Three-Dimensional Capacitive Sensing for Wearable Technology

A Development Example for Creative Technology

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BSc Report

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ABSTRACT

In this graduation project, the potential and implementation of three-dimensional capacitive sensing technology in wearable technology is explored. To give this project a clear scope, the potential of this technology is defined through its satisfaction in three requirements: the technology should be advantageous to other forms of Human Computer Interaction in specific contexts, the technology should be accessible for the Creative Technology bachelor programme of the University of Twente and the technology should be implementable in a form of wearable technology. The satisfaction of these requirements is evaluated through multiple methods. First, a state of the art and background research. Then, development of an exemplary prototype implementing the provided MGC3130 Hillstar development Kit, provided by MicroChip®, in a piece of wearable technology. A goal is set to evaluate the provided sensor set; get the dev-kit working, form a communication between the system and an accessible open source program, and create an interesting, meaningful interaction. This interaction is realized in the development of a touchless computer supported presentation controller using a pair of programmed Arduino Micro MCU utilizing wireless 2.4GHz RF transmission. Through the development of this exemplary prototype, including user- and prototype-testing, along with implicit research, it is found that this technology is accessible for developers, specifically students of the Creative Technology programme, and shows potential to be implemented in future products or projects. Additionally, from state of the art and background research, three-dimensional capacitive gesture recognition technology is found to be advantageous over multiple other forms of human-computer interaction or other forms of gesture recognition technology. Limitations in interaction and comfort as a wearable have been found due to body noise interference and electrode size, respectively. To solve this, extended electrode customization and future research is recommended.

ACKNOWLEDGEMENTS

I am very grateful to E. Dertien, A. Mader and R. Bults for creating the opportunity to fulfil this bachelor thesis. The support of E. Dertien has been inspiring and motivating to keep putting effort in this project, even in times where emotions were high. Furthermore I thank the participants of the conducted experiments who were willing to give their time and effort into creating this bachelor thesis.

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1 INTRODUCTION

1.1 CONTEXT AND GOAL STATEMENT

In 1991, Mark Weiser [1] argued that the computer must disappear in everyday objects: “The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it. From the end-user perspective, the interface will appear as a computer as long as there are buttons to press and mice to move, and thus will never truly disappear.”

The interaction with the computing devices used in daily life, such as laptops, tablets, smartphones, mp3 players etc. happens with buttons or touchpads that are integrated into the gadget, almost without exception. That is what a research by Paul Holleis et al., [2] states. Holleis continues to state that although the use of mobile computing has become an integrated part in our society, the input technologies have not evolved to an optimal level with regard to usability.

In this graduation project an alternative interaction technology called three-dimensional capacitive sensing is explored. Three-dimensional capacitive sensing technology is a long existing, simple, yet efficient interaction technology, based on the coupling of conductive objects in an electrical field emitted by the sensing system. This technology is based on the conventional 2D-capacitive sensing which is found in touchscreens. The location of the conducting object can be determined through influence of that object in the electrical field. This technology could be an alternative to physical switches or touch interaction, making them disadvantageous or obsolete in specific contexts. This graduation project will show a glimpse in the future of wearable, mobile computing featuring a 'natural' way of interaction using gestures.

The main objective of this graduation project is to obtain a deeper understanding on the already existing forms, and potential, of three-dimensional capacitive sensing itself, and its implementation in wearable technology. To evaluate this potential, three requirements have been defined which the technology should satisfy. First, three-dimensional capacitive sensing should prove to be advantageous to comparable forms of Human Computer Interaction (HCI). Secondly, three-dimensional capacitive sensing should prove to be an accessible technology for developers to employ in research and development, focussing on members of the Creative Technology bachelor programme of the University of Twente, specifically. Third, three-dimensional capacitive sensing should prove to be employable in wearable technology.

Consequently, in this graduation project a goal is set to give an insight in the accessibility of three-dimensional capacitive sensing for future developers. The accessibility of three-dimensional capacitive sensing is evaluated through the development of an exemplary prototype employing a provided system, the MGC3130 Development Kit, developed my MicroChip®. A goal is set to evaluate the provided sensor set; get the dev-kit working, demonstrators up and running and create an interesting, meaningful interaction. The three-dimensional capacitive gesture recognition sensors in the prototype should be implemented unobtrusively in a wearable piece of clothing or technology. Throughout this graduation project, this system will be used to represent the concept of three-dimensional capacitive gesture recognition technology. Also, in assessing the accessibility of the technology, the accessibility of this specific toolkit will be used as a starting point. If the technology proves to be inaccessible for custom development, a goal is set to develop a platform in which this technology becomes an accessible tool for future developers, focussing on students of the Creative Technology programme specifically.

1.2 RESEARCH QUESTIONS

As stated above, the goal of this graduation project is to construct an understanding in the potential of three-dimensional capacitive technology. From this goal, the main research question directly follows: *What is the potential of three-dimensional capacitive sensing in wearable technology?*

This question will be answered through multiple methods including literature research, state of the art research, developing an accessible tool employing this technology, the development of an exemplary prototype and prototype- and user-testing of that system. As stated above, the potential of three-dimensional capacitive sensing is defined as the satisfaction of the defined requirements of advantage, accessibility and employability. To reach the goal of obtaining a deeper understanding in the satisfaction of these requirements, the following sub-questions are formulated:

In what contexts would three-dimensional capacitive sensing be advantageous in comparison to other forms of human-computer interaction?

This question will be answered through background- and state of the art research comparing comparable types of HCI systems to three-dimensional capacitive sensing.

What is the accessibility of three-dimensional capacitive sensing for developers such as creative technologists?

This question will be answered through background- and state of the art research and the assessment of the accessibility of the provided MGC3130 Hillstar Development Kit system for developers, such as the members of the Creative Technology bachelor programme.

How can three-dimensional capacitive sensing be implemented in a piece of wearable technology?

This question will be answered through background and state of the art research and the assessment of the employability of the provided MGC3130 Hillstar Development Kit system in an exemplary prototype, being a form of wearable technology.

2 METHODS AND TECHNIQUES

2.1 INTRODUCTION

To come to a deeper understanding on current, and potentially future, implementations of three-dimensional capacitive sensing and wearable technology, this bachelor thesis will be constructed through pre-defined methods and techniques. In this chapter, the methods and techniques are explored for both implicit and explicit research for developing an answer to the sub-research questions: *How can three-dimensional capacitive sensing be implemented in wearable technology?* and *What is the accessibility of three-dimensional capacitive sensing for developers such as creative technologists?* By answering these sub-questions, a deeper understanding will be formed to answer the main research question: *What is the potential of Three-Dimensional Capacitive Sensing in Wearable Technology?*

2.2 DESIGN PROCESS FOR CREATIVE TECHNOLOGY AND TIME FRAMING

To ensure an efficient method of executing the graduation project, a structure is defined through which the progress of the graduation project can be monitored. This structure is based on two components. The first component is the pre-provided guideline to time division (Appendix I) of the Creative Technology graduation project manual by R. Bults [2]. The guideline extends to 2 quartiles (or 1 semester) and will be used as both a guiding and a reflecting component on the progress of the project.

The second component on which the structure of the graduation project is based is the design process for Creative Technology. The design process of Creative Technology is discussed in detail in the work of A. Mader and W. Eggink [3]. Mader divides the design process in four main phases; Ideation, Specification, Realization and Evaluation, as visualized in figure 2.1 [3]. Although this graduation project is based on the phases by Mader, components of the phases are exchanged to provide a more fitting structure to this graduation project. Details about exchanged components between phases are discussed in the corresponding sections. These main phases, with an addition of the preparation phase, will be individually addressed in the next sections along with a time frame for practical execution of the phase.

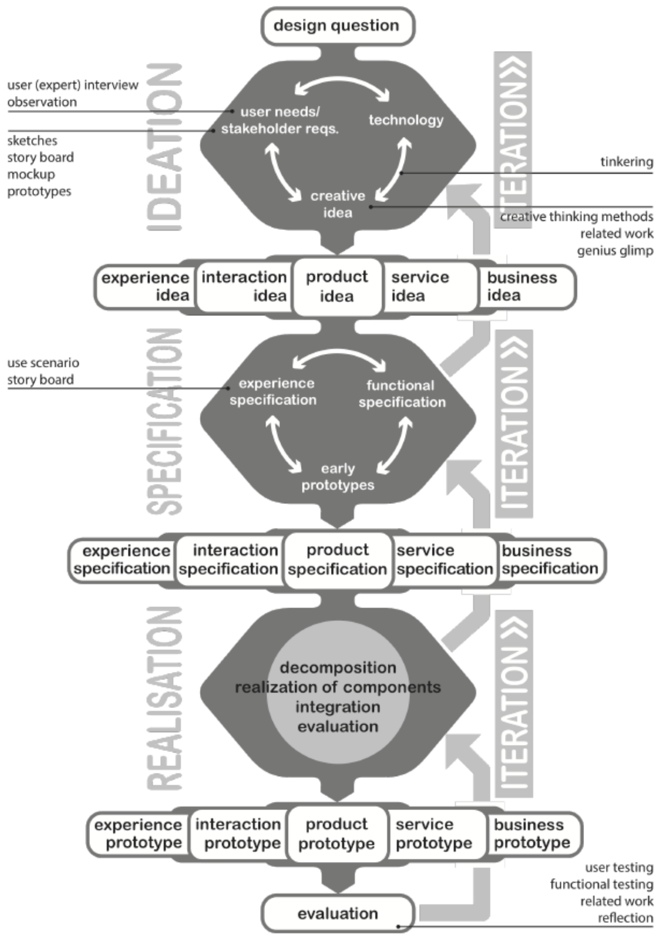


Fig 2.1. Design process based on spiral model [3]

2.2.1 Exploration

The purpose of the exploration phase is to explore the topic around which the graduation project will revolve, create a deeper understanding and a definition of the scope of the project and formulate one ore multiple preliminary research questions. In short, gain a level of expertise on this subject and using that expertise, define a goal for this project. To gain these understandings, multiple methods of researching will be applied. First, a literature review will be held on the topic of three-dimensional capacitive sensing. Then, this research is extended by a state-of-the-art research, exploring related work, followed up by an ethical research, reflecting on the possible risks and moral dilemma's revolving the subject.

2.2.1.1 Exploration time frame

The time frame for the preparation phase of the graduation project will extend to the first quartile. It is assumed that the following phases will require the entirety of the second quartile to be executed properly, thus, the preparation phase will be limited to the first 10 weeks.

2.2.2 Ideation

In the ideation phase, acquisition of relevant information and idea generation are performed. The goal of the ideation phase is to produce a range of project options that may provide an adequate answer to the research question(s) and make an educated decision on which option to further develop in the following phases. In short, explore the possibilities of reaching the goal of this project and choose the best design option. Methods that will be used for the ideation are mind maps, brain storming sessions, sketches, moodboards, and literature research. These methods will be based on the divergence-convergence principle by Jones et al., [4]. This principle will be discussed in detail in the ideation section of this report.

2.2.2.1 Ideation time frame

The time frame for the ideation phase is set to 5 weeks in the time division guideline by Bults [2]. The aim is to use a similar timeframe, however, this is not a strict requirement for developing an adequate concept to be specified in the specification phase. The ideation phase may consume more or less time, depending on the range of project design possibilities and the feasibility of those possibilities.

2.2.3 Specification

During the specification phase, a detailed definition of the utility, stakeholders and requirements of the solution is provided. Then, the design possibilities provided by the ideation phase are explored in more detail. The design possibilities are evaluated based on the defined requirements of the solution to develop a design for a prototype to be realized in the next phase. The specification section contains: the research and definition of the requirements, resources and stakeholders for this solution. These will be elaborated in the MOSCOW method, personas, scenarios and storyboards.

2.2.3.1 Specification time frame

The time frame for the specification phase is set to 2 weeks in the time division guideline by Bults [2]. Similar to the ideation phase, the aim is to consume an equal amount of time during this phase in this project. The time consumption during specification phase is more controllable because it consists of a range of specific tasks which can be appointed to a relatively stable time frame.

2.2.4 Realization

The goal of the realization phase is to provide and execute the solutions to meet the requirements from the ideation and specification phases. The components necessary are researched, selected and implemented. The realization phase contains: Component solutions, including description and elaboration, execution methods and results.

2.2.4.1 Realization time frame

The time frame for the realization phase is set to 5 weeks in the time division guideline by Bults [2]. The aim in this project is to consume an equal amount of time during this phase in the project. However, this is dependent of the progress and possible delays in the previous phases. Also, since the realization phase contains prototype realization, the time frame should leave space for unforeseen setbacks in the assembly.

2.2.5 Evaluation

In the evaluation phase, The goal of the evaluation phase is to provide a critical test on one or multiple parameters of the provided solution by one or multiple sources. This will be done to evaluate whether the provided solution suffices in meeting both the pre-provided and additional requirements. It may also provide a basis for further research or development. The evaluation phase consists of: User testing, prototype testing and ethical reflection.

2.2.5.1 Evaluation time frame

The time frame for the evaluation phase is set for 2 weeks in the time division guideline by Bults [2]. The aim in this project is to consume an equal amount of time during this phase in the project. However, the scope of this phase is highly dependent of the type of solution provided in the previous phases. A developer should anticipate on a prolonged evaluation phase, as type of testing or evaluation may differ, depending on the prototype.

2.3 Design process of the MGC3130 Hillstar development kit

In the GestIC® Design Guide provided by Microchip®, a detailed structure to which developers can realise prototypes employing the MGC3130 Hillstar development kit. This structure is based on 5 steps: Idea, Electrode Desgin, Hardware Integration, Software Integration and Parameterization. These steps are implemented in the Specification and Realization phases of the Design Process for Creative Technology, as described above. This implementation has been chosen as the steps provided by Microchip both overlap the elements of the phases in the Creative Technology design process and form a strong basis for this specific project. The steps, as visualized in the GestIC® Design Guide are shown in figure 5.1 [5] and are further elaborated in the specification and realization phases.

3 STATE OF THE ART RESEARCH

3.1 THREE-DIMENSIONAL CAPACITIVE SENSING

To obtain a deeper understanding in three-dimensional capacitive sensing, gesture recognition technologies, wearable technology and presentation principles, this state of the art research is conducted. Here, a deeper understanding to answering the sub-research question: "*In what contexts would three-dimensional capacitive sensing be advantageous in comparison to other forms of human-computer interaction?"* will be obtained through a literature review research. Furthermore, related work to both three-dimensional capacitive sensing technology and wearable technology will be explored to form a deeper understanding in the employment possibilities of three-dimensional capacitive gesture recognition technology in wearable technology.

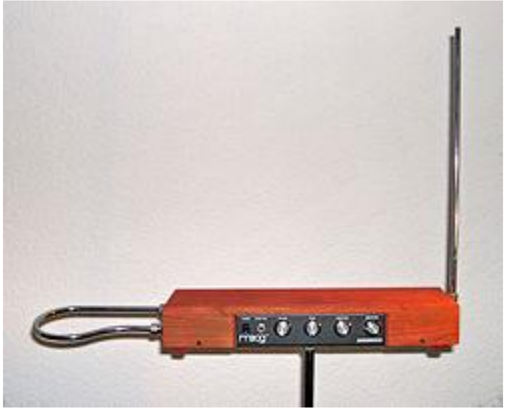


Fig 3.1. Theremin [94]

3.1.1 *History behind three-dimensional capacitive sensing*

As stated in the introduction of this graduation project proposal, Three-dimensional capacitive sensing technology is a long existing, simple, yet efficient interaction technology, based on the coupling of conductive objects in an electrical field emitted by the sensing system. The concept of capacitive sensing is currently found in 2D-capacitive sensing in touchscreens. The location of the conducting object can be determined through influence of that object in the electrical field (E-field). Holleis [6] refers to the musical instrument invented by Theremin (shown in figure 3.1). A system, employing three-dimensional capacitive sensing technology, that dates back as far as 1919.

3.1.2 *Theory on technology*

This research is focusing on Non-touch -based systems of E-field technology. The principle behind e-field technology is based on E-Fields: "E-fields are generated by electrical charges and propagate three-dimensionally around a surface, carrying the electrical charge. In case a person's hand or finger intrudes the electrical field, the field becomes distorted. The field lines are drawn to the hand due to the conductivity of the human body itself and shunted to the ground. The three-dimensional electric field decreases locally." This principle is explained by Holleis and supported by the research by Zhou [7] and the user guide of the MGC3130 gesture recognition chip developed by MicroChip [8], which is the hardware which will be used in the exemplary presentation prototype using three-dimensional capacitive sensing.

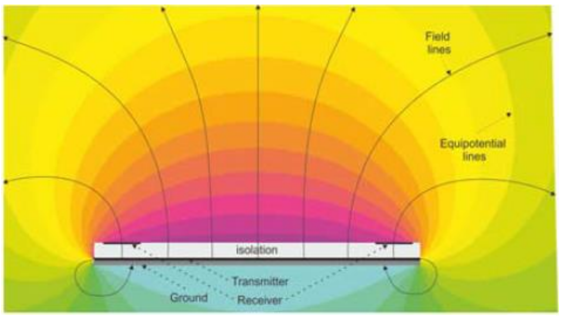


Fig 3.2. Equipotential lines of an undistorted E-field [8]

Figures 3.2 and 3.3, collected from the MGC3130 user guide, visualize the influence of an earth-grounded body to the electric field. The corresponding signal is processed by microcontrollers and its associated circuitry of wireless transmission that makes the controlling for electronic devices. This is further explained in a research by S. D. Gopravam et al., [9]. This concept of this technology is mentioned in various literature sources: J. Rekimoto [10] states: "Capacitance sensing" is a technique measuring distances of nearby conductive objects by measuring the capacitance between the sensor and the object and uses a transmitter and receiver electrode." This statement is supported by various sources, such as J. Cheng et al., [11] who explains: "A capacitor is, in essence, a device that can store energy in an electric field. The best-known example is the parallel plate capacitor, having two

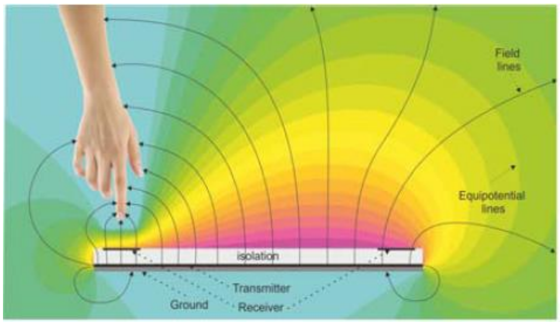


Fig 3.3. Equipotential lines of a distorted E-field [8]

rectangular conductive plates separated by a gap filled with a non-conductive dielectric material." The research by Munehiko Sato et al., [12], is also in agreement with the statement by Rekimoto, defining capacitive sensing as a malleable and inexpensive technology.

A general explanation of the functionality of three-dimensional capacitive sensing is given in the MGC3130 data sheet [13], stating: *"Applying direct voltages (DC) to an electrode results in a constant electric field. Applying alternating voltages (AC) makes the charges vary over time and thus, the field. When the charge varies sinusoidal with frequency f, the resulting electromagnetic wave is characterized by wavelength λ=c/f, where c is the wave propagation velocity – in vacuum, the speed of light. In cases where the wavelength is much larger than the electrode geometry, the magnetic component is practically zero and no wave propagation takes place. The result is a quasi-static electrical near field that can be used for sensing conductive objects such as the human body."*

Further exploration and a more detailed technical description of the exact technology behind three-dimensional capacitive sensing can be found in the research by Andreas Braun et al., [14] and the book by Larry K. Baxter [15]. Implementation options of this technology in the Creative Technology bachelor programme will be provided in a later phase in this graduation project.

3.1.3 *Three-dimensional gesture sensing vs two-dimensional touch sensing*

Three-dimensional capacitive sensing is evolved from two-dimensional capacitive touch sensing. Govaparam [9] defines touch sensing as the foundation for all touch interactions, i.e., technologies that capture human touch and gestures. A research by Du [16] states: *"Touch sensing, as a general HID, is widely implemented in various display products (e.g. smart watches, mobile phones, tablets and TV)."* Du mentions that projected capacitive touch (PCT) technology is regarded as the most popular capacitive sensing. It is also defined as the most relevant touch sensing technology. Du also refers to a to a recent market report by Statista [17], which states*: "There will be a 2.8 billion touchscreen shipped to the market in 2016."* Consequently, today we find capacitive touch in millions of consumer device controls and touch screens [12].

PCT touch screens are made up of a matrix of rows and columns of conductive electrodes. Touch detection is through applying a voltage to this grid to create an electrostatic field. A conductive object touching the grid will distort the field at an individual point through which, with proper processing, the position of the object can be determined.

The alteration from two-dimensional touch sensing to three-dimensional gesture recognition is accomplished through alterations in the type of capacitive coupling. Several approaches of obtaining capacitive gesture recognition have been used by multiple companies and institutions such as Princeton [18], UCLA [19], Fogale Sensation [20] and Microchip Inc. [8] An overview of these systems can be found in an overview by Li Du [16].

In the research by Govaparam, gesture based systems are divided into touch-based systems, such as the capacitive touch system as stated above, and non-touch-based systems. Even though the touch screen market is large and powerful, which may show to be difficult to compete with, portable sensor based touchless solutions become more popular after the recent success of touch screens technology. Du states that in recent years, several remote hand-gesture control systems for home-media systems have become commercially available. Development of SOC (System On a Chip) remote-sensing solutions that will lead to three-dimensional (3D) gesture detection has been inspired by the drawbacks that 2D sensing schemes have showed. In comparison to two-dimensional capacitive touch technology, three-dimensional capacitive gesture sensing shows to be advantageous in multiple contexts.

Touch-based systems pattern identification require direct contact between the user and the capture device whereas non-touch-based systems facilitate remote recognition. Since capacitive touch technology requires the user to make a physical connection with the interface, challenges arise in context where touch is not desired. Examples are sterile environments, wearing hand protection of various kinds and, as mentioned by Du, wet or dirty hands which cause unresponsiveness of the screen. Another major drawback in touch technology is mentioned in a research by Junhan Zhou et al., [7]. In smart watches, for example, touch technology relies on capacitive touchscreens for display and input, which inevitably leads to finger occlusion and confines interactivity to a small area.

When comparing three-dimensional capacitive sensing in the same context, it is employable in a larger range of motion, it is not restricted by dirty hands during interaction and it can be used in sterile environments since no physical contact is required.

Cheng [21] mentions examples of capacitive sensing currently used in the industry for proximity sensing and examination of the content of closed boxes on conveyor belts. But there are multiple other possible implementations that could be exploited, which will be explained in the next section.

3.1.4 *Capacitive Gesture sensing vs conventional forms of gesture recognition technology*

Although there are several ways of recognizing gestures and hand positions through technology, three-dimensional capacitive sensing technology for gesture recognition shows to be advantageous in comparison to the majority of alternative gesture recognition technology. Multiple sources have been found in literature research that state the drawbacks of alternative gesture sensing technology in comparison to three-dimensional capacitive gesture recognition. However, besides the disadvantageous methods, two types of gesture technology have been found which may show competition to three-dimensional capacitive sensing in the future.

In the research by Du [16], non-touch based gesture recognition systems are further divided into encumbered (requiring wearing/holding assistive devices) and non-encumbered systems. Govaparam [9] mentions that in encumbered systems, extracting a gesture trajectory is straightforward, and the difficulty of gesture spotting is greatly alleviated. A range of examples of these devices can be found in a survey on hand posture and gesture recognition techniques conducted by Joseph LaViola [22].

LaViola further divides gesture data collection systems in a third category. Next to encumbered devices worn by the user and non-encumbered systems, a combination of the two previous methods is introduced to increase accuracy and reduce errors.

Most of the non-encumbered systems explained by LaViola are computer-vision-based tracking methods. These systems show drawbacks in comparison to three-dimensional capacitive sensing. Since a visual connection is essential for the system to operate, functionality might suffer from low lighting/ darkness, grime or objects which block vision of the camera/sensor or high speed movement which is not as easily recognized on camera. In encumbered systems, vision-based motion sensors show limitations as well. Cheng and Du [21],[11] state: “First, attaching motion sensors is not practicable for every body location. This is particularly true for hands and the head. Second, signals from motion sensors can be ambivalent (as different actions are for example associated with similar motions).”

LaViola continues to show multiple encumbered systems, which will be addressed shortly, as they do not show considerable future potential in comparison to capacitive sensing technology.

First, magnetic tracking, which has a good range (15-30ft.) and is accurate (0.1 inches), but has a major flaw. Any conductive or ferromagnetic object will distort the magnetic field and cause inaccurate readings. Second, acoustic tracking, which uses high-frequency sound emitted from a source that is placed on the area to be tracked. However, as LaViola states: acoustic tracking has short range and is inaccurate. Also, it is very susceptible for external noise which interferes with the tracking signal.

Inertial tracking is the third and final encumbered-type tracking system mentioned by LaViola. Inertial tracking makes use of inertial measurement devices such as gyroscopes and accelerometers.

As stated above, LaViola shows a range of alternative gesture recognition systems that show to be disadvantageous when compared to three-dimensional capacitive sensing. These flaws in alternative gesture recognition technologies are supported by Zimmerman et al., [23] who states: “Acoustic methods are line-of-sight and are affected by echoes, multi-paths, air currents, temperature, and humidity. Optical systems are also line-of-sight, require controlled lighting, are saturated by bright lights, and can be confused by shadows."

Beyond the systems mentioned by LaViola, Zimmerman adds: "Infrared systems require significant power to cover large areas. Systems based on reflection are affected by surface texture, reflectivity, and incidence angle of the detected object Video has a slow update rate (e.g., 60 Hz) and produces copious amounts of data that must be acquired, stored, and processed. Microwaves pose potential health and regulation problems. Simple pyroelectric systems have very slow response times (>100 msec) and can only respond to changing signals. Lasers must be scanned, can cause eye damage, and are line-of-sight. Triboelectric sensing requires the detected object to be electrically charged."

3.1.4.1 Gesture recognition systems with future potential

The first gesture recognition system that shows potential for the future employs inertial tracking, as stated by LaViola, in combination with a technique called surface Electromyography. (sEMG). Cheng [11] mentions a large body of work on capacitive coupling electrodes for sEMG e.g. However, this work is based on a fundamentally different principle as three-dimensional capacitive sensing. The capacitive coupling electrodes cited above, measure the electric field generated by the body, whereas three-dimensional capacitive sensing generates an electric field and measures the influence of the human body on the capacitance.

The system implementing the combination of techniques is described in the research of Sergey Lobov et al., [24]. It is called the MYO Bracelet and it employs classification of five hand gestures for controlling various computing devices. It uses eight equally spaced sensors acquiring myographic signals from the muscles of the forearm, along with multiple accelerometers and gyroscopes to perform measurements of spatial coordinates of a hand.

This technique has been successfully implemented in cursor control on a PC in the research of Lobov [24] which is shown in figure 3.4, and also in a research conducted by I.A. Kastalskiy et al., [25]

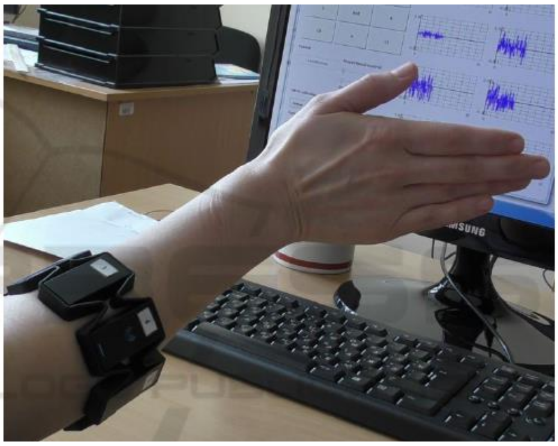


Fig 3.4. Use of a MYO bracelet as a cursor controller [24]

In comparison to three-dimensional capacitive sensing, inertial or electromyographic tracking devices, such as the MYO does show some drawbacks. First, it can only be implemented in an encumbered system, since it measures physical displacement or muscle activity through electrodes places on the skin. Second, this technology is able to detect posture, but not location. The type of movement and direction can be determined, but not the exact distance that is moved. Three-dimensional capacitive sensing does employ these features, which allow for an extensive range of interaction applications and form an advantage in comparison to systems such as the MYO bracelet.

