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Design and Characterization of a Vibrotactile Haptic Feedback System for Drone Operators

Bachelor Thesis

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Abstract

With a shift in focus from military to commercial applications, unmanned aircraft vehicles, known as drones have become more widespread. This leads to safety concerns regarding drones and potential incidents. Since a drone is a teleoperated system, in which the operator is physically separated from the environment, the user relies on feedback from the drone, usually only in the form of visual feedback. The control of the drone and the safety factor associated can be improved by providing haptic feedback, as demonstrated by previous research. The aim of this research is to design a system capable of providing haptic feedback to the drone operator and characterize the effects of the haptic cues. This research focuses on haptic displays providing cutaneous cues to the users. A vibrotactile vest is used to transmit additional information about the behaviour of the drone to the operator. The drone is simulated in a virtual environment and a test setup has been made in order to investigate the effect of haptic feedback. A user study, in which the participants had to fly the drone in a virtual environment, is performed in order to compare the performance of flight with and without the vibrotactile cues. The results of the user test are promising and show potential benefits for haptic feedback operation, despite not having a statistical significance. A majority of users have reported that the vest and the information encoded enabled them to have a better understanding of the drone behaviour and prefer this mode of teleoperation opposed to the mode where only visual feedback is provided. It can be concluded that haptic feedback has positive effects on drone operators with previous drone flying experience. The findings of this research have the potential to serve as a basis for future research in the area of haptic feedback and drone teleoperation.

Contents

Chapter 1

Introduction

1.1 Context

Drones, more formally referred to as unmanned aerial vehicles (UAVs), have been focused on military applications since their emergence. However, in recent years, there has been a shift towards commercial drones, which have the potential to impact a wide range of industries [21]. While, due to advances in software development, autonomous drones are becoming more viable and widespread, the majority of drone applications rely on input from a human operator. The remote teleoperation of a drone has a number of advantages for the operator, mainly the effect of telepresence, giving the operator the ability to be in a different, often remote, environment and move within that environment with great flexibility without having concerns regarding his or her safety.

To achieve this effect of telepresence, the operator needs to be provided with feedback in the form of visual, auditory or haptic feedback. Most common is the visual feedback which is also required for the teleoperation of the drone. However, the visual feedback provides a limited perception of the remote environment due to factors such as the field-of-view of the camera onboard the drone, the image quality and the latency with which the operator receives this information. This mode of teleoperation requires constant cognitive effort from the operator to determine the behaviour of the drone based on visual cues and his control input [20]. This makes the task of flying a drone an often difficult process. Moreover, extensive training is required to become proficient in accurately controlling a drone. These factors lead to a reduced safety factor when operating a drone, as well as an increased workload on the operator of the drone.

Employing additional feedback, in the form of a haptic display, in combination with the visual display, may not only provide sensory information which is lost due to the separation between operator and drone, but also reduce the cognitive workload levels of the operator [17]. This research focuses on using such a haptic display to provide additional feedback to the drone operator and to determine whether the effects are beneficial in terms of drone control, safety and workload on the operator.

1.2 Goal

The goal of this graduation project is to design a system which is able to provide a drone operator with haptic feedback, complementing the visual feedback provided by the on-board camera of the drone, and to investigate whether this additional layer of sensory information enables for a better interaction between the operator and the drone. Unlike the majority of the works mentioned in the previous section, this research will focus on the haptic feedback layer as an individual layer, separated from the control one. This is because this graduation project aims to investigate and isolate the effect of the haptic feedback on drone teleoperation, regardless of the control aspect. Moreover, taking this approch also reduces the complexity of the prototype device to be used in the user studies, which is desirable due to time constraints associated with the project. Therefore the operator should fly the drone using a standard method of control with two joysticks and the feedback should be provided via a separate interface. The haptic feedback should enable the operator to be more aware of the drone behaviour during flight and should enable him to control the drone more accurately and with an increased safety factor without increasing the workload required to perform a certain task.

1.3 Research Questions

Three research questions have been identified in order to achieve the goal presented in the previous section and will be treated in the current report. These research questions serve as a guideline in the investigations of the benefits of employing haptic feedback for the teleoperation of drones.

- To what extent does haptic feedback enable a more accurate control of the drone?
- To what extent does haptic feedback enable a safer operation of the drone?
- What kind of information should be encoded in the haptic feedback transmitted to the operator?

1.4 Report Organization

The report is organized in six chapters. Chapter one covers the context and motivation behind the report and outlines the goal of the project together with the supporting research questions. Chapter two covers the literature review, determining the theoretical basis of the research. In this chapter, topics like human perception, vibrotactile feedback, drone flight dynamics and spatial disorientation are investigated, together with related works that have been done in this area. Chapter three describes the design of the haptic interface in detail, more specifically how the different elements of the system are connected, together with the experimental set-up used to characterize the effects of the haptic feedback implemented. Chapter four is where the user testing procedure is detailed, first with a small scale pilot test and the insights obtained, followed by the actual experiment. Chapter five presents the main results of the user studies by analyzing and visualizing the data obtained from the experiments. In chapter six, conclusions are drawn and the research questions stated in the first chapter are answered. Indication for future work are also briefly indicated in this chapter.

