ROBOTICS AND MECHATRONICS

Increasing the immersive experience in the Leo Universal Cockpit

P. (Pamela) Shametaj

BSc Report

Committee:
Dr.ir. D. Dresscher
Dr.ir. E.C. Dertien

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037RAM2017
Robotics and Mechatronics
EE-Math-CS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

UNIVERSITY OF TWENTE.

MIRA BIOMEDICAL TECHNOLOGY AND TECHNICAL MEDICINE

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Abstract

This report will be about improving immersion inside Leo Universal Cockpit (LUC), a tele-control cockpit designed by i-botics. At the moment LUC does not truly immerse the controller. The setup of the cockpit is minimal and is not carefully chosen to accommodate the user and his needs. The first step to making this cockpit more immersive is to get a better understanding of immersion itself and what makes a system immersive. Secondly available technology will be researched and analysed. Later a re-design will be presented and one of the chosen technologies will be prototyped. This decision to prototype only one technology was because of time constraints so what would be prototyped had to be chosen carefully. A vibrio-tactile vest was used in the end to augment the senses of the controller. In this way the user would be able to better navigate in the remote environment through vibration. Summative testing was used to test three functionalities of the vest, the ability to convey a moving obstacle, usage of different vibration intensities to display an approaching object and its distance from the user, and the ability to properly present an approaching and moving obstacle. The results of the test were promising, however the usage of vibration intensities needs to be tested further for more significant results. In conclusion this report creates a very good basis on designing immersive tele-control cockpits and using vibrio-tactile feedback. The conclusions and results within this project could be truly beneficial for further research and prototyping within the world of tele-control and for LUC itself.

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1. Introduction

1.1 Context

The demand for robots has increased significantly in the last decade. They are being used in production facilities, medicine, space and underwater exploration, slowly making their way into everyone's daily life. Robots are efficient and can take over life threatening tasks. Nonetheless, robots lack the intelligence to perform complex tasks. Without the development of highly intelligent AI, humans are superior when an intuitive, social or intricate task has to be performed. The field of tele-robotics aspires to bridge this gap. Tele-robotics is a complex field that deals with the control of semi-autonomous robots from a distance. This control is achieved with the use of a tele-operator. Thomas B. Sheridan [1] defines a tele-operator as a setup that extends a person's senses and allows for operation of a machine in a remote location. He also mentions that such devices include artificial sensors of the environment, a vehicle for moving these in the remote environment, and communication channels to and from the human operator. One of the earliest examples of teleoperation was in 1951 when a mechanical master-slave manipulator arm was developed to work with radioactive material. [1]

I-botics is an innovation centre for research and development in interaction Robotics with specialization in tele-robotics and exoskeletons. Their main goal is to provide the human operator with full perceptual and manipulation capabilities to intuitively perceive the remote environment and act as if being present at the remote site. The main challenges they generally face under similar projects are situational awareness of the human operator, robotic sensing and adaptive automation for partial autonomy. The Leo Universal Cockpit is a control unit designed by i-botics to control a semiautonomous robot from a distance. The current design of LUC is the first version of this telepresence and tele manipulation unit. LUC provides sensory information via three screens, speakers and force feedback through a haptic device. A joystick and a haptic device can be used by the user to control the remote system.

2.2 Problem Analysis

Controlling a robot in a remote location sitting in a cockpit can feel unrealistic and tedious. For the user to feel comfortable and control the robot more accurately, they should be fully immersed in the experience. Although significant research has been done to understand immersion in both the context of virtual reality and tele-operation, very little is recent. This can be a challenge when trying to implement state of the art technology in your designs. Advancement of technology can also be seen as a challenge when designing immersive systems. Although different methods and technologies for teleoperation have been exploited and tested, a lot of the technology used on these existing systems is outdated. Last but not least LUC is a universal controlling unit designed for different kinds of robots that perform different tasks, while most of the existing tele-control systems are designed either for specific robots or specific tasks. Making the interaction within LUC comfortable and usable for users operating on different robots performing different tasks might become truly challenging.

At the moment LUC has the most basic setup required to create immersion; 180 degree view, 2-dimensional sound, one haptic device, no feedback when the robot malfunctions or collides and no possibility of intuitively managing the cockpits feedback. With limited sensory feedback the experience being presented to the user is not optimal. The goal of this project is to redesign LUC as a user centred control unit. The new design should be able to fully immerse the person controlling the cockpit while making them feel present in the remote area.

1.3 Goal

The goal of this project is to redesign LUC as a user centred control unit. The new design should be able to fully immerse the person controlling the cockpit while making them feel present in the remote area. To achieve this goal the user should be given more sensing possibilities and information regarding the environment that surrounds the remote robot. It should be taken in account that the components added in LUC, should adhere to the controls already present.

1.4 Research Questions

To achieve this goal the user should be given more sensing possibilities and information regarding the environment that surrounds the remote robot. It should be taken in account that the components added in LUC, should adhere to the controls already present.
To fulfil this goal three research questions will presented:

How to improve the immersion of the user inside LUC by integrating new technology?

- What sensory feedback should be taken in account to create an optimally immersive system and how should it be presented to the user?
- What technologies should be integrated in the final design of LUC to create an intuitive and optimal immersion of the user?

The limited time available for this assignment created a constraint on the improvements that could actually be physically implemented in LUC within the allotted time period. This prompted a third research question for this project:

- What will be implemented on LUC as a prototype?

1.5 Report Outline

This report will consist of seven chapters. On the first chapter the problem and the goal were presented together with the research questions. The second chapter analysis will be followed by a research regarding immersion and the available technology for tele-control cockpits. On the third chapter a new design will be presented and a prototype will be designed and built. Chapter four will be explaining how the testing of the prototype was done while the results will all be displayed on the fifth chapter. This is also where the results will be statistically analysed and visualized using charts. A conclusion will be drawn on the chapter six and the research questions that arise in the introduction will finally be answered. Lastly future work and improvements will be discussed on chapter seven.

2. Analysis

This chapter will be analysing the concept of immersion, what makes an experience immersive and the available technologies to make this possible. No decisions will yet be made on how LUC should be improved but different possibilities will be presented.

2.1 Immersion

Not a lot of research has been done on immersion of the user inside tele-controlled cockpits. Most of the focus has been on either creating telepresence or user immersion in virtual environments. Because of this reason, the understanding of immersion in the needed context will be done by answering two main questions. What the definition of immersion is and what requirements are out there for an experience to be thought of as immersive. In the end the findings will be compared with the current version of LUC.

2.1.1 Immersion Definition

It is known that when dealing with tele-robotics, presence and immersion are two principles of great importance. Cummings and Bailenson [2] state that presence represents the extent to which an individual experiences the virtual setting as the one in which they are consciously present, while immersion is an objective measure of the extent to which the system presents a vivid virtual environment while shutting out physical reality. After understanding the disparities of these two concepts the next step is asserting a definition for the one of importance, immersion.
The focus of this research will be on immersion because of two main reasons. Firstly, presence has already been thoroughly researched while immersion not as significantly. Secondly, this project is concerned only with objectively improving the experience inside the cockpit, and the technology and sensory information that can make that possible.

No clear definition about immersion exists in the context of virtual reality or tele-robotics, there are however three suggested definitions from the collected papers.
The first definition comes from Witmer and Singer [3] who suggest that immersion is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences. Just like Witmer and Singer, McMahan [4] also argues that immersion is a state of the user. He then cites Janet Murray's, an internationally known interaction designer, definition where immersion is compared with being submerged in water. This definition states that the same psychological and physical feeling is sought in both of the experiences and that an immersive system should just like water take over our attention and perceptual apparatus, while simulating a completely other reality.
Thirdly in contrast to the other authors Cummings and Bailenson [2] regard immersion as a quality of the system's technology rather than a state or experience. For them immersion is an objective measure of the extent to which the system presents a vivid virtual environment while shutting out physical reality as mentioned above.
Notwithstanding, two properties of immersion can be noticed as being present in all three definitions:

1) Isolation of the user
2) Provision of stimuli

By taking in account the mentioned properties that all these definitions have in common a new definition has been written. Immersion is a form of isolation from actual reality where the user is constantly being provided with artificial stimuli. This is the definition which will be used in this report.
Despite of the limited amount of articles used in shaping this definition of immersion, the chosen papers were extensive studies based on a considerate amount of references. What also stood out from the definitions was their relatability to the context of tele control.

2.1.2 Immersion Requirements

After the notion of immersion and its contrast to presence is comprehended the next step is extracting requirements that need to be fulfilled to create an immersive system. According to McMahan [3] there are two categories that all the requirements fall under. He states that in order to create an immersive system the user needs to be both perceptually and psychologically immersed in the experience.