The second gesture recognition methodology that shows future potential is using CMOS (Complementary Metal Oxide Semiconductor) radar technology. A technique which emits miniature radar waves, that are reflected by an object and returned to the receiver. The interaction principle is visualized in figure 3.5 [26]. By measuring time between sending and receiving of the signal, distance to an object can be determined. CMOS radar technology is currently in development in a research by Jaime Lien et al., [26] as a project called Soli. Soli employs a miniature gesture sensing technology for human-computer interaction

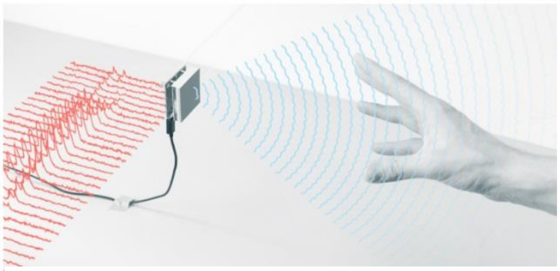


Fig 3.5. Interaction principle of CMOS Radar Technology [26]

based on millimetre-wave radar. This technology could be implemented in both encumbered or unencumbered systems.

Project Soli shows potential, but is currently limited to miniature gestures, whereas three-dimensional capacitive sensing is able to detect and recognize motions on a larger scale. As stated in the research: “We found that technical qualities and human needs overlap in design space we call micro gestures: hand-scale finger gestures performed in close proximity to the sensor.” However, it is still in the prototype stage.

It is concluded that three-dimensional capacitive sensing shows most potential for future development in the field of gesture recognition technology. This conclusion is based on the advantages that three-dimensional capacitive sensing shows in comparison to alternative gesture recognition technology such as cost, safety, employability, functionality at low lighting, engineering complexity, power consumption, processing speed and memory usage. Other systems such as the MYO bracelet and CMOS radar technology show potential, but are limited to either solely encumbered systems or miniature gestures, respectively.

3.2 WEARABLE TECHNOLOGY

According to Rekimoto [10], in encumbered systems, an unobtrusive wearable is preferred over a device which is handheld. Rekimoto states that his is due to the fact that: “*Hands-free operations* and *social acceptance* are key features of a wearable to be used in actual everyday life.” These features of wearable technology will be defined as a measure of quality of wearable technology throughout this research. This is due to the vast support of this statement by multiple sources. A more detailed discussion of these sources and their statements is documented in this section.

3.2.1 History and potential

The first wearable device ever created was the wristwatch, manufactured in 1868 by Patek Phillipe for the Countess Koscowicz of Hungary, as stated by Guiness World records [27]. Claims are made that pocket watches were adapted to be worn with wrist straps as early as the 1570’s, but no substantial evidence is available to support these claims. The first example of a wearable computing device was conceived in 1955 by Edward Thorp [28], in the form of a circuit board in a shoe which could predict roulette. Throughout the years, wearable computing has been further developed and the adoption rate of wearable technology is growing rapidly. In fact, the adoption rate is presumed to grow even more rapidly throughout the years.

According to Kurzweil’s Law of accelerating returns [29], technological change increases exponentially. Also, the ‘returns’ of this technological change (so improvements of technology), such as cost-effectiveness or computational power, increases exponentially. This means that there is an exponential growth rate of an exponential growth rate. This results in recently developed systems being adopted much faster than systems developed decades ago.

According to a research done by Vandrico [30], a database company on the topic of wearable technology, in 5½ years, 25% of the US population would have adopted wearable technology since its first commercial release by Fitbit [31] in 2008 and that it will continue to be adopted even faster. The curve visualizing Kurzweil’s Law of accelerating returns on inventions since 1860 is shown in figure 3.6 [30]. The introduction of wearable technology has been indicated.

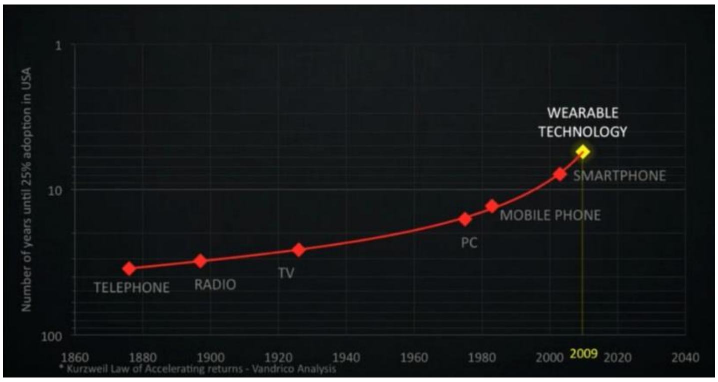


Fig 3.6. Kurzweil Law of Accelerating returns with wearable technology [30]

3.2.2 Definition

There are different approaches to define the principle of wearable technology, depending on the direction of the research conducted and the context in which the technology is applied. In this literature research, wearable technology is defined as an unobtrusive, encumbered, non-handheld computing system. This definition is supported by the researches of Steve Rekimoto [10], Mann [32], Subhas Chandra Mukhopadhyay [33], and Holleis [6]. Due to the vast support of this definition, these characteristics will be defined as a measure of the quality of a piece of wearable technology throughout this research.

According to Holleis, wearable computing and smart clothing have attracted a lot of attention the last years, as has been stated by the research of Vandrico [30] Besides the prediction of the Law of acceleration by Kurzweil, it can be seen as the potential future direction of a variety of applications of mobile user interfaces. This statement is also supported by Mann [32], Rekimoto [10], Mukhopadhyay [33] and a research conducted by Sungmee Park and Sundaresan Jayaraman [34].

Holleis' research continues to state that wearable computing offers an interesting approach for integrating new input methods to mobile computing technology and hence shows potential in mobile Human-Computer Interaction (HCI). Also, he states that accessibility is a key feature of wearable computing, which supported by both Mann [32] and Cheng [11]. Wearable computing offers large areas available for placing input controls and can embed controls into user's normal clothing.

Finally, Holleis states that an ultimate goal of wearable computing is that all technology is completely and seamlessly integrated into clothing or wearable accessories.

Cheng implies in her research that there are no specific requirements on the material from which the conductive plates, used for capacitive sensing, are made. Thus, enabling conductive textile to be used, which means that they are very unobtrusive and easily integrated in devices or clothing. This implies that three-dimensional capacitive sensing shows potential for integration in wearable technology.

3.2.3 Examples of wearable technology

Wearable technology is currently most common in three categories, according to Vandrico [30]: Activity monitors, Head worn devices and Smart Watches. In this research a fourth category is included; Smart clothing. These categories will each be shortly addressed to indicate their principle, advantages and current use.

3.2.3.1 Smart Clothing

There are multiple studies on the subject of smart clothing, as mentioned in the previous section. The research by Park et al,. [34] discusses a piece of smart technology with a very broad employability. The Georgia Tech Wearable Motherboard (GTWM), or Smart Shirt, was initially developed using optical fibers to detect bullet wounds, but as research progressed, new applications emerged. The Smart Shirt is based on a personalized flexible mobile information infrastructure that has been formed to a "wearable motherboard". This piece of smart clothing is an example of the extremely versatile applications for sensing, monitoring and information processing that could be implemented in smart clothing. In smart clothing, sensors can be placed on desired locations on the body, where data is obtained, signals are send through the clothing via flexible garments and processed either by a computing device on the body or send wirelessly to an external computing device. Park concludes by stating that this type of technology has been shown to be effective, comfortable and mobile information infrastructure that can be tailored to the individual's requirements.

3.2.3.2 Activity monitors

Activity monitors are wearable computing devices designed to track physical activity- and fitness-related metrics. In a review on consumer-wearable activity trackers by Evenson et al., [35] states that activity monitors are a popular and growing market for monitoring physical activity, sleep and other behaviors. Their popularity has risen due to the fact that they have become more affordable, unobtrusive and useful in their feedback. The activity monitor can provide feedback on the user via a smartphone for example, and store date over prolonged periods of time to provide the user with their activity behavior. A research by the Fox and Duggan from the California Healthcare Foundation [36], has concluded that approximately 69% of the U.S. adults tracked their health in some method (either by a tracking device, paper trail or "in their head"). From this survey 21% used activity trackers. An example of a well-known company producing activity monitor is FitBit [31]. FitBit develops activity monitors tracking heart rate, steps, distance, calories, activity time and sleep patterns. These trackers are recommended to be worn around at the waist, wrist pocket or brah, yet the majority of these trackers are worn on the wrist [35].

3.2.3.3 Head mounted devices (HMD)

"HMDs are computing devices worn as helmets, glasses goggles, lenses, earpieces and headphones" that is what a research by Motti can Caine [37] states. Motti et al,. continues to state that simulating a new virtual environment or virtual reality is often supported by helmets, glasses and goggles. There have been experiments in contact lenses. However, these are still in an early development phase. Hands-free interaction is made possible by for example Bluetooth earpieces in combination with (smart)phones. Examples of smart helmets are the safety helmets developed by Vandrico [38], not coincidently the company wearables database company mentioned earlier. Smart glasses are an example of Heads up Displays (HUDs), which have been around since the 1960s, according to Starner [39], the technical lead/manager on Google's Project Glass. Google glass is a well-known device, in the form of a small screen implemented in a pair of glasses, which allow the user in unobtrusive hands-free human computer interaction through for example blinking. An example of virtual reality goggles is the Oculus Rift. A review paper by Desai et al., [40], states: "Basically, VR (Virtual Reality) is a theory based on the human desire to escape the real world boundries and this is done by embracing the cyber world." The Oculus Rift is a ski-mask shaped goggle which allows interaction with PC's or smartphones. It tracks the head movement of the user allows looking around into the three-dimensional virtual world. The internal structure of the Oculus Rift is visualized in figure 3.7.

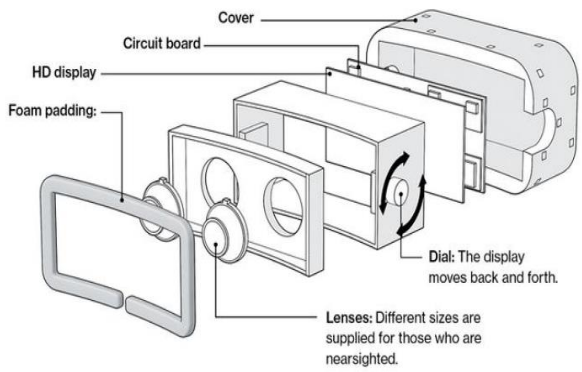


Fig 3.7. The internal structure of an Oculus Rift headset [40]

Although HMD's are categorized as wearable technology by the research of Vandrico [30], these type of systems are not unobtrusive and social acceptance of bulky goggles, such as the Oculus Rift, is debatable.

3.2.3.4 Smart Watches

The development in display and capacitive touch sensing technology leads to smaller screens being produced. Besides the implementation of these screens in PDAs, smartphones or tablets, these screens are used for smart watches. A research by Bieber et al,. [41] defines smart watches as displays in the form of a watch which provides wireless connectivity to the internet and the capability to use integrated sensors as well as haptic feedback functionality. Well-known smart watches are the products developed by Apple [42] and Samsung [43].

An example of a wearable smart watch employing three-dimensional capacitive sensing is discussed in the ideation section of this report.

4 IDEATION

4.1 INTRODUCTION

In this ideation phase the design options will be explored to obtain a deeper understanding in two sub-questions of this graduation project: *How can three-dimensional capacitive sensing or gesture recognition be implemented in wearable technology?* and *What is the accessibility of three-dimensional capacitive sensing for developers such as creative technologists?*

4.2 INTRODUCTION TO THE DIVERGENCE-CONVERGENCE PRINCIPLE

A research by Jones et al., [4] provides a model for creative design which will be used in this ideation phase. This model consists of two sub-phases, divergence, followed by convergence. In the divergence sub-phase, the design space is opened and broadened based on multiple factors such as the designers creativity, experience, cultural background hand current environment. The divergence sub-phase is meant to produce a maximum amount of varying design options to create a broad range of possibilities to select the best design from during the convergence sub-phase.

In the convergence sub-phase, the obtained design options are explored and compared. Based on factors determined by the designer, one design option is preferred over another and the least optimal solution is removed from further exploration. This way the design options are reduced until a single solution remains, the optimal solution. This method is effective, yet limited to the knowledge of the designer. Since the criteria and decisions are based on the incomplete knowledge of the designer, there are risks of losing valuable properties in design in the convergence sub-phase.

4.3 DIVERGENCE SUB-PHASE

To develop an understanding of the range of the design space, the divergence sub-phase will be executed. In this phase, multiple diverging methods will be applied to produce a maximum amount of design options. This method will be used for the development of design options for exploring both the accessibility of three-dimensional capacitive sensing for creative technologist and the implementation of three-dimensional capacitive sensing or gesture recognition in wearable technology.

4.3.1 Mind map

The first ideation method used is in the divergence sub-phase is the production of a mind map. For maximum divergence, two mind maps have been created; one based on the development experience of a creative technologist. Here, a brainstorming session has been held with a group of 6 creative technology students to gain an understanding in the experience and capabilities of a creative technology student. This brainstorming session has been documented in the form of a mind map to give a visualization of the divergence in topics in which a creative technologist hold expertise. The second mind map is based on the exploration of three-dimensional capacitive sensing and its implementation in wearable technology. These mind maps have been combined into a single mind map, which can be found in Appendix II.

4.3.2 Scenarios

The goal of producing scenarios is to develop an example of how a product, or service will be implemented in various situations. In the four provided scenarios, situations revolving three-dimensional capacitive sensing are described to further explore how this technology could be implemented in different contexts. These scenarios can be found in Appendix III.

4.3.3 Implicit research on three-dimensional capacitive sensing, related work

The last method of ideation is an implicit literature research on the already known implementation of three-dimensional capacitive sensing in previous researches and wearable technology, along with the accessibility of three-dimensional capacitive sensing technology for creative technologists.

4.3.3.1 MGC3130 documentation

The MGC3130 Single-Zone 3D Tracking and Gesture Controller Data Sheet [13] states the following application examples for the MGC3130: *"Audio products, Notebooks/Keyboards/PC Peripherals, Home Automation, White Goods, Switches/Industrial Switches, Medical Products, Game Controllers, Audio Control."*

4.3.3.2 Related work on three-dimensional capacitive sensing

The following projects and researches describe multiple design options in which three-dimensional capacitive sensing technology is implemented in everyday products, ranging from smartwatches to water bottles. These researches and projects are included in this divergence phase and considered to be sources of inspiration to new appliances with similar prototypes or technology. In the specification phase of this research, the elements that seem relevant to this project will be defined and implemented, whereas the irrelevant elements will be addressed and discarded in the following phases.

4.3.3.3 Aurasense

An example of the characteristics and goals of wearable technology being employed by three-dimensional capacitive sensing is the project developed by Zhou et al., [7]. In this project, it is found that three-dimensional capacitive electric field sensing is particularly well suited for around device interaction in wearable technology. The project, called AuraSense, is a smartwatch employing three-dimensional capacitive gesture recognition technology of both hands of the user. The interaction of AuraSense is visualized in figure 4.1 [7]. Besides of the characteristics of wearable computing, this projects states that three-dimensional capacitive sensing shows potential for future development is because of several other key properties: it is fast, low-cost (~$5), requires no additional instrumentation of the arm or finger, and does not suffer from line-of-sight issues, meaning it works through clothing.

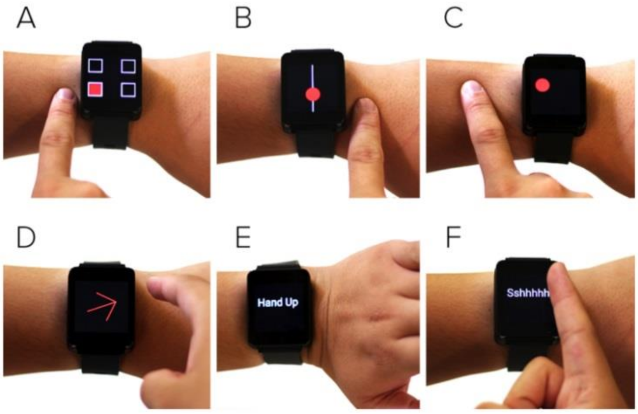


Fig 4.1. Interaction approaches in AuraSense [7]

Zhou does introduce a significant drawback in the setup. The sensing is susceptible to ambient electrical noise. It is found this generally limited finger sensing range to a few centimeters, permitting only close interactions. This can form a limitation in wearables where large gestures should be recognized.

Zhou states: "It is found that movement of the hand on the same arm as the smartwatch affected the EF signal. It is also possible to use the other hand for gestural input above the watch face." This implies that the second key feature of successful wearable computing, as mentioned by Holleis, complete hands-free interaction, is possible with capacitive-sensing based wearables.

4.3.3.4 Touché

A different approach in three-dimensional capacitive sensing in wearable computing is introduced in a research conducted by Sato et al.,[12]. Sato introduces a project called Touché, in which capacitive touch sensing technology is used as a basis for another type of sensing, called Swept Frequency Capacitive Sensing (SFCS). This technology measures capacitive change induced by touch over multiple voltages at different frequencies, whereas conventional capacitive sensing technology employs only a single voltage. This employs recognition of several types of touches, such as pinching and grasping of an object. The research states: “Touché proposes a novel technique that can not only detect a touch event, but also recognize complex configurations of the human hands and body.” These configurations are visualized in figure 4.2. In comparison to SFCS, conventional capacitive sensing is not particularly expressive; it solely detects touch in a binary manner, touching or not touching.

This technology can be applied as a wearable in the form of bracelets which send capacitive signals through the hands when touching fingers, as shown in figure 4.2. Several types of touching can be employed to control a computing device.

However, Sato mentions that the expressiveness of this technology comes at considerable engineering complexity: “The amount of signal change depends on a variety of factors. It is affected by how a person touches the electrode, e.g., the surface area of skin touching the electrode. It is affected by the body’s connection to the ground, e.g., wearing or not wearing shoes or having one or both feet on the ground. Finally, it strongly depends on signal frequency. This is because at different frequencies, the AC signal will flow through different paths inside of the body.”

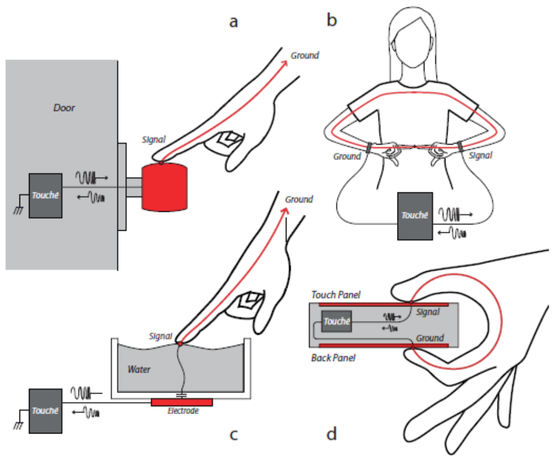


Fig. 4.2. Configurations of Touché Applications [12]

Furthermore, although this type of technology can be applied for various wearable applications, it requires a physical connection for the system to function. This is a fundamentally different principle than three-dimensional capacitive sensing as discussed throughout this research.

4.3.3.5 CapNFC

A project implementing three-dimensional capacitive sensing is Capacitive Near-Field-Communication (or CapNFC) introduced by Tobias Grosse-Puppendahl et al., [44]. It employs three-dimensional capacitive sensing in combination with NFC technology, which is also used in an inductive form as the well-known RFID technology, which is found in wireless payment services [45]. This technology is proven to be a very suitable technology for ubiquitous interaction and perception, allowing a large number of smart objects to operate in a highly interactive system at low power consumption and low cost.

5 SPECIFICATION

5.1 INTRODUCTION

For this project, a wearable, unobtrusive, intuitive piece of technology employing three-dimensional capacitive sensing is created to provide an example for future developers (read: Creative Technology students). It is believed that in the documentation of this exemplary prototype lies a guide for Creative Technology in the potential of this technology and the means to employ it in the developers design. The goal of this section is to give a definition to the Creative Technology developer and it's skills, to then provide a substantiated description of the principle, relevance, requirements and stakeholders of this project and exemplary prototype. Finally, additional implicit research will be performed on existing work related to the specific functionality of the exemplary prototype.

5.1.1 Convergence sub-phase

Characteristic for the specification phase, is the reduction of design options generated in the ideation phase. This reduction will be based on educated design decisions, called the convergence sub-phase. Throughout this specification section, convergence will be applied until all considered design options are reduced to a single, ideal design. Note that this does not mean a single superior exemplary prototype. The prototype is, as the name states, merely an example of the potential of this technology. The final 'design' in this phase will be the ideal manner to which this potential can be elaborated and exploited to its fullest.

5.2 DESIGN PROCESS OF THE MGC3130 HILLSTAR DEVELOPMENT KIT

As mentioned in the methods and techniques section of this report, the GestIC® Design Guide [5] provided by Microchip® describes a structure to which Microchip® recommends a developer should build a prototype to. This structure is taken in consideration during this project, as it forms a strong basis for the specification and realization phases of this project. The main components of the structure are shown in figure 5.1 [5] and will be discussed in further detail in this section.

5.2.1 Three-dimensional application design

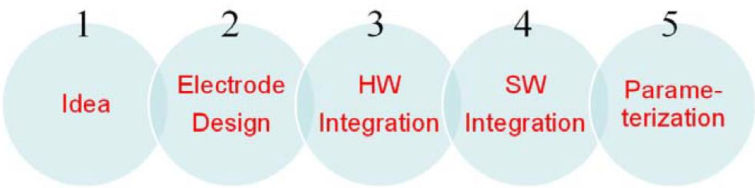


Fig 5.1 GestIC Design-in process according to Microchip

The first step as mentioned in the GestIC Design Guide reviews the entire 3D application before starting the design. This step contains multiple elements of the specification phase and is thus regarded as a suiting step to be fully executed. According to this design structure, the following points should be known by the developer prior to starting the design:

- Use cases
- Sensor range expectation
- Required 3D sensor features
- Available space for the sensor
- Battery operation
- Combination with Microchip 2D (touch controller) or 1D (buttons) solutions

In this report, the use cases will be explored by means of the definition of stakeholders and personas, whereas the other steps will be implemented in the requirements section. This step will utilized be the main convergence phase to reduce the generated design options from the ideation phase to a minimal of ideal design options for the exemplary prototype of this project.

5.2.2 Use cases of the input device

The use cases of the device will be explored by means of personas and scenarios in this project. These personas and scenarios will not only give insight into the essential aspects of the device, but also provide a better understanding of the possible stakeholders in this project.

5.2.2.1 Stakeholders

There are multiple stakeholders involved in this project. These stakeholders are based on the three pillars on which this project is build. The advantage of three-dimensional capacitive sensing over conventional human-computer interaction, the accessibility of the technology for developers and the employability in wearable technology, in the examplary prototype, specifically. Based on these criteria, the stakeholders are defined.

5.2.2.1.1 Based on potential

In regard to the advantage over conventional human-computer interaction, as described in detail in both the literature review and graduation project report, there is a multitude of stakeholders who might benefit from this technology or experience negative consequences.

First of all, the *manufacturers and manufaturers of competing technologies*; as Microchip® has developed an easy to access medium which allows for fast adaptation of this technology in a range of products, profits may rise rapidly when it is adopted as the related two dimensional capacitive touch sensing technology found in smartphones. Subsequently, manufacturers of touchscreens may need to adapt or improve their product to match the competition.

Second, the *primary, secondary users* of the technology are influenced by its potential. The primary user in this case is defined as the person who directly uses the technology to interact with any type of device. The secondary user is exposed to the technology, but not by its intention or initiative. This can occur through either being in close proximity of the primary user when the primary user is actively using the technology or being exposed to unobtrusive devices employing the technology, in an ubiquitous system for example.

Third, *society* can be considered a general stakeholder in this product. The introduction of the touchscreen has had a large impact in the way interaction is performed between humans and computing devices nowadays [16]. The introduction of a further advanced version of that technology might also be cause for change on a societal level.

5.2.2.1.2 Based on accessibility

Besides the stakeholders generated by the potential of three-dimensional capacitive sensing technology, another stakeholder can be defined, based on the accessibility of the technology for developers. *Developers* are defined as soft- and- hardware engineers or designers who hold knowledge related to the Creative Techology bachelor programme of the University of Twente. This stakeholder might be categorized under the previously mentioned manufacturers. However, manufacturers are regarded as large-budget companies who have the resources to produce this technology in bulk and invest in extensive research and development. Whereas developers are regarded as individuals who might use the provided hardware from the manufacturers for further development and personal projects.

To develop a deeper understanding in the stakeholders that are the students of the Creative Technology bachelor programme, implicit research has been conducted to construct a definition of what the focus points of the bachelor programme are. Through these focus points, a deeper understanding is developed on the topics which are essential to the creative technology student. Also, the capabilities of a creative technology student can be determined. Through these topics and capabilities, the essential hard- and software components can be chosen to be accessible to the skillset of the creative technology student. From the Study Information Centre [46], along with the Creative Technology website [47] and personal developer experience, a definition for the creative technology programme has been constructed: "*The development of high-tech solution through a combination of electrical engineering, IT and industrial design. Using sensors, programming and designing, respectively.*" The choices made in the specification and realization phase of this thesis will be based on this definition.

5.2.2.1.3 Based on the exemplary prototype

The stakeholders based on the exemplary prototype will be described in further detail after the exact decision of the exemplary prototype has been made.

5.2.2.2 Personas

The goal of producing personas is to develop an example of what the activities, capabilities and interests of the stakeholder might be. This is a form of specification in which assumptions of the developer on exemplary stakeholders are documented to describe a fictional stakeholder and create a better understanding in what types of stakeholders might be a good fit to a specific product. In the personas, primary users and secondary users, as well as the developers are considered. Personas can be used as a specific target group. However, it is also possible to use the development of these fictional stakeholders as a mental exploration, as is the case in this bachelor thesis. These personas can be found in Appendix IV.

5.2.3 Requirements

Based on the previous literature research, and the definition of the stakeholders in this technology, a list of requirements has been formulated. These requirements are based on the MOSCOW analysis [48]. This analysis divides the requirements of a project into four categories. First, the requirements that the prototype Must have are defined, then the requirements the device Should have, then the requirements the device Could have and finally the requirements the device Wont have. The requirements of the exemplary prototype categorized as such and listed below.

