies such as oversimplification of design, restricted human movement and lack of realism are subject to the fact that the technology was in its infancy in 2007. This paper deserved mentioning even though it is old relative to today's VR-technology capabilities, because of its close relation to the topic of this thesis.

Pontonnier et al. (2012) designs and evaluates workstation design using assembly operations. Three approached was compared; Assembly task in reality, assembly task in Virtual reality, and assembly task in an immersive setting, meaning a combination of virtual reality and a haptic device. The technology system used in this article is massive. The Visual Virtual reality used 15+ projectors for wall and floor displays. The motion tracking was done using 16 optical IR cameras, and muscle activity were tracked using electromyography. EMG can record and measure the electrical activity within the muscles of the operator (De Luca, 1997). The force feedback provided used a mechanical manipulator functioning as a haptic device. The assembly operation consisted of sorting and placing objects. With the technology used and the task completed by ten operators, they concluded that the virtual environment was more realistic than the immersive environment with haptics. The interaction also appeared less realistic. They observed less natural movement in the virtual environment than the real setting.

In Vosniakos et al. (2017) an immersive system comprising of motion capture through a Kinect II sensor and HMD is used to model an assembly operation of large mechanical parts. The assembly operation involved using hand-held tools. Positional data and ergonomics evaluations were developed to use the motion capture data from the manikin created in Unity3D. The article reported a lack of precision when tracking more delicate movement, and recommended adding inertial tracking to capture hand gestures better. Because of the technologies characteristics, the operator had to stay close to stationary because of the range of the Kinect and cables.

Caputo et al. (2018) created used inertial motion capture to perform preventative ergonomic evaluations of workstations. The authors created a 1:1 digital representation of the workstation being evaluated, and used the motion data captured from the suit-operator while executing tasks. The captured motion data is used to move a manikin inside the virtual representation, and all the forces and tool use is programmed in to be analysed by the programs ergonomic analysis features. There is no use of immersive reality in this paper.
Peruzzini et al. writes about a human-centred virtual simulation environment in their conference article about "redesign of workstations in the pipe industry"(Peruzzini et al., 2017a). In the article, the authors demonstrate benefits through an industrial case study the use of this environment to optimise physical ergonomics. In this article, they compare two methods of simulation. The first being a pre-programmed simulation of a digital environment with added digital manikins. Using camera footage of real-life tasks performed at the existing workstation, the movements of the manikins are meticulously programmed by a human into the system mimicking the workers in the footage. The other method they compared with is in what they describe as a "mixed reality immersive environment"Peruzzini et al. (2017a). The mixed reality consists of optical motion capture tracking in a controlled environment with a real-life physical mock-up. The operator acts out the movements associated with the workstation on the mock-up, and the motion capture system transfers the tracked movement data to software for evaluation. The transferred data connects to a manikin inside the

software, so the operator and manikin are linked and produces ergonomics reports from the manikins movements. Peruzzini et al. (2017a) shows that the quality of the results generated from the mixed reality was higher than from the programmed simulation. They also concluded that the level of detail increased with the mixed reality compared to the simulated. They show clear benefits in the use of mixed reality immersive environments in workstation design. The authors published a journal article containing the same case study and comparison Peruzzini et al. (2017b) but with a comprehensive qualitative comparison and not just a proof of the benefits like in Peruzzini et al. (2017a). Here they mention long preparation set-ups of 2-3 weeks of the system because of system complexity, creation of the physical mock-up, calibration, modelling and Mocap to VR interfacing.

Peruzzini et al. conducts a comparison in Peruzzini et al. (2019) between a standard desktop simulation using Digital manikins with programmed movement, and the mixed reality immersive reality. The results from that comparison are then subsequently compared with the traditional evaluations done on the real-life workstations written about in (Peruzzini et al., 2017b). The paper compares the effectiveness of the two tools in the redesign of operator actions during tasks by analysing both cognitive and physical workloads of the two different methods. The study shows that a mixed reality immersive environment improves the quality of ergonomics analysis compared to the desktop version. Virtual training of workers is also one of the great potentials of immersive technology.

Grajewski et al. argue that that simulations like this can be used to train future personnel and conduct ergonomics studies all without the need to produce a physical mock-up prototype of the workplace or product. The set of technologies in Grajewski et al. (2015) includes HMD coupled with positional tracking for stereoscopic vision, different haptic devices representing tools, and tracking gloves for gesture recognition. These technologies are tested as a system and isolated from each other. The authors mixed the use of physical and virtual objects in the study to enhance the immersion of the training operator. The article concludes that using haptics in this manner reduces the immersive experience of the user because of the need to maintain a stationary position.

Article	State-of-the-art	Consumer	Industrial
Anthes et al. (2016)	✓	✓	
Berg and Vance (2017)	✓		✓

Table 3.3: Central and Informative Surveys

Article	WS design	Pro design	IRIM	MOCAP
Jayaram et al. (2007)	✓		Desktop	
Cimino et al. (2009)	✓		Desktop	
Pontonnier et al. (2012)	✓		Haptics	OMC+EMG
Grajewski et al. (2015)	✓		Force feedback	Tracking gloves
Podkosova et al. (2016)			Mixed	IMC
Chagué and Charbonnier (2016)			Mixed	OMC
Berg and Vance (2016)		✓	Controller	OMC Projection
Vosniakos et al. (2017)	✓		Mixed	Kinect II
Peruzzini et al. (2017a)	✓		Mixed	OMC Projection
Peruzzini et al. (2017b)	✓		Mixed	OMC Projection
Peruzzini et al. (2019)	✓		Mixed	OMC Projection
Bligård et al. (2018)	✓		Desktop	
Guo et al. (2018)		✓	Controller	OMC CAVE
Caputo et al. (2018)	✓		Recording	IMC

Table 3.4: Overview of the articles and their topics. Acronyms: WS is short for Workstation, Pro is short for Product, IRS is short for Immersive reality interaction method, MOCAP is short for motion capture. OMC and IMC means Optical and Inertial motion capture

By looking at the relevant results of the use of immersive reality within workstation design, the trend is that the technology has been predominantly used for visual inspection, meaning that the function of the virtual environment is for observation only. Others have captured motion first then used that motion to program simulation in some pre-existing software with ergonomic evaluation capabilities, or increasing haptic response by using physical objects to achieve mixed reality. Most of the articles use limited motion capture, compared to the technology available in this thesis. By reading the articles in table 3.4 and table 3.3, an academic gap can be found surrounding the use of immersive reality combined with advanced inertial motion capture technology to design industrial workstations without the need to build a physical mock-up. In other words, an entirely virtual mock-up. When observing the IRIM-column in table 3.4 we can observe that there is always either some physical elements involved, where "mixed" is used as a description for mixed reality, "Haptics" and "Force feedback" is some form of device or object providing touch-response, which show that no virtual mock-up only have been done. Some of the articles have conducted digital simulations using programmed animation or recordings of motion capture, but not using real-time motion capture. Others have used real-time but use controllers for interaction, not realistic hand gestures like in this thesis. Observing the MOCAP-column in table 3.4, There is little use of lightweight inertial motion capture suits, except for in Caputo et al. (2018) which only uses recordings of worker-movements from real-life tasks, but multiple instances of large equipment heavy and spatially demanding optical motion capture systems is found. Compacting the workstation design process by using virtual solutions and as a consequence reducing the need for multiple physical iterations of light-material physical mock-ups has not been researched using a time-effort study. There is also a gap about where a virtual mock-up's natural place and to what degree its application is useful within the workstation design process itself. Given the findings from Cimino et al. (2009) concerning the significant improvements to productivity, reducing the amount of time used to conduct the evaluations, even more, will have considerable compounding effects on the productivity of a workstation.

Chapter 4

System Set-Up and Laboratory work

This chapter constitutes the laboratory work done in this thesis. It starts with an introduction to the system that has been used to perform the laboratory work. After this, it presents the suit-operators that has participated in this project and gives an introduction in the specificity of the skeletons used in the environment. Moving through the chapter, a presentation of the immersive environment created, the interactions that make it immersive and the assembly operation is explained. The rules of the environment are explained.

4.1 System Description

The system used in the laboratory work is quite extensive and includes the necessary technology to create an immersive environment and the associated assembly task. The information flow and data exchange between the different elements is illustrated in figure 4.1, and a description of all the components in the system and their function follows in the following subsections.

4.1.1 Software

Steam VR

Steam VR is the software that pairs all the devices constituting the HTC Vive system together. It also uses the devices to calibrate the space for VR-immersion and acts as an interface for VR-videogames purchasable on Steam^{TM}.

Siemens Tecnomatix Jack 9.0

The application of this product during the thesis is unorthodox. The software provides interaction capabilities and outputting stereoscopic video feed to the HTC HMD. There is no use of the software's integrated analysis functions or programmable animations.