Isolation is identified by all authors as one of the key factors to perceptually immerse the user in the virtual or remote environment [4], [3], [2]. If this isolation is not properly accomplished through narrative or technology, the user will be constantly reminded that the environment they are interacting with is virtual. Cumming and Bailenson [2] highlight that for a system to shut out physical reality and isolate the user, it should offer high fidelity simulations through multiple sensory modalities, finely map a user's virtual bodily actions to their physical body's counterparts and remove the participant from the external world through self-contained plots and narratives. Patrao et al. [5] and Pamungkas and Ward [6] state that perceiving the robot's body as your own is highly important in being immersed. According to them this ownership can be achieved by a better sense of control and sensory feedback.

Another important requirement that falls under perceptual immersion observed by Cumming and Bailenson [2]is low interface awareness. They argue that if interfaces require high awareness, they end up distracting the user and interfering with the process of isolation.

Part of the second category is the user's ability to have an impact on the virtual or remote environment. McMahan [4] argues that this impact is of importance when trying to psychologically immerse the user. Reasonably, in our context the user should be able to control the robot correctly and immediately to be able to manipulate the remote environment. This reasoning is also supported by Bobak et al. [7] and Witmer and Singer [3]. They demonstrate that there is indeed a close relationship between immersion, impact and control, and also point out that a high degree and immediacy of control are of high importance when aiming for significant impact. The other requirement noted by McMahan [4] , which ensures that the user is immersed psychologically, is consistent feedback. Understandably, non-consistent information could have a direct impact on the users psyche by creating confusion.

Sensory feedback was seen by all papers as one of the most important requirements for the user to feel immersed in the remote environment. This requirement seems to fit both of the above mentioned categories as it provides the user perceptual information while having a direct impact on their psyche. Uriel et al. [8] mentioned that to achieve a high degree of immersion the simulated feedback should mirror the human senses. That is why the presented feedback usually includes visual, tactile, proprioceptive as sense of the relative position of ones body, and audio, which also correlates with the findings of the previous chapter, emphasizing the beneficence of each of mentioned feedbacks.

In summary when creating an immersive system the user should be immersed both perceptually and psychologically. To achieve this, one should choose the appropriate technology needed to firstly be able to isolate the user, such as head mounted devices and headphones. Secondly the user should be able to have a high degree of control to have an impact on the remote environment. This can be interpreted as not only good control of the robot but the also the ability to communicate with the environment, get feedback on their actions and be able to look around. The feedback presented should also be consistent, where for each medium there is only one type of presented feedback. Last but not least the interfaces of the devices within LUC should require low awareness.

2.1.3 Leo Universal Cockpit

The current design of LUC is the first version of this telepresence and tele manipulation unit. The components can be categorized in two groups, control and feedback mechanisms. The control is achieved through a joystick and a haptic device. The joystick is only used to move the body of the robot around, while the haptic device controls the robotic arm. The present haptic device is called omega.7, seven standing for its seven degrees of freedom while it also offers a force-feedback hand gripper. Omega.7 is generally used in aerospace and medical industries and it is available in left and right hand configuration, while it can be integrated in a dual workstation setup for bimanual operation.

For immersion of the remote user, LUC provides visual, audio and haptic feedback. The visual feedback is presented using three computer screens, which give the user a very limited view of the surroundings. The audio feedback is achieved through a set of speakers. The sound of the speakers helps the user in confirming the visual and haptic feedback while also informing him on the presence of surrounding object or events that happen around the remote robot. However, being 2-dimensional the sound does not help with proper localization of such objects and events but is merely a confirmation of their presence. The haptic device is one of the only components that offers a very realistic feedback. Via force-feedback the user can feel the surface of the object he is touching, its shape and too composition. Despite it not being fully possible to understand texture it provides a lot of information to the remote user.

For LUC to be defined as an immersive system it should isolate from actual reality and constantly provide artificial stimuli. This can be achieved by both perceptually and psychologically immersing the user in the presented experience. Just as mentioned in the introduction the current setup of the cockpit is not optimal. This can also be seen by making a comparison between LUC and an ideally immersive system as mentioned in the previous section.

Firstly the current setup of LUC is not enough to isolate the user from the environment they are physically present in. Patched up screens and noises around the cockpit will be a constant reminder that the remote environment is simulated. Secondly the feedback presented to the user is not of high fidelity and also lacks variety. Better technology can be used to present the feedback while additional sensory feedback can be explored and integrated on the final design. Except the haptic device, most of the technology used in the cockpit do also not provide a high degree of control. The mentioned reasons are why LUC will be redesigned.

2.2 Available technology

The applied technology in existing immersive systems can be classified in four categories. Technology that provides visual input, control, audio input and haptic feedback, proprioceptive. The fore-mentioned technologies will all be explained and analysed on the coming chapters. In the end this technologies will be utilized to design an immersive system.

2.2.1 Visual feedback

The section explaining the visual feedback will consist of two subsections. The first sub-section will analyse the different types of visual display devices available on the market according to budget and drawbacks. The second subsection will focus on the available methods of capturing material that can be displayed on a head mounted device, while the third sub-section will list the available processing methods of the captured video.

2.2.1.1 Viewing

The preferred devices for displaying visual input were head-mounted-devices (HMD) suggesting they provide more realistic movement and higher degrees of freedom when scanning the environment [2], [6], [7], [9] . Patrick et al. [10] nonetheless refutes such hypothesis and states that there is little difference in immersion between very large projection screens which encompass entire field of view and HMD, but they are generally preferred because of lower costs.

HMD or VR headsets are devices worn on the head with an optic display in front of either one or each eye. In the last decade these devices have improved significantly by offering high quality experiences and fully immersing users, recently becoming available for the general public. Since 2013 the market has grown so rapidly that is estimated to reach a total revenue of 80 billion USD by 2025. [11]The commercial market of head mounted devices is at the moment dominated by two main companies, Oculus Rift and HTC with other alternatives from Sony, Samsung and Google offering similar products. Notwithstanding the drawbacks of using HMD are still numerous. One of the challenges that arises when using HMD are motion-to-photon latency problems. Fiala [12] states that such problems can degrade the immersive experience by disorienting the user and lowering immersive realism. He then demonstrates that panoramic cameras and panorama frame buffers are one of solutions for similar problems. The refresh rate is still not optimal for many of the available devices, and the same goes for the resolution. In addition to the technical issues there are several health warnings that come with VR headsets. Long exposure to this devices can cause dizziness, seizures and increased heart rates, which can be inconvenient when being used for long periods of time. Lastly the headsets can play two different types of content, rendered VR and captured VR.

On the other hand, large screens can display high resolution content and are far more comfortable for the user. They do not physically limit or put any weight on the controller. They also allow for a better view of the cockpit itself. However, the size needed for the screen to provide the same effect as the HMD can make the cockpit impractical, while also making it difficult for the user to have a detailed view of the environment. Screens also lack the mobility provided by the HMD and would require an extra mechanism for the user to be able to look around in the remote environment. This could create an uncomfortable situation for the user and consequently lower the immersion.

2.2.1.2 Capturing and Processing

There are two methods for capturing VR content, movable stereo systems and VR cameras. The latter can either be commercial or DIY. On the first option of movable stereo systems the user's head movements are tracked using a sensor placed on the HMD. This information is then sent to a rotating mechanism that moves the camera of the remote robot around to match the user's movements. Although this option is cheaper as it avoids stitching and creates clearer and generally higher quality images, it still creates mechanical latency. If this latency can be overcome, then using movable stereo systems would be considered as the optimal solution.

The second option, VR cameras, require significant work on either the camera itself or the receiving end. Even if this work were done, this second option would still provide processing delay. To build a VR camera, one needs to merge several stereo cameras together using 3D printed mounts. For decent quality streaming the cheapest alternative for a VR camera is around 400 USD. A self-made non-commercial alternative can be as cheap as 50

USD but it delivers bad quality content which also require very accurate calculations. When presenting actual 360 footage, price and quality are not the only issues one faces, live streaming and real time stitching is where things can get most complicated. Once again there are two methods presented for streaming 360 content onto the HMD, using available software or wrapping, stitching, compressing and projecting the content yourself. Similarly the available software are few in number, expensive and have several limitations. Two of the only ones that support real time stitching are Vahana VR and StereoStitch. Both of the alternatives come with errors and request state of the art specs. The second method requires abundant work, complicated calculations and a lot of trial and error.

2.2.2 Audio feedback

The addition of a 3-dimensional sound in a tele-controlling cockpit could be highly beneficial. Binaural sound, another synonym for 3D sound, fully immerses users by realistically emulating the way we hear sound in real life. Portilla et al. [13] states that auditory displays are widely used to enhance the scene of immersion in virtual environments. According to the authors the sound communicates information to a user and offers an alternative mean of visualization. The 3D sound provides extra help for the user to find objects when he is navigating, because the hearing system can determine the location of the sound sources. There are already commercial microphones that do real time sound processing and do not require work from the recipient. These microphones are however expensive and heavy. A perfect example would be the free space pro series by 3Dio, with product's price starting at 499 USD. There is however a cheaper way of streaming the sound, that is by hacking together a binaural microphone with the use of two stereo mics. It should be kept in mind that for the best quality recordings the microphones should be placed at a reasonable distance from each other simulating a human head. It should be noted that stereo sound speakers and headphones were the only two ways of audio feedback provided throughout all the collected material.