The device Must have:

- Implemented three-dimensional capacitive sensing
- Wearable technology features
- Accessibility to programming or adapting functions
- Hands free interaction
- A form of controlling functionality

The device Should have:

- Stand-alone functionality
- Scalability
- Unobtrusive integration
- Comfortable weight and size
- Un-restraining wiring
- Low power requirements
- Battery operated functionality
- Low computational requirements

The device Could have:

- Multiple pre-programmed gesture triggers
- Flexible electrodes

- Wireless communication

The device Won't have:

- Wiring through smart garments or smart clothing

The design guide recommends the developer to explore the requirements listed below:

- Sensor range expectation: preferably 0-100cm, as it is a wearable device, interaction should be in a reachable range. However, as is stated in the datasheet of the MGC3130, the range of the sensor reaches 0-15cm of interaction. This range will be tested during the evaluation phase, but in exemplary prototype decision, an interaction range of 0-15cm will be considered.
- Required 3D sensor features: both touch and gesture recognition in x-y-z directions.
- Available space for the sensor: As it is a wearable the space for the sensor is limited to the dimensions of the human body. It should be implemented unobtrusively, so either as a small accessory or worn beneath the clothes.
- Battery operation: as it is a wearable, battery operation is essential.
- Combination with Microchip 2D (touch controller) or 1D (buttons) solutions: no touch interaction is desired.

5.3 EXEMPLARY PROTOTYPE DECISION

The exemplary prototype which is selected to be developed in this project is the touchless presentation remote, as described in the scenario in Appendix III. This will be a wearable piece of technology using three-dimensional capacitive sensing to detect, analyse and recognize gestures to form an enhancing system for presentations. Using this prototype, the user will be able to manipulate media (such as, but not restricted to, imagery, video and audio) in a computer supported presentation. The prototype will be build using the system provided by the University of Twente, the MGC3130 Development Kit, developed my MicroChip®.

The primary reason for choosing the presentation context for this exemplary prototype is because it satisfies all requirements stated above. As the presenter should be able to control a PC-supported digital presentation using a small, wearable device implemented unobtrusively into the users clothing.

Also, both hand gestures and visual media have been proven to enhance the impact of the presentation to the audience, as will be explained in the next section of this report. Therefore it is believed that this prototype might seamlessly fit into the way we present our ideas. However, this is beyond the scope of this project and could be a subject for future research.

5.4 IMPLICIT RESEARCH ON PRESENTATION MODULES

To gain a deeper understanding in the concept of visually aided presentations and related work in touchless presentation remotes, implicit research has been conducted. Here, the connection between gestures, visual aids and the impact on the audience during a presentation will be shortly addressed. Furthermore, some related work in touchless presentation remotes is documented to give an insight in how this could be developed.

5.4.1 Gesturing and visuals in presentation

Visuals are proven to aid in the persuasiveness and attractiveness of presentations. Multiple studies have been conducted to explore the impact of visuals in presentations. Douglas R. Vogel [49] states in his research that presentations using visuals were found to be 43% more persuasive than presentations without visuals.

The concept gesture is regarded as a nonverbal signal performed by hands and arms to assist expression. H. Noot [50] identifies various functions of gestures to enhance expression: increase intelligibility of speech, augmentation or disambiguation, representation of concepts or acts and indicate emotion and cognitive state. A research by Justine Cassell [51] is in agreement the statement of Noot and adds a growing body of evidence showing gestures enhance the content of accompanying speech. Gestures have been shown to identify underlying reasoning processes that the speaker did not or could not articulate. David McNeill [52] defines gestures as: “An integral component of language, not merely an accompaniment or ornament. Herbert Clark [53] mentions the importance of inactive gestures in enhancing understandability and clarity of a conversation in his research. Clark defines inactive gestures as the reference to a nearby object by gesturing. This type of gesturing is used presentations in pointing, looking or touching an object or visual presented. It is also employed in technology such as a laser pointer.

Due to the proven enhancement of visuals and gesturing in persuasiveness and expression for the presenter, the implementation of technology to form a seamless bridge between the two aspects is believed to be profitable. However, there are known drawbacks to this type of presentation interaction. Baudel et al., [54] states that there are drawbacks in gestural hand input, First fatigue, as gestural communication involves more muscle activity. Second, non-self-revealing; the user must be aware of the pre-programmed gestures in the system. Third, unwanted interaction, as gesturing is a natural form of expression, precautions need to be taken to ensure that random gestures will not induce unintended commands which trigger interaction in the presentation.

5.4.2 Related Work

Systems employing gestures as a media input go back as early as 1970 in the “put that there” experiment by Bolt [55]. There are existing projects that enhance visuals and gesturing in presentation. These examples will be listed and discussed in this section. The advantages and disadvantages of these technologies in comparison to three-dimensional capacitive sensing will be discussed.

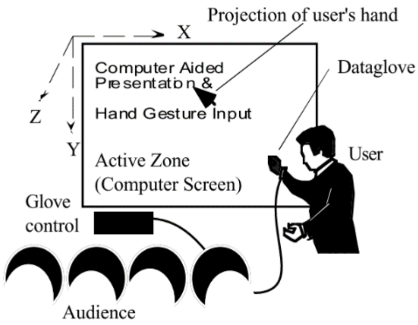


Fig 5.2. Setting of the application [54]

According to research on a project combining gesturing and visuals through technology by Baudel and Beaudouin-Lafon [54], the main three directions of systems employing hand gestures as media input are virtual reality systems (the user manipulates objects in the virtual reality), multi-modal interfaces (the user issues commands through natural forms of communication such as speech or gesturing) and recognition of gestural languages (such as sign language of conducting). This research embodies the last two of these categories as the user issues commands through gesturing.

The project by Baudel et al., uses an overhead projector and LCD display project the digital presentation on a screen, which is referred to as the 'active zone'. Also, a DataGlove, as described in a research by Zimmerman et al., [56], which uses fiber optic loops to measure the bendings of each finger in the hand. The position of the hand in 3D space is measured by a tracker by Polhemus [57]. Unfortunately, the type of tracker, or the technology employed by it, is not mentioned in the report. The data of the of the glove along with the data of the tracker is send to a PC for computing and reconstructing the position and gesture of the hand. The user can control a cursor and issue commands in the presentation through gesturing with the hand wearing the DataGlove in the active zone. A visual representation of this interaction is found in figure 5.2.

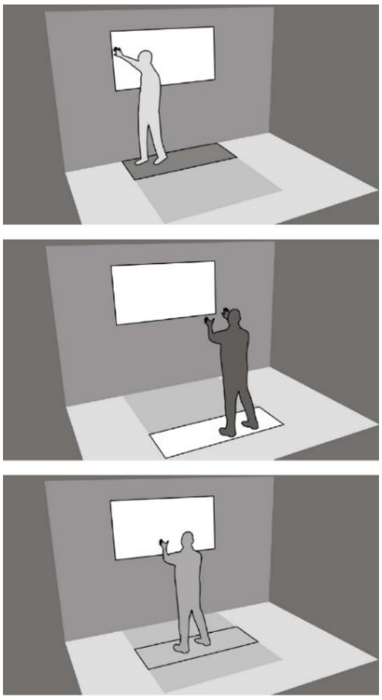
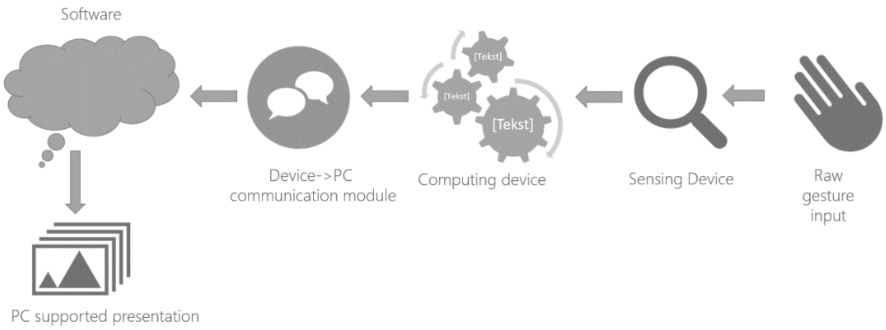


Fig 5.3. Interaction with the Funky Wal by drawing, replaying and exploring [58]

A similar system is discussed in the research by Lucero et al., [58], called Funky Wall. This is an interactive tool that supports the presentation of mood boards by designers. The interaction of the funky wall interaction consists of an interactive 2.0m x 1.5m screen along with a glove. During the presentation, the user is able to draw lines along the mood board, using the glove in proximity to the screen (<0.5m), and provide explanation to its elements. Both the drawing and explanation are recorded for reviewing. After the recording is finished, the user can step back and play back the recorded



presentation. Using gestures from a further distance (0,5m-2m), the user is able to pause, and play the presentation. On a moderate distance (0,5m-1,5m) zoom and highlight specific parts of the presentation. The glove movement is tracked using an ultrasonic tracking system. A visual representation of the interaction is found in figure 5.3.

Although in the research, the users evaluated the system positively, there are some drawbacks to include. First, there is a restriction of free movement during interaction. As ultrasonic signals have a short range, and the system is designed for the user to remain within 2 meters of the screen for interaction, the presenter is limited to the movement through space that can be performed during the presentation. Second, ultrasonic signals are easily distorted by echoes, other sounds and line of sight distortion as stated by LaViola [22]and Zimmerman [23].

Finally, Lucero et al., states the belief that the use of gestures allows designers to more clearly express the feelings and ideas for a mood board and therefore can enrich the presentation and improve the way that the client can later perceive the mood board.

5.4.3 Functionality

Now that a deeper understanding in the touchless presentation remotes has been obtained, the initial idea of the functionality of the exemplary prototype will be specified. To sense the raw gestures from the user, a sensing device should be implemented, the raw gesture data should then be analysed by a computing device to determine the x,y and z position of the users hand. Then, a communicating device should, preferably wirelessly, form a link between the wearable on the users body and the PC. Finally, the PC should have programmable software to control the running presentation software. This functionality is visualized in figure 5.4.

Fig. 5.4 - Functionality diagram

This functionality block diagram will be the basis for the functionality of the exemplary prototype. However, this functionality block diagram can be altered to fit any design a developer might want to create. The universal functionality block diagram is shown in figure 5.5.

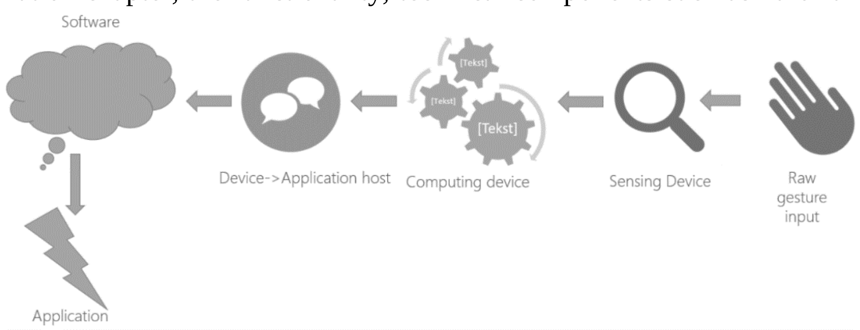
Fig. 5.5 - Functionality diagram

Now that the subject has been explored, there has been divergence in design solutions through creative thinking processes, followed by convergence to select the optimal solution through user and functionality analysis, the project enters the realization phase.

6 REALIZATION

6.1 INTRODUCTION

In this realization chapter, the functionality, technical components such as hard- and software, design and implementation of the exemplary prototype will be documented. The provided hard- and software from the MGC3130 Hillstar Development Kit will be evaluated and explored to obtain a deeper understanding in its functionality and accessibility for Creative Technology students. If the dev-kit is not deemed accessible, an accessible platform will be created through the addition of hard- and software in this phase. Technical components will be selected based on the known capabilities of Creative Technology students to create an accessible tool. Furthermore, the



design structure from the MGC3130 Hillstar Development Kit design guide will be continued in this phase.

6.2 PROVIDED MATERIAL – MGC3130 HILLSTAR DEVELOPMENT KIT

6.2.1 MGC3130 Hillstar Development Kit

As stated in manifold before, the core hardware that is explored in this project is MGC3130 Hillstar Development Kit developed by MicroChip [8]. This is the piece of technology that is provided by the University of Twente to be in the exemplary prototype. This system has been implemented in previous projects stated in the state of the art research such as the researches by Zhou [7], Gopavaram et al., [9] and Du [16]. Here, the hard- and software will be explored, evaluated and documented for personal understanding and possible guiding in future research.

There are multiple pieces of documentation, including user guides and datasheets, describing the features and interaction possibilities to this piece of hardware in detail. These pieces of documentation have shown to be very valuable in the development of an interaction prototype. The documentations related to the MGC3130 are listed below.

Fig 6.1. MGC3130 Hillstar Development Kit by MicroChip [8]

- MGC3130 GestIC Technology Quick Start Guide [59]
- MGC3130 Single-Zone 3D Tracking and Gesture Controller Data Sheet (DS40001667) [13]
- MGC3130 GestIC® Design Guide (DS40001716) [5]
- MGC3130 GestIC® Library Interface Description User's Guide (DS40001718) [60]
- MGC3130 Hillstar Development Kit User's Guide (DS40001721) [8]
- MGC3130 Hillstar Hardware References
- Programming MGC3030/3130 in Production [61]

Throughout this realization section, the interaction methods used to develop the exemplary prototype will be based on the methods described in these pieces of documentation. For a more detailed description of these methods referencing to the specific documentation is added.

The main features of the development kit, as stated in the documentation are:

- 5" electrode and variety of electrode reference designs
- GestIC Technology Electrode Design Guide
- MGC3130 unit (GestIC Technology Colibri Suite)
- I2C™/USB Bridge (USB-powered)
- GestIC Technology Library Manual
- I2C™ Interface Reference Code
- Microchip's Aurea Graphical User Interface (GUI) for Windows 7 and Windows 8
- Software Development Kit for Windows 7 and Windows 8

In this report, the main components that will be addressed in detail are:

- 5" electrode and variety of electrode reference designs
- MGC3130 unit (GestIC Technology Colibri Suite)
- I2C™/USB Bridge (USB-powered)
- Microchip's Aurea Graphical User Interface (GUI) for Windows 7 and Windows 8

6.2.1.1 MGC3130 Unit

Fig.6.2: MGC3130 microprocessor

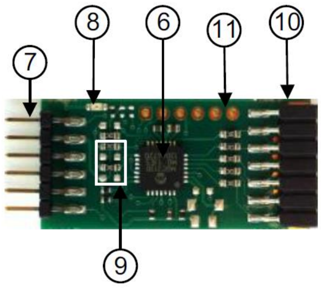


Fig. 6.3: MGC3130 Unit

The MGC3130 Unit is the main functionality component in this project. This hardware is a PCB containing the MGC3130 microprocessor, as shown in figure 6.2, along with additional components which are visualized in figure 6.3 and can be found in Appendix V. The microprocessor contains hidden Markov models [62] which form the main computing and analysing component in the Hillstar development kit. This chip is responsible for the stand-alone 3D data acquisition, digital signal processing and interpretation of gestures and the approach detection and tracking of the Cartesian x, y and z position of any conductive object. As stated in the datasheet [13]: "*Microchip's MGC3X30 are 3D gesture recognition and motion tracking controller chips based on Microchip's patented GestIC® technology. They enable user-command input with natural hand an finger movements. Applying the principles of electrical near-field sensi ng, the MGC3X30 contain all the building blocks to develop robust 3D input sensing systems. (...) Microchip's on-chip Colibri Suite obsoletes processing needs at the host (...)"*. The microprocessor's gesture recognition is based on E-field sensing, as explained in the "Technology" header of the "Three-Dimensional Capacitive Sensing" section in the State of the Art research. This gesture recognition and motion tracker is based on the GestIC® technology, as stated above. The GestIC® Technology consists of a Library loader which is stored on the Flash memory of the MGC3130. Using this loader, various compatible libraries can be uploaded to the microprocessor's Flash memory. GestIC libraries consist of:

- Colibri Suite: these are Digital Signal Processing algorithms and feature implementations. The Colibri Suite's gesture recognition is based on advanced stochastic classification based on Hidden Makrov Model. It includes predefined gestures which are sensed, analyzed and recognized within the microprocessor.
- System Control: This allows hardware control features such as interface control and parameters storage.
- The library loader: Allows for updating the implemented GestIC library through the application host's interface.

As stated before, the goal of this project is to either discover or create an accessible environment for this microprocessor. It is found that the microprocessor is based on algorithms which are not available to the public and not documented in any public materials. This discovery and realization is supported by the research as stated by Du [16]. Because of this, the MGC3130 unit will be considered a "Black Box Device". This means that any conversion or computation within the microprocessor will be considered to be beyond the scope of this project and will thus not be further explored. Other input- and output signals of the microprocessor will be discussed in more detail in the next sections. A description of the components, a schematic, and a description of the connections of the in/output pins of the MGC3130 can be found in Appendix V.

6.2.1.2 I2C/USB Bridge

The second PCB in the MGC3130 Hillstar development kit is the I2C-USB bridge. The functionality of this chip is the conversion of the I2C signal input from the computing MGC3130 unit to a USB-HID signal output to the PC with running software. The I2C and the USB-HID communication protocol will be explored in the communications section. This conversion is performed by the PIC18F14K50 USB microcontroller [63]. The I2C-USB bridge is visualized in figure 6.4 and its components are documented in detail in Appendix V. The I2C to USB bridge can simply be connected to the MGC3130 Unit through a 6 piece female header and to the users PC through an micro-USB connector cable.

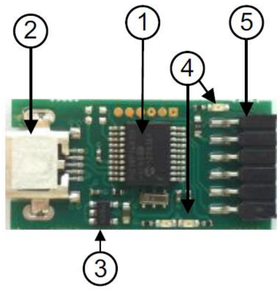
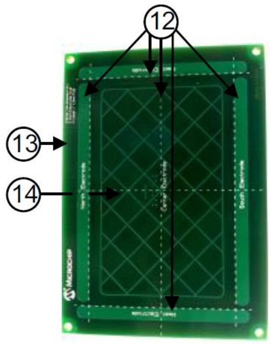


Fig.6.4: I2C-USB Bridge

The fatal drawback found in this I2C to USB bridge is the lack of access to the PIC USB controller. This means that there is no possibility to programming the microcontroller considered reasonable to be performed by a Creative Technology student. This means that programming should either be possible in software or replacement of the I2C to USB bridge by another microcontroller would be necessary.

6.2.1.3 5" electrode board and variety of electrode reference designs

The third and final piece of hardware in the MGC3130 Hillstar Development Kit is the 5" electrode board. This PCB contains 4 rectangular receiver electrodes in direction North, South, East and West, plus a fifth cross-hatched centre receiver electrode electrode. It furthermore contains a single transmitter electrode covering the full surface of the device and a ground layer. All layers are seperated by a layer of non-conductive PCB to create a capacitive sensing device. The layers are visualized in figure 6.5 [5]. The exact assembly of the electrode board can be found in Appendix V. This electrode board can easily be connected to the MGC3130 Unit trough a 7 piece header, transferring data from the 5 electrodes, the transmitter electrode and the ground pin. The dimensions of the provided electrode board is 120mm x 85mm, the sensitive area is 95mm x 60mm. As the electrode board is made from inflexible PCB and has sharp edges, it may not be suited for implementation in a piece of wearable technology.



There is a large piece of documentation on the design possibilities of the electrodes for different applications in the design guide [5] provided by MicroChip®. These design options for the electrodes are discussed in further detail in a later stadium of this realization phase.

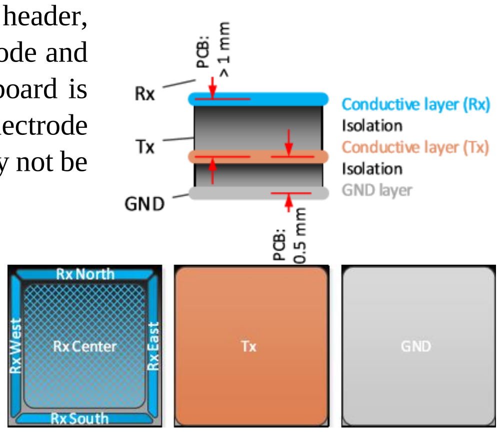


Fig.6.5: Electrode Design [13], [5]

6.2.1.4 Aurea 2.0.0 Graphical User Interface

A software package containing a Graphical User Interface (GUI) called Aurea is provided by MicroChip®. This GUI is compatible with the MGC3130 Hillstar Development Kit. The software allows for immediate, out of the box interaction when the kit is connected to the USB port of a PC with the Aurea software installed. Aurea allows for immediate insight in the interaction with the kit through an intuitive meaningful interface. It employs multiple calibration and parameterization options for altering data collection in several system setups The interface is visualized in figure 6.6. A user guide [64] to the GUI is provided by MicroChip. Also, multiple instructional videos on the functionalities within Aurea are available online [65].

The MGC3130, in combination with the Aurea GUI allows for multiple out of the box demo control options including slide control for PC-supported presentations, Windows Media Player control, cursor control and manipulation of a digital 3D cube animation in Aurea which can be moved with hand gestures, which is visualized in figure 6.6.

Fig 6.6. Aurea Graphical User Interface [64]

Furthermore, the Aurea GUI contains a detailed parameterization program. This program can be used for evaluation of the developers own electrode designs. Starting at basic adaptations such as electrode input selection, and advancing to precise parameterization and calibration techniques, all documented and provided with detailed step-by-step instruction for developers to evaluate their own electrode designs. For further instruction in these parameterization steps, either the GUI User Guide [64] or the provide online instruction videos [65] can be consulted.

In the provided GUI, a fatal drawback is found. Even though the GUI employs intuitive interaction with the dev-kit, detailed parameterization programmes and gives flawless feedback on the object position, sensor signals and recognized gestures, there are little to no options for custom programming of the software. No clear insight into the algorithm for object reconstruction has been found in any public materials. This problem has also been stated of L. Du [16]. It is concluded that besides the provided demo interactions of influencing the PC-supported presentation, the three-dimensional model and the mouse cursor, no controlling of other programs or devices is possible through the GUI. As no possibility for direct alterations in the GUI algorithm is found, alternative methods for open source programming of this technology should be considered. However, it is believed that combination with third-party software is possible, as the GUI User Guide [64] states: "Combine MGC3130 Unit and Electrodes to develop gesture-driven applications for PC-based or embedded software environments."

When including the elements of the MGC3130 Hillstar Development Kit in the functionality block diagram introduced in the specification phase, the diagram is altered as shown in figure 6.7.

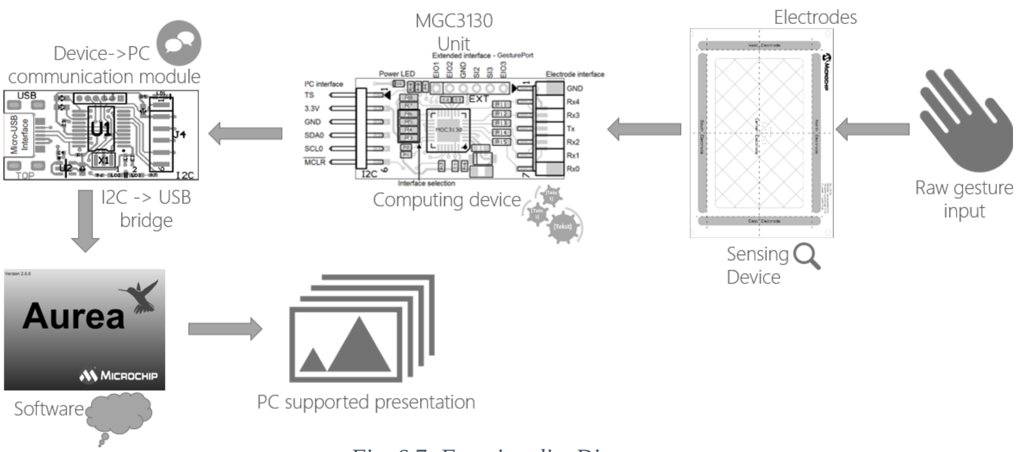


Fig. 6.7: Functionality Diagram

When considering the drawbacks found in the adaptability of the provided development kit, the MGC3130 unit is considered to be a black box device, meaning that the internal computation and analysis of the signals received by the electrodes will not be further explored. Also, the adaptability through programming of the I2C-USB bridge, along with the Aurea GUI are considered to be insufficient for this project. Therefore, an alternative solution in controlling the PC-supported presentation should be found. Consequently, the functionality diagram is altered, as shown in figure

6.8. How these drawbacks have been overcome during this project is discussed in the next section of this realization phase.

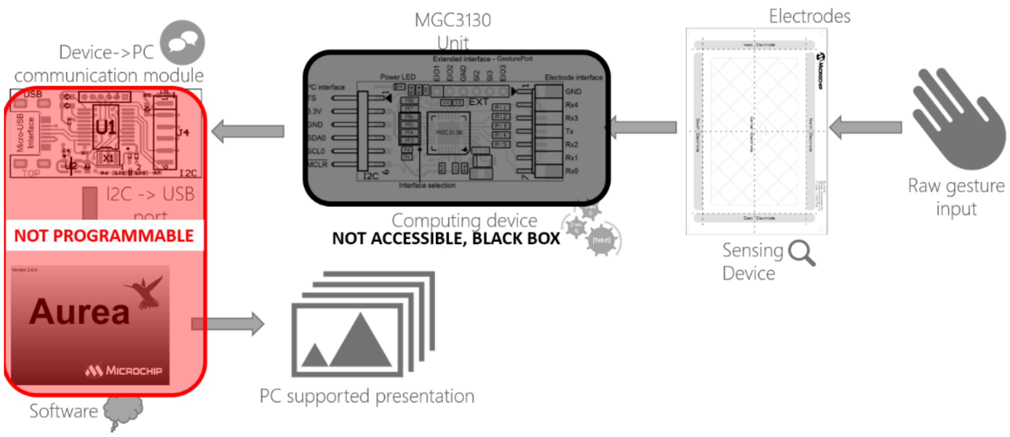


Fig. 6.8: Functionality Diagram

To conclude the review on the deliverables of the provided MGC3130 Hillstar Development Kit: the important functionalities of the MGC3130 Hillstar Development Kit that apply to the goal of this graduation project are:

- The MGC3130 Hillstar Development kit allows for out of the box 3D-gesture recognition with low computational requirements or user programming.
- Out of the box insights in the signals and parameterization of the MGC3130 in combination with the Aurea GUI.
- The possibility of combining the MGC3130 Unit and I^2C unit with customized electrodes to fit the developers design requirements.
- The availability to combine the MGC3130 and electrode module with gesture-driven PC-based applications

6.3 Additional Hardware

In this section, the hardware implemented to develop the "Creative Technology friendly" accessible environment and the exemplary prototype is discussed. The added material will be documented through description and explanation hardware, software and communication protocols. The definition of implemented hardware at this point in research is not in line with the Design process according to the Design Guide by Microchip as stated in the specification section. The electrode design exploration will be conducted in a later phase in this project.

6.3.1 Arduino microcontroller

An alternative method for three-dimensional capacitive sensing has been found in a DIY three-dimensional capacitive sensing project [66] including an Arduino [67] microcontroller, simple household items and a PC interface using Arduino software along with the Processing Integrated Development Environment (IDE) [68]. As Arduinos are highly adaptable microcontroller kits that allow for controlling of simple sensors and computing devices, these microcontrollers are considered possible hardware that may replace the I2C-USB bridge in development of the exemplary prototype. Furthermore, Arduinos are frequently used throughout the Creative Technology programme and thus considered to be familiar to the Creative Technology developer.

After further exploration, another project combining Arduino and the MGC3130 is found. This project is documented in extensive detail and provides both instruction and software material for this graduation project. The complete documentation and project is published on the open-electronics website [69].

Based on the accessibility and the example project found on the open-electronics website, the Arduino MCU will replace the I2C to USB bridge by Microchip. This means that the conversion of I2C signals to USB-HID signals should be pre-programmed to the Arduino. This also means that the Arduino should be compatible with the communication protocols of the MGC3130 unit, as well as the USB-HID protocols of the PC. The specifics of these protocols are discussed in the Communication section. There are multiple Arduino models considered be compatible with the MGC3130, the models are listed below, along with a short description about the application of the model to the MGC3130. For a detailed layout of the features of the models, see Appendix VI.