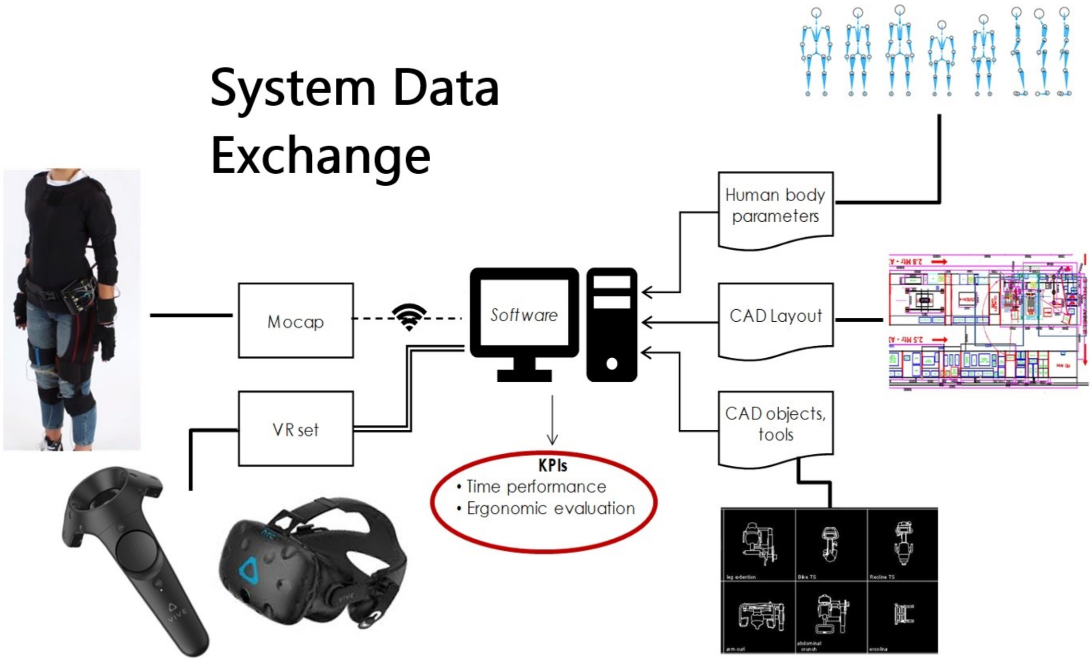

Figure 4.1: System data exchange diagram (modified from Battini et al. (2018))

Solidworks^{TM} 2018 student edition

CAD platform developed by Dassault Systèmes. The CAD software is needed to produce the desired models used to create the virtual environment.

Siemens NX v.12

NX is a Computer Aided Design (CAD), Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) program developed by Siemens. Needed for .jt file generation.

SynShow

SynShow is the diagnostic program used to identify and monitor the connectivity of the motion capture suit, cobra gloves. It displays the number of sensors transmitting and the quality of the signal, ranging from unreliable to High accuracy.

SynDash-PRO

SynDash is a computer program developed by Synertial^{TM} that receives data the Synertial^{TM} Motion capture suit with gloves. The program uses this data to generate an animated representation of the tracked motion, figure 4.2. The program allows interpolation between sensors to tailor the skeleton to match the human parameters of the suit-operator. The program acts as an interface with the HTC Vive by integrating the tracking capabilities of the HTC into the skeleton animation. The real-time tracking feed generated by the suit and HTC Vive trackers compiles into a feed which allows the technician to connect the feed with Jack 9.0 or other compatible platforms. SynDash-PRO supports recording and exportation of motion data into file formats for analysis. The software is also the calibration station of the system.

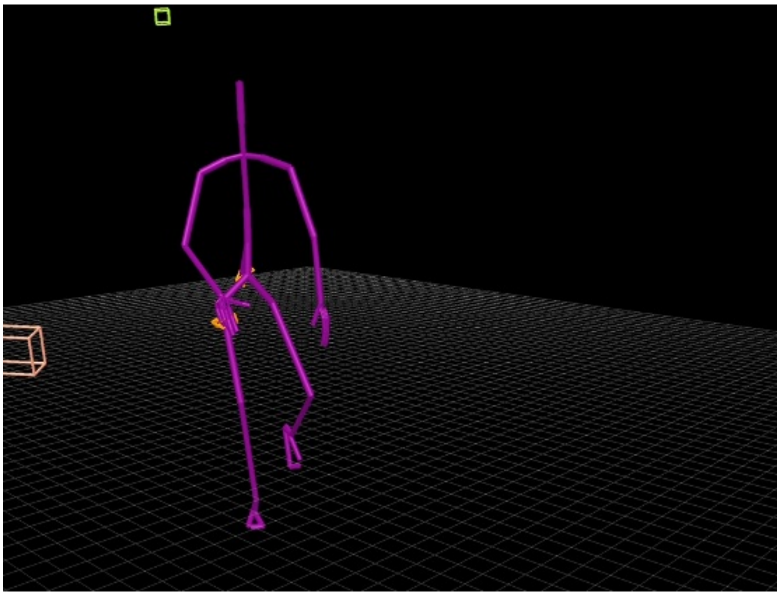

Figure 4.2: Male 3 represented as MoCap-animation in Syndash-PRO

4.1.2 Hardware

Synertial$^{\mathrm{TM}}$ Motion Capture Suit

The suit consists of sensors, jacket, pants, wifi hub, gloves and battery pack. The suit with the gloves has a total of 29 sensors, all of them are inertial measurement units (IMU's), distributed across the operator's body to capture body movement. Each sensor is a 9-axis IMU consisting of accelerometers and gyroscopes and magnetometers that transfers the real-time orientation of the IMU to a computer. With this information, it is possible to generate an extremely accurate real-time model of the operator. Data is processed using extended Kalman filtering, and the data is transferred using wifi. The number of sensors in the suit can be increased for higher accuracy.

Synertial$^{\mathrm{TM}}$ Cobra Gloves

The gloves used in this paper have 8-IMUs of the same type used in the suit. For a realistic representation of movement, the software gives the technician the ability to interpolate data points between the sensors, figure 4.3. The interpolation approximates the untracked finger joints.

Figure 4.3: Sensor placing of the Cobra Glove *(www.synertial.com/gloves)*

HTC-Vive™

The Vive VR-system used with a head mounted display (HMD) and positional trackers functions as the interface between the graphical software and the operator. In other words, it lets the suit-operator enter the VR-environment and move around inside it. Without the trackers, the operator's virtual representation would move-in-place, but no translational movement would be possible.

Laptop and Wifi-router

There is no need for any specific laptop or wifi-router, but a powerful laptop is recommended. The computer used in this thesis is a CEPTRE GAMING X540-01, using an 8.Gen Intel i7-CPU, Nvidia GeForce GTX 1060 GPU and 16GB DDR4 RAM. Any modern off the shelf Wifi-router can be used.

4.1.3 Suit-Operator

Suit-operator wears the suit and gloves over tightfitting clothes with empty pockets. When entering Immersive reality, the operator is also equipt with two HTC Vive tracking sensors and the HMD.

Human parameters

Generation of useful data from the animations is subject to the bone lengths of the suit-operator. The bones have to be a 1:1 representation in the animation model. There are two reasons for this; the first is because even if the angles of movements are pretty much the same across the distribution of body size, objects are not the same size to all humans, the same goes for the variation of reach and distance to floor varies across the percentiles. Leading to the system not generating ergonomic data that is true. The second reason is that

the skeletons of Syndash-Pro and Jack 9.0 have to match to move correctly. The mismatching parameters in the two software result in the suit-operator compensating with abnormal movement, rendering the data useless. A good description is GIGO - "garbage in, garbage out".
Parameters can be hardcoded into the system using measurements, as presented in chapter 3 using anthropometric tables and percentiles based on figure 3.4, Into Syndash-Pro. Another option is to use a tool provided to help with autocalibration of the skeleton and pictures of the suit-operator inside a cube called a jig, figure 4.4. Using white stickers placed on the operator's joints, seen on the profile picture in figure 4.4 and the black corners of the jig, the creation of a Syndash-Pro skeleton file happens in minutes.

Figure 4.4: Male 3 standing inside the JIG used for skeleton calibration

Participants

The drivers for participant selected was availability and proximity; no other specific selection criteria were considered.In table 4.1 is an overview of participant characteristics. The academic operators had some connection to the laboratory, and the author of this thesis contacted male 2. Male 3 attended the initial training together with the author. Male 4 was found to be incompatible with the suit because of his body size, more comments on this in Chapter 5.

4.2 The Environment

The virtual environment created, figure 4.5, consists of two desks, an assembly operation and tools.The desks and the motor-casing of the pump are immobile. The disassembled

Operator	Age	Occupation	Nationality	Height	Weight
Assembly operators					
Male 1	22	MSc student	India	178cm	68kg
Male 2	29	Plumber	Norway	176cm	84kg
Female 1	24	MSc student	Norway	176cm	72kg
Female 2	32	Doctoral student	Ukraine	169cm	60kg
Training					
Male 3	29	Doctoral student	Italy	178cm	78kg
Incompatible					
Male 4	26	MSc student	Norway	196cm	86kg

Table 4.1: Table of Participant Characteristics

pump is distributed across the table of the workstation.The desks are not movable by the suit-operator, but the tools (2x screwdrivers) and components of the pump excluding the motor-casing are movable. The manikin is generated in front of the workstation in what is considered origo in the virtual environment. The manikin is generated in that specific position such that it is assured that the entirety of the environment is accessible and inside the boundary of the HTC Vive tracking system.