2.2.3 Controllers

The mentioned types of control devices used were exoskeletons with seven degrees of freedom, haptic devices, joysticks, keyboards and touchscreen displays [3]. Nevertheless Bobak et al. [7] showed that tangible devices, which reaffirmed users' confidence and controllability and had manual control possibilities were most comfortable for the users. They also stated that touchscreen devices made users uncomfortable. Uriel et al. [9] supports his statement by pointing out that haptic devices are generally preferred being they provide more feedback to the user. It was noticed, that exoskeleton type controllers and haptic gloves were mostly used to control humanoid robots or robotic limbs but not for devices that share no similarity to humans.

2.2.4 Haptic feedback

According to Pamungkas and Ward [6] immersion in a teleoperation system is achieved through multisensory feedback and usually with the inclusion of haptics. Haptic feedback is the sense of touch in an interface that provides the user with information. This information can be volatile and can vary depending on application. There are however two types of feedback incorporated in haptic systems, force feedback and cutaneous feedback. In the following sections each type of feedback will be explored and analysed. Because LUC already incorporates a highly advanced force feedback system the main focus will be on cutaneous feedback; vibrotactile and electrotactile feedback.

2.2.4.1 Cutaneous feedback

A new type of feedback presented by Piacherotti et al [14] was cutaneous feedback. Cutaneous stimuli are detected by mechanoreceptors in the skin, enabling humans to recognize properties of objects such as shape, edges, and texture. Such perception has been mainly implemented on the fingertips for navigation.
Despite the vibrotactile and electrotactile feedback that also fall under this category, two other popular methods used to provide cutaneous feedback are using moving platforms and pneumatic balloon based systems.
What was found of interest however is the system presented by Piachierotti et al. [14] themselves shown in the picture below. By controlling the cable lengths, the servos apply planar deformations to the fingertip, while the vibrotactile motor conveys fingertip vibrations. In some configurations, the platform does not contact the fingertip, enabling the device to portray the making and breaking of contact. Like mentioned in the paper this can be redesigned to create a more comfortable device, however the idea is quite original.

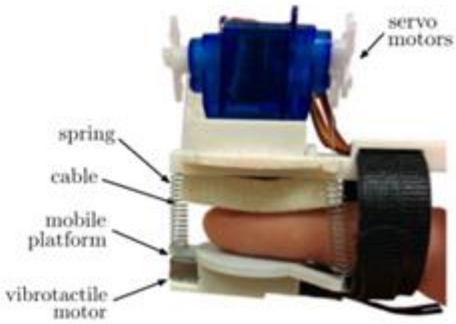

Figure 1. *Cutaneous feedback using a servo mechanism [14]*

2.2.4.2 Vibrotactile feedback

Pacchierotti et al. states that many researchers have turned to sensory substitution techniques when incorporating feedback, wherein force information is presented via an alternative feedback channel such as vibrotactile cues. Vibrotactile feedback is likewise stated to have the potential to improve the rate of learning and the accuracy of the learned motion. A study done by Rye et al. [15] also concluded that the addition of vibrotactile feedback added to the realism and naturalness of the experience.
So far the addition of vibration in telecontrol systems has been limited to the hands of the user. This is because several body regions are of higher sensitivity than others. Zengin et al [16] demonstrates the relation between the vibration signal frequency and skin sensitivity. Seemingly, lower frequencies seem to penetrate deeper areas into the skin, while higher frequencies more superficial ones. It was also stated that for a better distinction between different vibration frequencies the motors need to be placed apart starting from a minimum level 55.7 [mm] for the back body and 36.2 [mm] for upper arm for a stationary stimuli. Different frequencies also need to be applied at different time frames for the user to be able to

distinguish them. However, frequencies higher than 160 Hz are the ones most easily differentiable for the least amount of time (100ms) when using vibration feedback.
When implementing vibrotactile feedback there are two types of vibration actuators that are generally used, Eccentric Rotating Mass motor (ERM) and Linear Resonant Actuator (LRA). ERM works similarly to a DC motor, and can be driven by the use of a DC current. The most commonly used type in wearables is called pancake shaftless motor. The vibration intensity can be regulated through a modulated signal (PWM). Yet the biggest drawback of ERM actuators when using a PWM signal is that the amplitude and frequency cannot be changed independently.
LRA's on the other hand use a voice coil instead of a DC motor, meaning they require an AC input. Because of this reason LRA circuits are more complex and usually require a driver chip. Nonetheless, they offer advantages such as less power consumption, faster start-stop times, less noise and the ability to set the frequency and amplitude separately, something not offered in ERM motors.

2.2.4.2 Electrotactile feedback

Electrotactile feedback is a type of feedback that uses electric current to stimulate nerves within the skin while providing stimuli that vary both in amplitude and frequency. These displays are small, have high spatial resolutions and can be easily controlled [14]. Consequently, such feedback can simulate a diverse range of sensations without desensitizing the nerves. Electrotactile feedback has also shown to overcome limitations of electro mechanical systems, which are usually heavy and expensive making it very beneficial in control systems that require the user to move [5].
The majority of electrotactile displays nowadays provide only symbolic information through on and off signals something which is yet to be overcome, however a display that is capable of presenting the distribution of force was proposed by Sato and Tachi. [14] Their design was based on the concept of tactile primary colurs, simulating natural tactile sensations by selectively simulating each mechanoreceptor. Different types of mechanoreceptors sense different types of stimuli, and the body can be tricked by simulating the specific receptors. To implement such systems however, the authors used highly advanced self-built TENS systems, which require time and a good background in biomedical engineering [5]. Another notable disadvantage of using electrotactile feedback is the humidity required for the sturdy connection between the user's skin and the electrodes necessary when transmitting precise signals.

2.2.5 Proprioceptive feedback

Proprioceptive feedback is described as the sense of relative position, is another beneficial type of feedback which can be provided by a motion base as mentioned by Susumu et al [10]. This motion bases can convey kinematic changes and false gravitational forces to the user. In this manner the user is fully immersed in the controlling experience. The maximum degrees of freedom in motion bases are six, where three degrees stand for linear degrees and the rest stand for rotational degrees. It should be noted that the rotational degrees are not necessary if there is only interaction on land or if the robot won't rotate around its axis. However the usage of motion bases in tele-control is a generally new concept noticed in only one of the researched projects. Yet there is usage of similar bases in gaming and driving and flight simulations.

2.3 Sensory augmentation

Out of all the alternative feedbacks researched, vibrio-tactile feedback was chosen to be researched further as it presented a new dimension of information to the user that could be utilized in numerous ways. Sensory augmentation and force simulation proved to be the two most promising implementations. For the final decision on which is the most feasible and interesting implementation, both were further researched and an expert in the field was also consulted. It was noted that force simulation would require more time than was available, and thus sensory augmentation was chosen to be prototyped further.

Before exploring the idea of sensory augmentation, the first step of the research was focused on sensory substitution - a non-invasive way of compensating sensory loss by feeding the information through alternative channels. While the most common substituted sense is that of sight followed by sound and force feedback [17], [18].Bach-y-Rita et al [17] mentioned in their research that information provided from artificial receptors may change brain structures, including those anatomically and physiologically related to the lost sensory modality. The authors also explain that the reason behind the success of sensory substitution is due to brain plasticity, or the adaptive capacities of the central nervous system. An alternate definition for this plasticity is the brains ability to modify its own structural organization and functioning. [17] Sensory augmentation works in a comparable manner by taking advantage of the brains adaptive capabilities. This adaptability is beneficial when sending information through only one channel is overwhelming for the user. Wahn and Konig [19] concluded that tasks requiring a high demand of visuospatial attention could be facilitated if the information is received via several sensory modalities. Moreover, research has shown that sensory augmentation can aid in task performance and that prolonged exposure to the ‘new sense’ can lead to both physiological and perceptual changes [19].

Another important aspect of sensory augmentation is its practical usage in the real world. Examples of sensory augmentation already in practice can help in getting a better idea of what is possible with vibrio-tactile feedback. It was also beneficial when deciding what approach should be taken when making decision for the prototype. Some of the most interesting applications found were grip force information for prosthetic applications, interaction force information in tele-operated assembly, tissue interaction force information in robot-assisted surgery and mediation of magnetic north [17]- [19]. What all these examples had in common was their usage of vibration, proving my theory that vibrio-tactile augmentation was a promising approach on sensory augmentation. It was also stated that such feedback was preferred over more traditional feedbacks such as force feedback due to the small size, economical price and its non-invasiveness [19].

3. Design

As discussed on the analysis chapter, LUC’s setup is at the moment not optimal. The cockpit lacks the ability to perceptually immerse the user and isolate him from reality. Simultaneously there is a lot of place for improvement when it comes to psychological immersion. The amount of the available artificial stimuli is small while, the way they are presented is outdated. Tackling these problems would significantly improve the immersion experience of the user inside LUC thus, making the control more realistic. In this chapter solutions to these problems will be presented, discussed and visualized. The presented solutions are a product of the meticulous research on the available technology documented in the previous chapter.