6.3.1.1 Arduino Uno

The Arduino Uno, shown in figure 6.9, is the first considered model, as it is used in the example project form open-electronics. The Arduino Uno rev. 3 [70] is based on the ATmega328P microcontroller [71]. This particular model is known to the Creative Technology student due to its use in multiple courses throughout the first two years of the Bachelor program. Also, it is compatible with the I2C protocols from the MGC3130 due to its SCL and SDK pins, which will be further discussed in the communications section.

Fig. 6.9: Arduino UNO

6.3.1.2 Arduino Leonardo

The Arduino Leonardo [72], shown in figure 6.10, is similar to the Arduino Uno in many aspects. It also contains I2C compatibility for communication with the MGC3130 Unit. However, an essential difference is the ATmega32U4 microprocessor implemented in the Arduino Leonardo. This microprocessor employs USB-HID compatibility, which allows for interaction with the PC through hexadecimal addressing, which is discussed in further detail in the communications section. This functionality is considered essential to this project, as the analog input from the electrodes and the MGC3130 need to be linked to the controlling system of the presentation, therefore the Arduino Leonardo is selected over the Arduino Uno model. Furthermore, the open-electronics example project includes a library and instruction for interaction with the Arduino Leonardo as well.

Fig. 6.10: Arduino Leonardo

6.3.1.3 Arduino Micro

The Arduino Micro [73], shown in figure 6.11, employs identical features to the Arduino Leonardo. However, it is more compact. This allows for more flexibility in integration options in prototypes. The Arduino Micro is considered to be the optimal microprocessor to be used due to its accessibility for Creative Technology students and its employability in combination with both the MGC3130 through I2C communication and controlling of the PC-supported presentation through USB-HID functionality and hexadecimal addressing. Finally, it is suited for wearable technology due to its unobtrusive integration through small size (48mm x 13mm x 8mm).

Fig. 6.11: Arduino Micro

6.3.2 NRFL01+ 2.4GHz RF transceiver

As stated in the requirements section in the specification phase, wireless connectivity is desired in this exemplary prototype as it allows for unrestrained movement for the user. This wireless connectivity is realized through the implementation of the NRFL01+ Radio Frequency Transceiver, shown in figure 6.12 [74]. This device has been selected due to its compatibility with Arduino through SPI communication, which

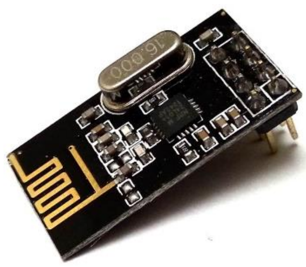


Fig. 6.12: Arduino Micro

will be explained in further detail in the communications section. It has a broad range (up to 1000m) and its line of sight independency and small size (29mm x 15 mm), allowing unobtrusive integration.

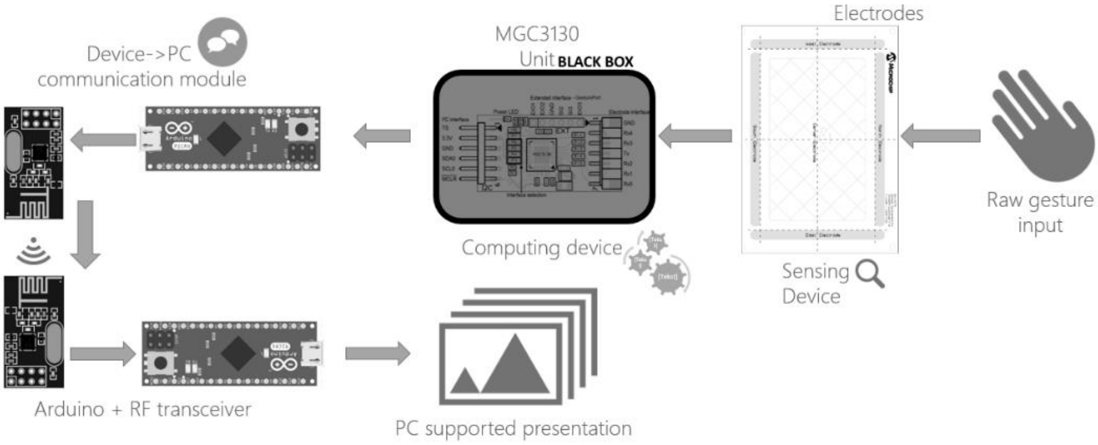


Fig. 6.13: Functionality Diagram

When including this hardware in the functionality diagram as stated in the specification section of this report, the functionality diagram as visualized in figure 6.13 is developed. As can be seen, the functionality of communication between the MGC3130 Unit and the PC controlling the presentation, previously fulfilled by the I2C and the Aurea GUI have been replaced with the two Arduino Micro MCU's. Furthermore, the diagram now allows for wireless communication between the device worn on the body and the device controlling the PC-supported presentation.

The assembly and integration of the hardware in the exemplary prototype is described in the implementation section.

6.4 COMMUNICATIONS

As stated before, multiple communication protocols are implemented in the hardware employed in the exemplary prototype. In this section, the protocols will be discussed in further detail to develop a deeper understanding in the functionality, adaptation and combination of the hardware in the exemplary prototype.

6.4.1 I2C protocol

The I2C communication protocol which is employed in the MGC3130 Unit, is based on a master device and multiple slave or multiple master devices. In the I2C protocol, a master device sends commands to the slave devices on the I2C line. This communication is performed on 2 wires. These wires are:

1. SCL: The serial clock, this line synchronises data transfers of all devices on the I2C bus. The SCL line is generated by the master device and alternates between HIGH and LOW, continuously sending bits at either 100kHz or, in the case of the MGC3130, 400kHz. [13]
2. SDA: This is the serial data line, this line carries de data transferred from device to device.

These lines need to be open drain, meaning that 2 pull-up resistors are connected to a voltage source to set the lines to HIGH, as the devices are active LOW. Common values of these resistors are 2k Ohms (1.8 kOhms for the MGC3130) (for data speed of 400 kbps) up to 10k Ohms (for data speed of 100 kbps).

I2C has the capability of connecting up to 128 devices when using 7-bit addressing, which is the case for the MGC3130 unit, and 1024 devices when using 10-bit addressing.

The data over the I2C bus is send in sequences of 8 bits, which are described in further detail below.

- First bit: Start condition
- First 8-bit seq.: Slave devices address
- After each 8 bit seq.: Acknowledge bit.
- Second 8-bit seq.: Internal Register address
- . Ack.
- Third and further 8-bit seq.: Data
- . Ack
- Final bit: Stop condition

This protocol is visualized in figure 6.14 and described in further detail below.

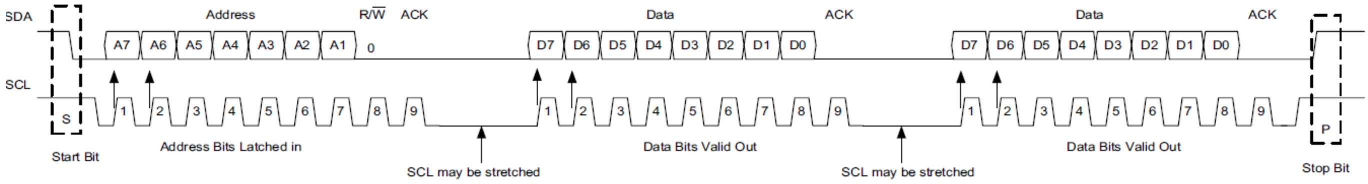


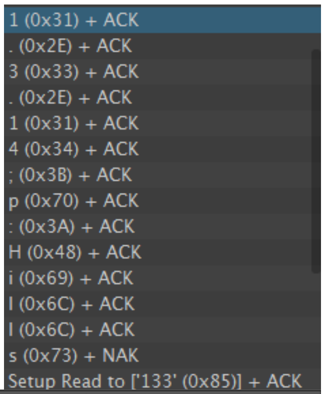
Fig. 6.14 – I2C data protocol from MGC3130

- The start condition starts when the data line drops low and the clock line is still high. After the data line drops low, the clock line will start to alternate, keeping the time. When the clock has started, each data bit will be send during a clock pause.
- The device address sequence will start with the most significant bit (MSB) and end with the least significant bit (LSB). These are only 7-bits, as the 8th bit is the used to determine whether the master device will write (logic HIGH) or read (logic LOW) from the slave device.
- After the first 8-bit sequence, the slave device will use the Ack. Bit to determine whether it has successfully received the 8-bit sequence. The master hands control over the SDA line to the slave device, which will pull the SDA line down to LOW if it has acknowledged the data.
- Next is the internal register addressing. Devices can have both a device address and a internal register addresses for different elements within the device. The address will be determined in this 8-bit sequence.
- Afterwards, the data will be transferred in the next 8-bit sequence(s) to the device in particular.
- Finally the stop condition will occur if the SDA line goes to HIGH while the SCL line is also HIGH.

Further detailed descriptions of the protocol and appliances in the MGC3130 can be found in the provided documentation [60], [13].

6.4.1.1 Saleae Logic Analyzer

It is stated in the MGC3130 User Guide [8] that it is possible to visualise and analyse the I2C signals from the MGC3130 with the use of the Salae Logic Analyzer. In this project, the Saleae Logic 8 is used to analyse the I2C signals from the MGC3130 unit. After connecting the probes from channels 0, the first ground channel and channel 2 of the logic analyzer to SDA, GND and SCL pins respectively, the I2C signals can be read from the MGC3130. These signals are visualized through the provided Logic software. Detailed explanation of the use of the Logic analyser, in combination with the



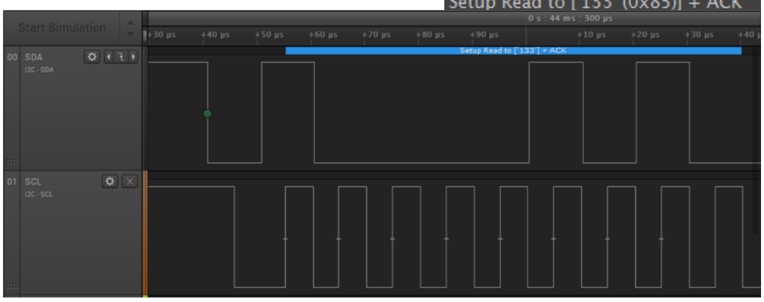


Fig. 6.15: Screenshot from Saleae Logic

Logic software is found in the provide User Guide [75]. A screenshot of the analysed signals from the raw-firmware version data (“`1.3.14; p: Hills`”), along with a screenshot of the bits send over both the SDA and SCL line for the final “Setup Read to [‘133’(0x85)] + ACK is shown in figure 6.15. This data will be further addressed in the software section. The connection from the MGC3130 pins to the Arduino will be further addressed in the implementation, connections and schematics section.

6.4.2 Serial Peripheral Interface (SPI)

For communication between the Arduino Micro MCU and the NRFL01+ 2.4GHz RF transceiver, the SPI protocol is used. This protocol is explained on the Arduino website [76]. As the webpage states: “Serial Peripheral Interface (SPI) is a synchronous serial data protocol used by microcontrollers for communicating with one or more peripheral devices quickly over short distances. It can also be used for communication between two microcontrollers.”

The SPI connection consists of one master device (in this project the Arduino Micro MCU) which controls the peripheral devices (which in this case is the NRFL01+ RF transceiver). Typically there are three lines common to all the devices:

MISO (Master In Slave Out) - The Slave line for sending data to the master,

MOSI (Master Out Slave In) - The Master line for sending data to the peripherals,

SCK (Serial Clock) - The clock pulses which synchronize data transmission generated by the master

The connection of these lines to between the devices can be found in the implementation, connection and schematics section.

6.4.3 USB-Human Input Device (HID) (Hexadecimal addressing)

For controlling the PC-supported presentation, the hexadecimal addresses of the keys on the PC’s keyboard need to be triggered. This will be done through the USB-HID functionality of the ATmega32U4 microprocessor implemented in the Arduino Micro MCU, as stated before. Here, the theory behind this protocol will be discussed in further detail.

6.4.3.1 Hexadecimal addressing

Hexadecimal addressing is a protocol in which addresses on computing devices are coded through the hexadecimal coding system. This system is a base 16 number system, using number 0 up to 9 along with the letters A, B, C, D, E and F to represent numbers and codes with a 0x*** standard structure. This system is further explained in the book “Programmable Controllers” by L. A. Bryan et al., [77]. The number system is constructed a shown in table 6.1.

Hexadecimal number system			
0	4	8	C (12)
1	5	9	D (13)
2	6	A (10)	E (14)
3	7	B (11)	F (15)

Table 6.1: Hexadecimal number system

6.4.3.2 USB-HID interaction

In this prototype, hexadecimal addressing is utilized to trigger keyboard commands on the PC running the PC-supported presentation. This triggering is realised through the USB-HID functionality. Examples of devices with USB-HID functionality are a computer mouse, keyboard or standard presentation remote [78]. When the gesture is sensed, computed analysed and communicated wirelessly through the 2.4GHz RF protocol to the PC, the pre-programmed corresponding address of the keyboard key is triggered through software programmed on the Arduino Micro connected to the PC. The exact programming of the triggering of these keys can be found in the software section of this realization phase. The virtual key codes, containing the hexadecimal addresses of all keys on the windows keyboard, is provided by Microsoft® [79]. The exact programming of the key triggering per specific gesture are discussed in further detail in the software section.

6.5 SOFTWARE

Now that the selected hardware and the communication protocols between the hardware is discussed, the implementation of software in the exemplary prototype is discussed. In this section, the software obtained from third parties will be clearly distinguished from original written code. Lines of code essential to the functionality of the technology are documented within this section, further supplementary code is included in the corresponding appendices. All software discussed in this section programmed to one of the two the Arduino Micro MCU's, which allows for stand-alone functionality. This way, the exemplary prototype can be connected to any PC and control the keyboard with the hexadecimal USB-HID functionality. This way, no additional computation or software running on the PC is required.

6.5.1 Libraries

To enable communication and programmability of the multiple types of hardware, code libraries have been included in the programming of the Arduino MCU's. The libraries that are included in the exemplary prototype are:

- `#include <SPI.h>:` This library allows for the Serial Peripheral Interface (SPI) communication between the Arduino Micro MCU and the NRFL01+ 2.4GHz RF transceiver. This library is a built in library in the Arduino IDE, version 1.0.0. It allows for the communication over the MISO, MOSI and SCK lines. A more detailed description is available on the Arduino website [76].
- `#include <RF24.h>:` This library is downloaded from the Arduino library manager, version 1.3.0. This library allows for easy interaction between the NRFL01+ and the Arduino Micro MCU. Further information can be found on the library fork page [80].
- `#include <Wire.h>:` This library is a built in library in the Arduino IDE and allows for communication through I2C or two wire interface devices. Version 1.0.0. A more detailed description can be found at the Arduino website [81].
- `#include "MGC3130.h":` This is the library introduced by the open-electronics project. This library [82] is found through the project page on the open-electronics website. Version 1.1.0.0. The files provided are:
  - `MGC3130.h & MGC3130.cpp:` The library files, containing the protocols for communications over the 6 lines from the MGC3130 Unit. These libraries allow for easy programming and interaction of the Arduino Micro MCU to read data from the MGC3130 Unit.
  - `MGC3130_Demo:` The demo file for interaction between the MGC3130 Unit and the Arduino Uno MCU.
  - `MGC3130_Leonardo:` The demo file for interaction between the MGC3130 Unit and the Arduino Leonardo MCU.
- `#include Keyboard.h:` This library is a built in library in the Arduino IDE and allows for controlling and programming of the keyboard input. Version 1.0.1. This Library is plugged onto the HID library, allowing for USB-HID input.

The MGC3130.h and MGC3130.cpp files are explored through the Visual Studio IDE for exploration of the algorithms. No changes are made to the files.

6.5.2 Written code

To realize the functionality of the exemplary prototype, and to provide an example of the combination of multiple devices with the MGC3130, the Arduino Micro MCU is programmed through original written code. This original written code is an addition to the provided demo file from the open-electronics project [82] and the previously mentioned provided libraries. The full written code is documented in **Appendix XIV.**

6.5.2.1 MGC3130 programming

The provided code includes a large work of code for controlling an MCP23017 I/O expansion board, which is not included in this project, considered unnecessary and therefore removed from the code. This example can still be found by accessing the original provided code. Furthermore, there is a large work of controlling LED's connected to the I/O expansion tool, which is removed as well. When running the provided code, data from the output of the MGC3130 Unit is captured by Arduino, converted to intuitive descriptions by the provided library and printed to the serial monitor by the provided code. This way, performed gestures can directly be read from the serial monitor. The documentation in the serial monitor of the initial connection, raw firmware data and a registered flick gesture from the west to the east electrode is shown in figure 6.16.

```
MGC3130 initialization in progress...wait
MGC3130 device is ready
#####################################################################################
Row Firmware Info from MGC3130
Header: 84000083
Payload: AA | 6380 | E6 | 136415 | 20 | 312E332E31343B703A48696C6C7300000000000000000
#####################################################################################

FW Version: ▯ 1.3.14;p:Hills
#####################################################################################
Row data from MGC3130
Header: 1A080C91
Payload: 1F01 | AA | 90 | 0067 | 02100000 | 00000000 | 0000 | 000000000000
#####################################################################################

Gesture West to East
#####################################################################################
Row data from MGC3130
Header: 1A080D91
Payload: 1F01 | 8A | 80 | 1067 | 00000000 | 00000000 | 0000 | 000000000000
#####################################################################################

The X coordinate is:
xxxxx
The Y coordinate is:
yyyyy
The Z coordinate is:
zzzzzz
#####################################################################################
Row data from MGC3130
Header: 1A080291
Payload: 1F01 | 97 | 80 | 0073 | 00000000 | 00000000 | 0000 | 5FA720FB167E
#####################################################################################
```

Fig. 6.16: Serial communication MGC3130 - Arduino

6.5.2.2 NRFL01+ programming

Here the programming through originally written code for the NRFL01+ is documented.

6.5.2.2.1 Transmitting 2.4GHz RF signals'

For transmitting the data captured by the Arduino Micro MCU from the MGC3130 Unit, code is written to be send by the NRFL01+ transmitter connected to that Arduino. This is done by first defining a struct containing a data ID and Action int. This action int is set to be equal to a certain number, depending on the recognized gesture. As shown in figure 6.17.

Afterwards, the defined data is send over the 2.4GHz RF. This is done by first initializing the connection and repeating the transfer continuously. As shown in figure 6.18. The data is send as a continuous stream of 0 (no gesture data), interrupted by Action integers when a gesture is performed.

```
RF24 myRadio(10, 11);             // Set CSN and CE pins to be 10 and 11
byte addresses[] [6] = {"0"};

struct package {                  // Define package struct to be send over RF
  int id      = 1;                // ID, tracking amount of data send
  int Action = 0;                 // Action, communicating the recognized gesture
};

typedef struct package Package;
Package data;

// List of gestures with corresponding action number
int Centre_Tap    = 1;
int North_Tap     = 2;
int South_Tap     = 3;
int West_Tap      = 4;
int East_Tap      = 5;
int North_South   = 6;
int South_North   = 7;
int West_East     = 8;
```

Fig. 6.17: Definitions NRFL01+

```
// Wireless communication through NRFL01+ 2.4GHz RF transceiver //

// Initialization of connection (executed in void setup())
void wireless_init(void) {
  data.id = 1;
  myRadio.begin();                          // Start RF communication
  myRadio.setChannel(115);                  // Set the channel to 115 (matching with the receiver)
  myRadio.setPALevel(RF24_PA_MAX);          // Set the power supply to max (to obtain maximum signal strength/range)
  myRadio.setDataRate( RF24_250KBPS );      // Set the frequency to 250 Kbits/second
  myRadio.openWritingPipe(addresses[0]);    // Open the writing pipe
}

// Transferring of gesture data from the first Arduino to the second through the NRFL01+ (executed in corresponding gesture voids())
void wireless(void) {
  myRadio.write(&data, sizeof(data));       // Write the data in the struct to the RF transmitter
  Serial.print("\nRadioData:");
  Serial.print(data.id);
  Serial.print("              ");
  Serial.print("Gesture RadioSend:");
  Serial.print(data.Action);
  data.id = data.id + 1;
  digitalWrite(Led, HIGH);                  // Indication Led ON
  TimeOutLed = T_50MSEC;
}
```

Fig. 6.18: NRFL01+ transmitting code

6.5.2.2.2 Receiving 2.4GHz RF signals

The programming of the second NRFL01+ RF transceiver, the receiving unit is similar to programming of the transmitting unit, this is because both units should be programmed to the same frequency, channel, address and data interpretation. Here, the Arduino is programmed to read the received data from the NRFL01+, analyse the data and assign the right action to the received data. The essential code is shown in figure 6.19.

6.5.2.3 USB-HID programming

The data received by the Arduino, connected to the PC controlling the presentation, then triggers the pre-programmed pressing of key on the keyboard through hexadecimal addressing. The hexadecimal addressing of keys on the keyboard can be found in Appendix VII. The code triggering the key, in combination with the keyboard.h library, is shown in figure 6.20.

The finalized functionality diagram, including the raw gesture input, the MGC3130 Hillstar Development Kit, the implemented hardware and software and the PC supported presentation is visualized in figure 6.21.

```
void setup() {

  pinMode(Led, OUTPUT);
  Serial.begin(9600);
  myRadio.begin();
  myRadio.setChannel(115);
  myRadio.setPALevel(RF24_PA_MAX);
  myRadio.setDataRate( RF24_250KBPS );
  myRadio.openReadingPipe(1, addresses[0]);
  myRadio.startListening();
  Keyboard.begin();
}

void loop() {
  if (myRadio.available()) {
    while (myRadio.available()) {
      myRadio.read(&data, sizeof(data));
      Serial.print("\nRadioData:");
      Serial.print(data.id);
      Serial.print("\n");
      digitalWrite(Led, HIGH);
    }
    PressButton();
  }
  delay(10);
  digitalWrite(Led, LOW);
}
```

Fig. 6.19: NRFL01+ receiving code

```
int Centre_Tap    = 1;
int North_Tap     = 2;
int South_Tap     = 3;
int West_Tap      = 4;
int East_Tap      = 5;
int North_South   = 6;
int South_North   = 7;
int West_East     = 8;
int East_West     = 9;

void PressButton(void) {
  // Centre Tap
  if (data.Action == Centre_Tap) {
    Serial.println("Centre_Tap");
    Keyboard.press(0xC6);   // F5
    Keyboard.releaseAll();
  }
```

Fig. 6.20: Hexadecimal triggering of keys

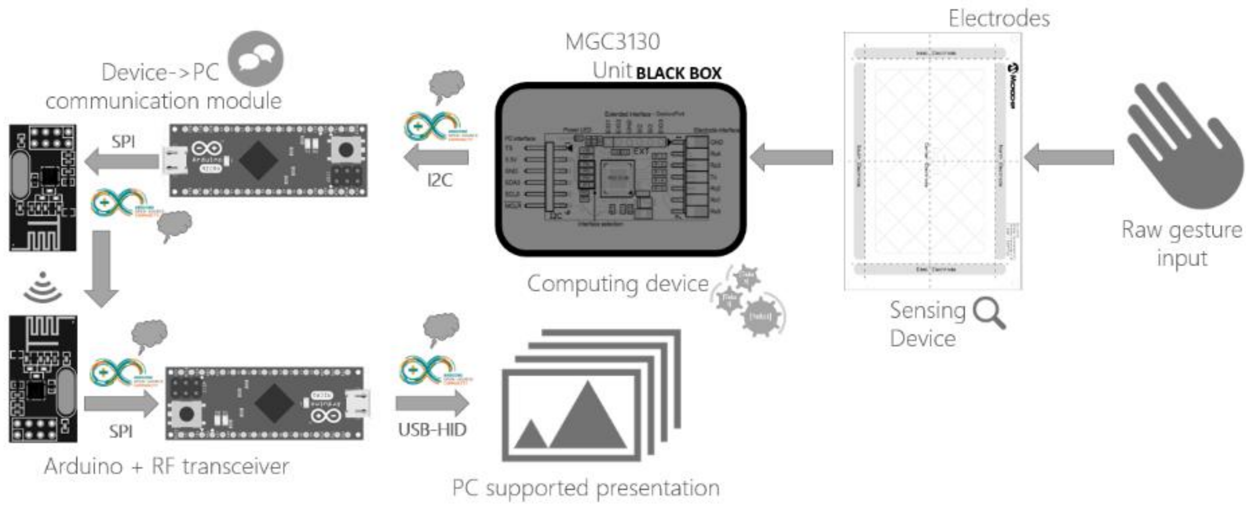


Fig. 6.21: Functionality diagram

Implementation, connections and schematics

Now that all technical components have been defined and discussed, the implementation of these components, the specific connections between the components and the internal schematics will be discussed to provide an understanding in how these devices should be implemented in the developers design.

6.5.2.4 Connections and schematics

To document the needed connections of the exemplary prototype, the two Arduino Micro MCU's are considered the centre of connectivity as they employ the running software and form the controlling device in this prototype. In table 6.2 the connections of each Arduino to the other hardware has been documented. Furthermore, the connections have been visualized in Appendix VIII.

Arduino Micro 1 (MGC3130-connected)		**Arduino Micro 2 (PC-connected)**	
Arduino Pin	Device Pin	Arduino Pin	Device Pin
3.3v	NRFL01+ Pin Vcc	3.3v	NRFL01+ Pin Vcc
GND	NRFL01+ Pin GND	GND	NRFL01+ Pin GND
10	NRFL01+ Pin CSN	10	NRFL01+ Pin CSN
11	NRFL01+ Pin CE	11	NRFL01+ Pin CE
MOSI	NRFL01+ Pin MOSI	MOSI	NRFL01+ Pin MOSI
SCK	NRFL01+ Pin SCK	SCK	NRFL01+ Pin SCK
MISO	NRFL01+ Pin MISO	MISO	NRFL01+ Pin MISO
6	MGC3130 Pin TS	3.3v	100µF Capacitor
3.3v	MGC3130 Pin 3.3v	9	Blue LED
GND	MGC3130 Pin GND	USB Micro female	POWER + USB-HID connection to PC
2	MGC3130 Pin SDA		
3	MGC3130 Pin SCL		
4	MGC3130 Pin Reset		
USB Micro female	POWER (5V, 1A)		
3.3v	100µF Capacitor		
7	IR LED		
9	Blue LED		

Fig. 6.2: Pin Connections

As can be seen in table 6.2 and Appendix VIII, a capacitor is added in parallel to the connection with the NRFL01+ and the Arduino. This is done to provide a stable 3.3v dc power supply, as the NRFL01+ range performance can be influenced under fluctuating voltages. Furthermore, both Arduino's have been fitted with a notification LED op pin 9 that illuminates whenever data is being transferred. The Arduino connected to the MGC3130 has also been fitted with a IR LED for controlling of IR remotely controlled devices, such as TV's. However, this has been a minor prototyping detail and will not be addressed any further in this report. Detailed pinouts of the Arduino Micro MCU, including functionality of each pin, can be found in Appendix VI. Pin connections have also been documented in the written code in the Arduino IDE.

6.5.2.4.1 Schematics

Schematics of the MGC3130 Unit are included in Appendix V. Detailed schematics of other components of the MGC3130 Hillstar Development kit can be found in the provided documentation [5], [8], [13].