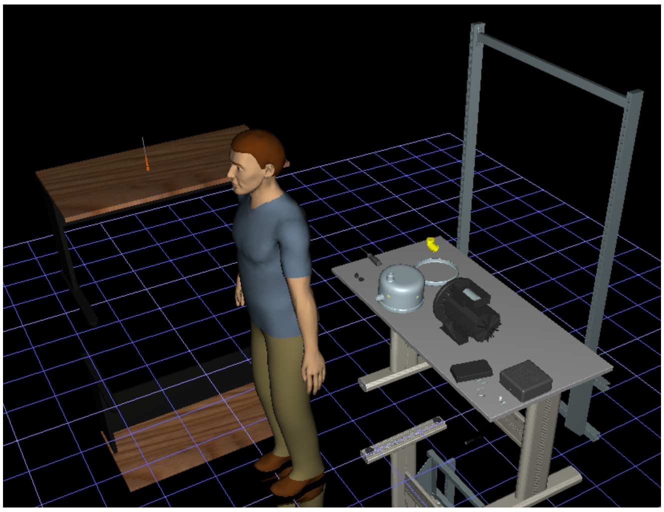

Figure 4.5: The environment before the assembly operation is carried out

4.2.1 Assembly model - Grundfos JP6 Booster pump

The pump is a replication of the Grundfos JP-6 booster pump at a 1:1 Scale, figure 4.6. The pump was chosen because of the ability to quickly replace parts if the pump is damaged during assembly and disassembly in the laboratory in real life. The pump has been disassembled

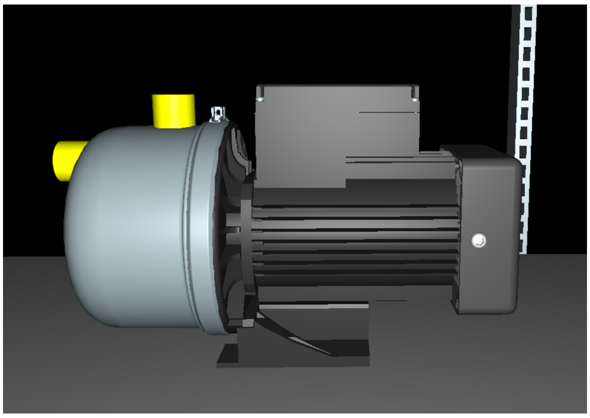

Figure 4.6: Fully assembled JP6 pump

into 16 parts listed in table 4.2 and depicted in figure 4.7, whereas all parts are movable objects within the simulation except for the motor casing which is a fixed object, and functions as the anchor piece of the assembly operation. Using an anchor piece is not necessary, but it ads some simplicity to the environment in the form of marking where the assembly is going to take place for a more intuitive experience.

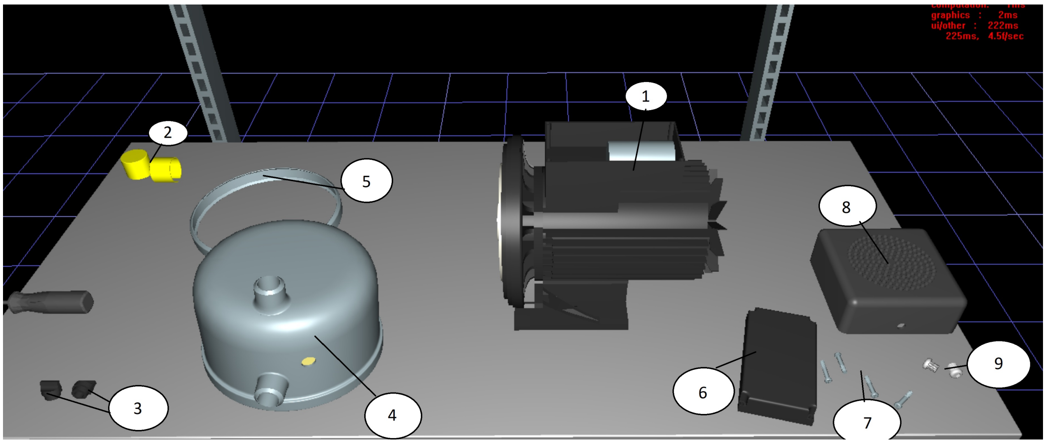

Figure 4.7: CAD of the JP-6 Assembly

Index number	Part Description	Number of parts
1	Motor-casing	1
2	Outlet Caps	2
3	Drainage Plugs	2
4	Pressure Chamber	1
5	Compression Ring	1
6	Electrical Box Lid	1
7	Electrical Box Screws	4
8	Rear Fan Cover	1
9	Rear Fan Cover Screws	2

Table 4.2: Parts constituting the assembly 4.7

4.3 Environment interaction

4.3.1 Object manipulation

Inside the environment there are two sets of objects; movable and immobile objects. The movable objects are designated specifically within the program to differentiate between the interaction possibilities of the two. In order to grab and let go of an object the program needs different inputs to carry out the commands.

Selecting an object

For the selection of objects there is a need for designation of a point-of-interaction (POI) on the manikin. In this simulation, it is possible to designate either the centre of the palm, the tip of the index finger, the tip of the thumb or at the midpoint between the three already mentioned points. It is also possible to designate POIs on both hands, thus enabling the use of two hands simultaneously. Bounding boxes form the basis for interaction between the suit-operator and the objects. A bounding box is a name used in computer science to describe the coordinates of the faces on a cube that is generated to envelop all points of a 3D-object. The bounding box is used to check for collisions between the box and the POI designated by the technician. An extra margin of 3cm added to the bounding box, expanding it to facilitate ease of gripping on small parts like screws. When the POI intersects with an objects bounding box, the software changes the colour of the object to solid yellow signifying that the object is selected and ready to be grabbed, depicted in figure 4.8 and 4.9. If the POI moves outside the bounding box, the object returns to its original colour rendering. The movable objects are loaded into the system and organised in a list. If the operator has the POI inside the bounding boxes of two objects at the same time, the object that is featured first on the list will be selected and the other ignored.

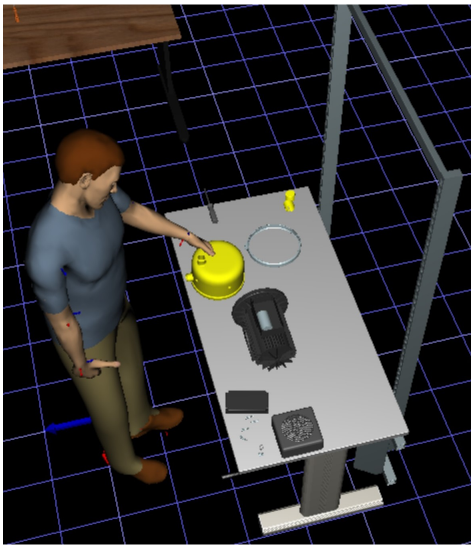

Figure 4.8: Birdseye view of Yellow glowing part ready for grabbing

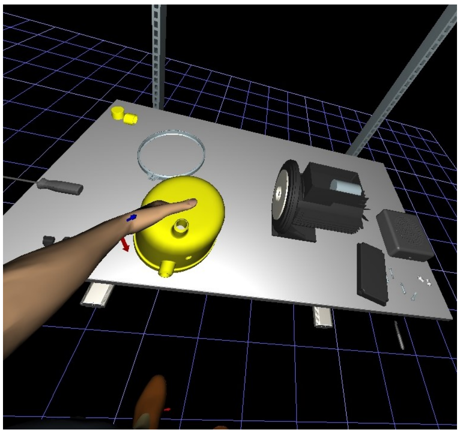

Figure 4.9: Operator view of Yellow glowing part ready for grabbing

Attaching and detaching an object

While the selected object is coloured yellow, it is ready to receive the attach command. Since the software should mimic the real-world as much as possible, attaching must feel like a human grabbing gesture. In the software, the command for attaching is the distance between the tip of the suit-operators index finger and thumb. The tolerances can be set to activate between 2.1-8.0 cm, meaning that when the fingertip distance becomes lower than the set value, the object attaches. Setting the threshold to 0.0 cm for attaching, which is possible, but in order to activate the grabbing-command, the operator has to open the fingers at least 2cm to signify grabbing-intent, avoiding involuntary interaction. The objects colour changes from the yellow selection colour back into its original rendering while being attached. It is possible to grab two things at the same time with both hands set to POI, but it is not possible to hold the same object at the same time with both hands. The object only connects to one POI at a time. To detach an object increases the distance between the fingertips until the distance is greater than the set range from 7.5-20.0cm.

4.3.2 Assembly interaction

Like the object-manipulation command, the assembly operation uses bounding spheres with an interaction radius of 11 cm. To assemble any part to the motor-casing (Table 4.2), grab the part of choice and move the part towards its intended assembly position on the motor-casing. Once the part held by the suit-operator is moved inside the 11cm radius of the bounding sphere of the corresponding assembly position if released it automatically reorients itself and attach to the assembly. For disassembly without restarting the environment, grab the part, and it detaches from the assembly, then remove it outside the 11cm radius and let go. If the part has not left the bounding sphere, it re-attaches to the assembly.