Chapter 2

Literature review

2.1 Haptics and Human Perception

Haptics is the representation of information through the sense of touch. The information received can be categorized into two classes, namely cutaneous cues and kinesthetic cues. The cutaneous, or tactile, information involves a passive sensing of the stimuli such as temperature, vibration or pressure while the kinesthetic information involves an active sensing of the stimuli such as motion, location or force. The two types of cues are often perceived together and are not mutually exclusive [8]. Kinesthetic feedback cues are more suitable for tasks which involve object manipulations, while tactile cues are more suitable to provide alerts. [12]

These stimuli are received through different receptors of which of interest is the mechanoreceptor which deals with sensory information such as touch, vibration or pressure. These mechanoreceptors are further categorized in receptors which deal with different types of stimulation and have different frequency ranges for the stimulation. The Pacinian Corpuscles respond to vibratory stimulations, cover most of the body and have a broader frequency range compared to the other receptors, between 100 and 1000 hertz, however they have a poorer spatial acuity relative to the other receptors. [12]

The spatial acuity of the skin gives an indication of the amount and arrangement of the stimuli that can be perceived by humans on the skin surface. Two measures are commonly used in practice which describe the tactile spatial acuity, namely the two-point threshold and the point of localization. The two-point threshold is based on the distance between two stimuli applied at the same time that are perceived by the subject as one stimulus, while the point of localization is based on the distance between two successive stimuli, that are identified by the subject as two separate signals. Extensive studies have been done to investigate the spatial acuity for pressure perception, however for vibrotactile perception there has been less research performed. There is slight degree of disagreement between different studies performed, however, it has been shown that a point localization value of between 40mm and 60mm leads to accuracy levels of between 70 to 80% for individual vibrotactile stimuli recognition on the torso and back area of the body [14]. These results vary depending on factors such as the type of devices used to produce the stimuli, their proximity to the skin and whether there is a layer of fabric between the signals and the skin. Moreover, different areas of the body have slightly different values for the spatial acuity, for instance the area around the spine has a better acuity which decreases as you move towards the side of the body

2.2 Vibrotactile Haptic Feedback and Teleoperation

Vibrotactile feedback is the representation of physical information through vibrational cues on the skin surface. Generally, the vibrotactile signals are generated as a response to the actions of an operator in a teleoperation context or in a simulated physical world [5]. This information can be used to improve teleoperation tasks since it uses a sensory channel which is free, unlike the visual channel which often serves as main source of feedback to determine the control actions in such tasks.

It is common that the vibrotactile feedback is provided at the level of the hands of the teleoperator. This is due to two factors. One factors is that the majority of controllers for teleoperation tasks are handheld devices and the vibrotactile feedback is directly implemented in those devices, called haptic interfaces, without requiring an additional device to provide the tactile cues, which would lead to an increased complexity and potentially cost. The second factor is that the skin covering the hands has a higher degree of sensitivity compared to the skin on other areas of the body. The most pervasive such haptic interface is a game controller. However, the type of haptic information transmitted through such devices is relatively basic, often having only one parameter which can be altered to convey different meanings, namely the intensity of the vibration. Moreover, directional information cannot be reliably encoded in this manner.

Unlike haptic interfaces, haptic displays only focus on the feedback part of the loop, leaving out the control. Vibrotactile displays excel at transmitting physical information about the material properties of an object and the contact location with an object. However, given that the information is encoded in an appropriate manner, these types of displays can be used to convey more abstract information, for instance for navigation purposes, as they provide an intuitive cue for egocentric orientation [5]. These types of cues have a promising potential in applications which involve teleoperations of UAVs or other robots since the orientation of the frame of reference of the operator coincides with the one of the teleoperated device.

According to Van Erp [27], vibrotactile feedback can be used to provide directional information since the spatial coordinates of such a stimulus on the skin is well represented in the nervous system. Despite a common assumption that these directional cues on the area around the torso have an internal reference point which coincides with mid-axis of the body, his research and observations are consistent with the existence of two internal reference points, one for each half of the body. However, the bias only leads to errors of about 10 degrees which are negligible in low-resolution navigation applications of vibrotactile displays [27].

An important and obvious characteristic of teleoperation is the physical separation between the operator and the device being operated. While this attribute can be viewed as an advantage, since the operator does not have to physically present in the, potentially hazardous, environment of the controlled device, this separation often results in the loss of important information otherwise conveyed through different sensory channels such as the auditory channel, the vestibular channel or the kinesthetic channel. This is due to the fact that the teleoperator mainly uses the visual feedback provided by the onboard cameras to operate the remote system. A good perception of the operating environment is important for teleoperation tasks, therefore only relying on visual information can result in a suboptimal performance. Research shows that additional haptic feedback which relays information about the remote environment can result in increased efficiency for operators and more optimal task performance. Moreover, providing haptic feedback in an appropriate and sufficient manner can result in the effect of telepresence or even in a feeling of immersion, which not only increases its efficiency and safety of operation, but gives a feeling of realism to the task of teleoperation [7]. Extensive studies have been performed which indicate that vibrotactile alerts can successfully replace visual alerts and also lead to an increase in performance of tasks, but vibrotactile cues cannot reliably replace visual cues when it comes to directional and spatial orientation [19]. However, when vibrotactile cues are offered complementary with visual cues, there is strong evidence that performance is significantly increased compared to the visual feedback only condition [19].

2.3 Drone flight

The term UAV, which stands for unmanned aerial vehicle, is a more general term and encompasses a number of different types of UAVs, namely, fixed-wing UAVs, helicopter UAVs and multi-rotor UAVs [29]. The term drone is a more common term and used interchangeably with the term UAV, however it is more often used to refer to multi-rotor UAVs. Drones are a very clear example of teleoperation, since the operator is ground-based, receives visual feedback from the camera on board of the drone and uses that feedback to determine the control input. As mentioned in the introduction, drones have seen an increasing adoption in civilian and commercial applications, a shift from their original military field. However, due to this increased adoption of the technology, there is also an increased concern regarding the safety of drone use, regardless of their application field. Small mistakes in their control made by the operator can result in crashes, potentially threatening the health and safety of people, when flown in public areas, as well as damaging infrastructure such as electricity poles [21]. Therefore, drone flying is a relevant example of teleoperation task which has the potential to benefit from haptic feedback for an improved safety factor, as well as to enhance the capability of this technology.

Unlike their fixed-wing counterpart, multi-rotor drones have a much greater flexibility, being able to move omnidirectionally as well as hover at a fixed point, making them more versatile for different types of applications type of applications. Moreover, multi-rotor drones are easier to control than helicopter ones, since all motors are placed in the same plane, thus making them less prone to undesired sideways drifting [29]. Throughout the rest of the report, the term of drone will be used to refer to multi-rotor category. The most common type of drones are the quadrotors, with four motors, followed by the hexarotors with six motors. The control method is the same, regardless of the number of motors. A drone is an underactuated system since it has 6 degrees of freedom and only 4 degrees of control, which coincide with the four basic types of movement of a drone: lift, pitch, roll and yaw [29]. These types of movement can be seen in Figure 2.1.