6.5.2.4.2 Power

Now that all hardware has been connected, power sources should be implemented in the prototype. In table 6.2 and Appendix VIII can be found that the Arduino Micro MCU connected to the MGC3130 Unit is powered by a 5V voltage source. This voltage is supplied by the portable power bank with USB A 5V 1000mA output and it contains 2600mAh power storage capacity. The Arduino connected to the PC is powered through the PC's USB port.

6.5.2.5 Design

Here, the designing of the prototype to satisfy the requirements of a piece of wearable technology is discussed. This is the final stage realisation of the prototype. The NRFL01+ transceivers are soldered tightly onto the Arduino board, along with the LED's and the capacitors to create a small, unobtrusively implementable prototype. The final prototype is shown in figure 6.22

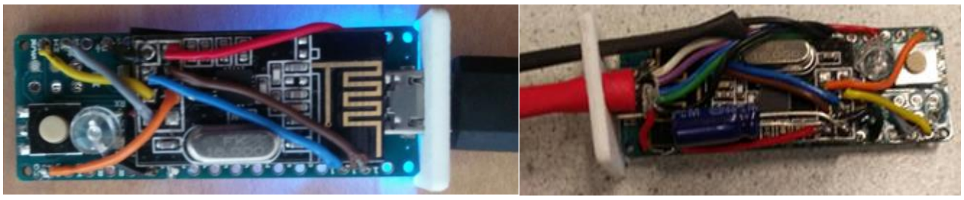


Fig. 6.22: Finalized prototype

6.5.2.5.1 3D printing

To create a custom fit casing for the Arduino Micro, the NRFL01+ and the other components, design is made to be 3D-printed. Since 3D printing is an accessible tool for Creative Technology students, it is believed that this way of developing the casing for the prototype contributes to the accessibility of this prototype and implementation of this technology for a Creative Technology student. The to be printed design is created in FreeCAD, an open-source 3D designing program [83]. The created designs and the final prototype, including the 3D-printed casings and connections are shown in figure 6.23.

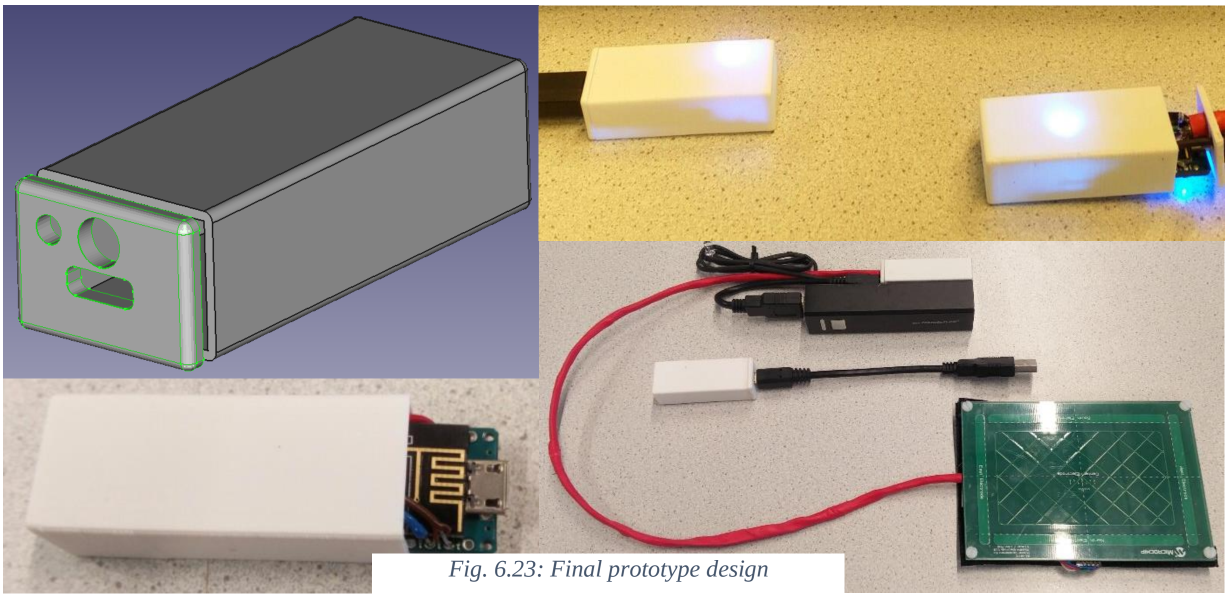


Fig. 6.23: Final prototype design

6.5.2.6 Electrode design options and connection to the MGC3130 Unit

In the GestIC Design Guide [5] provided by Microchip® electrode design options are discussed in detail, including various electrode designs suited for various contexts. These electrode design options will be discussed in this section, to obtain a deeper understanding in the accessibility of this development kit for future Creative Technology students and the employability of this technology in a wearable.

The GestIC Design Guide includes a design schematic to determine the type of electrode design necessary for the users prototype or project. This design schematic is shown in figure 6.24 [5].

In this research, the implementation of three-dimensional capacitive sensing in wearable technology is explored. As a connection to a wall socket is considered restraining for the user when wearing a piece of technology, the target sensor size, according to the flow-chart in the Design Guide, is a 3 layer, standard electrode, sized 20-140mm.

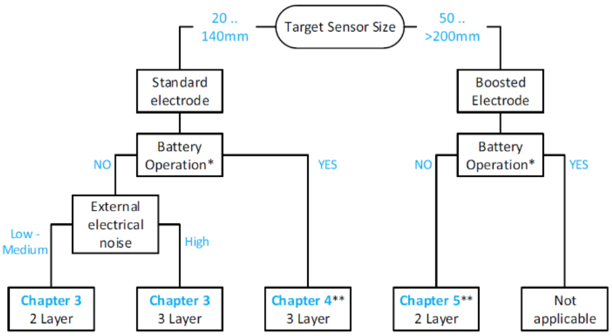


Fig. 6.24: Electrode design flowchart

As can be seen in the flow chart, the Design Guide references to a specific chapter for documentation on electrode designs for battery operated systems. These designs are discussed to explore the optimal design to be implemented in the exemplary prototype.

According to the GestIC Design Guide, a battery operated system has a lower expected performance than a standard or boosted electrode system. This is visualized in figure 6.25. This is due to the fact that a battery-operated system is often not sufficiently connected to the ground to maintain the loop to the human hand.

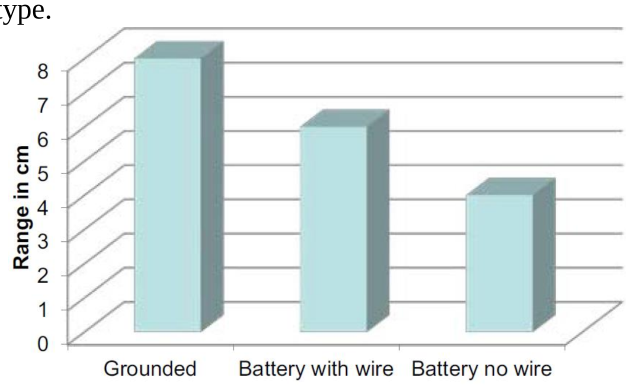


Fig. 6.25: Electrode range in various contexts

The battery-optimized electrode design is shown in figure 6.26. A prototype electrode is developed according to the design guidelines. The electrode developed is a 3 layer design, employing a 0.3mm steel sheet as conductive layer and 0.8mm PET plastic as isolation layer. The dimensions of the final prototype are 72x72mm. The electrode is visualized in figure 6.26. The performance of the developed electode is tested in the evaluation phase of this report.

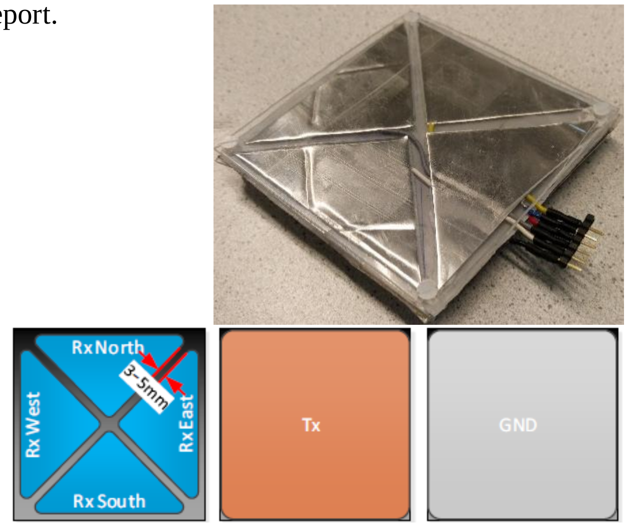


Fig. 6.26: Battery-optimized electrode design

7 EVALUATION

7.1 INTRODUCTION

Now that the subject of this graduation project is explored, divergence and convergence of design options have been conducted in the ideation and specification phase and the exemplary prototype has been developed in the realisation phase, this evaluation phase will evaluate the developed prototype. This evaluation is categorized in functionality testing, in which the technological performance of the prototype is evaluated, user testing, in which the usability of this prototype and the technology in general is tested and reflection, in which possible ethical challenges are evaluated.

7.2 FUNCTIONALITY TESTING

To test the functionality of the finalized prototype, a testing setup has been designed. In this functionality testing, the range and functionality of the exemplary prototype is evaluated. This evaluation is performed using both the provided 95x60mm standard 5" electrode and the developed battery-optimized 72x72mm 4" electrode.

In this testing setup, the proximity and gesture recognition range of the system is evaluated. This will be tested by the development of a swing-installation, mimicking the flick gesture. This setup is developed to give an estimation of the range of the setup. The setup is shown in figure 7.1.

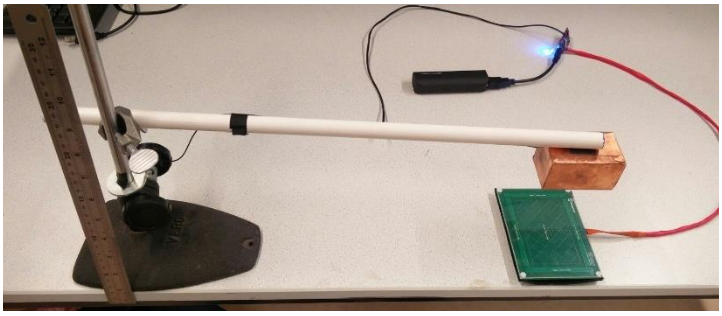


Fig. 7.1: Range test setup

The swing consists of non-conductive PVC tube, with a styrofoam cube covered with conductive copper tape, attached to the end of it. The styrofoam cube is then connected to ground with a wire. The height of the PVC tube is adaptable and measured. In the testing procedure, an amount of 30 swing gestures are performed above the sensing area of the electrode. The z-distance between the electrode and the Styrofoam cube is decreased by 10mm between each 30 measurement. The amount of successful measurements are registered. This testing procedure is performed for gesture or proximity recognition, for grounded or not grounded setups and for both the provided and developed electrode. This procedure is shown in table 7.1.

Provided 95x60mm standard el.				**Developed 72x72mm battery-optimized el.**			
Grounded		Not Grounded		Grounded		Not Grounded	
Gesture	Proximity	Gesture	Proximity	Gesture	Proximity	Gesture	Proximity

Table. 7.1: Testing setups

During the testing procedure, it was found that the developed 72x72mm battery is not compatible with the MGC3130 Unit. A stable signal could not be obtained through the parameterization procedure, using the provided Aurea GUI, meaning the MGC3130 could not be calibrated sufficiently to fit the signals from the electrodes. Therefore, no measurements have been performed using the developed 72x72mm battery-optimized electrode. It is therefore decided that the provided 95x60mm standard electrode is used in the exemplary prototype.

The results of the measurements using the 95x60mm standard electrodes are documented in Appendix X and visualized in figure 7.3. When comparing these results to the range

	Standard Electrode – (Hillstar 95x60)	Battery Operation – Setup A (70 x 70 mm)	Boosted Electrode 8" (210 x 135 mm)
Flick Recognition N-S	60 mm	40 mm	140 mm
Flick Recognition E-W	50 mm	40 mm	130 mm
Proximity Range	140 mm	100 mm	320 mm

Table. 7.2: Ranges of MGC3130 [5]

values, shown in figure 7.2 as claimed in the Design Guide [5] provided by MicroChip®, it is found that these results show resemblance to the claimed results, although showing a 10-20mm decreased detection range. It is suspected that this detection range reduction is due to interference with external noise, whereas the testing setup of MicroChip® might reduce external noise to a minimum.

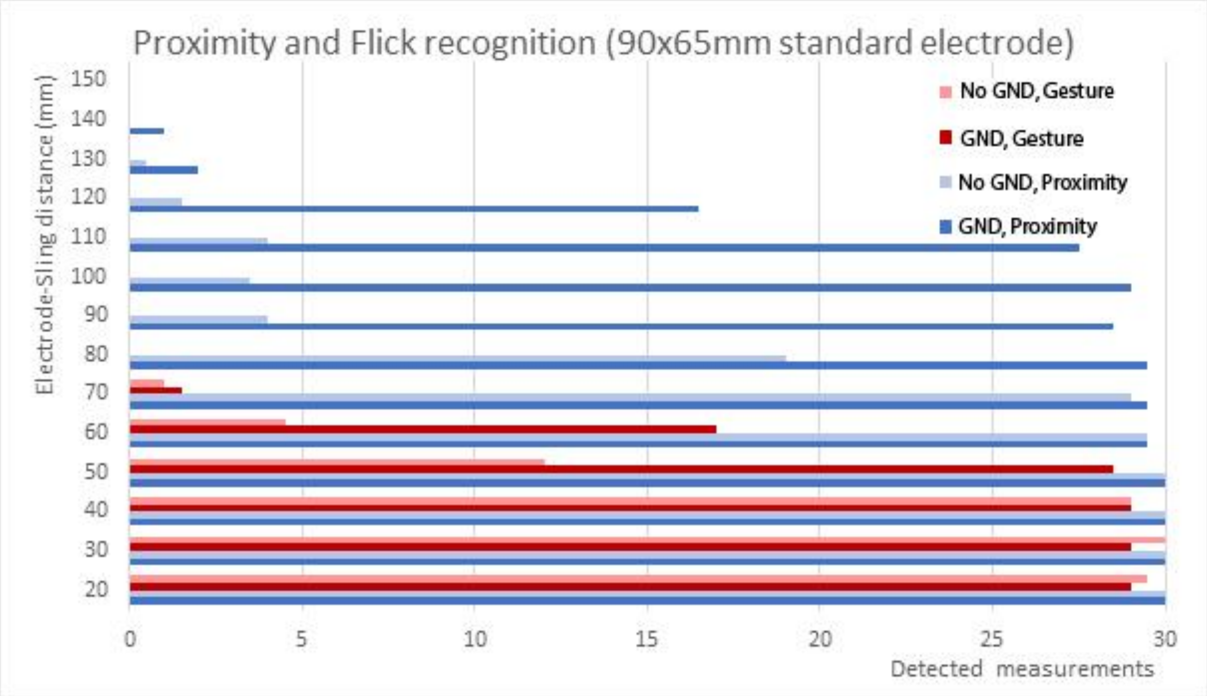


Fig. 7.3: Range Test results

It is found that for reliable gesture recognition, a maximum distance of 40-50mm can be used. How this interaction range is best employed in a piece of wearable technology is evaluated in user testing.

7.3 USER TESTING

In user testing, the ideal manner of implementing the prototype and three-dimensional capacitive sensing in a wearable is evaluated. In this section, the ideal placement of the electrodes on the presenters body will be evaluated through user testing. For the placement of the electrodes, the locations that will be tested are: Torso, forearm, upper arm and pocket. These placements are shown in figure 7.4. For each of these locations, the functionality of the prototype will be tested on three aspects: Comfort in wearing, unobtrusiveness in placement, unobtrusiveness in utility and naturality of gesturing. Furthermore, the prototype will be evaluated on how intuitive it is for the user.

All participants are selected to be Creative Technology students, as in this user testing, the accessibility for Creative Technology students is tested. Furthermore, the participants should be able to give an expert opinion on the sensor and its implementation in the Creative Technology bachelor programme.

Fig. 7.4: Electrode placements

The user tests are conducted in a presentation context. All participants are handed an information sheet, along with a consent form, explaining the conditions of the experiments. The information sheet and consent forms can be found in Appendix IX. After filling in the consent form, the participant starts the experiment. During the experiment observations are made relevant to the functionality of the prototype. Afterwards, the participant is handed a questionnaire to provide an opinion on the sensor and its functionality. The questions are designed to develop a deeper understanding in the applicability of the sensor in the Creative Technology Bachelor programme. The filled in questionnaires are documented in Appendix XI.

According to all participants, this prototype could be implemented as a presentation controller in lectures or project presentations. Furthermore, the sensor could be implemented in subjects such as Smart Environments or the Smart Technology elective programme to be implemented in projects.

During the experiment, the participant is asked to wear the sensor on one of the four pre-defined placements and perform a series of tasks using the controller. These tasks were displayed in the form of a PC-supported presentation. The PC-supported presentation for experimenting is documented in Appendix XII. The tasks include: controlling slides with use of the prototype, unprepared pitching allowing either hands movement or not and answering questions. The tasks assigned during the experiment are designed to develop a deeper understanding in the ideal placement of the electrode. During this experiment the electrode placement is changed once from an arbitrary placement to the pocket, as the pocket placement is expected to be the most comfortable and most unobtrusive. The documentation of the experiments are listed in Appendix XIII. The results of the experiments are shown in table 7.3.

REQUIREMENT	LOWER ARM	UPPER ARM	CHEST	POCKET
MOST COMFORTABLE		1 occurences		5 occurences
NATURAL GESTURE AREA			x	
INTUITIVITY	Equal	Equal	Equal	Equal
IDEAL GESTURE AREA	0	3	1	2
UNOBTRUSIVE PLACEMENT	3,666666667	2,833333333	2,166666667	1,333333333

Table 7.3: User test results

As expected, based on the four electrode placement options and the six experiment participants, it is found that the pocket is the ideal placement for the electrode. As shown in table 7.3, in 5 out of 6 participants, the pocket was considered to be more comfortable than the other placement. Also, the pocket is considered the most unobtrusive from the audience perspective.

A drawback which is found in the prototype is that without explanation of the functionality of the sensor, it takes the participant 2 minutes on average to understand the functionality of the sensor. It is also found that the placement of the electrode does not influence how intuitive the sensor is to the user.

During the experiment, observations have been made on the conscious and unconscious gestures of the user. The gestures unconscious gestures observed frequently were clamming of hands and pointing. The conscious gestures that were observed frequently were: crossing arms, clamming hands, spreading arms, and scratching of the head. From the observed movements, in combination with the participants unanimous suggestion that the chest is the natural area for hand movement when explaining something, it is concluded that the red area, as shown in figure 7.5 is considered to be the active region for hand gestures when explaining something. This area should be avoided when implementing sensors as accidental triggering of these sensors is considered likely. Based on this assumption, it is assumed again that the pocket is the best placement option for the electrode.

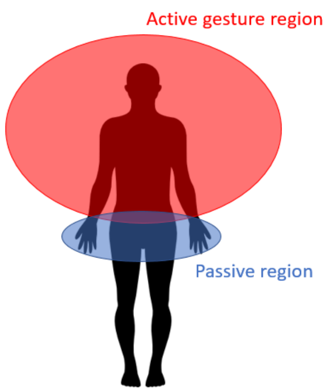


Fig. 7.5: Active and passive gesturing region

7.4 REFLECTION

7.4.1 Introduction

It can be argued that social impact of new technology is not to be taken lightly. Matters like privacy, behaviour steering (nudging), intellectual property, impact on both physical and mental well-being or potentially harmful or offensive systems should be considered in new technology. Also the implementation of technology for malicious means should be taken into consideration by a developer. In this section, possible ethical controversies will be discussed to evaluate whether design changes should be made in the project.

In this reflective analysis, detailed context is essential. Therefore, this section will be built upon a pre-defined structure. First, the stakeholders have been defined, based on the previously mentioned pillars on which this project is based. For the definition of the stakeholders, please refer to the stakeholder section of the specification phase. Then, the impact of the pillars on those stakeholders will be addressed and explored in detail. Afterwards, options to prevent negative impact and promote positive impact will be elaborated, followed up by concluding whether design changes should be made in the exemplary prototype.

7.4.2 Impact on stakeholders

To gain a better understanding in how this technology or this project can influence each of the previously mentioned stakeholders, the impact of this technology and project will be defined. Impact is considered in its broadest meaning. This can be either positive or negative impact, with either short- or long-term effects and either self-evident or unthought-of impacts. To take every option in consideration, worst case-scenarios are explored to identify the possible impacts that this technology or project can have on the different stakeholders. The impact will be analysed based on its severity and likelihood of occurrence.

7.4.2.1 Manufacturers

First and foremost, the impact of a new technology on the manufacturer is highly dependent on the success of the introduction (and consequently the acceptance) of this technology. As a rule of thumb, technology is adopted according to Roger's bell curve [84], as shown in figure 7.6.

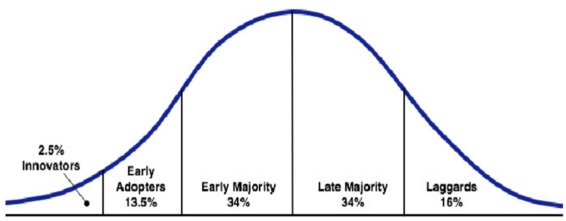


Fig 7.6. Roger's bell curve [6]

The highest severity of impact on the manufacturers is likely to occur in the early or late majority section of the bell curve, as these sections contain 68% of the adoption. When the demand for this technology rises rapidly, manufacturers need to meet the demand while taking in consideration not to cause harm in the production process. Phenomena like increased pollution, fair production (avoiding child labour or dangerous working conditions) and lawful trade are essential elements that should not go overlooked when entering mass-production. Also product safety is essential, since electronic components are produced, risks like electrocution, burning or other forms of harm should be reduced to a minimum to ensure safe interaction between the user and the product.

This same principle holds for competing manufacturers. As competition rises, reduction of production costs might be a mean to enable offering the product at a lower price than the competition. However, the above mentioned ethical elements should not go overlooked in this process.

7.4.2.2 Primary Users

In this project, the primary users of the product are defined as the users who are intentionally, directly interacting with the technology in any form. The main elements that should be taken into consideration when focussing on the primary user are physical, mental and intellectual safety. First and foremost; the product should physically be safe to use. Since this product is an electrical device, safety risks like electrocution, radiation, overheating, explosion and chemical poisoning should be reduced to a minimum. Furthermore, since interaction with this technology is very delicate, controlling large moving objects is potentially dangerous.

Second; this product should not cause any form of mental harm. A relatively self-evident example is flashing lights that may cause epileptic seizures. However, a less obvious impact is behavioural influence. A research by Hourcade et al., [85] on the impact of touchscreens on toddlers showed that 90% 2 year olds had moderate interaction skills with a touchscreen. As this technology shows close resemblance to touchscreen technology, a scenario might be that children are subconsciously taught that all surfaces have gesture-interaction and start waving in front of random objects, expecting it to interact in some manner.

Third, intellectual safety might form a moral issue in the use of this technology in products. Since the functionality of this product is based on invisible electric fields, private data might be collected and potentially used without the primary user being aware of it. An example is the implementation of a three-dimensional capacitive sensor in the keyboard of a laptop, sensing the presence of the user. Without the user knowing, it might keep track of the frequency with which the user uses its laptop, at what times and for how long. This data could be used for example to provide information to the laptop's manufacturer to advertise on laptop models fitting the users behaviour.

7.4.2.3 Presenters

Regarding this project's exemplary prototype specifically, the awareness of the user is considered to be present when using the device. Since the user is wearing the device and actively using its functionality, the user will always be aware of the device measuring the movements made. An unlikely scenario can be discussed where the user is unknowingly given a piece of clothing in which 3d-capacitive sensing is implemented. However, it is believed that this is not realistic and will not be discussed in this report. Furthermore, physical or mental health risks are not considered a significant threat as the voltages used in the prototype do not form health risks and the LED's are not considered to be a trigger for epileptic shock. The mental influence of this technology on small children is not taken into consideration.

7.4.2.4 Secondary users

As stated above, ethical issues might arise when intacting on an individual conscious level. These issues are enhanced when interaction occurs unconsciously or unwillingly. When considering secondary users, the likelihood of unconscious interaction is significantly higher than the primary user. Since three-dimensional capacitive sensing is easily employed unobtrusively [11], it is possible for the secondary user to interact with a device without knowing so. There are two scenarios considered in which the secondary user might interact with this technology.

First, the user is in close proximity of a primary user employing the technology at that specific moment. This might be a malicious intent of the primary user to gather information of the secondary user. Furthermore, there is a possibility that subjects surrounding the primary user might influence the interaction of the technology or be influenced by the technology. This may cause unwanted interaction of the device on the user. For example, when controlling physical devices, such as robotic arms or prostheses safety might be an issue.

The second scenario is that the secondary user is observed by an unobtrusive ubiquitous system. Subtle examples are changing the lighting on a product in a supermarket isle when a user is reaching towards it for marketing purposes or collect sensitive private data (such as walking patterns on a floor with embedded capacitive sensors). Obviously, this might be in conflict with the users privacy, since data is collected of the user, without him knowing so. This is an example where this technology nudges the user in his behaviour by creating an interaction that is based on the gestures of the user. More severe examples are potentially harmful devices, for example landmines that explode on proximity instead of physically stepping on it.

7.4.2.4.1 Audience

In this project and specifically the exemplary prototype, the risks for the subject in proximity of the user can be prevented. According to a research by Jun Rekimoto [10], it is possible to implement a “shield layer” in a wearable piece of technology using three- dimensional capacitive sensing. This shield layer is able to distinguish interaction input of the user wearing the device from input by another subject. Using this shield layer, the signal change caused by subjects around the user can be cancelled out or ignored, eliminating the risk of unwanted interaction.

7.4.2.5 Society

When considering a societal scale, the impact of this technology might be more difficult to predict. A scenario is concidered where a large proportion of the population encounters this technology on a daily basis. This can either be consious or uncounsious. Ubiquitous implemetation of this technology could be used to monitor movement or beahviour throughout an environment. In public spaces, this could invade privacy. On a societal scale the ehtical problems are regarded as more severe than on an individual level due to the large impact.

An example: the touchscreen technology is currently highly adopted and according to a market research [17], 2.8 billion touchscreens were shipped in 2016. When this adoption rate is similar in three-dimensional capacitive sensing, a scenario arises in which 2.8 billion smartphones employ an electric field in which movement can be tracked. Since this technology can be implemented invisibly, the probability of encountering it unconsiously is high. Access to this data raises serious privacy and safety issues.

7.4.2.6 Regarding the examplary prototype

The goal of this project is to create a functioning presentation-enhancing wearable. If this project would be implemented on a societal scale, in this case be used in the majority of the presentations given, there is no significant ethical issue that can be considered. A case could be made that presenting using this technology could become natural and distort the way in which public speaking or media presentation is performed. This way our natural capability to be inspiring or charismatic could be influenced. However this is not a likely scenario.