3.1 Re-Design

After the options presented on the previous chapter on available technologies decisions had to be made for the re-design of LUC. However, the current state in technology gives little choice when deciding what to include in the cockpit.
Regarding visual feedback, size, mobility and isolation were prioritized over image quality and comfortability which led to the choosing of HMD. The decision to use HMD was based on the choice to make the cockpit more practical, the interaction more realistic and to provide a higher degree of vision to the user. Simultaneously, HMD are cheaper, are updated frequently and are easier to replace. On the other hand, the capturing method that will be selected is using movable stereo cameras. This choice was made only because less image processing is required.

The restrictions when selecting a controller for the cockpit are that the device should be tangible, have high immediacy of control and provide necessary feedback. Haptic devices, such as exoskeletons and haptic pedals, fall under the requirements and thus both exoskeletons and haptic devices will be used in the final design. Despite taking a lot of space and being heavy, they seem to provide the most realistic feedback out of all the other possibilities. They also provide a more intuitive and higher degree of control. Exoskeletons will be used in the hands and arms for the grip and robotic arm movement respectively, while haptic pedals will be used for moving the base of the robot. However, exoskeletons are a better solution for movement than pedals when dealing with humanoid robots.

An additional mechanism that will be included in the final design is the motion base, a setup that can simulate kinematic changes and gravity. It will be included because it has been documented to be highly effective in immersing the user in the experience. The combination of VR and motion bases might also reduce motion sickness, as the movement conveyed by the image won’t feel unnatural for the body.

Another important aspect in tele-control is sound. Despite sound not being a core component in tele-control, it is beneficial to the experience. In addition to visual feedback, sound creates another layer of information which improves the user’s ability to navigate remote locations. For the final design binaural sound will be used instead of stereo sound. The reason for the preference over stereo sound is the ability of binaural sound to simulate depth and thus make the user more aware of their surroundings. With most sound options, one must also decide whether to display sound through speakers or headphones. This decision is generally based on user preference and the tranquillity of the cockpits surrounding environment. However, as binaural sound was chosen for the final design, the choice is limited to headphones due to them being the best option for presenting such sound.

The re-design of LUC is depicted below in figure number one. This sketch shows how the cockpit would look if all the mentioned elements were set up inside the LUC. An exploded view is shown in the appendix and displays the different elements separately without the motion base.

***Figure 2**. Final design including all components chosen to display the necessary feedback*

3.2 Prototype conceptualization

The core concept of the prototype is utilising vibrio-tactile feedback to augment the users senses. Vibration will be used to give the user an improved sense of navigation inside the cockpit. This will be done by making up for the blind spots of visual feedback and increasing the user's awareness of the obstacles that are around the remote robot. Vibrational information can also be used in analysing the intensity of collision and narrowness of passages. This type of information is problematic to convey through other means of feedback because the environment is "virtual" and metric systems can be difficult for the user to conceptualise. By using an array of vibrating motors, the information provided through vibration can also be extended to the size and speed of obstacles in motion. However, it is still important not to overwhelm the user and thus only objects within a certain range should be visible to the user.

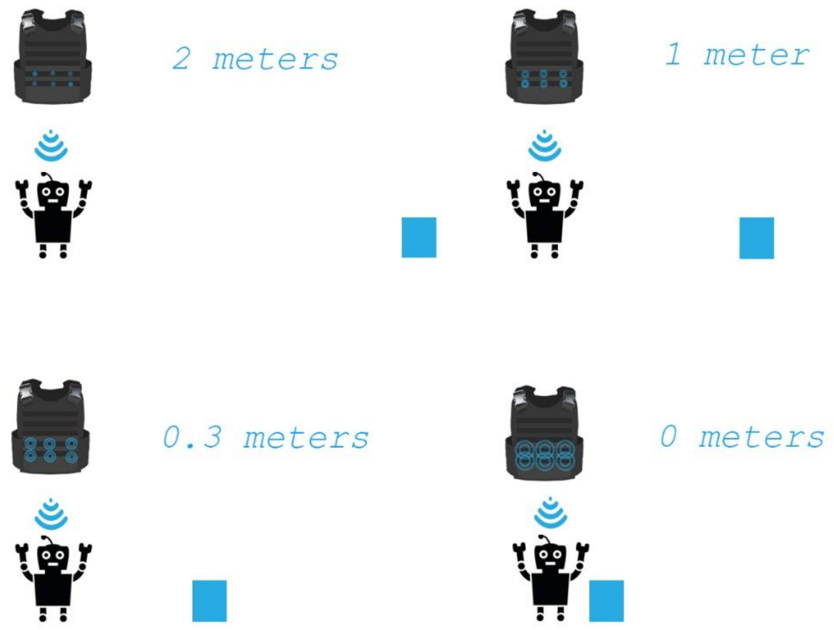

Figure 3. *Diagram of the prototype concept*

The initial range was chosen to be two meters as it is believed to be close enough to not overwhelm the user with data but far enough for the robot to be able to react. The efficiency of this range will be seen through proper testing. The distance of the obstacle will be conveyed through vibration intensity in an inversely proportional manner. The further the object is, the weaker the vibration will be. For the user to be able to distinguish the scale of vibration, the intensity will be defined in six understandable vibration intensities. This decision was made after the testing of one ERM motor at different voltages. This prototype concept is visualized better in figure 3.

3.3 Vibrio-tactile Vest

After deciding to use ERM motors, the second step was deciding on the amount and positioning. The amount of the motors would be equivalent to the resolution of the presented information, while the positioning had to be done strategically to increase sensitivity. The usage of the Tactile Torso Display from TNO was decided upon after consulting a specialist.

The Tactile Torso Display is a vest with 64 ERM vibrating motors defined as tactors. This array of tactors is capable of displaying moving, complex tactile patterns by turning the motors on and off. The original setup of the vest consists of an USB module, an amplifier, a distributing circuit and the vest. The module is a DT9835 digital I/O unit from Data Translation that converts the serial USB input into 64 parallel digital outputs through a standard 100-pin connector. A major downside of using this device in my project is the lack of Linux compatibility. This can be quite problematic when integrating the vest in the control cockpit and communicating with the robot's platform.

The amplifier has a 100-pin connector which uses the output of the module's 100 pins as input and four 20-pin connecters labelled from 'A' to 'D' as output as shown in figure five. The amplifier has to be powered by a 12-volt DC power supply to be able to switch all the tactors simultaneously while constant voltage is supplied through pins 9–10 and 19–20. When a tactor is switched on, the corresponding pin is pulled down to 0 Volts. The distributor also has four 20-pin connectors labelled 'A', 'B', 'C', and 'D', just like the amplifier. All the connections between pins have been done using flat cables.

Figure 4. *The amplifier with the 100-pin connector and the four 20 pin connectors labelled from A to D*

The vest itself is shown in figure six and is made of non-stretchable cotton while elastic cord was used to create a sizable fit. This was done to attach the tactors as close as possible to the user's skin. However, there is no direct contact with the skin due to the help of a thick cotton material as the innermost layer of the vest. In between the two cotton layers, vertical strips of Velcro to which the 64 tactors can be attached are available. Next to each strip of Velcro, a band of fabric functions as a 'channel' to assemble and conceal the cables of the tactors. The cables of the 64 tactors go up to the distributor. The distributor is attached to the upper back of the vest, under the back flap. The tactors (TNO JHJ–3) are small boxes with the dimensions of 2× 1.5 ×1 cm where (l× w × h). Beside the connector and wired to the connector is a small unbalanced excitator: a small electric motor with a decentred load. It requires 3 Volts to operate and it draws a maximum current of 50 mA.

Figure 5. *The TNO vest containing with the 64 tactor array. The picture was taken from the original documentation of the paper.*

Two methods were available for controlling the vest. The first GUI was a simple interface allowed one to try different vibrating patterns. Although it relied on manual control, this interface was helpful for understanding the positioning of the tactors and their capabilities. The second interface was a flight simulation that displayed north through vibration. This interface did not significantly help in getting a better understanding of the vest and was not utilizable for the project. Both interfaces had been programmed in C++ and most of the documentation available dealt with the creation of the GUI. Very little information was available on how to control the module. However, the biggest issue was the codes' incompatibility with Linux and their lack of documentation.

3.4 New setup

The original software together with the module (DT9835) used to control the vest will be disregarded due to the incompatibility with Linux. Secondly, two Arduino megas will be used instead of the module. The Arduino megas are fast, practical, compatible with Linux and have enough digital pins. Since the Arduinos will only send a signal to the tactors, a connection with the amplifier is necessary. For this connection to be sturdier, a PCB was designed as can be seen in the appendix. The PCB itself shown in figure seven contains space for two 50 pin headers, two jumper connections and the Arduinos as shown in figure. Flat 50-pin cables were used to connect the two headers with the amplifier. However, the original 100-pin connector was kept on the amplifier side, causing the two 50-pin cables to have to be assembled together on the connector. The first fifty tactors are actuated by the first mega and thirteen by the second. Pin 100 is grounding the setup while pin 48 gives a 5-volt input which turns on the LED of the amplifier. When dismantling the old setup, some conflict about the last three pins arose. Both pin 49 and 50 were seen to be grounded while pin 48 was a 5-volt pin. Therefore, jumper wires were used for the above-mentioned pins to avoid the possibility of a short circuit. No changes were done on the amplifier itself or the previous connections between the amplifier, distributor and vest. The tactor positioning inside the vest was also kept the same. This new setup is presented in figure 8 in the form of a diagram.