The majority of the drones are controlled from a handheld device with two joysticks, one which corresponds to the lift and yaw parameters and the other which corresponds to the pitch and roll parameters. These handheld devices are not intuitive to use for the control of a drone, since the 3-dimensional movement of the drone is mapped to two 2-dimensional control inputs. Moreover, due to the underactuation aspect of drones, constant compensation is required. For instance, if the operator desires to move the drone forward and uses only the pitch control parameter, this will result in a slight decrease in altitude, since part of the thrust generated by the rotors is no longer directed vertically to displace the effects of the gravitational force. To compensate for this effect and maintain a constant altitude, the operator needs to increase the thrust generated and engage the lift control parameter as well.

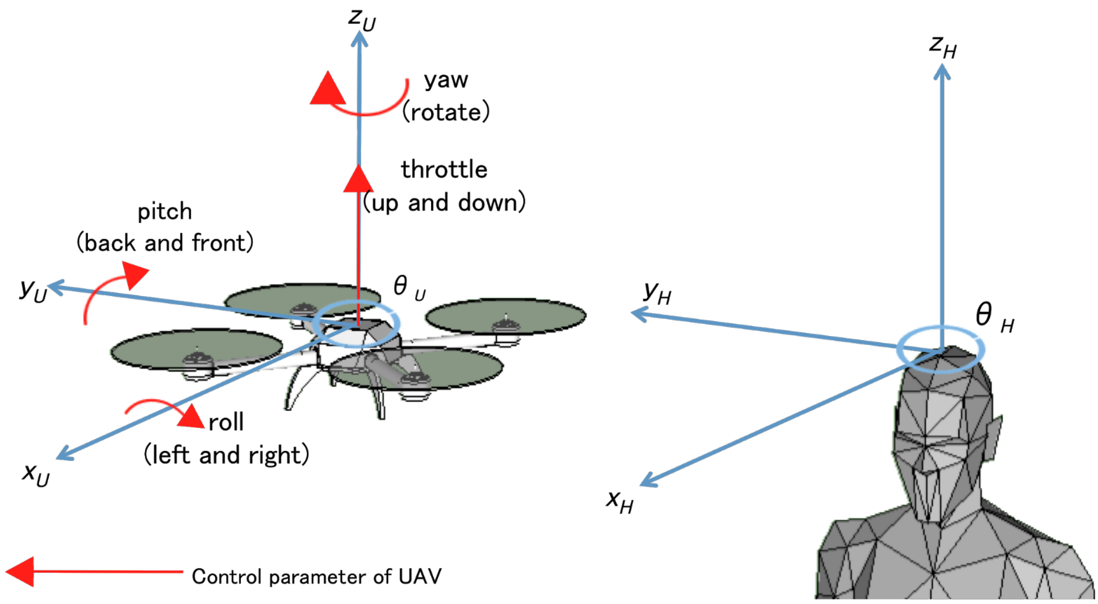

Figure 2.1: The four basic control movements of a drone and the relation between the frame of reference of the drone and of the operator [13]

These factors make the control of a drone a difficult task, requiring significant training times to accurately fly a drone [13]. A question arises, whether haptic feedback could be employed to improve the control precision of teleoperated of a drone.

2.4 Manned aircraft pilot spatial disorientation

During flight in a manned aircraft, the pilots capability of being aware of the aircrafts behaviour and having a sense of orientation is absolutely vital. The loss of orientation during operation, referred to as spatial disorientation, means that the pilot is no longer aware of the aircrafts attitude and spatial position relative to Earths frame of reference and can have fatal consequences [25]. The attitude of an aircraft refers to the pitch and roll angles relative to Earths frame of reference. Spatial disorientation can be caused by wrongly perceiving visual cues or force cues via the sensory system, and interpreting them erroneously. A block diagram of the process that is happening during flight in order for the pilot to determine the orientation of the aircraft can be seen in Figure 2.2.

During flight, pilots do not have a lot of reference points and are prone to visual illusions, especially in conditions where visibility is poor, or flying at high altitudes. This can cause pilots to misinterpret the visual cues, gaining a false sense of the orientation of the aircraft relative to the ground. In the case of helicopter piloting, without visual references, and under no acceleration, the pilot does not feel the direction in which he is moving, nor the magnitude of the velocity of movement. In addition, while executing certain maneuvers, such as banked turns, due to the forces acting on the aircraft and pilot, the vestibular sensory system can receive misleading information. This effect is known as somatogravic illusions and causes the pilot to wrongly identify the resultant of the forces acting on the aircraft to be the same as the force of gravity acting perpendicularly to earth surface [25]. As a result, the pilot experiences

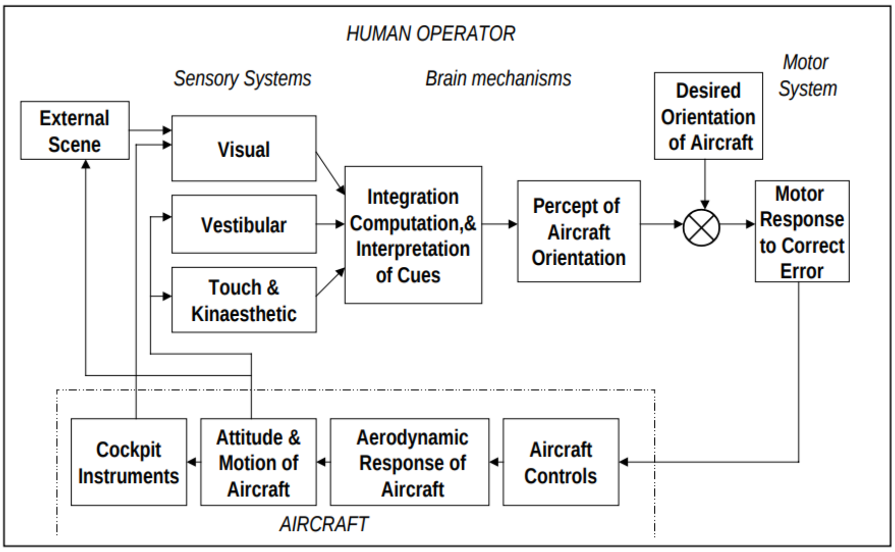

Figure 2.2: Block diagram of internal cognitive processes performed to determine the orientation of an aircraft [2]

spatial disorientation, having a wrong indication of the aircrafts attitude and behaviour.