Size of parts

As mentioned before under object manipulation, the size of the bounding box of the parts corresponds to the size to the bounding boxes on the assembly, meaning that the bigger the part, the easier it is to attach that part to the assembly, since the interaction zone is also larger.

Orientation of parts

The local orientation, meaning the parts inner cartesian axes, does not have to point in the same directions as the global orientation, the immersive environments cartesian axes. The part can arrive at the assembly position and be oriented upside down and still assemble correctly. For realism purposes, this has to be taken into account when performing the assembly operation.

The uniqueness of parts

Even though in reality, a screw is a screw, in this simulation, every part is unique. This uniqueness entails that each screw has a specific assembly position, but no unique marking to tell one from another. To be able to assemble seamlessly, the suit-operator needs specific knowledge of which part goes where. This uniqueness is true for all parts of the assembly.

Intangibility of objects

Objects not under manipulation are intangible, meaning the suit operator and movable-objects can phase through objects like ghosts, figure 4.10. This ability means that it is possible to perform assembly operations by moving components through other objects, resulting in impossible procedures. There are no collision indicators used in this enviroment, but the software can give objects the ability to change colour when the suit-operator is colliding with it. There is no haptic response available to the suit-operator.

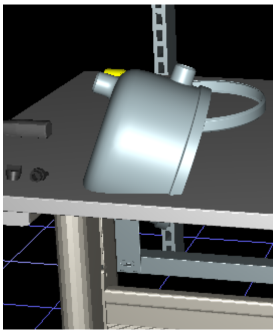

Figure 4.10: Pressure chamber phasing through desk

Sequence of assembly

The assembly operation has no specific sequence. Because of this, the pump can be put together in ways that would be considered impossible in reality. Consequences are parts floating in mid-air, figure 4.11, in the correct location but without the real-life prerequisite components.

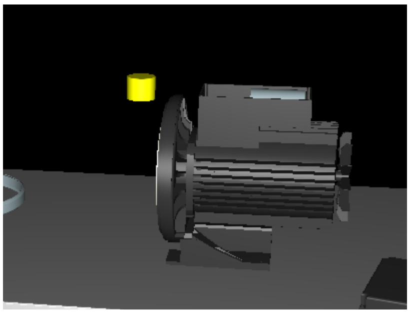

Figure 4.11: Yellow outlet cap floating in mid-air

Tool use and interaction

There is no interaction between the tools loaded into the scenario and the parts for which they are intended for in real life. When using a tool inside the simulation environment, the suit-operator has to simulate the movements of a real-life tool use.

Physics enabled objects

There are no physics-enabled objects in this simulation environment, objects have no mass, and no forces are working. The consequences are that if an object is detached from the POI in mid-air, it will stay there awaiting new interaction.

Chapter 5

Results and Discussion

This chapter presents the results produced through laboratory work. The results are combined with knowledge gained through the theoretical background presented in Chapter 3, and a time-effort estimation study is done. The time-effort estimation study works as a base for the discussion of research question 2, which is followed by the discussion of research question 3.

5.1 Findings and Observations

5.1.1 Observations

The suit-operators reported several factors of interest concerning the following topics. The tight-fitting elastic jacket of the motion capture suit has the cables and sensors mounted inside the jacket. The elastic fabric is supposed to stop a short distance beneath the elbow on a person with a body size inside of the 50th percentile, such that if the wearer's body differentiates to much from average body portions, it is not certain it will fit satisfactorily. If the operator is muscular in the upper body, like Male #2, the suit is very tight and needs to be equipped with care in order to avoid the sensors sliding out of place. Also, if the operator is very tall and long-limbed, like Male #4, there is a possibility that the operator is incompatible with the suit. Even though the operator is lanky and able to fit inside the jacket, natural movement may not be possible because of limited cable-length between the sensors. The length of the operator's body segments will pull the sensors through and outside of the jacket, putting to much strain on the connections and potentially damaging the apparatus.

The pants of the suit are equipped using elastic straps. These straps are meant to fasten the sensors to legs. If the operator has curves like female #1 and like most women naturally have, the suit is quickly at its limit. Female #1 is athletically built, meaning that larger or overweight people, especially women fitting this description, will have issues using the equipment. When investing in wearable equipment, it is essential that it fits the demographic that is meant to use it.

When multiple people use the same equipment, especially if it ha contact with skin, it is important to make a note of possible hygiene problems, since spreading of contagious elements can lead to increased absenteeism in the staff because of sickness. There was no choleric expenditure measurement study conducted during this thesis, but some interesting observations where made. Operators exhibited increased sweating after prolonged use of the suit, even while wearing little clothing underneath the suit. The sweat transferred to the suit jacket producing the need to create some form of hygiene maintenance.

How user-friendly is the technology to use? All participants, except for Male #4, found the suit easy to equip and use if the technician provided verbal instructions. The MoCap-suit can be fitted in under 5 minutes using personnel with some experience. The suit needs instructions during training since it is possible to assemble it the wrong way. Another aspect of when using the technology comes with the fact that the operator's HMD connects via wires to the computer. As with most devices connected via cable, the cables produce some constraining factors to the movement of the operator. While wearing the HMD, operators voiced concern about the potential of tripping on the power-cables exiting the HMD. While immersed, operators cannot see the cables, since they are not part of the virtual environment. The fear of tripping sometimes led to unwanted movement when simulating the assembly task. This tendency diminished with increased experience wearing and moving with the system equipped, and the operators with the most experience showed very little of abnormal movement.

During the laboratory work, there were several observations concerning the elements of interaction and realism inside the environment. The realism associated with grabbing small objects during the assembly operation is strictly related to the location of the Point-of-interaction's(POI) on the operator's hand. POI was introduced in chapter 3. The visual realism of object manipulation is different depending on if the POI is at the palm, midpoint, or the fingertips. The operator gives the grab command, when the tip of the index finger and thumb are touching, basically the operator grabs the object like he would in real life. When executing the gesture command, with the POI set to fingertips, the grabbed object does not follow the fingers when the hand of the operator closes as to grab the objects. It is attached, but the visual representation makes the object float in midair a few centimetres from the operator's hand. This property brakes the illusion of just grabbing the object and moving it naturally. However, when having the POI at the palm or the midpoint of the hand, users intuitively grab objects without any instruction from the technician, indicating a large amount of realism. When grabbing smaller objects, like screws, the bounding boxes are small, and since there is no haptic feedback from the objects, it can be challenging to pick up the objects. The object glows when it is grabbable, but it is hard to see if the POI is centred on the hand and not the fingers. When small objects relative to the manikins hand, lies on a surface, it is not possible to know when the object changes colour to yellow, indicating it is ready to attach. One observation is that even if it is possible to move the hand under the surface of the table and move it through the surface to grab the object, not one of the operators used this approach. When asked about why they did not grab it through the table, the operators answered that it would be unrealistic. Designating the POI to be on the fingertips removes this problem, but as explained, reduces the realism. Another break in realism is that it is with this set of technologies. It is not possible to seamlessly move the assembly as one piece after the completion of the assembly task. Because of this, to move the assembled pump as one, another environment with different initial and final scenes have to be created, and the assembly has to be imported into the Jack 9.0 as one single figure and loaded as a movable element. This feature also puts a constraint that the assembly cannot be rotated to increase assembly speed since the assembly end location has a fixed position and orientation. Tool use also has some flaws. When using tools, there is no interaction between the assembly parts and the tools used in the assembly. This means that the operator has to pretend to use tools or mount objects in a realistic matter. During the entire thesis, there was only one instance of VR motion sickness. Female #2 reported experiencing motion sickness after using the system for about an hour.

5.1.2 Data extraction and Analysis potential

There are several ways to generate data using this system; it just depends on the desired data format. From Syndash-Pro, motion output data exports in many different formats. Some of them are third party software specific, but it is possible to export the positional data with frame and time stamps in CVS-files and the angles between limbs in the BVH-file format. The CVS file exports data that seem to be skeleton dependent and with the skeleton used in the environment and the number of sensors, the file outputs 244 columns of data. This data is raw data from the motion capture suit. There are ways to export data from Jack 9.0 as well. All the sensors produce three-dimensional data such that plotting of the data is not straight forward and not every analysis programs, such as excel, has the functionality of 3D-plotting useful for this data. Because of this lack of capability, it is essential to know which data point to measure and when. Using the captured data available from the output files it is possible to conduct motion-time and ergonomic studies.

5.2 Analysis and Identification

5.2.1 Identification of Prerequisites: A System-technician's skills

Since the system is comprised of multiple software and technologies, the laboratory work identified certain skills that are prerequisite for a technician using the system. There also has to be a clear distinction between using the system and having enough skill to troubleshoot problems when they arise. This list is the skills needed to perform the latter. There is a need for several skills to be able to set up and use this system.

Device Understanding. The technician needs to understand at least the concepts behind the communication between the different electronic devices and software that make up the system. The technician has to be able to evaluate and locate where in the system, a communication error is happening and isolate which part of the system that is malfunctioning to fix the issues that can arise. Basic engineering understanding of sensor and network technology provides insight into the functions of the components of the system. For increased ease of use, there is potential for the development of procedures concerning the physical set-up of the hardware, and this could lower the need for a deep understanding of the system.