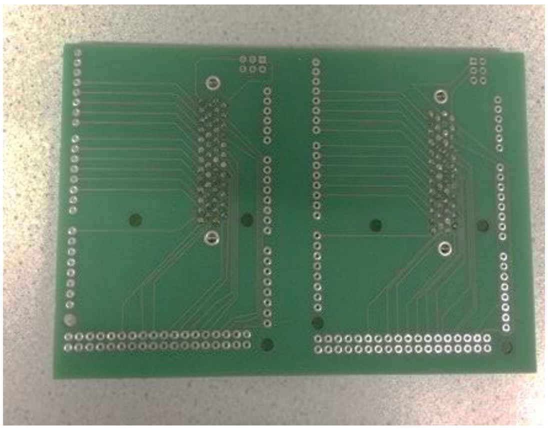

Figure 6. PCB used to connect the arduinos with the amplifier

The second challenge of this prototype was the interfacing, which can be divided into two sections - the Arduino IDE and the ROS connection. The code on the Arduino itself is quite simple, for every tactor a Pulse with modulation (PWM) signal is sent. Because the number of PWM pins on the megas is limited, a software PWM had to be implemented. SoftPWM, an Arduino library created by Rogue Robotics, was used to make the code more compact. The library itself included premade functions that made the implementation of the software PWM as easy as using the physical pins on the Arduino. The values of the vibration varied from 255 to 0 where 0 is on and 255 is off. An array of 64 values is sent from a ROS node to get the PWM signals. The first Arduino containing 50 connections loads only the first 50 values, while the second Arduino loads the rest of the values. Currently, the communication through ROS and the Arduinos is being done using a wire connection to achieve the best performance. This means that both Arduinos need to be running at the same time in two different ports of a laptop.

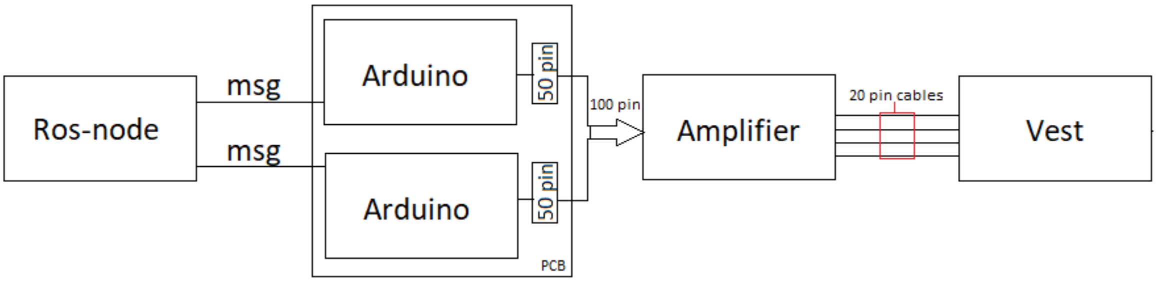

Figure 7. Schematic displaying the current electronic setup of the Vibrio-tactile vest

The ROS code consists of the master node, one publisher node, two subscribers and a launch file as depicted in figure 9. The common topic of the nodes is called vest, while the data being sent is of UInt8MultiArray type. As mentioned above, this array contains 64 integers that can take a value from 0-255. This data is published by the publisher node and sent through the master. The launch file then connects with the two Arduino subscribers. To integrate the ROS subscriber inside the Arduino, the ROS library (ros_lib) had to be added to the Arduino code and a callback function with the topic “vest” had to be created. It is inside this callback function where the signal is sent to the tactors. Now that the full setup of the prototype has been explained, the following chapter will be dealing with the testing phase.

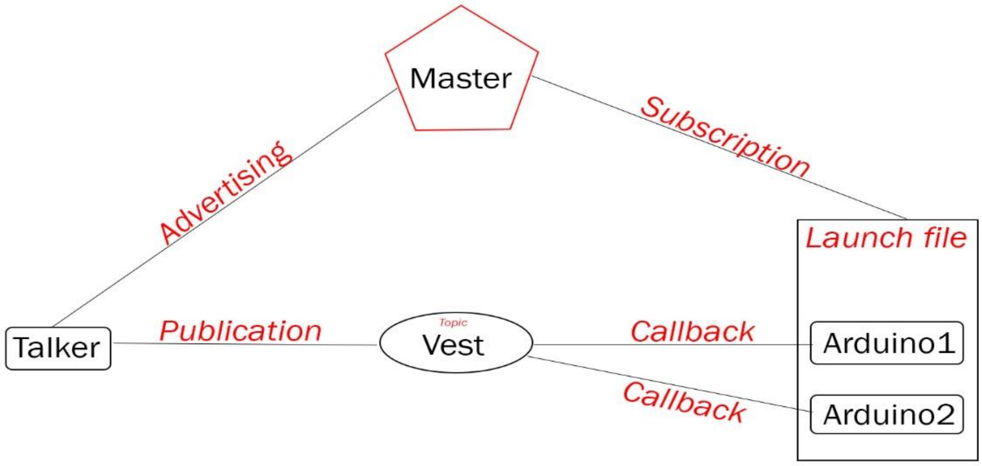

Figure 8. ROS diagram

4 Testing

The testing of the vibrio-tactile vest will mainly be used to understand whether sensory augmentation through vibration is a feasible option for obstacle and environment recognition. Simultaneously, several specific functionalities of the vest will be analysed. Finally, the results of the testing will also help improve the prototype itself and introduce points of discussion for future work.

The first step of usability testing is deciding the specific objectives of the prototype. The table below outlines these specific goals needed to be reached for the prototype to be counted as successful.

Objectives
The user should be able to understand the presence of an obstacle
The user should be able to feel that the obstacle is moving and its direction
The user should be able to recognize the different vibration intensities
The user should be able to relate the vibration to the distance
The user should be able to feel the obstacle coming towards them
The user should be able to feel comfortable with the vibration

Table 1. The noted down prototype objectives

The second step of the usability testing is understanding the stakeholders. Having this information allows certain assumptions and expectations to be made for how the product might be used by the users. Although the tele-control setup is designed for various uses and the stakeholders can be people of differing backgrounds, they still share certain similarities. For example, it is believed that when using such high-tech equipment, the users are usually trained. By knowing this, we can assume that the users will have knowledge of the technology available inside the cockpit, including the vibrio-tactile vest. To make sure that the cockpit is not limited to a certain body type, the test subjects should be of varying builds. The users should be expected to have full cognitive abilities, no physical disabilities and most importantly - have sensation on the body parts where the vibration is located. Something that is not very crucial for the project is the age of the stakeholders. Therefore, this also will not be taken in account when recruiting the test subjects.

The type of usability testing also must acquiesce to the above-mentioned objectives and limitations. The usability testing that will be conducted for the vibrio-tactile vest is "summative usability testing". Summative usability testing is designed to test overall usability in the form of effectiveness, efficiency and satisfaction of the product and use the results to determine whether the prototype is meeting the usability goals. The requirements of the test should also be task based and tie directly to prototype requirements. This type of testing is usually done when the prototype design has been finalized and is conducted in a lab or field setting. Because the prototype is not truly integrated within the control cockpit, there will be some small deviations from the formal structure of the test. For example, the test subjects will be helped during the testing procedure. This will be done because the user doesn't engage in a physical task but instead partakes in an experience, or a virtual task. The presence of a supervisor is crucial since this can be quite confusing without the help of an outsider. The usual number of subjects in Summative usability testing is 6-12. The tests will not be timed or recorded. This is to avoid pressuring the user and making them uncomfortable. As learning a new sense is usually a lengthy process that requires practicing for a significant amount of time, this test will only give an idea on the feasibility of the prototype. To get more meaningful results, the vest needs to be tried in conjunction with the entire cockpit for an extended period. However, time constraints did not allow this possibility to be available during this project.

The actual test can be found in the appendix and will include three small "tasks" to be conducted by the user. The user will also be allowed to try the patterns of the tasks as many times as they require. First the user will be equipped with the vest and sat down. Then a form will be handed out where they must write their name, surname and date. The user should start by reading the first descriptive paragraph of the form which gives general information about the vest and its general purpose. The user is then asked whether they have further questions. If the user is unclear about something regarding the vest or the experiment, they will be clarified at that time. Before conducting the actual tasks, the user will be given a test round where they get comfortable with the vest and setup. This will be done to get the subjects more familiar with the device and rid them of any anxiety or excitement that might come from using unfamiliar technology. The test round will include three different patterns, turning one tactor on, turning one tactor on with a PWM signal and turning all the tactors on. After going through the practice round, the three "tasks" will then be conducted.