When information from different channels is contradictory, the pilot has to consciously choose which information to consider and which to disregard. Making this kind of a decision in a correct manner requires training and experience, however there are still situations where this is not sufficient and can lead to spatial disorientation. A first step to reduce these effects was the introduction of flight instruments which offered visual cues about the attitude of the aircraft, however, this ultimately did not fully prevent accidents from taking place, since some pilots chose to trust their own vestibular sensory information. According to research, the use of flight instruments is certainly useful and brings many benefits in terms of safety of flight, however too many visual cues can place a high demand on the visual sensory system. This increased workload determined by the increased visual feedback received by pilots, has lead in some situations to accidents [2].

To mitigate the causes of spatial disorientation, researchers have turned their attention towards the haptic sensory system as a channel to transmit information regarding he behaviour of the aircraft. Use of vibrotactile feedback in the form of a vest embedded with vibrational motors, called tactors, has been successfully implemented and allowed for flight without conventional visual indicators. While flight with only haptic cues was shown possible, the goal was to use these cues complementary with visual feedback. The information encoded in the vibration patterns was the aircraft attitude relative to the ground frame of reference [2]. Research performed by the Naval Aerospace Medical Research Laboratory was focused on vibrotactile system that provided pilots with cues about the horizontal and vertical velocity of a helicopter during flight. Experiments with human in the loop have shown that the additional haptic feedback provided increases the precision of hovering in a helicopter. Moreover, participants have subjectively reported that the haptic feedback also helped with decreasing the workload experienced during the flight task [23].

2.5 Related work

In the scientific literature related to this topic, there is a number of different approaches to the implementation of haptic feedback for drone flight. There is a strong focus on haptic interfaces which integrate the control of the drone with the haptic feedback into one device while the haptic feedback is focused on providing kinesthetic cues. The feedback provided usually aims to give information about the surroundings of the drone for the purpose of collision prevention or obstacle avoidance.

The effect of haptic feedback in the teleoperation of an UAVs has been investigated, along with different techniques of providing feedback, namely repulsive force feedback, by means of force offset, and stiffness feedback, by means of spring load variation. A haptic interface was used which had both the layer for control and the layer for feedback integrated in the same device. The investigated application of the haptic feedback is represented by collision avoidance. This is achieved by means of artificial force fields, namely a Parametric Risk Field which takes into account both the distance to the obstacle and the velocity of the drone and creates a 3-dimensional field around the drone using data from an array of 32 horizontal lasers [6]. It has been shown that the haptic feedback provided can lead to an increase in the safety regarding the control of a drone without an increase in the workload experience by the operator [6, 16]. However, an improper tuning of the force or stiffness can lead to a higher workload, which can counteract the safety benefits of the haptic feedback. Moreover, when time delays were introduced in the system, the safety benefit of the feedback was reduced, while the workload of the operators was increased [16].

More novel approaches have also been investigated. A 6 degrees-of-freedom controller was prototyped that was also capable of providing force-feedback for translational as well as rotational types of feedback. Such a device has the potential of alleviating the problem of underactuation of drones through conventional controllers. The device consists of a touch-sensitive handle suspended in a cage by 8 wires connected to motors. Direction-specific feedback is provided by limiting the motion of the handle on certain axes. Feedback provided is used for obstacle avoidance and can be provided in two modes, reactive feedback, which tells the operators that the drone is approaching an obstacle, or preventive, which stops the operator from flying into the obstacle. [1]

A different use of feedback is represented by trajectory adherence, where, in contrast with the obstacle avoidance application, attractive force feedback is provided. The operator receives a force feedback which is associated with the deviation from the planned trajectory. This type of feedback acts as a sensory substitution, and provides cues intuitively to which action the drone operator should take in order to maintain the drone on the desired path. [3]

More immersive system have also been investigated. A Birdly platform, which is an immersive virtual reality flight simulator, has been used to enable an embodied type of interaction between the user and the drone. The platform enables the control of the drone via body gestures and provides vestibular feedback back to the user. This enables a more natural flight experience for fixed-wing UAVs and provides a high degree of immersiveness. Moreover, the control based on the flight simulator is reportedly more natural than compared to the regular control using a remote with two joysticks.[17, 21]

A different approach uses a vibrotactile display in the form of a belt to provide feedback about the the wind resistance experienced by the UAV. Wind sensors attached to the drone map the direction and relative intensity of the wind to the eight vibration motors embedded on the belt and thus provide directional feedback so that the operator is aware of wind gusts that could affect the behaviour of the UAV. Moreover, a head mounted display was used together with a head tracker to map the movements of the operators head to the camera on the UAV for a more immersive sensation.[22]

While existing research in the area of haptic feedback and drone flight focuses predominantly on providing information via the kinesthetic sensory system, a different approach is undertaken in the case of haptic feedback for manned aircrafts. Since the kinesthetic channel is already employed for the movements of controls during flight of such aircrafts [28], haptic feedback tries to employ a different channel, namely the cutaneous one, by use of vibrotactile displays. One such example is already described in the previous section of the report. A study by Van Erp et al, investigates the use of haptic feedback in providing waypoint navigation cues using a vibrotactile waist belt in two situations, one involving an aircraft and one involving a fast boat. The vibrations were encoding information regarding the direction, by using the localization of the stimulus on the torso, and information regarding the distance, by using the rhythm of vibrations. The findings of the research show positive results, thus haptic feedback can be successfully employed to provide cues for waypoint navigation in an intuitive manner [9].