Understanding of computer code Programming skills are not critical for just using the system if excluding analysis of the output data. Understanding of how a machine reads computer code would be of immense value to the technician. A few times during the environment creation process there was a need to change lines of codes inside software files, and the loading sequence of objects into the VR-software are subject to the characteristics of how a computer reads code. Being oblivious to computer code will create an increased dependence on supplier support, which can lead to project delays.

A solid foundation in analysis software and statistics. Since the data is outputted in spreadsheets a solid foundation in some version of a analysis program (e.g. Microsoft Excel, Matlab, R or equivalent) is needed. No analysis tools are provided by the software suppliers.
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Knowledge in Specific field of the Analysis. To be able to use the data in ergonomics analysis, the technician has to have knowledge of the different evaluation tools, such as OWAS and RULA, and knowledge of industrial ISOs extract anything useful from the spreadsheet data exported from Syndash-PRO. Another way to conduct ergonomic evaluations is to use the integrated tools that are native to JACK 9.0, but this constrains the technician to one specific software supplier. The same goes for motion-time studies and workstation design.

Computer-Assisted-Design A significant amount of time of this thesis was used to produce CAD-models for the immersive environment. There are several advantages to having experience with CAD-design. Understanding the relations between components and parts in a CAD assembly helps understand the import procedure between the model files and the environment software platform. CAD software has complex user interfaces; experience in such environments can potentially speed up the learning time of the other software. Having experience in CAD-software can increase the precision and quality of the feedback about re-design iterations.

5.2.2 Time and Effort Estimation

One way to show the application value of virtual mock-ups is to make a time-effort comparison of a workstation design process, presented in chapter 3 when using an immersive virtual mock-up and a traditional physical mock-up. This comparison would give insight into the usefulness of the immersive mock-up. A time and effort estimation can be done by using the experience acquired during the empiric phase of this thesis.

With the experience gained during the laboratory work and some assumptions, a scenario can be constructed. The time effort estimation is based on the scenario of if this or a similar system, with the same capabilities, were implemented by a company to design a workstation of the size shown in figure 3.3 in chapter 3. The assumptions made are as follows:

1. The interaction properties of the software is already in place.
2. The product which is going to be produced worked or assembled at the workstation has available CAD models.
3. The Company Technician is competent in the use of the system.

Using the design process presented in chapter 3, we can estimate the time the process would take and how it would be different from a traditional method. This estimation study will go through the entire process and comment on the differences between the two approaches and base the estimations on experience and prior knowledge of how much time each activity could take. The steps presented in the design process is as follows:

Gather general information

This step would take the same amount of time, and there is no difference in the process unless virtual models of existing workstations are available.

Gather Human Parameters

The software has readily available presets of anthropomorphic data, which are industry standards in the most significant industrial nations in the world, Japan, Korea, USA, Germany, among others. It is also possible to scale the manikin to fit any percentile of the chosen demographic with the click of a button. To get the motion capture skeleton to fit the manikin to ensure correct movement takes a skilled technician about an hour because of the need to change skeleton parameters. If the demographic does not fit the industrial presets available in the software, it can be hardcoded into the software. This task would add between thirty minutes to about an hour.

Evaluate Work height

This task is mostly the same as with the traditional method, except it is possible to already at this point, prepare for ergonomic evaluation associated with the working height of the future workstation. The preparation is just a matter of opening some programs, which only takes a few seconds. If the workstation is operated from a seated position, there will be a need to add a real-life physical chair, since the probability of a human being able to levitate in a seated position is low.

Include Material Flow And Information Flow

This part will remain the same as before.

Task layout

Creating virtual objects to represent the different tools, levers, controls, and bins needed at the workstations is fast if a low detail abstraction is allowed. In a traditional process, this part of the process is done by drawing a proximity layout on paper based on the maximum work area. It is a preliminary plan only, and not the actual layout. The actual layout has to be found through testing; this part of the process is only to uncover tool needs, frequency of use and get an idea of the objects future placement. Doing this using the system proposed in this thesis allows having all objects, or at least three-dimensional abstractions, available for interaction from the start, not having to sit and try to visualise the process mentally. The workstation product can be added to the environment together with all the task objects, to get a better understanding of the future layout. By having the operator conduct the task, or pretend to do it, but still grabbing the objects in the virtual environment, the grabbing command is automatically registered and can be used to generate a rapport about the frequency-of-use of the objects. This feature will give a numerical value to which objects to prioritise for placement inside the normal work area, and which not to. Acting out the task can uncover needs that could be overseen during a purely abstract drawing and mental process. Uncovering this at an early stage saves costly redesigns if flaws are discovered later in the process. Another benefit is that only one person is needed to do this stage with an immersive system; this is not certain in the traditional process. This process would also make the time estimation of this part of the process more precise because it depends less on the imagination of the engineers since the task is performed virtually and a computer generates a rapport. The time estimation is as follows: The process of loading the objects into the software one hour, setting up an operator thirty minutes, grabbing and moving all the parts five minutes and acting out the task takes set-up (task dependent). This gives an estimated value of one and a half hours, excluding the task time. The primary time saver here is the automatic generation of the rapport of the frequency of object use which in the traditional process, would need many hours and even a couple of days, depending on the complexity of the task and productivity of the engineer, with the use of spreadsheet software to produce documentation.

Clearance Analysis, Display placement and Drawing a scaled version

There is no reason to divide these parts of the process into stages because they can all be conducted at the same time when using an immersive environment. Clearance analysis has been used in immersive technology for a long time and therefore when such a feature is enabled, it will give the technician real-time feedback. The manikin can be changed in a matter of seconds to the largest of the 50th percentile of the worker population to test for clearance and of course change to the smallest of the 50th percentile to test for reach impediments. Possible displays can just be added like any other object and placed in an ergonomic location with an ergonomic evaluation of the mounting height. Drawing of a scaled down can be done directly in a CAD program seen from a top-down view. The ground layout can then be added to the immersive environment in the form of boxes to be used for the clearance study and the placing of the task equipment. This simplistic mock-up would act as a draft of the more detailed mock-up that will be used for testing, reducing the total amount of time considerably. The total time used here is a few hours to a couple of days, While with a traditional method, it would take close or longer than a week.

Build Mock-up

Physical mock-up Building a full-scale physical mock-up in cardboard, sturdy enough, to endure testing is very time consuming, workforce intensive and demand materials. It is not uncommon to change a design during the build, that is the main reason for building a mock-up, to find problems associated with the design. Implementation of changes to the design creates a need for extra work and materials. During testing, necessary rebuilds happen many times, because when testing different layout candidates, the physical model has to be changed to represent that specific layout of a candidate. The number of candidates increases with the complexity of the workstation task, and the complexity of the process increases with the number of candidates. This complexity originates because the workstation must reset between candidate tests. Usually, the completion of these tasks is achieved using an entire team of personnel, with the initial build taking several days, and the subsequent testing modification and testing also add several days to the process stage. Time and effort estimation of the initial build of a workstation mock-up, like the one in figure 3.3, is estimated to three days using several employees. The testing of ten candidates takes around five days, again using several people. A good design team video record the process.

Immersive virtual Mock-up The mock-up build has already started during the previous stages, and a more detailed version is created at this stage. The testing of the layout candidates begins with the creation of making all the possible layouts within the program. These layouts can then be loaded into the immersive environment and tested without the use of materials or extra employees. Employees that have the skills to create environments in the system can help each other by working with the same virtual mock-up but in different instances such that when created the environments are sent to the testing area for an operator to perform the tasks. Real-time ergonomic evaluation can be done to eliminate the layouts faster than with a traditional post-video screening of the recordings of the physical mock-up. A virtual mock-up automatically measures the movement-time of all motion performed by the operator. This information helps to choose the most efficient layout by comparing the data generated while conducting the testing of the layouts. It is cheaper to redesign on a virtual mock-up than on a physical one, take less time, and it can go back in time to a previous version without rebuilding if the need should see a rise. The building of the virtual mock-up should take around one to one and a half days if the level of detail only includes necessities, and with the same estimate as for the physical mock-up for ten candidates setting up the sequences takes half a day.

Create Prototype

The creation of the prototype must be assumed to take the same amount of time because there is no indication that there is any head start when constructing the prototype after having used a virtual mock-up or a physical one. Every part has to be drawn in a high level of detail such that the dimensions form the mock-up is used to order existing parts and components or the dimensions are used to draw new products. It is the time to get here that is the most benefit of the virtual mock-up.