The first test requires the user to identify a moving object around the virtual robot without knowing the distance to the object. The user will not be able to see the robot but must only rely on vibration. The obstacle will be moving with three different speeds: slow, medium and fast. This will be done to understand whether speed makes a notable difference in identifying obstacles. The users also must write down the direction in which the obstacle is moving. The second task is a test of vibration intensity. Eight different vibration intensities will be felt by the user at a slow pace and their task is to identify the jumps where the difference is almost non-existent. They must also recognize that the robot is approaching an obstacle. The same tactors will be on at different vibration intensities. The last part of the second task tests the user's ability to guess the distance to an obstacle. The range of detection was decided to be two meters with five different intensities corresponding to a 40-cm difference. The user is not expected to succeed in this test, as research has shown that users require a lot of practice to learn the new sense to an advanced degree. To make it easier for the user, the highest and lowest intensities will be displayed first. After displaying the actual obstacle signal, the user will be required to write their guess on the form. The final test will be a combination of the first and last test. Here the user must identify that a moving object is moving closer. After the tests, the users will be asked two questions by the person present in the room. Question one asks the user whether they felt comfortable in the vest while question two asks whether they would change anything about the vest.

To be able to collect quantitative data, most of the questions are in a form of a scale. The user will be required to choose from a scale of one to five on how easy it was to identify what was asked of them. The two other answering methods will be circling Yes or No and writing down the answer. The secondary methods will be used to gather qualitative data. During the experiment, the tester will also be observing the test subject. Every user request to retry the pattern will be written down by the tester. It will also be recorded if the user felt frustrated during the experiment, and if they took longer to answer. In the next chapter the results of this controlled experiment will be recorded and analysed. The outcome of the results will give an initial idea on the usability of the vibrio-tactile vest.

5 Results

For each of the seven tests, both quantitative and qualitative data was gathered. All the gathered data will be displayed and analysed in this chapter.

5.1 Test one

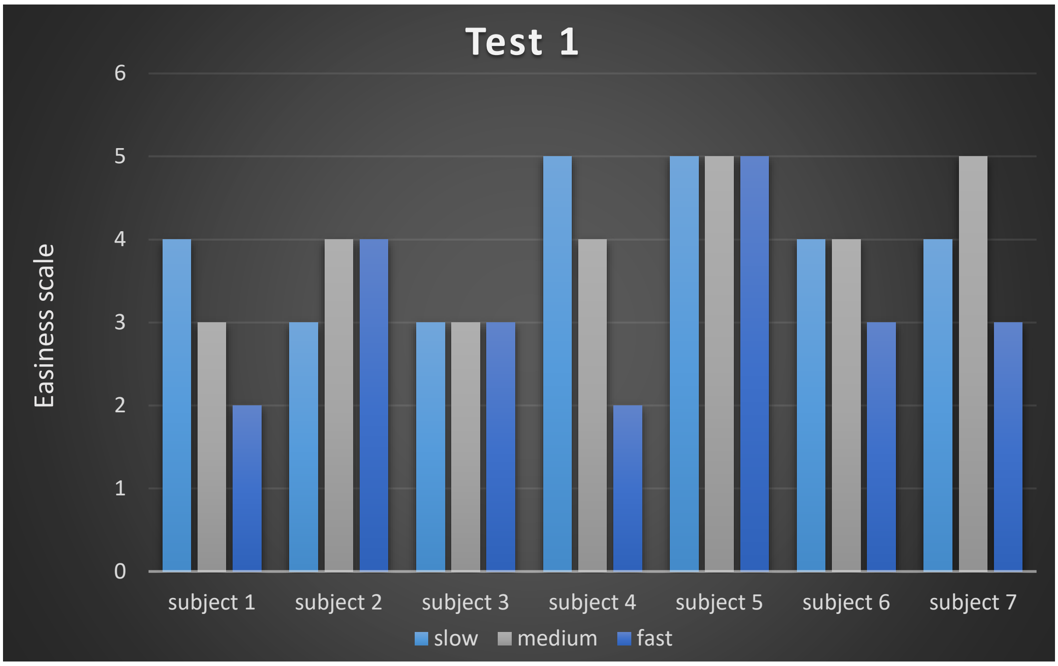

Table 2. Bar chart displaying the results of test one where the obstacle moved at different speeds

In the first test, the users had to define how easy it was to recognize that the object was moving from a scale of 1 being difficult and 5 the easiest. This was done for three different speeds: slow, medium and fast. As noted on the chart, the answers had no visible pattern. For this sample, statistical one sample t-tests were conducted to understand how significant the results are.

Looking at the data for the slow speed, we set the hypothetical population mean to be 4 or 3. If there was no significant difference, it would mean that our population mean falls around 4 or 3 as well. Consequently, the ability to tell that an obstacle is moving would be moderate at slow speed. After doing the two-tailed t-test with 6 DF and $\alpha=0.05$ that shows 95% assurance that the actual population mean is different from our guess. The p value appeared to be 1 for a population mean of 4 and 0.0177 for a population mean of 3. Because $1>0.05$ and $0.0177<0.05$, the difference is not considered to be significant and thus the population mean falls around 4.

For the medium speed data, we set the hypothetical population mean to be 4 or 3 as well. If there is no significant difference it would mean that our population mean falls around 4 and 3 also. Consequently, the ability to tell that an obstacle is moving would be moderate at medium speed. After doing the two-tailed t-test with 6 DF and $\alpha=0.05$ that shows 95% assurance that the actual population mean is different from our guess. The p value appeared to be 0.0127 at 3 and 0.6109 at four. Because $0.0127<0.05$ and $0.6109>0.05$ the difference is considered as significant for 3 and insignificant for 4, so the population mean probably falls only around 4. Therefore, the ability to recognize that an object is moving is moderately high.

In the data for the fast speed, we set the hypothetical population mean to be 4, 3 or 2. If there is no significant difference, it would mean that our population mean falls around one of the mentioned values. Consequently, the ability to tell that an obstacle is moving could be moderately high, moderate or moderately low at fast speed. After doing the two-tailed t-test with 6 DF and $\alpha=0.05$ that shows 95% assurance that the actual population mean is different from our guess. The p value appeared to be 0.7358 for 3, 0.0781 for 4 and 0.0300 for 2. Because $0.7358>0.05$, $0.0781>0.05$ and $0.03<0.05$ the difference is considered insignificant for 3 and 4, but significant for 2. Thus, the population mean probably falls around 3 or 4.

By comparing all the different results, we can conclude that it is easier to distinguish the object and its direction at medium speed and slow speed, but it is still easy to recognize it at fast speed. When asked whether the test subjects could recognize the direction the obstacle was moving they all answered yes. All the subjects were as also correct when writing down the direction of the obstacle

5.2 Test two

In the second test, the users were given eight different vibration intensities. They had to describe the situations where the changes in vibration intensity felt unrecognizable. All the jumps and the amount of users that did not recognize any intensity change are depicted in table three. Some of the users were more sensitive than others and they managed to fully recognize the changes, while others had more trouble with certain jumps in vibration. As can be also seen in the table 3, jumps from intensity 1 to 2 and intensity 2 to 3 were the easiest to recognize while the jumps from 3 to 4 and 4 to 5 were the toughest with three and four people not recognizing a difference respectively.

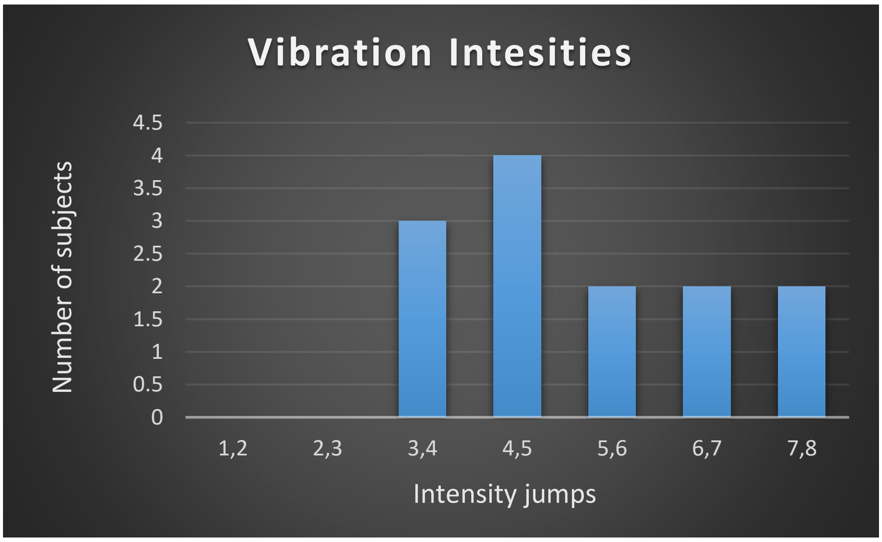

Table 3. *Bar chart displaying the results of test two where the users were asked to note the jumps in vibration where they felt no difference*