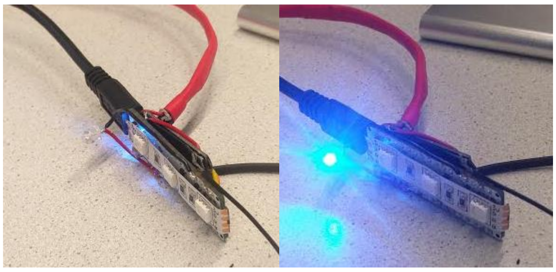


Fig 7.7: *LED interaction notification system*

7.4.2.7 Developers

One of the three pillars on which this graduation project is based is the accessibility of this technology to future developers. In this project, it has been found that three-dimensional capacitive sensing is relatively easily implemented in developers’ prototypes. In other words, accessibility is high, regardless of the developers intentions. That means that the technology could also relatively easily be implemented in malicious devices challenging either privacy or safety of various stakeholders. This should be prevented as much as possible. However, this is not a realistic goal, as malicious intent is not a measurable or controllable trait in developers. Another risk would be mental or physical health risks. When considering these risks, developers could be categorised under primary users and hold the same risks.

7.4.3 Impact prevention and promotion

7.4.3.1 Manufacturers

To prevent unethical production and trade from manufacturers, multiple human rights laws and environmental treaties have been produced [86]. As for this project, the prevention or promotion of manufacturing methods is beyond the scope.

7.4.3.2 Primary users

To prevent unintentional interaction with devices employing three-dimensional capacitive sensing technology, various forms of interaction indication are possible. Examples are visual, audio or tactile cues notifying the user of interaction. In this project, a visual interaction notification system is implemented. This system consists of a status-LED, which illuminates when data is being transmitted by the exemplary prototype. This system can be seen in figure 7.7. Physical safety risks could be prevented through prototype design, by implementing resistances or fuses to prevent high voltages that may result in electrocution or overheating for example. But also by providing information, such as manuals including health risk warnings for epileptic patients.

7.4.3.3 Secondary users

The main ethical issue revolving secondary users is unintentional interaction. This could be prevented through interaction notifications, as described above. The risk of unwanted interaction of secondary users in proximity of the primary user can be eliminated by using the shielding layer which enables the technology to distinguish primary user input from influences from subjects near the primary user.This might also be prevented by the implementation of privacy laws, which is beyond the scope of this research.

7.4.3.4 Society

Prevention of malicious data usage on a societal scale could be realised through implementing extensive security protocols in products employing both three-dimensional capacitive sensing technology and forms of mass communication, such as internet connection. However, these security protocols are beyond the scope of this project.

7.4.3.5 Developers

As stated earlier, malicious intent is considerered an immeasurable factor in a developer. It would be possible to prevent data misusage through internal security protocols, as stated above.

7.4.4 Conclusion

In light of the performed analysis, it is concluded that there are multiple factors that produce ethical issues. These factors are: risk on unethical production, physical or mental health risks, risk on privacy invasion or behavioural nudging through unobtrusive or unintentional interaction, development of malicious devices and data misusage. These factors per stakeholder, and the possible design changes to prevent these issues is listed below.

7.4.4.1 Manufacturers

It is concluded that there are ethical issues revolving the manufacturers of this technology and competing manufacturers. These are unethical production, such as excessive CO_2 emission or production under unfair or dangerous labour conditions. However, the prevention of these ethical issues are beyond the scope of this project.

7.4.4.2 Primary & secondary users

Primary and secondary users are exposed to both physical and mental health risks, risk of privacy invasion and behavioural nudging. It is concluded in the exemplary prototype a LED notification system is implemented to notify the user when data is transmitted. The risk of unwanted interaction of secondary users in proximity of the primary user can be eliminated by using the shielding layer which enables the technology to distinguish primary user input from influences from subjects near the primary user. Mental or physical health risks are not cause for change in the exemplary prototype as the used technology does not cause any significant harm for either the primary or secondary user.

7.4.4.3 Society

On a societal level, the main risk is privacy invasion and malicious data usage. This could be prevented by implementation of advanced security protocols for devices with internet connection for example. However the implementation of these protocols are beyond the scope of this project.

7.4.4.4 Developers

The main risk factor for developers is malicious intent. However, this is considered an immeasurable trait.

8 Conclusion

8.1 Regarding three-dimensional capacitive technology

At the introduction of this bachelor thesis, a set of research questions have been formulated, with the main research question being: *"What is the potential of three-dimensional capacitive sensing in wearable technology?"*. Furthermore, multiple sub-questions have been formulated, being:

1. *"In what contexts would three-dimensional capacitive sensing be advantageous advantage in comparison to other forms of human-computer interaction?"*
2. *"What is the accessibility of three-dimensional capacitive sensing for developers such as creative technologists?"*
3. *How can three-dimensional capacitive sensing be implemented in a piece of wearable technology?*

Through the exploration, ideation realization and evaluation phases, answers have been found to each of these sub-research questions and consequently, to the main research question. In this conclusion section, the answers to these questions will be formulated.

8.2 In what contexts would three-dimensional capacitive sensing be advantageous in comparison to other forms of human-computer interaction?

During the exploration phase, background and state-of-the-art research has been conducted, comparing three-dimensional capacitive gesture sensing to both two-dimensional capacitive touch sensing and other forms of gesture recognition technology. From research, it can be concluded that three-dimensional capacitive gesture sensing technology is advantageous in touchless contexts where close range, line of sight independency, low cost, low power consumption, easy integration and programming, wearable or non-wearable designs and environmental resistance are desired. Three-dimensional capacitive sensing has been proven to be versatile in the implementation in either wearable or non-wearable products and a widely applicable technology. However, there are gesture recognition technologies that might be more applicable in other contexts, for example where long range and ambient noise resistance is desired.

8.3 What is the accessibility of three-dimensional capacitive sensing for developers such as creative technologists?

In the exploration, ideation, specification, realization and evaluation phase, the accessibility of this technology for Creative Technology Students is explored. Creative Technology has been defined as: "*The development of high-tech solution through a combination of electrical engineering, IT and industrial design. Using sensors, programming and designing, respectively."* In the exploration, ideation and specification phase, three-dimensional capacitive sensing has been proven to be employable in a multitude of sensor programming and designing-based projects, which form the basis for the Creative Technology programme. Furthermore, the MGC3130 Hillstar Development Kit is proven to be programmable through the accessible Arduino MCU and IDE, which are already implemented in the Creative Technology programme. Also, the MGC3130 Hillstar Development Kit is relatively accessible in price range. However, the interaction with the sensor does require some minor instruction, as it has not been proven to be intuitive according to Creative Technology student. They do unanimously recommend both the exemplary prototype as the sensor to be implemented in the programme though.

8.4 How can three-dimensional capacitive sensing be implemented in a piece of wearable technology?

In the exploration, ideation, specification, realisation and evaluation phase, the implementation of three-dimensional capacitive sensing has been explored in detail. In the exploration phase, multiple examples of implantation of three-dimensional capacitive gesture sensing in either wearable or small scale device have been found. Furthermore, in the ideation phase, a range of solution designs have been defined as to which three-dimensional capacitive sensing could be implemented in a piece of wearable technology through creative thinking processes. Then, in the specification phase, an exemplary prototype has been defined satisfying the requirements for a wearable employing three-dimensional capacitive sensing. With wearable technology being an unobtrusive, encumbered, non-handheld computing system. This exemplary prototype has been successfully been developed in the realization phase. In the evaluation phase, the exemplary prototype has been found to be functional, but for more flexible integration, there are still some drawbacks which could be improved by improving wearing comfort and increasing intuitive interaction, sensing range and noise cancelling.

8.5 WHAT IS THE POTENTIAL OF THREE-DIMENSIONAL CAPACITIVE SENSING IN WEARABLE TECHNOLOGY?

Based on the previously answered sub-research questions, the main research question can be answered. To summarize the main conclusion in a sentence: *"Three-dimensional capacitive sensing has been shown to be* ***advantageous*** *in various interaction contexts,* ***accessible*** *for developers and* ***implementable*** *in wearable technology. Therefore, it is concluded that three-dimensional capacitive sensing has shown* ***potential*** *for future research and development of HCI in* ***wearable technology****."*

Furthermore, it can be concluded that based on various sources, market for three-dimensional capacitive sensing technology is growing, thus showing potential for future investment for either developers or manufacturers. This is partially due to the found advantages when compared to two-dimensional capacitive touch sensing technology.

9 DISCUSSION & RECCOMENDATIONS

9.1 DISCUSSION

Now that the final conclusions of this research have been defined, the findings will be discussed and compared to related research. Furthermore, found drawbacks in the technology, along with elements considered beyond the scope of this project are discussed and recommended for future research.

9.1.1 Electrodes

The electrode board used in this project is the provided 95x60mm 5” electrode board developed by Microchip®. There is a large piece of documentation on the customization of electrodes and there are significant design advantages in developing application-adapted electrodes. Examples are: comfort, range, unobtrusiveness and size weight and cost reduction. The most prominent subjects for future research in custom electrodes will be discussed.

9.1.1.1 Shielding

No additional shielding has been implemented in the current design. It is found during evaluation that the electrode worn directly on the body, is highly influenced by the noise from the body, resulting in an unreliable prototype with incorrect readings and overall decreased sensitivity. The influence of the surrounding noise, such as the human body, could be decreased through the implementation of a shielding layer in the electrode design. There are multiple pieces of documentation by D. Wang [87], [88] on the shielding of electrodes and wiring revolving three-dimensional capacitive sensing. It is highly recommended that for implementations of three-dimensional capacitive sensing, shielding layers are included in future research.

9.1.1.2 Range

The GestIC Design Guide [5], states that ranges between 0mm and 200mm are the maximum interaction range in three-dimensional capactive sensing, using the MGC3130 Hillstar Development Kit. In this research, the practical interaction range is limited to only 50mm to 110mm. To allow more implementation options, future research should explore adaptations causing an increasing in interaction range. An example could be increasing of electrode size or ground-connection improvement for wearable implementations.

9.1.1.3 Flexible electrodes

For implementation in wearable technology, it is expected that the development of flexible, lightweight electrodes will drastically improve the comfort and unobtrusiveness of the electrodes in the worn sensing system. However, due to time limitation and expected increased parameterization difficulty, the exploration of flexible electrodes is beyond the scope of this research and is suggested to be explored in future research. Also, materials compatible with lasercutting technology should be explored to allow for easy, fast and precise production of custom electrodes.

9.1.2 Parameterization

In this research, parametrization of custom developed electrodes is performed through the provided Aurea GUI. However, this software forces the developer to translate the I2C signals from the MGC3130 with the I2C-USB bridge provided by microchip. It is recommended that for complete independent research and development, an open source parameterization environment is developed.

9.1.3 Competing manufacturers

In this research, the only considered technology provider is MicroChip® and the only development kit considered is the MGC3130 Hillstar Development Kit. However, there are competing manufacturers producing similar products that might show to be advantageous over the MGC3130 Unit. For example, Texas Instruments® produces a similar product called the FDC1004 [89]. With this product multiple development options are available, as wel as extensive documentation and instruction [87], [88].

9.1.4 Findings in evaluation phase

Even though the findings in the evaluation phase matched the expectations, this evaluation was based on a small population (n=6) of specific target participants (Creative Technology Students). Further research in the intuitive interaction and accessibility of this technology to the large public should be explored.

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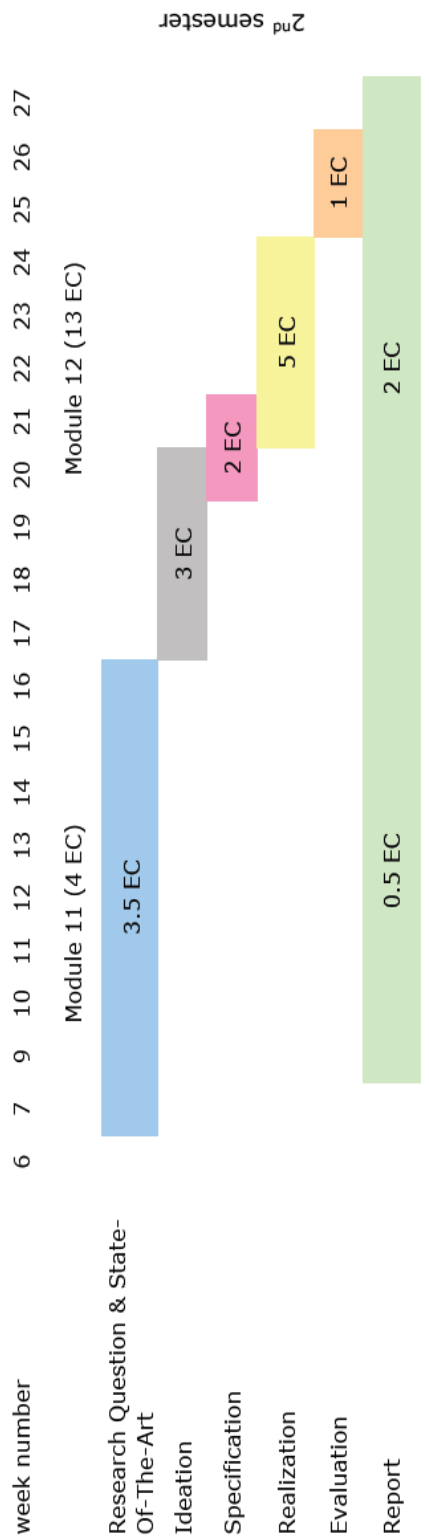
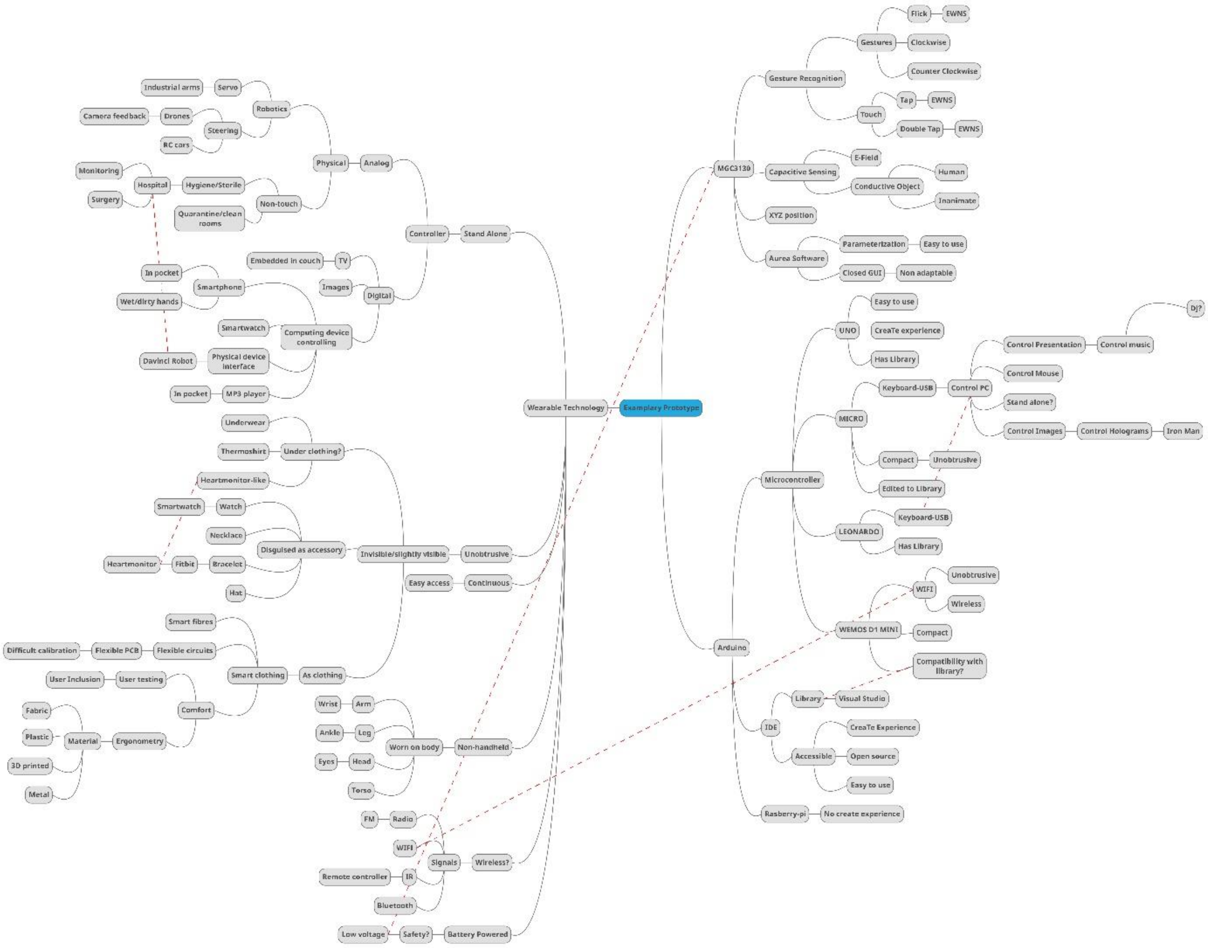
10 APPENDICES

10.1 APPENDIX 1 – TIME DEVISION OF THE GRADUATION PROJECT



Appendix 1: Timetable [2]

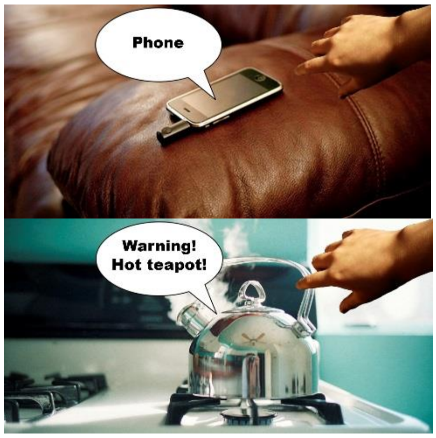
10.2 APPENDIX II – MINDMAP



10.3 APPENIX III - SCENARIO'S

Scenario 1 – Talking house, audible ubiquitous home-system for the visually impaired

Visually impaired or blind people face challenges everyday due to their lack of sight. These challenges may be caused due to interacting with devices providing visual feedback or orientation. Within the home of a blind person, these challenges may be less frequent as the person knows where to find his belongings and how to navigate through the house. However, there are still situations where the lack sight creates a challenge. When an object is lost for example. This is where an audible feedback system might be of use. Important objects like keys, a cell phone or a remote control may be fitted with an electrode employing three-dimensional capacitive sensing and NFC technology, as described in the research by Puppendahl et al., [44]. The user might use an capacitive-NFC in either an accessory (like a smart watch) or in his clothing (sleeve) to sense nearby objects also employing capacitive NFC.



Appendix 3.1: Scenario: Talking House

Scenario 2 – Pickpocket Alarm

Pickpocketing is a way of stealing ones belongings by taking them out of carriers close to the users body, like pockets or handbags. A way of alerting the user that his belongings are being stolen is to implement a three-dimensional capacitive sensor in either the clothing or carriers in which the user is carrying his valuables. By intruding the electric field emitted by the three-dimensional capacitive sensor with a conductive object, for example the human hand, the alarm system will recognize the presence and alert the user of the fact that a conductive object is close to his personal belongings through either, visual, audible or tactile notification.

Appendix 3.2: Scenario: Pickpocket Alarm

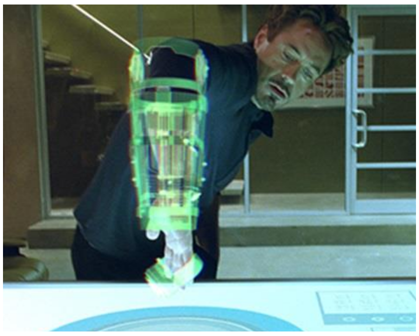
Scenario 3 – Touchless presentation module

When presenting information, visual or audible support can be used to enhance the impact on the viewer. This media can be implemented in many forms, such as drawings or schematics on paper, sound files, prototypes or a slide show. When using a PC-supported slide show, a device that may be used to control the slide show is a wireless presentation remote. A device which allows control of the presentation by pushing a button. This device could be replaced by an electrode employing three-dimensional capacitive sensing worn on the users body, to allow touchless control of the digital slide show.

Appendix 3.3: Scenario Touchless Remote

Scenario 4 – "Iron Man" hologram controller

Holograms are three-dimensional digital images that can be produced in multiple manners of reflecting light. One of which is the hologram pyramid, as described in the research by Phd. Dragi Tiro et al., [90]. The synchronization of hologram media with gestures might be possible using three-dimensional capacitive sensing. The XYZ coordinates of the conductive object intruding the electric field could be synchronized with the XYZ coordinates of the displayed hologram, allowing it to move in a similar manner as the conductive object does. This way, holograms could be controlled by hand gestures of the user to present three-dimensional objects.



Appendix 3.4: Scenario: Hologram Controller

10.4 APPENDIX IV - PERSONAS

10.4.1 Persona 1

Developer

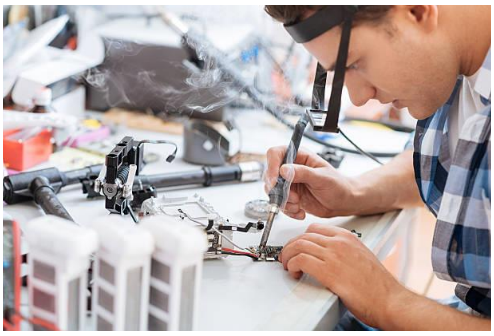


Fig 2. Developer persona [95]

Name: Steve Redfoot

Age: 27

Profession: Student of Creative Technology bachelor program, aiming for Electrical Engineering master program

Physical/Mental capabilities: Above average intelligence, capable of solving advanced problems. Fine-tuned hand eye coordination and capable of performing precise movement to assemble electronic parts. Able to understand the underlying protocols and electronic components of various computing devices.

Social influence: This technology does not directly bring a social influence in the daily life of the developer.

Everyday activities: Studying, soldering, programming, designing, football, listening to music, going out for a beer

Why would this product interest him?: This product offers an opportunity to broaden his portfolio of design options. This product allows for the development of a range of touchless products which may solve design problems in the future. As the interaction between human and computer is becoming more natural, this technology might form the bridge in total touchless interaction with computing devices.

What other products would he use?: Smartphone, tablet, laptop, backpack, calculator, headphones, smartwatch, drone, glasses.

<u>Interview</u>

Do you see potential in this technology, and if yes, in what way?: *I most definitely see potential in this technology. As a creative technology student, sensors play a large part in my daily activities and projects. This type of sensor might show to be useful in ubiquitous computing, environment observation and various types of controlling.*

Use cases: Development of new products in which this technology is implemented. For both personal use and for broadening his portfolio. Using this module to explore the principle of three-dimensional capacitive electric fields and their influence on their surroundings.

10.4.2 Persona 2

Secondary User - Teacher

Name: Claire Sandwater

Age: 35

Profession: Electronics and programming teacher in the bachelor program Creative Technology of the University of Twente

Fig 3. Teacher persona [96]

Physical/Mental capabilities: Above average intelligence, capable of solving advanced problems. Fine-tuned hand eye coordination and capable of performing precise movement to assemble electronic parts. Able to understand the underlying protocols and electronic components of various computing devices. Highly skilled in presentation, multilingual and strong social capacities.

Social influence: This technology might bring a social influence in the life of the teacher in the way that the course program is taught might influence the behavior of the creative technology students, the colleagues of the teacher or that of the teacher himself.

Everyday activities: Meeting, teaching, documenting, tutoring, reading, sporting.

Why would this product interest her?: This product offers her a new tool in which the curriculum of her course can be broadened. It is a very intuitive and yet sophisticated technology which is implementable in many projects of the Creative Technology programme. Since it is both programmable and allows for custom electronics design, it is a good medium for students to be educated in electrical engineering and the combination of soft- and hardware.

What other products would he use?: Smartphone, laptop, briefcase, earbuds, agenda, drone, glasses.

<u>Interview</u>

Do you see potential in this technology, and if yes, in what way?: *Absolutely, there is currently a CapSense project running in one of my classes. This teaches my students about the principles of capacitive sensing. However, these sensors are very limited and require quite some programming effort to get some usable results. With this product, the conversion of raw data to usable and programmable content is performed in the blink of an eye. Ideal to provide this course with a next step in development of usable products.*

Use cases: Impressive and inspiring tool to teach the concept of three-dimensional capacitive sensing. Allows students hands-on interaction with the technology and the opportunity to explore design options within the short time schedule in which the courses are offered.

10.4.3 Persona 3

Primary professional user - Surgeon

Fig. 6 Primary User Persona [97]

Name: Neil Rogers

Age: 39

Profession: Cardiac surgeon

Physical/Mental capabilities: Highly intelligent, capable of solving extremely advanced problems. Extreme precise hand eye coordination skills and capable of performing precise movement in both 3D and 2D images. Advances knowledge in the human body and skilled with various types of robotic controlled tools.

Social influence: This technology may form to be a great asset in the portfolio of the surgeon. Being skilled in new operational technology may increase both professional and social status of the surgeon. Also, it may show other surgeons or hospital management the advances in the use of this technology. Furthermore, it may be that through this technology, surgeries will be successful that may otherwise have failed, this also increases the professional and social status of the surgeon.

Everyday activities: Meeting, meditating, gaming, studying, reading, listening to music.

Why would this product interest him?: This product offers him a new tool with which the surgeon might operate in a different way. Due to the touchless interaction, it is possible to create more sterile environments. Through gesturing, the surgeon may be able to control surgical robotics like the da Vinci robot [91].

What other products would he use?: Smartphone, notebook, stethoscope, laptop, briefcase, earbuds, agenda, glasses.

<u>Interview</u>

Do you see potential in this technology, and if yes, in what way?: *Perhaps, the possibility of touchless interaction may open new surgical possibilities to operate in a more sterile environment. However, I first need to be convinced that this technology can determine my hand position accurately enough for me to operate on a microscopic level. Also, it should be completely noise-free. No interference should occur when I control a robotic scalpel near someone's artery.*

Use cases: Touchless cleaning system, touchless control of surgical robotics, touchless interaction with information systems to keep tools/electronics clean during surgery.

10.4.4 Persona 4

Primary personal user – Housewife

Fig 5. Primary User Persona [98]

Emily Leefer

Age: 42

Profession: Secretary/mother

Physical/Mental capabilities: Mentally and physically healthy. Experienced with the use of, able to interact with and understands a multitude of electronic devices such as smartphones, laptops and various electronic communication systems. However, lacks knowledge in the exact electronic components or pre-programmed protocols present in the electronics.

Social influence: This technology could be used in various situations in either her personal or professional life. This technology would not influence her life socially, as it is not a cause for significant behavior change, but may influence interaction with her electronic devices, which is a minor aspect of her social life. It might provide a higher satisfaction in her daily activities as it may provide easier or more intuitive interaction with the products she uses every day. However, it might also show to hold social status to own a device employing three-dimensional capacitive sensing technology as it might show a 'wow-effect' in the early adoption phase, as explained in Roger's bell curve of technology diffusion [84].

Everyday activities: Cooking, reading emails, tennis, planning, driving, listening to music, meeting.

Why would this product interest her?: This product might show to be a new trending technology which may hold social status when employing it in her everyday activities. Furthermore, it may offer interaction options that fit seamlessly in her everyday activities. For example touchless controlling of her TV, car navigation system or other household electronics.

What other products would he use?: Smartphone, notebook, stethoscope, laptop, earbuds, agenda, glasses.