Design Process Stage	Virtual time	Traditional Time
1.) Gather General Information	Same	Same
2.) Gather Human Parameters	1-2 hours	4 - 8 hours
3.) Evaluate Work Height	same	same
7.) Include flow data	same	same
4.) Task Layout	1.5 hours + Task pretend time	8-16 hours
Combination of 5.) Clearance evaluation, 6.) Display Placement and 8.) Draw scaled version of layout	0.5-2days	4days-7days
9.) Building mock-up	2 days	8days
10.) Creating protoype	Assuming the same	same
Minimum Total time	22.5 hours	108hours

Table 5.1: Time & effort estimation of the different stages of the design process, days are considered to be 8 hours

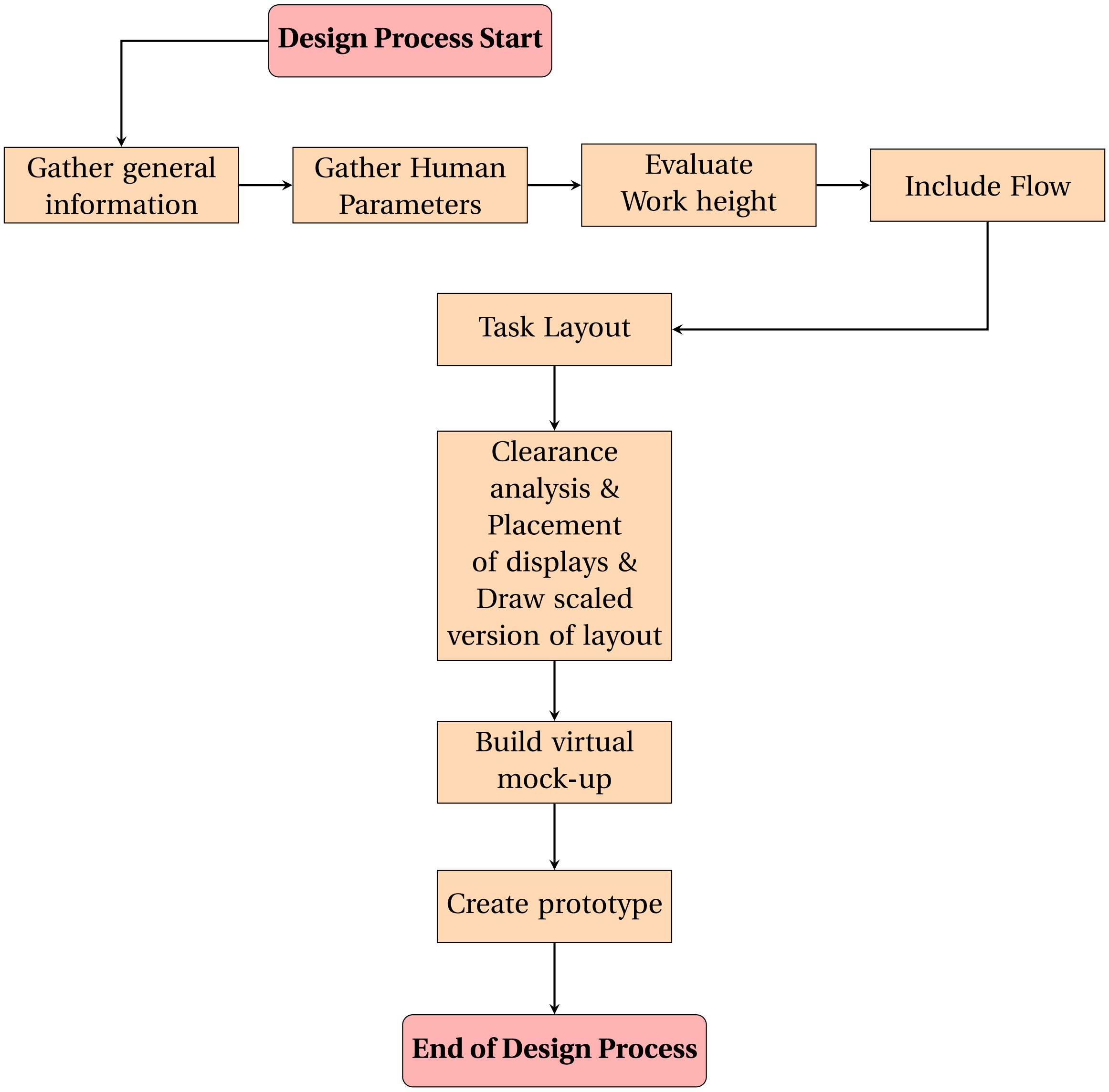

Figure 5.1: Change in The Workstation Design Process when using Table 5.1.Modified from figure 3.2 in chapter 3, Inspired from Das and Sengupta (1996)

5.3 Discussion

5.3.1 When can a immersive virtual mock-up replace a physical mock-up in the workstations design process?

By looking at table 5.1 and the time-effort estimation study some stages in the workstation process has presented themselves as good possible stages to utilize an immersive virtual mock-up, and others have shown not to be affected. With a scenario of creating a workstation of the size figure 3.3 the use of an immersive virtual mock-up is shown in the modified figure 5.1 modified from figure 3.2 in chapter 3. The stages of interest are displayed vertically, and the horizontal moving processes are not that interesting. The reason for the horizontal stages, (stages 1,2,3,7 in table 5.1), not being interesting is that these stages have to be done to have enough information to build a mock-up independent of the immersive or physical nature of the mock-up. In table 5.1, there is a time estimation on the gathering of the Human parameters where the stage is estimated to take four times as long when using traditional methods like surveys, data tables or company information, compared to using the internal features of the software. This time-estimation has some assumptions connected to it. The time it takes to gather information about the worker demographics and creating a skeleton is just a matter of clicking on a menu. Modifying a skeleton or two to fit the 50th percentile's smallest, largest and mean worker of the desired demographic, and changing between genders can be the click of a button. However, this estimation carries the assumption that one of the software that is part of the system has this feature such as Jack 9.0, but this is not a thesis about Jack 9.0, and the system can be created with the same capabilities using comparable software, though some development would be needed. A company with a design history of using immersive mock-ups could achieve the same results without third-party anthropometry software because the library generated over time of skeletons of different demographics. This library could be used to scale the skeleton used in the motion capture software easily. However, arguments can be made that the design team would still have to gather information such that system features like this are more useful during the later stages concerning clearance, reach and testing, than in the data gathering itself. Thus, even though there could, in some instances, be a considerable amount of time saved using integrated features, it depends on the specific software that makes up the system. Using an immersive virtual mock-up needs a base of information to be used efficiently making the initial stages not a place to start using the immersive approach.

As mentioned before, with the experience gained through the laboratory work, the first stage that would be suitable for the implementation of an immersive approach is the task layout. There are vast libraries of simple models of CAD tools available, for purchase and included in many software. Using the lists of necessary objects, which was generated in previous stages, and such libraries to determine the best position of each article makes the immersive approach very potent. Let us use an assembly task as an example. The workstation task, an assembly operation, in this case, can be acted out in thin air using the CAD model of the product. This activity generates a layout for all the tools inside the maximum working area and automatically create a frequency list, numbering the number of times an object was used and for how long. Therefore, the analysis of this aspect is much faster than if you have to do it using a camera or several people. One person could also do this task by themselves in a short amount of time.

As written in the Time-effort estimation even if the workstation process presented in chapter 3 has stages, with the use of immersive reality, multiple steps can be combined. They still have to be done inside the immersive environment to be sure that the stages and the design factors they are meant to include, can be done with the suit. Combining the ability to scale skeleton to represent the largest and smallest of the worker demographic, really simplifies the effort to establish the clearance and reach demands of the model. This feature simplifies the need to get hold of real people with the same human parameters like the desired demographic. The clearance property can be coded into all the objects such that is there is highlighting when the manikin intersects with an object. During intersection, the object changes colour and the event can be logged with a time stamp such that when testing for clearance it is easy to check the recording for colour changes and change the dimensions of the objects. The recording is of the movement only such that there is no need to do a new motion capture to test if the changes have fixed the clearance issues because the manikin will retrace its steps through the recorded mocap feed. This "rerun" will indicate if the issues have been addressed or need further attention. With reach and the placement of displays requires an active operator but because of the possibility to do real-time or at least swift analysis of ergonomics concerning body and neck posture, the issues can be addressed quickly by just moving the objects, so the positions are within the desirable range.

The drawing of a scaled version of the workstation can be transformed into being the first draft of a virtual mock-up. After deciding on the scaled version, a mock-up with an increased level of detailed could be made to be used for testing of layout candidates. This is, as mentioned before in the time-effort estimation study, where the approach of using immersive reality shines. The ability to reset, load new and automatically recording them and have data available for analysis are far and beyond that of the physical version. Moreover, the amount of time reduced is undeniable.

As an answer to the research question of "When can a virtual a virtual mock-up replace a real-life mock-up of future workstations in the workstations design process", the answer is after the gathering phases. The immersive virtual mock-up can be applied as early as the conceptual design, fully replace a physical mock-up, and you could argue the use in redesign situations, especially if the existing workstation has available CAD models.

5.3.2 What are the benefits, challenges and limitations of using immersive virtual mock-up approach vis a vis a physical mock-up approach?