Additionally, such haptic displays were used to provide directional warnings to fighter pilots for incoming missiles. The results of the study do not show a significant objective effect in the reaction time of the pilots when executing maneuvers to avoid the missiles, however subjective effects were reported by the participants, claiming that the feedback provided enabled them to better focus on the visual flight environment while still maintaining a low mental workload [26].

2.6 Summary

This chapter of the report presents the theory behind haptic feedback and how humans are perceiving such tactile cues, followed by a short investigation of how vibrotactile feedback can be employed in teleoperation tasks. These sections conclude that humans can perceive vibratory signals on their skin with a frequency between 100 and 1000 hertz, while two signals should be provided at a distance of about 60mm between each other on the area around the torso for a person to be able to correctly identify the signals as being distinct, however this distance can increase as the signals move towards the side of the body. Additionally, it was found that vibrotactile feedback can be successfully employed in teleoperation tasks, having the potential to improve the operation in such tasks, especially when they complement other types of feedback such as visual feedback. Research concluded that vibrotactile feedback is particularly useful in providing directional information for teleoperation applications which require egocentric orientation.

The topic of drones and drone control was approached as well. While drone use has become more widespread, the safety of their operation has also become of more concern. In this circumstances, and due to the fact that the most common type of control make drones and underactuated system, haptic feedback could prove useful in increasing the safety and precision of their teleoperation. Moreover, spatial disorientation experienced by pilots of manned aircrafts and how haptic feedback was used to tackle this problem was also researched for the purpose of examining which parameters were most appropriate and useful to be encoded in the haptic feedback. The motivation behind this is that these flight parameters could be transferable to drones and might prove useful as additional information about the behaviour of the drone during flight. Experiments performed found that information about the attitude of the aircraft and its velocities in the horizontal and vertical plane could be most appropriate to encode through vibrotactile haptic feedback in order to alleviate the issue of spatial disorientation.

Lastly, a brief review of the different implementation of haptic feedback for drone flight was performed. It was discovered that the general approach was to use haptic interfaces which allow for the simultaneous control and haptic feedback of drones, while the feedback was mostly provided via the kinesthetic sensory system. The findings of this chapter will serve as a background for the design of a system which complies with the goal stated in the first chapter of the report.

Chapter 3

Design

The findings of the previous chapter will serve as a background for the design of a system which complies with the goal stated in the first chapter of the report. Since the goal of the graduation project is to provide the haptic feedback as an additional layer, separated from the control one, the focus will be on haptic displays and vibrotactile cues. To characterize the effects of the designed haptic display, an experimental setup must also be conceived in which users are able to control a drone and receive the haptic feedback. This chapter presents the solutions used and choices made to achieve the goal and an overview of the system.

3.1 Haptic Display

Based on the theory presented in the previous chapter, it became evident that best approach to provide haptic feedback as an individual layer is to focus on the cutaneous sensory channel, since the kinesthetic one is more suitable for use when integrated in the same device used to control the teleoperated device. Moreover, since the general approach found in the literature review was to provide vibrotactile cues to convey information to the operator, this approach will be adopted in the current haptic display as well.

Drone operation is a task which involves egocentric orientation, thus the orientation of the frame of reference of the operator will coincide with the orientation of the drones frame of reference. This means that the operator perceives the drones behaviour through their body-centered coordinates, limiting the degrees of freedom that the operator needs to consciously control from 3 translational and 3 rotational down to only the translational ones. This implies that the haptic display should also be able to provide feedback in egocentric orientation manner in order to be relevant and to exert too much cognitive workload on the operator.

The initial idea at the start of this graduation project was to create a head-worn device that would provide the haptic feedback. The idea was based on the fact that it is common for drone operators to use a head mounted display to receive the visual feedback from the drone. Thus, there was the possibility to integrate the haptic with the visual cues into a single device, while maintaining the separation between the control interface and the haptic feedback one. This idea was supported also supported by the development of such a head-worn device capable of providing haptic feedback, called the HapticHead [15]. This device consists of a spherical grid of tactors which were used to provide vibrotactile cues to users for the purpose of finding objects in a 3-dimensional virtual space, around the user. Therefore, such an approach could potentially be employed to provide directional cues as well. However, this idea was not pursued since the focus of the graduation project is to characterize the effects of haptic feedback and not to prototype such a device, and also due to time constraints and the complexity which prototyping such a device would imply.

In order to avoid the time constraints involved with building a prototype device from ground up and after consulting with the researchers supervising this graduation thesis, a decision was made to make use of the Tactile Torso Display developed by TNO. Moreover, the use of mentioned device is inline with the approaches used in the literature reviewed related to this topic, and meets the requirements associated with the goal of the project.

The Tactile Torso Display is a vest embedded with vibration motors, referred to as tactors, positioned on five circular rows around the abdomen area of the body, each row consisting of twelve tactors. Additionally there is a tactor placed on each of the shoulder areas and two more which, according to the original documentation of the vest, were intended to be placed under each of the users legs. In total there are 64 tactors which can be actuated to provide vibrational cues to the user. The vest can be viewed in Figure 3.1.

Figure 3.1: The TNO vest, picture taken from original documentation of the vest

According to the original documentation of the vest, the tactors model is TNO JHJ-3 and contain an Eccentric Rotating Mass (ERM) motor, requiring 3 Volts and a maximum of 50 mA to operate, with a decentred mass attached which produces the vibrational signals. The tactors are attached to vertical strips of Velcro and are covered by a layer of textile fabric which does not allow for the direct contact with the skin. Nonetheless, to ensure sufficient contact between the tactors and the skin, five rows of elastic cords are on the outside of the vest, approximatively at the same position as the tactors. A view of the inside of the vest and how the tactors are attached can be seen in Figure 3.2. The original setup of the vest consisted of the vest itself, the tactors, a distributor, an amplifier and a USB module used to connect to a computer. A software running on the computer was used control the tactors. However this setup was not appropriate for use in the current project for reasons that will become clear in the next section of this report.