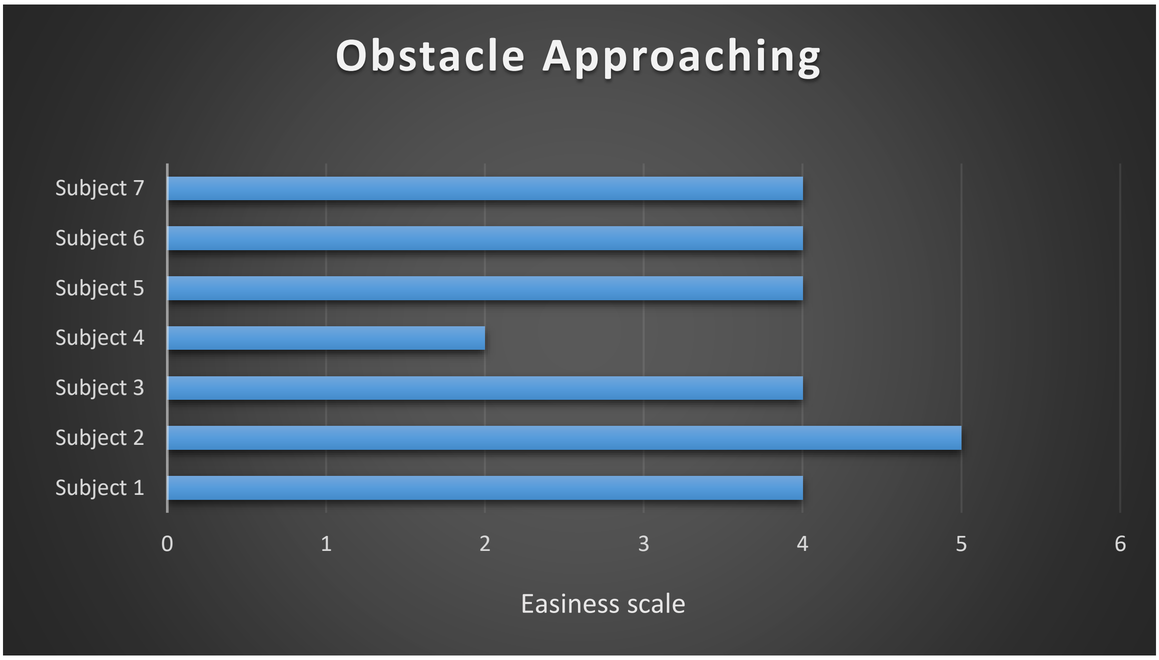

Table 4. *Bar chart displaying the results of test two where the users were asked to define how easy it was to recognize that the obstacle was approaching the robot.*

In the test of where the obstacle was felt approaching through changes in intensity all but one outlying user had an easy time recognizing what was happening. The outlier did manage to understand that the obstacle was moving towards them but found it more difficult than the other test subjects.Motivated by the data in table four, we set the hypothetical population mean to be 4 or 5. If there is no significant difference, our population mean should fall around 4 or 5. Consequently, the ability to tell that an obstacle is moving could be moderate, moderately high or high. After doing the two-tailed t-test with 6 DF and $\alpha=0.05$ that shows 95% assurance that the actual population mean is different from our guess. The p value appeared to be 0.0152 for 5 and 0.6891 for 4. Only $0.6891>0.05$, which is considered insignificant, so the population mean probably does fall around 4 and the ability to understand that an object is approaching is moderately high.

Test Subjects	Real Value	Guessed Value
Subject 1	102	204
Subject 2	51	153
Subject 3	102	204
Subject 4	102	102
Subject 5	102	153
Subject 6	0	102
Subject 7	102	51

Table 5. *Table displaying the results of test two part three where the user had to relate vibration to distance*

However on the last section of test two as seen in table five only one test subject managed to correctly guess how far the object was by using vibration. Most the other test subjects were off by two intensities.

5.3 Test three

Looking at the data for the ability to recognize the vibration intensity of a moving object in table six we have set the hypothetical population mean to be 2, 3 or 4. If there is no significant difference it would mean that our population mean falls around the mentioned values. Consequently the ability to tell that an obstacle's vibration intensity is changing could be moderately low, moderate or moderately high. After doing the two tailed t-test with 6 DF and α=0.05 that shows 95% assurance that the actual population mean is different from our guess. The p value appeared to be 0.0618 for 2 and 4 and 1 for 3. All the values are smaller than 0.05 and the differences are not considered to be significant, so the population mean probably does fall around all the mentioned values. This result does not give further clarifications on the pattern of the subject's answers.

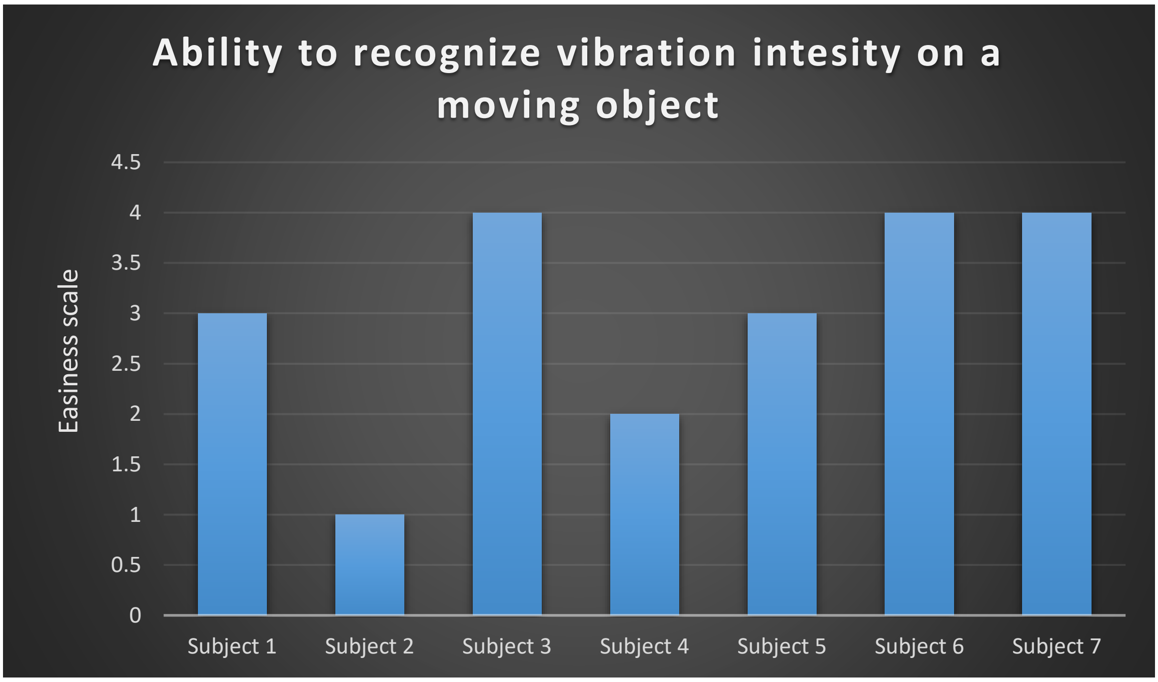

Table 6. Bar chart displaying the results of test three where the users had to recognize a change in vibration on a moving object. The users had then to define from a scale of 1 to 5 how easy this task was

In addition to the form, the users had to answer two other questions. In the first question of the vests comfortability, only two people said that the vest is comfortable. Out of the people that answered no, two mentioned that it is mainly because of the vest design rather than the vibration. The others mentioned that they were generally sensitive in the areas of vibration. When asked on the second questions for suggestions everyone one believed that the vest design had to be improved. They also mentioned that they needed a bit more time to understand which vibration related to which distance.

6 Conclusion

Using the research and prototyping, an answer can be given to the initial research questions. We can now conclude creating an optimally immersive control cockpit requires the sensory feedbacks to include audio, visual, haptic and proprioceptive feedback. These feedbacks present different layers of information which can create a very realistic simulation of the virtual environment when integrated together. To present each feedback, the technologies selected were: HMD for visual feedback captured by movable stereo cameras, binaural sound on headphones for audio feedback, exoskeletons, haptic pedals for haptic feedback and motion bases for proprioceptive feedback. The chosen technologies allow for natural movement and provide very realistic feedback that enables the interaction to be both intuitive and immersive. What will first be implemented inside LUC in the form of a prototype is the vibrio-tactile vest. This assures that the user will have one type of consistent information per technology and won't feel overwhelmed. A better understanding of the concept of using vibrio-tactile feedback for navigation and environment recognition was also achieved while the testing phase presented very interesting results.