The information that is the basis for the following discussion is observations and experience gained from creating an immersive environment. When using a purely immersive virtual approach, there are benefits challenges and limitations associated with the approach. With the basis in the time-effort estimation with the same assumptions done in the study, there is a severe reduction of time when using the immersive approach. With the minimum estimated time, there is a difference the physical approach uses 4.8 times the amount of time compared to the immersive approach. Bias might be a concern with these numbers tilting toward the immersive approach because of the author's enthusiasm for the virtual design process, but even if the numbers vary a lot compared to actual time, and a complete experiment with two groups with comparable skill level used the two different approaches. The experience gained through creating an assembly task in an immersive setting gives ground to make an educated estimation. The difference gap of 4.8 times the time it takes to complete the design process of the two approaches it is still going to be over twice as fast, even at half the difference. So there is a benefit in reducing the total time of the process. The author also has previous design experience using physical mock-ups form courses completed during his time at university as well as job experience through summer internships, which increase the accuracy of estimating the amount of time need when using the physical approach. Another benefit is the reduction of the amount employees needed for the workstation design process, or at least reduce the number of people at certain times in the process freeing them up to do other work further speeding up the process, especially if multiple people are trained to create models or testing candidates. The time used for the analysis of the mock-up will also reduce since a lot of the ergonomic issues can be eliminated earlier because if the real-time tracking resulting in fewer redesigns late in the design process. It also reduces the number of times where an ergonomics engineer is needed, if not removing the need completely, so there is no need to employ an in-house engineer full time. The time consuming motion-time studies will also be less expensive since all motion receive time stamps and analysis can be done using recorded data ready for analysis in software.

Another huge benefit is the ability to reset any scenario created instantly. This ability removes the need to rebuild the mock-up for every new layout test physically. The virtual mock-up can also defy gravity such that there is no need to build sturdy carrying mechanisms for each test if this is needed to test a particular solution. The possibility for the increased ease of hanging of objects overhead or around the workstation is high since an object can float in mid-air. Doing the same using a physical moc-up can demand a lot of time or personnel to hold or fasten objects in place. There is little to no waste associated with an immersive mock-up, but with a physical mock-up, all the materials used during the design process is pure waste. There is also the space use, the immersive system uses some space to perform the immersion process, but this area is available the second the operator is not in-game. Comparing this to the physical mock-up where the need for space is constant through the entire process and can occupy large areas for long periods of up to several weeks to complete.

When the immersive approach has so many benefits, why are not everybody using this method? Several challenges and limitations need discussing. One of the big ones is scale; if the design of the workstation exceeds the size of the tracking area covered by the VR-hardware, then there will be a need for additional equipment or another solution. This thesis cannot argue for or against scenarios concerning vast areas, but if it is workstation design, most designs should not exceed 5.5 meters at the longest axis, which is the limitations of the system. This system limitation should not be a limitation of the approach; however, the approach is confined to the available technology. The sense of realism can also be a challenge given that there is no haptic feeling without the adding of physical props with trackers. As mentioned before a seated posture must also be facilitated with a physical chair, or it cannot be simulated correctly. When lifting objects inside the immersive environment, the operator has herculean strength. The operator could easily lift buildings with one finger since there is no way to simulate the weight of an object unless made immobile. This may produce scenarios where the ergonomic evaluation has to be done differently, but as long as the real-life objects can be handled without the potential of acute injury, the ergonomics should be correct. In the immersive environment, all the pump when assembled can be picked up and carried without compromising the posture of the carrier, such that the ergonomics analysis needs to use the mass of the real object in their force and strain equations. It is also hard to simulate lighting in an immersive approach compared to a physical approach.

A common challenge when using VR-technology is the issue with motion sickness. Some of the motion-sickness can go away after extended use of a system like that but is also set some challenges form a management position. Women are three times as likely as men to experience motion sickness and its not uncommon for men to experience it. This phenomenon will have some implications from a managerial point of view in choosing who can function as operators and technicians when using the immersive approach compared with the physical method where anybody can participate. An additional selection and screening session of who of the personnel will conduct the tests have to be made, and that could create some issues if it turns out that all or a most of the design team gets sick from participating in the process. During the entire thesis, there was only one instance of VR motion sickness. Female #2 reported experiencing motion sickness after using the system for about an hour.

Another aspect that should be taken into consideration if a business acquires a system such as this is hygiene. Since the equipment will be used by the dedicated personnel, which most likely includes several people, the probability that individuals, including guests, will use this equipment, is very high. The technology has great appeal and observations from this thesis indicated a pattern where people approached the author and wanted to experience the immersive environment. Cleaning Procedures and removable buffers, such as inserting washable liners inside the skin contact areas on the HMD, can hinder the spread of bacteria, viruses and fungi within the workforce. Thus, reducing absenteeism.

There is one last challenge that needs, and that is the fact that in order to immerse an operator has to wear the suit. This suit does not fit everybody, seen during the laboratory work; male # 4 was not able to wear the suit, such that this has also to be taken into account when choosing personnel to the positions during the design process. The human parameters differ across the planet such that the suit has to match the demographics of the engineers.

There are also some limitations associated with the application of the immersive approach. Through the testing of the immersive approach, the author identified the prerequisite skills needed to operate such technology successfully. These prerequisites set a limitation on what level of academic background or prior experience needed. Virtual mock-ups is a high-tech design approach that demands a certain level of tech-savvy at the level of a masters degree in engineering or computer science, and it should be possible only to have a Bachelor degree in engineering if the employee has experience in design and computer-assisted-design technology to compensate. Using an immersive virtual approach is not, for the time being, a plug-and-play experience such that anyone can use the tools required to use the approach.

One is that the technology is still new, at least for this type of application, and some features can be underdeveloped. This fact may lead to that specific interaction-capabilities are not readily available, but needs to be developed for the system being able to produce a realistic enough experience to be used as a replacement to the real-life equivalent. This might limit or at least impact the workstation design time because of the need to develop plugins to the software, and the technician or the company does not have this competency making the approach not usable in a satisfactory way. It will also have financial consequences by increasing the total acquisition cost of such a system if development needs outsourcing. There are always economic limitations associated with technology acquisition. Financial limitations are relative to a company's available capital and have to be taken into consideration when considering which approach to go for, immersive or physical. There are costs involved in using an immersive approach; acquisition costs for a system that is capable of the feats described in this thesis. Hiring, training, and maintaining personnel with the necessary skills to use the system efficiently and possible development costs if non-existing interaction features are needed. These costs have to be lower than the costs of using a physical approach, such that a threshold exists. The frequency of design activity governs the physical approach cost. Meaning, the costs are strictly related to the number of workstation designs needed to justify the cost of acquiring an immersive system. Other factors can add to the value gained by acquiring an immersive system such as if the company does other types of design work it can be used for product inspection and customer demonstrations. Also, the value generation gained through the advertisement of a high-tech image-profile in order to attract future customers can argue towards acquiring such a system. It might be more economical to hire a consulting company that offers immersive design capabilities and qualified personnel than investing in the acquisition in their own company. So the type of company that would benefit enough from using an immersive virtual mock-up approach would be companies that need frequent workstation re-design, produces innovative products, are a consultant company that offers workstation design, or companies that already have a large design department.

As an addendum to the limitations concerned with this specific system is that if there is a need to design a workstation were several workers need to work together. It is not possible unless the program can track two input-feeds of motion capture data and produce two instances of manikins simultaneously. This feature is not possible with the system.

5.3.3 Challenges and Discussion other factors

The suit hardware contributed to the plight of the entire thesis. From the beginning of the acquisition of the suit, abnormally long calibration times and connection malfunctions plagued the system, with the problem identified to concern the sensors in the suit. Calibration times should only take minutes but could take as long as up to six hours before achieving a proper calibration rendering the suit useless for large periods of time. In most cases, during the semester, the calibration time took 1 to 1.5 hours to achieve a fully functioning working suit. There were a few instances where the suit calibrated instantly, but this happened so seldom that when it happened, it surprised the users of the system. The suspicions of malfunctioning sensors were reported to Synertial. The company provided support over the internet, and both times this happened, the system responded correctly after 10-20 minutes. These events made the author of this thesis think that the calibration issue was a product of inexperience on behalf of the student and not a technical issue in the hardware itself. A lot of the time during the creation of the immersive environment, the preliminary testing was conducted using a partially working suit. With a partially working suit, there was enough functionality to test the interaction capabilities during the early stages of the design, but no data generated during this workaround would be usable for any form of analysis since it was corrupt and incomplete. After testing the suit in different spatial locations together with the supervisor Fabio Sgarbossa, the suit was declared to have malfunctioning sensors and sent back to Synertial. Because of this, there was not enough time to wait for a new suit to arrive, produce data and conduct analysis. It was not until May 2019 that the decision to send the suit back to the technology supplier for repairs. During the semester the suit had sessions where it functioned at near perfect calibration This calibration made it possible to conduct sessions such that the laboratory observations in this thesis are still valid, but analysis of the corrupt motion data would produce useless results. Therefore, the data cannot be used for further analysis.

There are some limitations to the results used, though the observations made during the testing of the virtual mock-up as valid, they are subjective and poorly planned out. There should have been made a questioner for the suit-operators to answer after each time they used the suit. The number of operators was also small such that it would be better with more observational data. Also, the time estimation used in the time-effort estimation study most likely has a high level of error associated with it.
There are also some issues that are not discussed that needs mentioning, and that is there are

issues with reducing the number of people in a design process. There is a great value to be found in team ideas, the more people that can add ideas and analyse the needs of a system, the more likely the chance to achieve good results, until The "law of diminishing returns" kick in. There is a real risk of silo thinking when sitting alone at the computer working for hours with a design and not having anyone to spar ideas. So this is not a perfect solution, but a solution worth studying.