Instead, a different setup was used, developed by another student which has used the

Tactile Torso Display for their graduation project [24]. In the new setup, the USB module was replaced with two Arduino Megas and a printed circuit board shield which allowed for a stronger connection of the pins and cables going from the Arduinos to the amplifier. Their thesis report was used as documentation for using the vest with the new setup, however the available information was sometimes insufficient and there were also some cases which the information given in the report did not coincide with what was found when working with the vest in practice. For instance in the report it is mentioned that the first 50 tactors are actuated by the first Arduino, while 13 tactors are actuated by the second one. In practice, it was found that the first Arduino only actuates 40 tactors while the second is responsible for actuating the other 24 tactors. The tactors need a pulse width modulation (PWM) type of signal to be actuated, however since the Arduino has a limited number of PWM ports, the digital ports are used in combination with an Arduino library called SoftPWM [11] which is able to emulate the PWM signal through software. Thus, a value between 0, which corresponds to the tactor being on, and 255, which corresponds to the tactor being off, is sent via the digital pins mentioned previously.

Figure 3.2: The inside of the TNO vest, picture taken from original documentation of the vest

The PWM signals were sent at a rate of 60 Hz which was a characteristic of the Arduino library used. The use of the library had a number of disadvantages, one of them being the maximum number of channels which could be used. Initially the library was coded to handle a number of 20 channels, meaning that each Arduino could send PWM signals to only 20 tactors at a time. It was found that the number of channels could be increased to a maximum of 25 without impacting the performance of the system, however any value above 25 would introduce growing time delays in the system. This latency is something that would counteract any potential benefits that might arise from the implementation of haptic feedback. Due to the limited number of tactors which could be actuated, it was decided to not use the bottom row of tactors. Moreover, the mapping of the tactors to the digital pins of the Arduinos was random, therefore the tactors had to be actuated individually to create this mapping. Because of the random mapping, a number of actuators were repositioned to allow for the implementation of the vibration patterns described in one of the following sections of the report.

3.2 Simulation

In order to investigate the effect of the haptic feedback on operators flying a drone, a decision was made to use a simulation instead of flying an actual drone for several reasons. First of all, it is much safer to to fly a drone in a simulation, rather than the real environment. As mentioned previously in the report, flying a drone accurately is a difficult task and often requires long periods of training, therefore for an increased safety factor and to avoid potential damages to equipment or other infrastructure it was decided to opt for the simulation. Secondly, the simulation allows for a better control of the conditions in which the experiment will take place. Moreover, it allows for simulating sensor data and leads to an easier interfacing between the vest and the data generated by those sensors. Taking the advice of one of the researchers supervising this thesis, it was decided to use ROS and Gazebo for the simulation of the drone and the virtual environment in which users would control it. Gazebo is a simulation environment in which the physics and the visual rendering of a robot can be realistically simulated. ROS, which stands for Robotic Operating System, is a software framework which is aimed at programming for robot development purposes and provides a way to interface with the simulated robot. In more simple terms, ROS is a system consisting of independent running programmes, referred to as nodes, which are communicating between themselves using messages broadcasted on predefined channels.

ROS and Gazebo are best suited for the Linux operating system, and due to the fact that the software provided with the vest was designed for a Windows operating system, the original setup was not suitable for interfacing with the simulation environment. With the new setup, ROS programs can run on the Arduino, therefore resulting in a easier interfacing between the vest and the simulation. The behaviour of a drone can be successfully and realistically simulated with ROS and Gazebo and since it is an open source type of platform, there are many available packages for this purpose.

The package used in this project is RotorS, developed by the Autonomous Systems Lab of ETH Zurich [10]. This package provides a very realistic simulation of drone flight and sensors on board of the drone such as the inertial measurement unit (IMU), which is one of the most important sensors on board of a drone, as well as simulates camera mounted on the drone to provide visual feedback. The sensors also have noise implemented to simulate a more realistic behaviour. While the package was designed to be ran out of the box, a few dependencies and bugs had to be fixed before the simulation was working.

There are different drone models included in the simulation, however the most realistic one seems to be the Firefly AscTec from Ascending Technologies, since certain constants regarding the flight behaviour or the drone were based on the recorded flight data of a real Firefly drone

[10]. The Firefly drone is a hexarotor drone, and it is somewhat more stable during flight compared to other quadrotor drones. Therefore, a decision was made to use the same model of the drone in the simulation, however some parameters have been constrained to make the drone easier to control for users with little previous experience with drones. These parameters concern the maximum airspeed, range of thrust, maximum pitch and roll angle and the yaw rate, and do not influence the physics realism of the drone behaviour in the simulation. The package provides a method of controlling the drone using a joystick such as PS3 joysticks. The control commands are mapped to the two joysticks as described in drone flight section of the report, replicating the controls as on a standard controller, with one exception. The difference consists in the fact that on a standard controller used for drones, the joystick corresponding to the thrust parameter has a range of 0 to 1 and can be set and maintained to any value in between, while the joystick corresponding to the same parameter on the PS3 controller has a range of -1 to 1, with a return to center behaviour, making the drone behaviour in the Z-axis very unstable and hard to control, especially for operators with no prior experience. To mediate this return to center behaviour, the thrust range values of the drone have been constrained, therefore instead of having a range from 0 to 36 Newtons, corresponding to the real values of a Firefly drone, the range in the simulation was limited between 10 to 20 Newtons. When the joystick was returned to the center position, the drone would develop 15 Newtons of thrust, which is just below the force threshold required to overcome the weight of the drone. This made the drone a lot easier to control in the simulation, predominantly for people with little to no experience in drone flight. A virtual environment has been created to allow for flight in a more realistic scenario. This environment will be described in more detailed in the next chapter of the report.