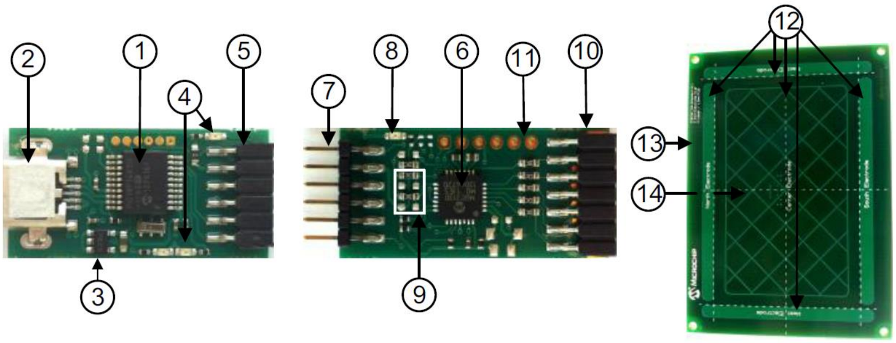
Interview

Do you see potential in this technology, and if yes, in what way?: *It might be cool to have some gadgets which I can simply wave towards and it will do something for me. I like the idea of not having to touch my stove when I have wet hands or just having to wave above my phone when I'm on my lunch break and eating a bagel.*

Use cases: Touchless interaction with office electronics, household electronics or car dashboard.

10.5 APPENDIX V - ELEMENTS OF HILLSTAR DEVELOPMENT KIT

10.5.1 Overview MGC3130 Hardware [8]



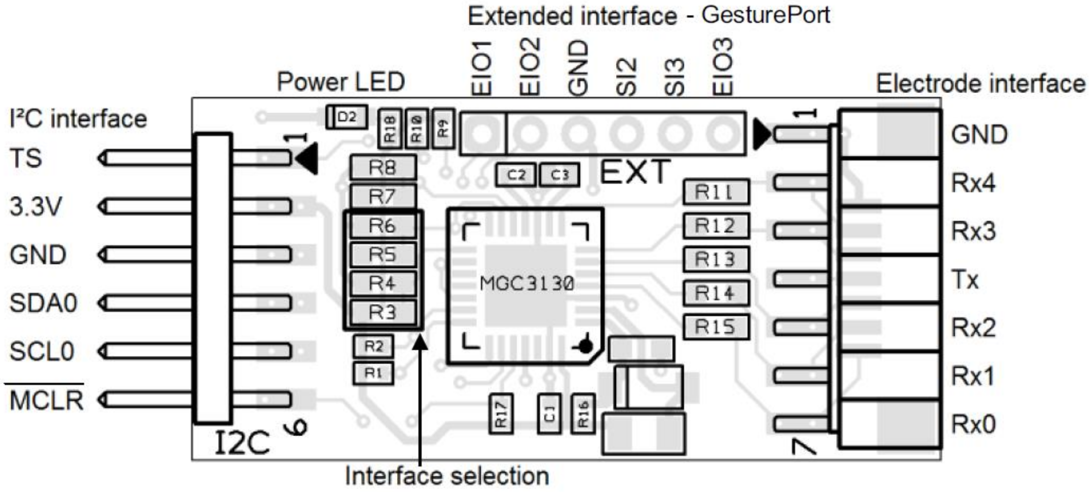
Appendix 5.1: Overview MGC3130 Hardware [8]

- I²C to USB Bridge
1. PIC18F14K50 USB microcontroller
2. Micro-USB connector
3. MCP1801T LDO voltage regulator (converts 5V USB to 3.3 V board supply)
4. Status LEDs (power, communication status)
5. Data interface: 6-pin socket for data communication and power supply

- MGC3130 Unit
6. MGC3130 3D Tracking and Gesture Controller
7. Data interface: 6-pin header for data communication and power supply
8. Status LED (power)
9. Interface select
10. Electrode interface: 7-pin socket
11. GesturePort interface (pads for 5 EIOs, 1 GND)

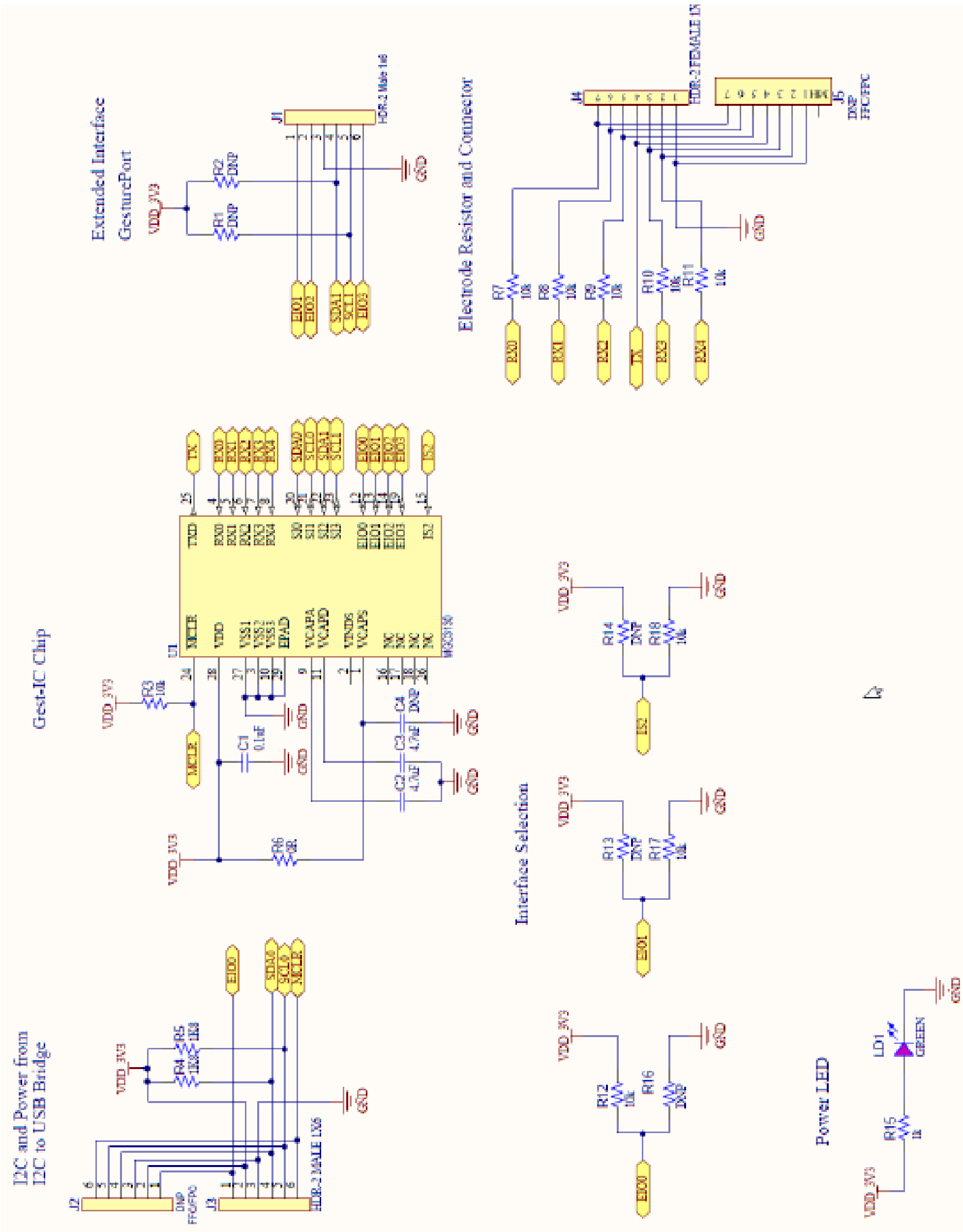
- 95x60 mm Reference Electrode PCB
12. Receive electrodes
13. Acrylic cover glass (120 x 85 x 2 mm)
14. Electrode interface: 7-pin header (mounted on backside)

10.5.2 Schematic MGC3130 Unit [13]



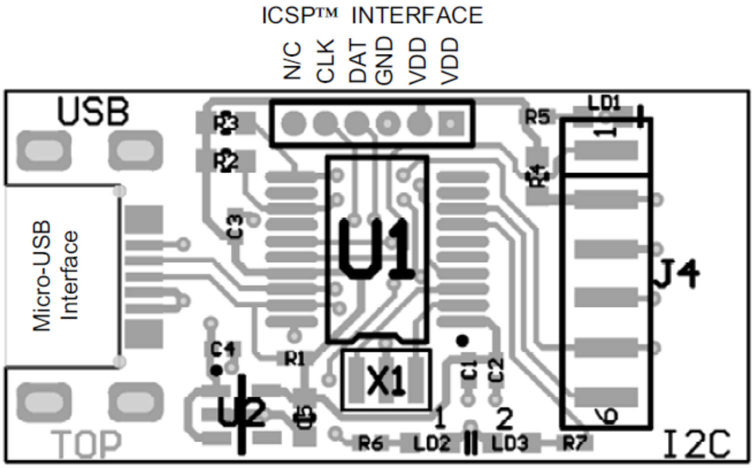
Appendix 5.2. MGC3130 Unit [13]

The unit provides a 2 mm 7-pin board-to-board connector (socket) to connect the electrode. The interface includes the following signals: GND, Rx4, Rx3, Tx, Rx2, Rx1, and Rx0. The five Rx channels of the MGC3130 (Rx0…Rx4) are connected to the receive electrodes via 10 kΩ resistors in order to suppress irradiated high-frequency signals (R11, R12, R13, R14, and R15). The MGC3130 signal generator is connected via the Tx signal to the transmit electrode.
The data connection to the Hillstar I2C to USB Bridge is realized by a 6-pin 2 mm board-to-board connector (header). The interface includes the following signals: EIO0, 3.3V, GND, SDA0, SCL0, and MCLR.



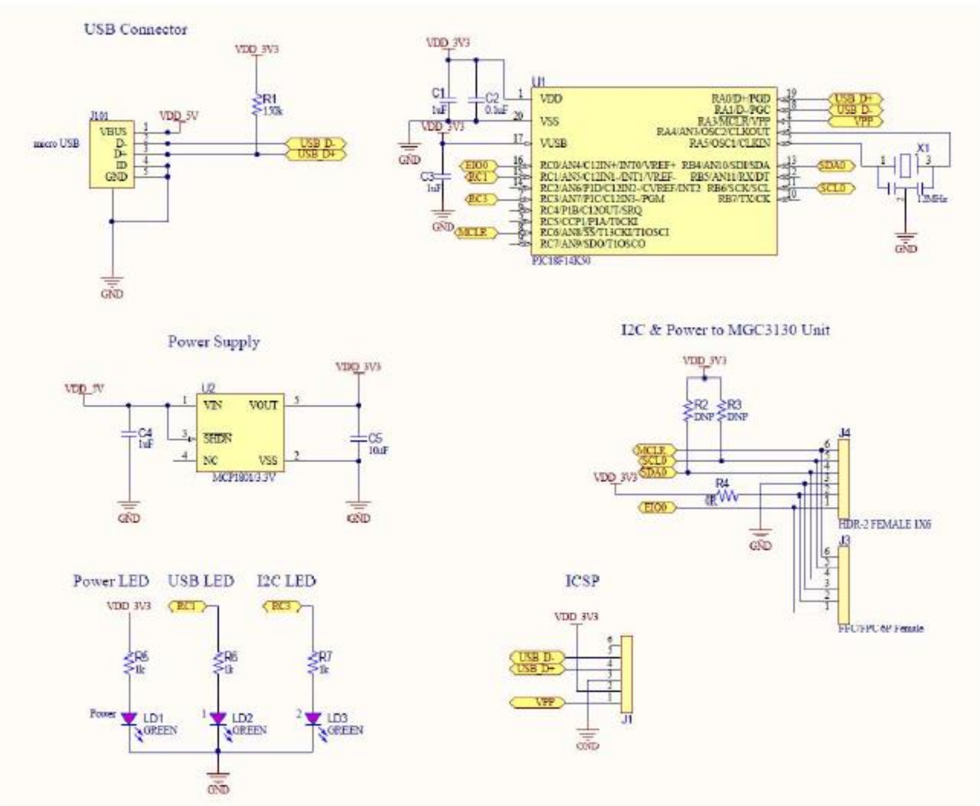
Appendix 5.2: MGC3130 Schematic [13]

10.5.3 I2C-USB Bridge Schematic



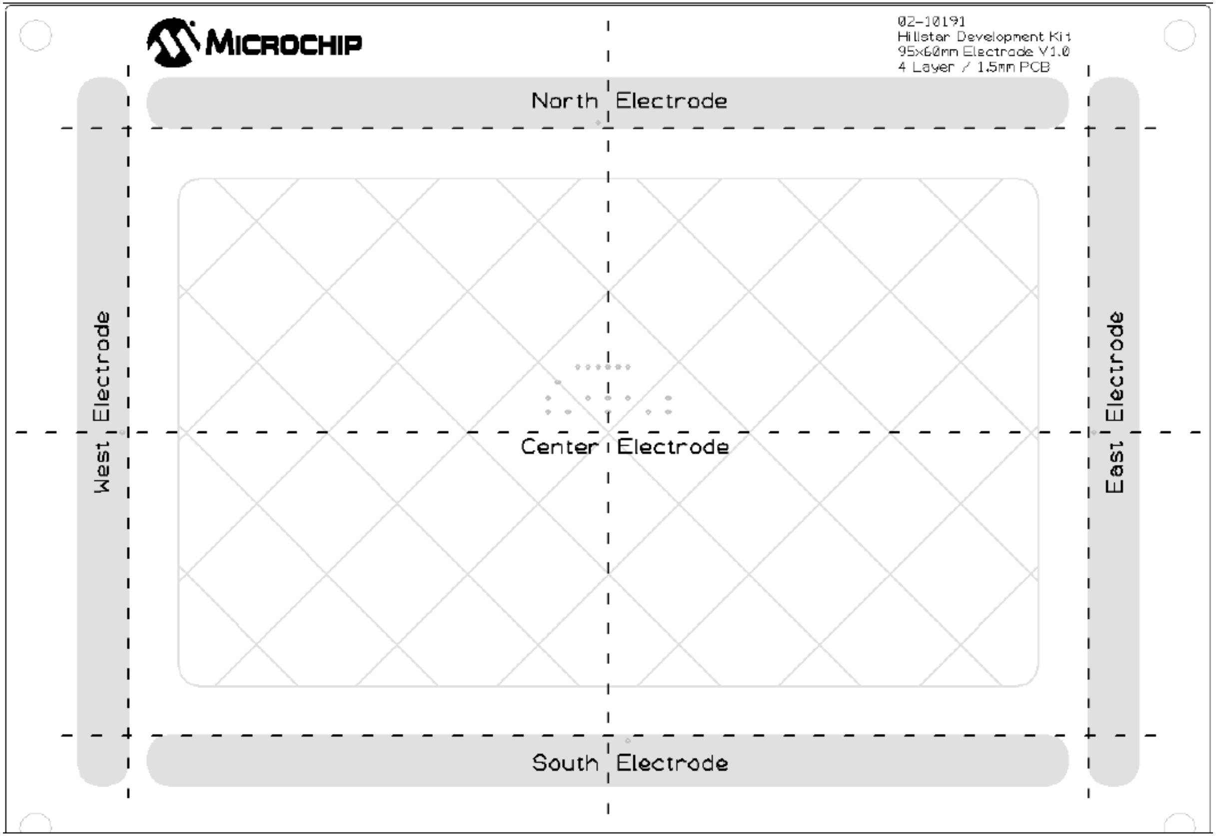
Appendix 5.4. I2C to USB Bridge [5]

The I2C to USB Bridge is powered via the USB port. Microchip's Low Dropout (LDO) Voltage Regulator MCP1801 is used to transform the 5V USB power to 3.3V required for the PIC18F14K50. By default, 3.3V are also routed to the MGC3130 Unit via the I2C interface. The 3.3V power supply towards the MGC3130 Unit can be cut by removing the 0Ω resistor R7.



Appendix 5.5: I2C-USB Bridge schematic [13]

10.5.4 Hillstar PCB Electrode



Appendix 5.4. Hillstar PCB Electrode [13]

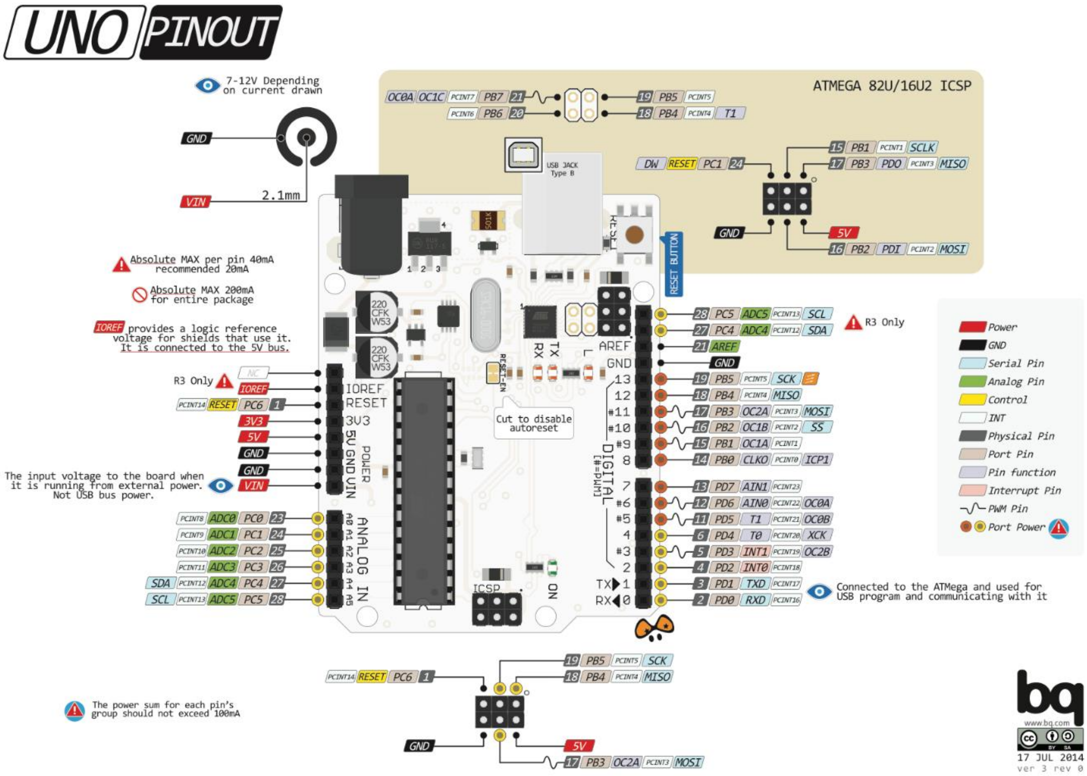
The PCB is connected to the MGC3130 Unit by the 2 mm 7-pin board-to-board connector. The interface includes the following signals: GND, Rx4, Rx3, Tx, Rx2, Rx1, and Rx0. The dimension of the board is 120 x 85 mm; the sensitive area is 95 x 60 mm.

The five Rx electrodes include four frame electrodes and one center electrode. The frame electrodes are named according to their cardinal directions: north, east, south and west. The dimensions of the four Rx frame electrodes define the maximum sensing area. The center electrode is structured (cross-hatched) to get a similar input signal level as the four frame electrodes.
The Tx electrode spans over the complete area underneath the Rx electrodes. It is cross-hatched to reduce the capacitance between Rx and Tx (CRxTx). The Tx area below the center electrode covers 50% of the copper plane, the area around only 20%.
The Rx feeding lines are embedded into the Tx electrode in the third layer. This supports shielding of the feeding lines.

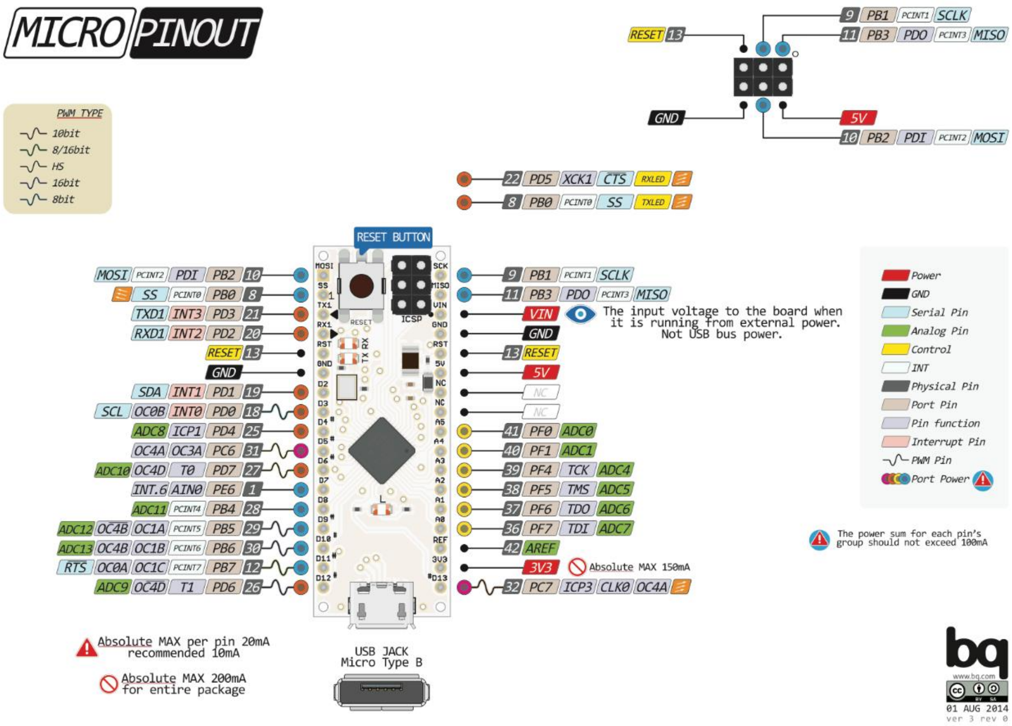
	Length	Width	Design
Horizontal Electrodes (Rx)	91.7 mm	5 mm	solid
Vertical Electrodes (Rx)	70.5 mm	5 mm	solid
Center Electrode (Rx)	85.7 mm	50.5 mm	3% cross-hatched
Tx Electrode (refer to Figure 3-4**)** **Part I (under center electrode)** **Part II (outside Part I)**	120 mm 85.7 mm 120 mm	85 mm 50.5 mm 85 mm	 50% cross-hatched 20% cross-hatched
Ground Area	120 mm	85 mm	solid

Table 5.1: Dimensions of electrodes [13]

10.1 Appendix VI – Pin Layouts of Arduino Models



Appendix 6.1 – Arduino Uno pinout [92]



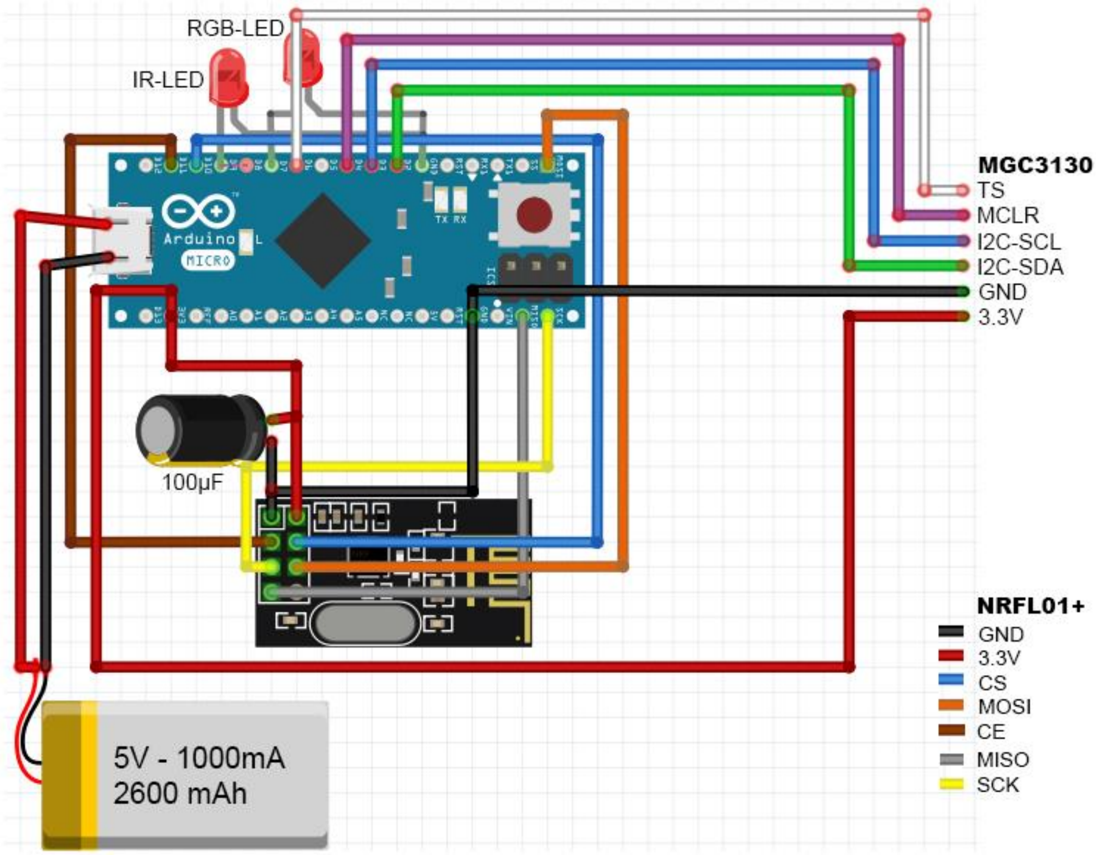
Appendix 6.2: Arduino Micro pinout [93]

10.2 APPENDIX VII – HEXADECIMAL ADDRESSES OF KEYBOARD KEYS

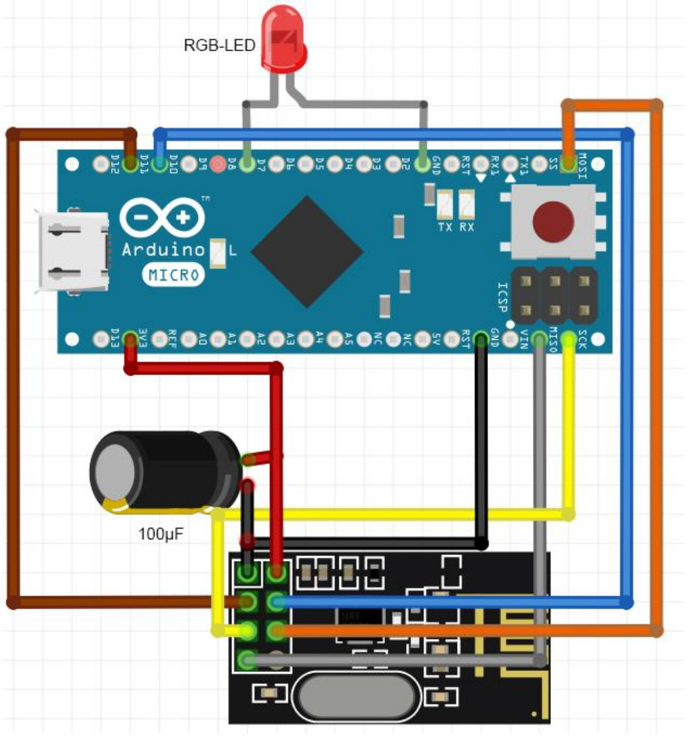
```
# Key                 Hex value  Dec value

# KEY_LEFT_CTRL       | 0x80 | 128 |
# KEY_LEFT_SHIFT      | 0x81 | 129 |
# KEY_LEFT_ALT        | 0x82 | 130 |
# KEY_LEFT_GUI        | 0x83 | 131 |
# KEY_RIGHT_CTRL      | 0x84 | 132 |
# KEY_RIGHT_SHIFT     | 0x85 | 133 |
# KEY_RIGHT_ALT       | 0x86 | 134 |
# KEY_RIGHT_GUI       | 0x87 | 135 |
# KEY_UP_ARROW        | 0xDA | 218 |
# KEY_DOWN_ARROW      | 0xD9 | 217 |
# KEY_LEFT_ARROW      | 0xD8 | 216 |
# KEY_RIGHT_ARROW     | 0xD7 | 215 |
# KEY_BACKSPACE       | 0xB2 | 178 |
# KEY_TAB             | 0xB3 | 179 |
# KEY_RETURN          | 0xB0 | 176 |
# KEY_ESC             | 0xB1 | 177 |
# KEY_INSERT          | 0xD1 | 209 |
# KEY_DELETE          | 0xD4 | 212 |
# KEY_PAGE_UP         | 0xD3 | 211 |
# KEY_PAGE_DOWN       | 0xD6 | 214 |
# KEY_HOME            | 0xD2 | 210 |
# KEY_END             | 0xD5 | 213 |
# KEY_CAPS_LOCK       | 0xC1 | 193 |
# KEY_F1              | 0xC2 | 194 |
# KEY_F2              | 0xC3 | 195 |
# KEY_F3              | 0xC4 | 196 |
# KEY_F4              | 0xC5 | 197 |
# KEY_F5              | 0xC6 | 198 |
# KEY_F6              | 0xC7 | 199 |
# KEY_F7              | 0xC8 | 200 |
# KEY_F8              | 0xC9 | 201 |
# KEY_F9              | 0xCA | 202 |
# KEY_F10             | 0xCB | 203 |
# KEY_F11             | 0xCC | 204 |
# KEY_F12             | 0xCD | 205 |
#
===============================================================================
```

10.3 Appendix VIII – Total prototpye circuit connections

10.3.1 Arduino Micro MCU 1 (MGC3130 Unit connection)



10.3.2 Arduino Micro MCU 2 (PC-connections)



10.4 Appendix IX – Experiment Information Sheet and Consent Form

10.4.1 Information sheet

UNIVERSITY
OF TWENTE.