Several challenges retarded the progress of the thesis. With some being obvious throughout the thesis, and others not realised until the amount of time to compensate for them was too limited to complete all the planned objectives of the thesis. One of the reasons of not uncovering the real reason for a lot of the problems is because of the non-linear learning progress and the sheer amount of information needed to be digested in a short amount of time when receiving training from the technology provider. The training period was intense, and many hours needed to go into achieving a certain level of proficiency using the system. The training also was not tailored towards the thesis such that much time was "wasted" learning to use software and functions that is not relevant for the focus of this thesis. There was also a limited and lacking understanding of which topics and functions were essential to the thesis during the training sessions.
This so extensive learning period comes with the complexity of the system. There are so many types of software to function together and much-sophisticated hardware that also needs to function correctly. Many things can go wrong during a session, and it can be challenging to locate the source of the problem. Most of the problems arise as a consequence of the inter-dependency and different interfaces between the software. Another factor is that some software demand specific sequences when connecting one software to another to achieve any form of useful output. The sequencing is not self-evident and requires experience on the part of the technician to identify. One example of this is the connection of the motion capture data-feed output from Syndash-PRO onto the manikin generated in Jack 9.0. The system is at times volatile, and without the ability to see which software fails or which hardware has issues, because of the lack of experience of the technician, there is much time lost in system restarts.

Another challenge was that the technology providers also was in uncharted territory. The system provided and the orientation of the training received was done on the assumption of "traditional" use. The most common way for using the motion capture suit is to have a worker wear the suit while conducting tasks, and then the data is saved. The recorded data is then used to move the manikin inside jack on a model that is prepared such that all movements are known in advanced. This data is then used for ergonomic evaluation. Another common use of the system is for observational activities inside virtual models such that the HTC vive is used to enter a model in a program, and the user can teleport around. There was no functioning solution provided from Synertial which enabled the wearer of the suit to see through the eyes of the manikin while using it as an avatar. There was also no software provided from Siemens or Synertial that enabled interaction inside the immersed environment without using controllers. My supervisor provided the experimental plug-in created by a third party. This plug-in was designed for different hardware but happened to function very well with the HTC vive and the Synertial motion capture suit. Since the producers of the technology and the software used had no prior experience with the way the system was being used during this thesis, it limited the amount of support they could provide, and often illuminated bugs and future improvements to the software for software developers. Communication with the technology suppliers also had delays such that questions and training sessions could take several days to a couple of weeks before support was available. This latency in communication forced the author to continue working on other aspects of the system without being able to address faults. Adding to the chaos two extensive software-updates for Syndash-PRO during the thesis. These updates were supposed to improve functions and removed bugs associated with the system. The updates had some adverse effects that introduced problems that manifested themselves in crashes and changes in output files.

There are several issues associated with the motion capture skeleton. They arise mostly because of the technician's inexperience, underestimation of the importance to attain very high proficiency in the configuration of skeletons, and unclear communication from the suit support team. The training was provided in producing skeletons that matched the operator, but a lot of the information got lost in the sheer amount of information provided during the training to use the software as mentioned before there was uncharted territory on the intended use of the technology such that unique skeletons were produced. This complicated the learning process of the technician since there was no default procedure presented, only many advanced customisations. One of the most significant challenges associated with the skeleton was the mismatch problems between the manikin limb lengths and the skeletal bone lengths. As an example, the skeleton arm, excluding points representing the hands, is projected from Syndash-PRO into Jack 9.0 as three points markers for connection to the manikin. One at the shoulder joint, one at the elbow joint and one at the wrist. If the bone length between the points, (e.g. shoulder-to-elbow or elbow-to-wrist), is longer then the limb length of the manikin, Jack 9.0 will prioritise connection points to be the shoulder and the wrist. For mental visualisation consider the connection points as the three corners of a 90° triangle, if the length of the bones surpasses that of the manikins limb, the manikins arms will manifest along the hypotenuse of the triangle. This prioritisation corrupts the data because the operator compensates or is not able to perform the workstation tasks. This priority also makes ergonomics evaluation using Jack 9.0 features useless. This was partially remedied by using one of the skeletons produced during the training period matching male #3, since this had a good fit with the default manikin in jack. This problem was discovered late in the thesis but was a smaller problem than the fact that there were hardware problems with the motion capture suit itself. Another challenge was that the user manual provided by

Synertial covering the creation and modification of skeletons was incomplete, making that problem only solvable with the support from Synertial. The skeleton dictates the motion capture suit's output-data file structure. The headers of the CVS file indicates which sensor produces the corresponding data listed in the column beneath. The problem with this is that some change in the software or skeleton structure made the software produce data files with no headers, and columns to numerous compared to the number of sensors in the suit, such that identifying what the data represented was not possible. This problem needs solving before analysis of the data is possible. This change in data generation was also a surprise to the technology suppliers.

Chapter 6

Conclusion and Recommended Future Research

The creation of a spatially immersive environment with a virtual assembly workstation was a success. The thesis included the creation of an interactive assembly operation, that was intuitive and easy to use. The application prospect for the system of technologies was studied, and aspects such as set-up time, ease of use, training time for the technician and suit operator discovered. After conducting a literature study about the related and prior work done on the related topics an academic gap was found and acted as the basis for this thesis and as the answer to research question 1.

In the results, there is a lot of observations available concerning the testing of creating an immersive environment. The suit-operators provided valuable feedback about their use and experience with the system. Their reflections include realism, interaction, intuition and side-effects of virtual reality, and a large amount of movement data is available for exportation for use in ergonomic and motion-time evaluations of workstation layout and tasks.

The research question 2, was about when in the design process, an immersive virtual mock-up could function as a replacement for the physical mock-up was answered using a time-effort estimation study. In this study, a comparison of the design process, presented in the theoretical background, and how an immersive virtual mock-up would influence the process. What the study discovered was that the immersive approach would be useful in the mid to late stages of the process, with the possibility to fully replace the use of a physical model. The study also provides a suggestion about combining several of the stages into a more compact process because of how a virtual process is different from a physical one.

Other observations made during testing of the immersive mock-up provided the basis for answering research question 3. A discussion of the benefits, challenges and limitations of the use of an immersive approach in workstation design provides an understanding about the capabilities of an immersive approach and what to consider before committing to using such an approach. The main benefits found through the results concerning the immersive approach were the reduction in total building time associated with physical mock-ups and layout testing, here the entire process was estimated to be 4.8 times faster than the physical approach while using fewer people in the process. There was also an indication that there would be less need to pay for experts like ergonomics engineers and motion time study experts since the Human factor and motion evaluations could be done continuously throughout the process using data produced. There was also no waste generated compared to the large amounts produced when building a physical mock-up.

The challenges are mostly connected to technology and not the approach, but it is hard to say that the tools used will not influence the approach. The challenges found was related to the scale of mock-up, if its longer than 5.5m at its longest axis the company would need to buy additional equipment. Realism issues had some impact on the level of evaluations that is possible since there are no physical laws that can be experienced without haptic devices. Motion sickness from using technology can influence the hiring process. Moreover, some smaller challenges connected to the sizing of the equipment and hygiene concerns were presented.

The limitations of the immersive approach were related to technology maturity, financial limitations and skill level of technicians using the technology. These aspects limit the approach in when it is possible to use it since depending on the frequency of use and the financial balance between acquiring such a system and using a traditional approach will limit the implementation of such systems.

The objectives of this thesis were to gain insight into what skills and effort needed to set-up, use and maintain an immersive environment, was thoroughly answered in this thesis. Moreover, the objective of producing a workstation environment and perform a task to gain insight into the capabilities of the immersive virtual mock-up approach by using a workstation environment was also done through continued research into this final objective would be of interest.

6.1 Recommendations for Further Work

In the short term the development of analysis tools for ergonomics and time-motion studies would be of great benefit to the use of motion capture technology in industrial settings. This could be done using the output data from the motion capture suit and a analysis tool. When considering research in the long term a very interesting test would be to have a industrial case study and have two groups conducting workstation design, One traditional and one virtual, and compare them. Another interesting topic would be the development of a immersive platform based on Unity3D so there is no need for Jack 9.0.

Appendix A

Fileformats

A.1 .jt fileformat

Jt fileformat is used in Product lifecycle management. It is used to communicate between CAD systems and the PLM systems. Owned by Siemens.

A.2 .STEP fileformat

The STEP-file is one of the most common file exchanges used in CAD. The file format is developed by ISO and has the magic number of ISO-10303-21. The file format can be used to represent CAD models.

A.3 .CVS fileformat

CVS or Comma-separated values is a text filethat uses commas to seperate values. Not fully standatdized, but can easily be read with a spread sheet program.

A.4 .BVH fileformat

BVH stands for Biovision Hierarcy and is a file that is used in motion capture to keep data about the hiercy of body segments that make up the skeleton of the animation.

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