3.3 Vibration Patterns and Encoding

The information provided through the haptic feedback must be encoded in the vibration patterns in the vest. These vibration patterns must be clear and intuitive, otherwise they would be ineffective and require more cognitive effort from the operator, which is undesirable. In the setup used, to drive the tactors, PWM signals were used. One characteristic of powering ERM motors using PWM signals is that the frequency and amplitude of the vibration cannot be varied independently. Therefore, changing the duty cycle of the PWM signal provided to the motor will change both the frequency and intensity of the vibration, making it somewhat difficult to reliably use these parameters to provide a finer discretization of the information encoded. Because of this reason, it was decided to maintain a low resolution of the haptic display, the main parameter of the vibration patterns encoding being the location of the vibration. The intensity of the vibration was also used as a parameter. However, this was used either in the case where using the localization parameter of the vibration was not available, such as the tactors on the sholders, or it was used to more clearly differentiate between the types of information provided in different location. This latter aspect will become more clear in the following paragraphs.

While initially, in the proposal preceding this graduation project, the haptic feedback was to focus one two aspects regarding the flight of drones, namely information about behaviour of the drone and about the environment in the proximity of the drone, the latter was dropped for a number of reasons. One of the reasons concerns the use of the vest as the haptic display through which the information was transmitted. Because of the position of the tactors, which can be described as stacks of 2-dimensional horizontal planes, it was difficult to make a clear separation between the areas in which the two types of feedback were provided. This could potentially lead to confusion for the operators regarding what cues were being transmitted. The second reason is that the feedback about the proximity of the drone would have been used for collision avoidance purposes, the effects of which have already been sufficiently investigated in literature. Therefore, it was decided to focus on providing haptic feedback about the drone behaviour during flight and to investigate its effects.

3.3.1 Information encoded

Based on the literature research performed, it was found that the type of information about the behaviour of a manned aircraft which reduced the effects of spatial disorientation among pilots was the attitude and velocity of the aircraft. Based on these findings, it was decided to implement the same type of information about the behaviour of drone for the task of teleoperation. There were three iterations of the type of haptic feedback provided, which encoded different types of information. The encoding method remained, at large, the same throughout the different iterations. The first two iterations were compared in a test pilot type of experiment, and based on the feedback of the participants, adjustments were made for the third iteration which was also used in the final user testing experiments.

3.3.2 Tactor mapping

The feedback provided was based on the egocentric orientation of the task of teleoperating a drone, thus the area of the torso around the navel and the spine was mapped to the direction of the x-axis of the drone, while the sides of the body were mapped to the direction of the y-axis of the drone. The orientation of the x axis and y axis can be seen in Figure 2.1. In the tactors on the placed on the shoulders, information about the z axis was provided. There can be identified five areas in which feedback is transmitted: front, back, left side, right side, shoulders. The front of the body had an array of 3 columns by 4 rows of tactors. The back of the body similarly had an array of 3 by 4 tactors. The left and right side of the body each had a column of 4 tactors. This distinction between a row of 3 tactors for the x axis and a row of only 1 tactor was made since the sides of the body have a decreased spatial acuity and to increase the clarity for the information being transmitted. Having 4 rows of tactors in each of the areas around the torso, meant that the resolution for the four areas around the torso was on 4 levels. This directional mapping was done to ensure that an intuitive type of feedback was transmitted, so that the operator did not have to put cognitive effort into determining in which direction relative to the drone, the feedback was given. Additionally, this type of mapping could lead to an increased feeling of telepresence or immersion, since the orientation of the two frame of references, of the operator and the drone, coincide.

3.3.3 First and second design iterations

In the first iteration, further referred to as V1, and the second iteration, referred to as V2, the attitude of the aircraft was mapped to the vest. The attitude of the drone can be divided into four states. These states are pitch forward, pitch backward, roll left and roll right and they were encoded to the front, back, left side and, respectively, right side of the body. The parameter which encoded the angle of tilt was the location of the vibration. Therefore, if the drone was pitching forward, the row of tactors on the front of the body, corresponding to the amount of pitching, would actuate. The vibration sensation would move downward, to the next row of tactors, while the previous row would stop being actuated, once the degree of pitching would increase. Thus, the maximum angle of pitch corresponded to the bottom row of tactors, while small angles of pitch corresponded to the upper rows of tactors. Similarly, when the drone would roll to the right, the tactor on the right side of the body would actuate, depending on the degree of the roll. Likewise, the maximum roll angle corresponded, to the tactor on the bottom of the column. During stable hovering, no tactors were actuated. If the drone would have both a pitch and a roll angle, the corresponding tactors were actuated simultaneously. The tilting of the drone in a particular direction corresponds to an acceleration in the same direction, however that does not necessarily mean that the drone would also move in that particular direction on the moment. To transmit the information that the drone was still moving in the opposite direction of the tilt, the entire area of the body opposing the tilt direction was actuated with a lower intensity. For instance if the drone was pitching backwards, but still had a forward velocity, the corresponding row of tactors on the back would actuate, depending on the angle of pitch, while simultaneously, the whole 3 by 4 array of tactors on the front would vibrate with a lower intensity. Once the velocity in the opposing direction of the tilt become zero, or in other words, the drone would move in the same direction of the tilt, the 3 by 4 array of tactors would stop actuating.

The only difference between V1 and V2 were the information transmitted through the shoulder tactors. In V1, information about the yaw of the drone was encoded, therefore if the drone was yawing to the right, the right tactor would actuate. In V2, the information encoded in the shoulder tactor concerned the velocity on the z-axis of the drone. The way this was achieved was that if the drone was gaining altitude, the tactor on the right shoulder would vibrate, while if the drone was losing height, the left shoulder tactor would vibrate. The information encoded in V1 regarding the shoulders was more intuitive, however the cues in V2 proved more valuable after the feedback gathered during the small pilot test, despite being not as intuitive and required getting used to.