It can be said that using the vest to feel the presence of a moving object is a very feasible concept. All the subjects could tell that there was an obstacle in the environment. The same goes for understanding the direction in which the obstacle was moving. However, depending on the speed of the object itself the subjects had undeniable differences in their level of obstacle recognition. The more moderate the speed was, the easier it was to tell where the object was going. Only four of the eight vibration intensities were clearly recognizable, making the resolution of the vest very low. It was also concluded that the recognition of intensity varied significantly from subject to subject, making the method even more unreliable. Nonetheless, using the vibration intensity to tell that an object was approaching was found to be very successful and improved with each time the subjects repeated the test. This would raise the question on whether the ability to recognize the different intensities improved with time just like mentioned in the research material regarding sensory augmentation. Relating this intensity to distance was also unsuccessful as only one subject could guess the correct distance. The third test of understanding the change in vibration intensity of a moving object produced confusing results, varying significantly from subject to subject. Even after a two-tailed t-test, no specific pattern was found. When the users were asked about the vibration pattern, they explained that they believed the pattern itself was confusing, and they might have needed a bit more time getting used to the different vibrations. All the users seemed generally positive about the concept of the vest and what can be achieved with it, but felt that the design of the vest could be improved upon.

In conclusion, it can be said that using a vibrio-tactile vest is indeed a feasible idea as supported by both research and testing. Using vibration intensities on the other hand should be researched for longer periods of time to ensure more significant conclusions. It should be noted that based on previous research, the users weren't expected to be able to tell the difference between vibration intensities immediately. On the contrary, the results of the testing turned out more positive than expected. Another thing that to be noted is the low amount of test subjects and inability to test the vest in conjunction with the cockpit, which could have significantly changed the results. In summary, it can be concluded that the vest itself seems promising, but further testing needs to be done regarding the vest as a component of the cockpit itself.

7 Future Work

There is a lot of work that can be done in the future to build upon this project. This work can however be divided in two main sections; building the whole re-designed LUC and improving the vibrio-tactile vest. The first section is quite self-explanatory, where all the different components mentioned are prototyped and integrated into a final setup. After successfully prototyping the different components, proper testing can be done to decide whether the re-designed setup truly fulfils the immersion requirements. Despite having abundant theoretical evidence that it does fulfil all the requirements, practical results can sometimes be beyond the scope of the expectations.

On the other hand, various routes can be taken when improving the vibrio-tactile vest. More testing can be done to understand whether using different vibration intensities provides enough information for the user. Extended testing can also prove whether it was just the problem of time constraints and if longer exposure to the different vibrations would improve the user's ability to identify the position of the obstacle. An alternative method such as using different frequencies of vibration can also be prototyped and compared with the intensity test results. Finally, the most optimal solution can be implemented in the latest version of the vest. The physical aspect of the vest can also be improved upon. Alternate materials and tactor positioning can be researched and a more practical vest designed based on the research. This part is crucial as the fit of the vest can be the biggest boon or detriment to the users' sensitivity and especially comfortability.

Another thing that can be improved upon is the testing method. Sending the data manually can decrease realism, thus distorting the results to appear more negative. One solution to this issue can be creating a separate interface that simulates the tele-control experience. The user should then be able to navigate through the virtual environment and have the data be displayed in the vest accordingly. This way the user will also be able to have visual information feedback, and won't need help during the testing. The user will thus be provided with more information while making the testing data more reliable.

After making all the improvements mentioned in this chapter, enough data should have been collected that a significant conclusion can be reached. This conclusion will describe whether the re-designed setup is optimally immersive and if vibrio-tactile feedback is appropriate for environment recognition. However, it should be noted that the conclusions made in this report are already promising and a good basis for future research.

8 Appendix

8.1 Test form

Name:
Date:

The vibrotactile vest will be used by the user that is tele-controlling a robot in a remote area. The vest gives the user cues about the location of objects around the robot through vibration. This is done mainly to cover the blind spots that the user might have when only relying on visual feedback. Vibration as an alternative feedback is said to not overwhelm the user as much as extra visual feedback.

The following tests will be conducted to receive feedback on the functionalities of the vest. The users feedback will then be processed and taken in account to further improve the vest.

Test 1

The first test will be on identifying a moving object around the robot without having an idea on their distance. Three speeds will be tested.

Slow

From a scale of 1-5 how easy is it to recognize that the object is moving?
1 2 3 4 5

Can you recognize the direction in which the object is moving?
Yes No
Direction : ___________________

Medium

From a scale of 1-5 how easy is it to recognize that the object is moving?
1 2 3 4 5

Can you recognize the direction in which the object is moving?
Yes No
Direction : ___________________

Fast

From a scale of 1-5 how easy is it to recognize that the object is moving?
1 2 3 4 5

Can you recognize the direction in which the object is moving?
Yes No
Direction : ___________________
Test 2

Vibration intensity.

Circle the jumps where you could not tell a difference:
1 2 3 4 5 6 7 8

Object moving towards you.

From a scale 1-5 how easy is it to recognize that the object is coming towards you?
1 2 3 4 5

The range of the detection is 2 meter and each different intensity is 40 cm.

How far is the object from you?

____

Test 3

From a scale of 1-5 how easy is it to tell that the object is getting closer?
1 2 3 4 5

8.2 LUC exploded design

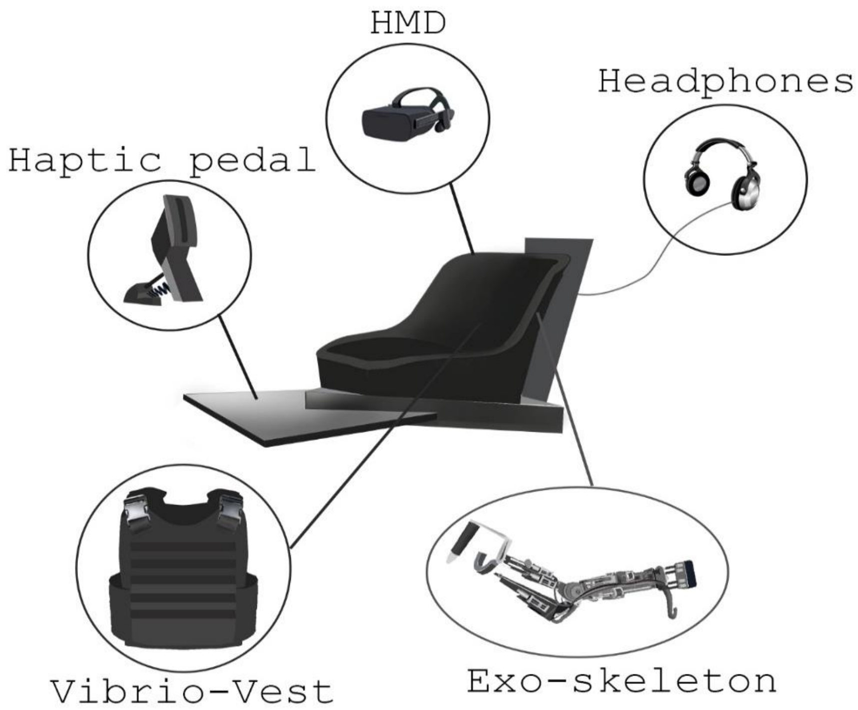

Figure 9*. An exploded view of the components inside the LUC*

8.3 PCB Eagle Design

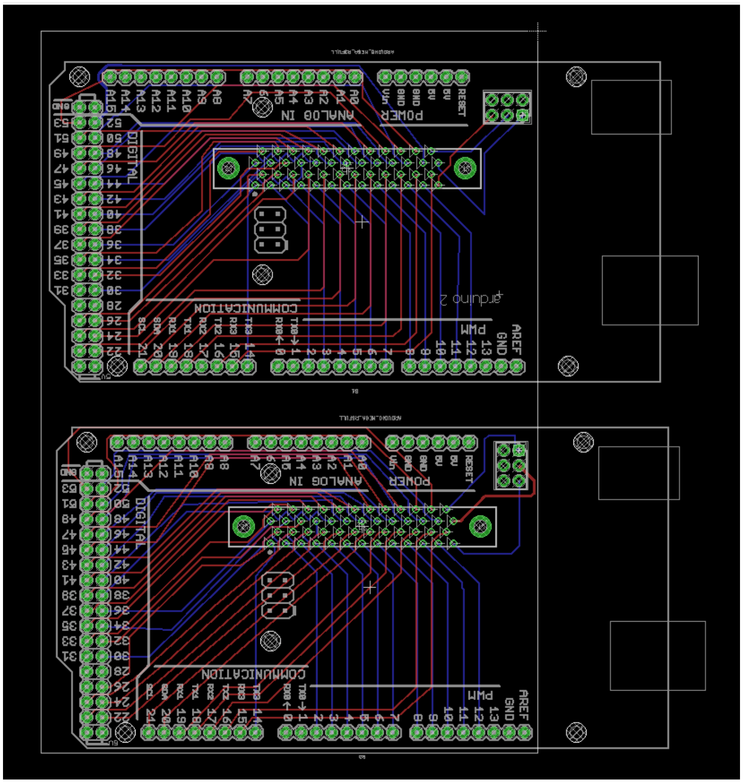

Figure 10. *PCB design on Eagle*

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