Participant Number

Research: Three-dimensional capacitive sensing for wearable technology

Information sheet

In this graduation project, the potential of three-dimensional capacitive sensing in wearable technology is explored. To scale this project, the potential of this technology is defined through extensive background research, the accessibility of this technology for the Creative Technology bachelor programme of the University of Twente and the development of an exemplary prototype implementing the provided MGC3130 Hillstar development Kit, developed by MicroChip®, in a piece of wearable technology. A goal is set to evaluate the provided sensor set; get the dev-kit working, form a communication between the system and an accessible open source program, and create an interesting, meaningful interaction. This interaction is realized in the development of a touchless computer supported presentation controller.

In this experiment, the usability and comfort of the presentation controller is tested. First you will be asked to fill out a questionnaire, afterwards you will be asked to perform a series of tasks in this experiment whilst wearing the controller on your body. Finally, another questionnaire will be given.

This entirety of this experiment will have a duration of approximately 15-20 minutes.

10.4.2 Consent forms

UNIVERSITY OF TWENTE.

Participant Number

1

Research: Three-dimensional capacitive sensing for wearable technology

Consent Form

Thank you for reading the information sheet about the interview sub-study. If you are happy to participate then please complete and sign the form below. Please initial the boxes below to confirm that you agree with each statement:

	Please Initial box.
I confirm that I have read and understood the information sheet dated **[27-06-2017]** and have had the opportunity to ask questions.	✓
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.	✓
I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials, and will not be identified or identifiable in the report or reports that result from the research.	✓
I agree for this interview to be recorded. I understand that the audio or video recording made of this interview will be used only for analysis and that extracts from the interview, from which I would not be personally identified, may be used in any conference presentation, report or journal article developed as a result of the research. I understand that no other use will be made of the recording without my written permission, and that no one outside the research team will be allowed access to the original recording.	✓
I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study.	✓
I agree to take part in this interview.	✓

Jap Paulissen	27/06/17	[signature]
Name of participant	Date	Signature
Jules van Dijk	27/06/17	[signature]
Principal Investigator	Date	Signature

UNIVERSITY
OF TWENTE.

Participant Number

2

Research: Three-dimensional capacitive sensing for wearable technology

Consent Form

Thank you for reading the information sheet about the interview sub-study. If you are happy to participate then please complete and sign the form below. Please initial the boxes below to confirm that you agree with each statement:

	Please Initial box:
I confirm that I have read and understood the information sheet dated **[27-06-2017]** and have had the opportunity to ask questions.	V
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.	V
I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials, and will not be identified or identifiable in the report or reports that result from the research.	V
I agree for this interview to be recorded. I understand that the audio or video recording made of this interview will be used only for analysis and that extracts from the interview, from which I would not be personally identified, may be used in any conference presentation, report or journal article developed as a result of the research. I understand that no other use will be made of the recording without my written permission, and that no one outside the research team will be allowed access to the original recording.	V
I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study.	V
I agree to take part in this interview.	V

Tom Onderwater	27-06-2017	[signature]
Name of participant	Date	Signature
Jules van Dijk	27-06-2017	[signature]
Principal Investigator	Date	Signature

UNIVERSITY OF TWENTE.

Participant Number

3

Research: Three-dimensional capacitive sensing for wearable technology

Consent Form

Thank you for reading the information sheet about the interview sub-study. If you are happy to participate then please complete and sign the form below. Please initial the boxes below to confirm that you agree with each statement:

	Please Initial box:
I confirm that I have read and understood the information sheet dated **[27-06-2017]** and have had the opportunity to ask questions.	√
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.	√
I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials, and will not be identified or identifiable in the report or reports that result from the research.	√
I agree for this interview to be recorded. I understand that the audio or video recording made of this interview will be used only for analysis and that extracts from the interview, from which I would not be personally identified, may be used in any conference presentation, report or journal article developed as a result of the research. I understand that no other use will be made of the recording without my written permission, and that no one outside the research team will be allowed access to the original recording.	√
I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study.	√
I agree to take part in this interview.	√

Felicia Elskamp	27-06-2017	[signature]
Name of participant	Date	Signature
Jules van Dijk	27/06/2017	[signature]
Principal Investigator	Date	Signature

UNIVERSITY
OF TWENTE.

Participant Number

5

Research: Three-dimensional capacitive sensing for wearable technology

Consent Form

Thank you for reading the information sheet about the interview sub-study. If you are happy to participate then please complete and sign the form below. Please initial the boxes below to confirm that you agree with each statement:

	Please Initial box:
I confirm that I have read and understood the information sheet dated **[27-06-2017]** and have had the opportunity to ask questions.	V
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.	V
I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials, and will not be identified or identifiable in the report or reports that result from the research.	V
I agree for this interview to be recorded. I understand that the audio or video recording made of this interview will be used only for analysis and that extracts from the interview, from which I would not be personally identified, may be used in any conference presentation, report or journal article developed as a result of the research. I understand that no other use will be made of the recording without my written permission, and that no one outside the research team will be allowed access to the original recording.	V
I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study.	V
I agree to take part in this interview.	V

Vaso van Dinksteren	27/06/2017	[signature]
Name of participant	Date	Signature
Sules van Dijk	27/06/2017	[signature]
Principal Investigator	Date	Signature

UNIVERSITY
OF TWENTE.

Participant Number

5

Research: Three-dimensional capacitive sensing for wearable technology

Consent Form

Thank you for reading the information sheet about the interview sub-study. If you are happy to participate then please complete and sign the form below. Please initial the boxes below to confirm that you agree with each statement:

	Please Initial box:
I confirm that I have read and understood the information sheet dated **[27-06-2017]** and have had the opportunity to ask questions.	✓
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.	✓
I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials, and will not be identified or identifiable in the report or reports that result from the research.	✓
I agree for this interview to be recorded. I understand that the audio or video recording made of this interview will be used only for analysis and that extracts from the interview, from which I would not be personally identified, may be used in any conference presentation, report or journal article developed as a result of the research. I understand that no other use will be made of the recording without my written permission, and that no one outside the research team will be allowed access to the original recording.	✓
I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study.	✓
I agree to take part in this interview.	✓

Max van Ysselmuiden — 27/07/2017 — [signature]
Name of participant — Date — Signature

Jules van Dijk — 27/07/2017 — [signature]
Principal Investigator — Date — Signature

UNIVERSITY OF TWENTE.

Participant Number

6

Research: Three-dimensional capacitive sensing for wearable technology

Consent Form

Thank you for reading the information sheet about the interview sub-study. If you are happy to participate then please complete and sign the form below. Please initial the boxes below to confirm tha you agree with each statement:

	Please Initial bo
I confirm that I have read and understood the information sheet dated **[27-06-2017]** and have had the opportunity to ask questions.	✓
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.	✓
I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials, and will not be identified or identifiable in the report or reports that result from the research.	✓
I agree for this interview to be recorded. I understand that the audio or video recording made of this interview will be used only for analysis and that extracts from the interview, from which I would not be personally identified, may be used in any conference presentation, report or journal article developed as a result of the research. I understand that no other use will be made of the recording without my written permission, and that no one outside the research team will be allowed access to the original recording.	✓
I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study.	✓
I agree to take part in this interview.	✓

Sverre Boer	28/06/2017	SEB
Name of participant	Date	Signature
Jules van Dijk	28/06/2017	[signature]
Principal Investigator	Date	Signature

10.5 APPENDIX XI – QUESTIONNAIRES

UNIVERSITY OF TWENTE.

Participant Number: 2

Research: Three-dimensional capacitive sensing for wearable technology

Questionnaire

Question 1: How are you connected to the creative technology programme?

Student

Question 2: Can you describe the creative technology programme in no more than 10 sentences?

It is a mix between IT and different disciplines. Focussing on making you capable of creating a product and marketing them.

Question 3: How does the use of sensors contribute in the creative technology programme?

used often in projects

ASK FOR SENSOR

Question 4: Do you think that this sensor would aid in the toolbox of a creative technologist? (if yes, why? -> **Question 5**. If no, why? -> **Question 7**.

yes, now it only detects swipes but it could detect a whole lot more

Participant interview consent form, dated 27/06/2017 Page 1

UNIVERSITY OF TWENTE.

Participant Number: 2

Question 5: How would you introduce this sensor in the programme?

as a 3 dimensional capacitive sensor

Question 6: If you would compare this technology to the cap-sense project, what, in your opinion would be benefits of this sensor?

That it also measures depth

Question 7: Would you buy this sensor for your personal use? (if yes, what for?)

if i had a project where I would need it for. Can be handy for some forms of interfacing

Question 8: Can you think of a practical example where this sensor would be used?

an application that needs 3D positioning & 3D modelling?

Question 9: Do you have any design suggestions/improvements for this prototype?

It is a bit bulky but wireless which is nice

Participant interview consent form, dated 27/06/2017 Page 2

UNIVERSITY OF TWENTE.

Participant Number 3

Research: Three-dimensional capacitive sensing for wearable technology

Questionnaire

Question 1: How are you connected to the creative technology programme?

I am a second-year student of Creative Technology.

Question 2: Can you describe the creative technology programme in no more than 10 sentences?

It combines aspects of electrical engineering, computer science and industrial design, teaching us how to create user-friendly applications/technology thingies.

Question 3: How does the use of sensors contribute in the creative technology programme?

It is very important because it allows you to design intersting human-computer interaction. It also allows to design for a certain context.

ASK FOR SENSOR

Question 4: Do you think that this sensor would aid in the toolbox of a creative technologist? (if yes, why? -> **Question 5**. If no, why? -> **Question 7**.

yes

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UNIVERSITY OF TWENTE.

Participant Number 3

Question 5: How would you introduce this sensor in the programme?

Teacher could use it as well as students during presentations (to switch between slides)

Question 6: If you would compare this technology to the cap-sense project, what, in your opinion would be benefits of this sensor?

It can be used for more situations since you don't need to touch it. A cap-sense sensor cannot be used with your shoe, this sensor can.

Question 7: Would you buy this sensor for your personal use? (if yes, what for?)

For now, no. But if it is smaller and cheap, it is a nice gadget to have.

Question 8: Can you think of a practical example where this sensor would be used?

Help elderly by opening doors or whatever.

Question 9: Do you have any design suggestions/improvements for this prototype?

Make it smaller.

Make it an accesoire (bracelet, necklace)

Participant interview consent form, dated 27/06/2017 Page 2

UNIVERSITY OF TWENTE.

Participant Number: 4

Research: Three-dimensional capacitive sensing for wearable technology

Questionnaire

Question 1: How are you connected to the creative technology programme?

I also do this study.

Question 2: Can you describe the creative technology programme in no more than 10 sentences?

Finding innovating ~~[illegible]~~ solutions.

Question 3: How does the use of sensors contribute in the creative technology programme?

With sensors it is possible to more smarter installations which interact with the user.

ASK FOR SENSOR

Question 4: Do you think that this sensor would aid in the toolbox of a creative technologist? (if yes, why? -> **Question 5**. If no, why? -> **Question 7**.

Yes, student can be more comfortable with giving presentations but they've to know how it works. Otherwise it is more a hickup.

Participant interview consent form, dated 27/06/2017 Page 1

UNIVERSITY OF TWENTE.

Participant Number: 4

Question 5: How would you introduce this sensor in the programme?

Let every student try to give an easy presentation about himself.

Question 6: If you would compare this technology to the cap-sense project, what, in your opinion would be benefits of this sensor?

Question 7: Would you buy this sensor for your personal use? (if yes, what for?)

Yes, but if it would work better.

Question 8: Can you think of a practical example where this sensor would be used?

Yes also for on your laptop when you want to change screens.

Question 9: Do you have any design suggestions/improvements for this prototype?

Make it less flat more form of the body

Participant interview consent form, dated 27/06/2017 Page 2

UNIVERSITY OF TWENTE.

Participant Number: 5

Research: Three-dimensional capacitive sensing for wearable technology

Questionnaire

Question 1: How are you connected to the creative technology programme?

I study the same programme

Question 2: Can you describe the creative technology programme in no more than 10 sentences?

A cool combination of electrical engineering, industrial design and IT development.

Question 3: How does the use of sensors contribute in the creative technology programme?

Sensors are used in a lot of projects or installations to provide contexts of input.

ASK FOR SENSOR

Question 4: Do you think that this sensor would aid in the toolbox of a creative technologist? (if yes, why? -> **Question 5**. If no, why? -> **Question 7**.

Yes, it is a cool tool to provide easy interaction.

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Participant Number: 5

Question 5: How would you introduce this sensor in the programme?

During Smart Environments.

Question 6: If you would compare this technology to the cap-sense project, what, in your opinion would be benefits of this sensor?

More precise, and a lot of calculations are pre-programmed in the chip.

Question 7: Would you buy this sensor for your personal use? (if yes, what for?)

Yes Netflix, or turning on my Philips Hue lights.

Question 8: Can you think of a practical example where this sensor would be used?

PowerPoint presentation

TV-control

Lights control

Question 9: Do you have any design suggestions/improvements for this prototype?

Make it smaller (?) if possible.

A larger strap :)

UNIVERSITY OF TWENTE.

Participant Number: 6

Research: Three-dimensional capacitive sensing for wearable technology

Questionnaire

Question 1: How are you connected to the creative technology programme?

It is my study

Question 2: Can you describe the creative technology programme in no more than 10 sentences?

It's a study in which we learn to develop new products with new techology as a base for them.

Question 3: How does the use of sensors contribute in the creative technology programme?

In basically every project sensors are incorporated

ASK FOR SENSOR

Question 4: Do you think that this sensor would aid in the toolbox of a creative technologist? (if yes, why? -> **Question 5**. If no, why? -> **Question 7**.

It would improve the quality of presentations and make them ~~mak~~ more interactive

Participant interview consent form, dated 27/06/2017 Page 1

UNIVERSITY OF TWENTE.

Participant Number: 6

Question 5: How would you introduce this sensor in the programme?

In either design courses or programming couses (work with electronics)

Question 6: If you would compare this technology to the cap-sense project, what, in your opinion would be benefits of this sensor?

It is on your body and connected to your PC

Question 7: Would you buy this sensor for your personal use? (if yes, what for?)

No, I don't do much presentations.

Question 8: Can you think of a practical example where this sensor would be used?

3D modelling, twist and turn your hands around the sensor to move it around

Question 9: Do you have any design suggestions/improvements for this prototype?

Think about the orientation in which it is held or in your pocket

Participant interview consent form, dated 27/06/2017 Page 2

UNIVERSITY OF TWENTE.

Participant Number 7

Research: Three-dimensional capacitive sensing for wearable technology

Questionnaire

Question 1: How are you connected to the creative technology programme?

I am currently studying Create

Question 2: Can you describe the creative technology programme in no more than 10 sentences?

Using existing technology to create new products.

Question 3: How does the use of sensors contribute in the creative technology programme?

The sensors provide the input for the new products. It is possible that the created products revolve around newly developed sensors.

ASK FOR SENSOR

Question 4: Do you think that this sensor would aid in the toolbox of a creative technologist? (if yes, why? -> **Question 5**. If no, why? -> **Question 7**.

Yes, Creators benefit from having as ~~many possible~~ many sensors as possible so they can choose what sensor fits their application best

Participant interview consent form, dated 27/06/2017 Page 1

UNIVERSITY OF TWENTE.

Participant Number 7

Question 5: How would you introduce this sensor in the programme?

In Smart Tech there is a sensors course where this could be used as an example.

Question 6: If you would compare this technology to the cap-sense project, what, in your opinion would be the benefits of this sensor?

If it were to work all the time, even for a beginner it would definetely benefit from the fact that it has a range, while the cap-sense project you actually have to touch stuff.

Question 7: Would you buy this sensor for your personal use? (if yes, what for?)

No, there are sensors which are more reliable (i.e. the LEAP motion)

Question 8: Can you think of a practical example where this sensor would be used?

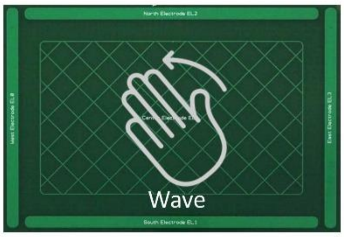
Touchless doors, for instance in a toilet. However that doesn't use the wearable aspect and can be done more easily with infrared.

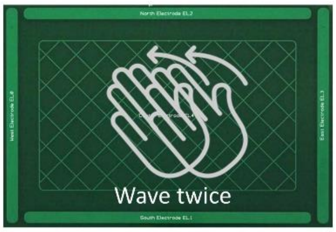
Question 9: Do you have any design suggestions/improvements for this prototype?

Make it easily attachable to any piece of clothing

Participant interview consent form, dated 27/06/2017 Page 2

10.6 APPENDI





DESCRIBE WHAT YOU JUST SAW

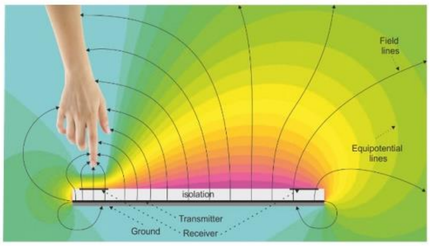
WITHOUT MOVING YOUR HANDS, PITCH YOUR CURRENT BACHELOR PROGRAMME

ON A SCALE FROM 1 TO 10, HOW COMFORTABLE WERE YOU WITH YOUR PITCH?

ON A SCALE OF 1 TO 10, HOW COMFORTABLE IS THE TOUCHLESS CONTROLLER?

ON A SCALE OF 1 TO 10, HOW INTUITIVE IS THE TOUCHLESS CONTROLLER?

PLEASE SWITCH THE PLACEMENT OF THE ELECTRODES



DESCRIBE WHAT YOU JUST SAW

YOU'RE IN AN ELEVATOR WITH THE CEO OF YOUR DREAM JOB. 30 SECONDS TO PITCH YOURSELF AS THE BEST CANDITE...

GO!

ON A SCALE FROM 1 TO 10, HOW COMFORTABLE WERE YOU WITH YOUR PITCH?

ON A SCALE OF 1 TO 10, HOW COMFORTABLE IS THE TOUCHLESS CONTROLLER?

ON A SCALE OF 1 TO 10, HOW INTUITIVE IS THE TOUCHLESS CONTROLLER?

IN YOUR EXPERIENCE, IN WHAT AREA DID YOU PERFORM GESTURES WHEN EXPLAINING SOMETHING?

THIS IS SUBJECT #13, WHERE WOULD YOU SAY THE ELECTRODE IS FITTED MOST UNOBTRUSIVE?

THIS IS SUBJECT #13, WHERE WOULD YOU SAY THE GESTURES LOOK LEAST INTERRUPTING?

THANK YOU!

PLEASE FILL IN THE REST OF THE QUESTIONNAIRE

10.7 APPENDIX XIII - EXPERIMENT RESULTS & DOCUMENTATION

Participant	**Requirement**	**Lower Arm**	**Upper Arm**	**Chest**	**Pocket**
1					
	Sensor comfort			7	8
	Natural Gesture Area			x	
	Intuitivity			9	9
	Ideal Gesture area		x		
	Placement rank	3	4	2	1
Participant	**Requirement**	**Lower Arm**	**Upper Arm**	**Chest**	**Pocket**
2					
	Comfort		6		7
	Natural Gestures			x	
	Intuitivity		8		8
	Ideal Gesture area		x		
	Placement rank	3	2	4	1
Participant	**Requirement**	**Lower Arm**	**Upper Arm**	**Chest**	**Pocket**
3					
	Comfort	4			6
	Natural Gestures			x	
	Intuitivity	4			4
	Ideal Gesture area		x		
	Placement rank	4	3	2	1
Participant	**Requirement**	**Lower Arm**	**Upper Arm**	**Chest**	**Pocket**
4					
	Comfort			5	8
	Natural Gestures			x	
	Intuitivity			8	8
	Ideal Gesture area			x	
	Placement rank	4	2	3	1
Participant	**Requirement**	**Lower Arm**	**Upper Arm**	**Chest**	**Pocket**
5					
	Comfort	8			8
	Natural Gestures			x	
	Intuitivity	6			7
	Ideal Gesture area				x
	Placement rank	4	3	1	2
Participant	**Requirement**	**Lower Arm**	**Upper Arm**	**Chest**	**Pocket**
6					
	Comfort		9		4
	Natural Gestures			x	
	Intuitivity		8		8
	Ideal Gesture area				x
	Placement rank	4	3	1	2

UNIVERSITY OF TWENTE.

Participant Number 2

Research: Three-dimensional capacitive sensing for wearable technology Experiment

Three-Dimensional Capacitive Sensing Experiment

Candidate #: 2

Date: 27/6

Time & Place: 16:10

Placement 1: Upper Arm

Comments pitch: points to self, gesture with hand

Comfort pitch scale (1-10): 6

Comfort controller scale (1-10): 6

Comfort intuitive scale (1-10): 8

Placement 2: pocket unresponsive

Comments pitch: ① image with functionality ~~hand~~ hands clapping scratch head

Comfort pitch scale (1-10): 3/4

Comfort controller scale (1-10): 7

Comfort intuitive scale (1-10): 8

Natural gesture ... chest,

Electrode placement: 2, 3, 1, 4

Ideal gesture area: upper arm

Participant interview consent form, dated 27/06/2017 Page 1

UNIVERSITY OF TWENTE.

Waved down -> up

Participant Number 1

Research: Three-dimensional capacitive sensing for wearable technology Experiment

Three-Dimensional Capacitive Sensing Experiment

Candidate #: 1

Date: 27/7

Time & Place: 15:45

Placement 1: chest

Comments pitch: ~~pointing~~, gestured once, clammed hands pointed.

Comfort pitch scale (1-10): 1

Comfort controller scale (1-10): 7

Comfort intuitive scale (1-10): 9

Placement 2: unresponsive poket

Comments pitch: hands on hips, hand gestures, overall

Comfort pitch scale (1-10): 7

Comfort controller scale (1-10): 8

Comfort intuitive scale (1-10): 9

Natural gesture ... stomach / chest / hip / ~~[illegible]~~

Electrode placement: ~~upper arm~~, chest

Ideal gesture area: upper arm

Participant interview consent form, dated 27/06/2017 Page 1

waves in Air } 1,5 min
unresponsive }
logo confusing

UNIVERSITY OF TWENTE.

Participant Number 4

Research: Three-dimensional capacitive sensing for wearable technology Experiment

Three-Dimensional Capacitive Sensing Experiment

Candidate #: 4

Date: 27/06/2017

Time & Place: 17:10

Placement 1: chest

Comments pitch: shrug shoulders

Comfort pitch scale (1-10): 6, spontaneous

Comfort controller scale (1-10): 5

Comfort intuitive scale (1-10): 8

Placement 2: pocket

Comments pitch: hands clamped, arms crossed "thinker", hands on hips, hands in front of crotch

Comfort pitch scale (1-10): 8

Comfort controller scale (1-10): 8

Comfort intuitive scale (1-10): 8

Natural gesture … arms crossed / gestures in front of chest.

Electrode placement: 1, 3, 2, 4

Ideal gesture area: chest

Participant interview consent form, dated 27/06/2017 — Page 1

waves sensor/electrode
unresponsive

UNIVERSITY OF TWENTE.

Participant Number 3

Research: Three-dimensional capacitive sensing for wearable technology Experiment

Three-Dimensional Capacitive Sensing Experiment

Candidate #: 3

Date: 27-06-2017

Time & Place: 16:30

Placement 1: Fore arm

Comments pitch: points with finger/thumbs up → unresponsive

Comfort pitch scale (1-10): 6

Comfort controller scale (1-10): 4

Comfort intuitive scale (1-10): 4

Placement 2: upper leg

Comments pitch: clams hands, [illegible], imagination movement jazz hands.

Comfort pitch scale (1-10): 7

Comfort controller scale (1-10): 6, side > front

Comfort intuitive scale (1-10): 4

Natural gesture … chest / sides.

Electrode placement: 1, 2, 3, 4

Ideal gesture area: upper arm

Participant interview consent form, dated 27/06/2017 — Page 1

UNIVERSITY OF TWENTE.

Participant Number: 6

Research: Three-dimensional capacitive sensing for wearable technology
Experiment
Three-Dimensional Capacitive Sensing Experiment

Candidate #: 6

Date:

Time & Place: 12:30

Placement 1: upper arm
Comments pitch:
no body language

Comfort pitch scale (1-10): 5

Comfort controller scale (1-10): ~~7/5~~ 9, holding battery

Comfort intuitive scale (1-10): 8

Placement 2: pocket: not responsive
Comments pitch:

Comfort pitch scale (1-10): 2, not to do with

Comfort controller scale (1-10): 4

Comfort intuitive scale (1-10): 8

Natural gesture ... stomach, chest

Electrode placement: 1, 2, 4, 3

Ideal gesture area: pocket/and fore arm

Participant interview consent form, dated 27/06/2017 — Page 1

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waves to screen
gets used to: 3 minutes.

UNIVERSITY OF TWENTE.

Participant Number: 5

Research: Three-dimensional capacitive sensing for wearable technology
Experiment
Three-Dimensional Capacitive Sensing Experiment

Candidate #: 5

Date: 27/06/2017

Time & Place: 17:50

Placement 1: chest
Comments pitch:
pinch fingers, hand gestures, turning hands
hands spread

Comfort pitch scale (1-10): 4

Comfort controller scale (1-10): 8

Comfort intuitive scale (1-10): 5/6

Placement 2: pocket -> not paying attention
Comments pitch:
arms crossed, shrug shoulders,

Comfort pitch scale (1-10): 6

Comfort controller scale (1-10): 7/8

Comfort intuitive scale (1-10): 7

Natural gesture ... stomach/chest

Electrode placement: 1, 2, 4, 3

Ideal gesture area: stomach/legs.

Participant interview consent form, dated 27/06/2017 — Page 1