3.3.4 Third design iteration

In the third iteration (V3) of the haptic feedback, which was also used during the final experiment, the information about the attitude of the drone during flight was disregarded since it was redundant. Given that the operators of the drone would be able to kinesthetically get information about the attitude of the drone from the position of the joystick on the controller, providing vibrotactile cues about the same parameters was unnecessary, and often confusing, especially when coupled with the feedback about the movement of the drone in the opposing direction of tilt. Therefore, the haptic feedback provided in V3 was focused on providing cues about the velocity components of the drone on the x, y and z axes. This was done in an intuitive way, mapping the x axis on the front and back area, while the y axis was mapped on the lateral area of the body. Similar to V2, the shoulder area was used to provide cues about the velocity of the drone in the z axis, however, different from V2, the z axis was normalized, so that even if the attitude of the drone changed, the z axis remained perpendicular to the surface of the ground, providing better information about the changes in height of the drone. If no feedback was received from any of the tactors, the drone was hovering over a fixed point, however a small deadzone was implemented for each of the directions. The range of velocities the drone could achieve in a horizontal plane in the simulation was divided into 4 equally spaced intervals. Those 4 intervals were mapped to the 4 rows of tactors on each area of the body, except the shoulders. The smallest velocity range was mapped to the uppermost row, while the highest velocity range was mapped to the lowest row. This was done for both x and y axes. Since in the shoulder areas, the location of the vibration could not be used as a parameter to encode different values of height gain or loss, vibration intensity was used as a parameter. Thus, 4 levels of intensity were used to encode different ranges of velocities. The 4 velocity ranges were also spaced equally, between no velocity and the maximum climb rate the drone is capable of. While the drone was gaining height at its maximum rate, the intensity of the vibration was the strongest, and decreased with a decrease in velocity on the z axis. The vibration patterns and the information encoded can be seen in Figure 3.3.

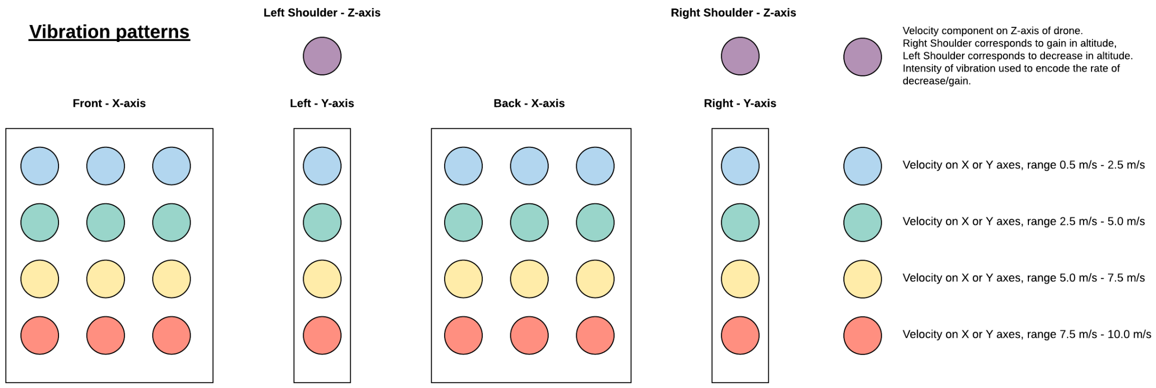

Figure 3.3: Diagram of vibrotactile patterns on vest. Depending on the value of the velocity and the direction of motion, the appropriate set of tactors will actuate

3.3.5 Vest actuation

The way the vest was actuated was through the messages received on the ROS nodes running on the two Arduinos. These messages contained an array of values which corresponded to the intensity of the vibrations, while the index of the non-null values in the array corresponded to the location of the tactors which needed to be actuated. Null values in the array meant that the corresponding tactors were not actuated. These messages were compiled by a publisher ROS node, running on the computer with the other ROS nodes responsible for the simulation. This publisher node was subscribed to messages received from the simulation nodes on two different topics. The two topics provided information about odometry, which among other parameters, contained the drones velocities on the three axes, and, respectively, information about the attitude of the drone. These messages were broadcasted with a frequency of 20 Hz, ensuring a good resolution of the flight parameters. The approach used ensured that most of the processing required was performed on the computer running the simulation, while the two Arduinos only sent the signals to the tactors, thus maintaining the latencies involved at a minimum.

Chapter 4

Testing

In order to characterize the effects of the haptic feedback provided for the task of flying a drone, user testing is required. For this purpose, an initial small scale pilot test was performed followed by a bigger scale user experiment. The initial pilot test was used mainly to investigate the test setup and its usability, as well as gather feedback about the vibration patterns and the information encoded in them and make adjustments if necessary to the test setup. For the user test, a few parameters have been devised which will be used as a measure of how participants are performing on their task, and should give an indication of the effects of the haptic feedback implemented. Next to these parameters, which will be determined objectively based on the users course performance, a questionnaire will also be used, together with a set of open questions, to give a more subjective insight on the effects of the haptic feedback and the way it was provided to the user. This chapter first describes the setup of the pilot test and the insight gathered as a result, then present the procedure adopted for the user studies, together with its respective setup.

4.1 Pilot test

As mentioned in the previous paragraph, the goal of the pilot test was to improve the design of the full-scale user test, however, it also generated insight about the information encoded in the vibrotactile patterns and how it was provided based on the feedback of the participants. In this initial pilot test, the participants had to fly the drone in two different simulated scenarios, after a brief session of practice in which they could get used to the controls of the drone. The first scenario involved a short course in which the user had to take off from a starting point, follow a path along the top of a wall at a certain height and land the drone on a fixed target at the end of the path. The goal of this course was for the users to control the drone with precision and fly in close proximity to the visual cues given in the simulated environment. In the second scenario, participants had to fly over a longer course, which better resembled a real environment. This course can be seen in Figure 4.1. The aim of the second course was to record certain parameters about the flight performance, namely the completion time for the course, the number of crashes and the number of obstacles bypassed. The participants were separated by condition into four groups, altering between flying the short course while receiving haptic feedback or not and training while receiving haptic feedback or not. After participants completed the flying tasks, they were asked to fill out a two-part questionnaire. The first part consisted of a set of questions with answers on a scale from 1 (strongly disagree)

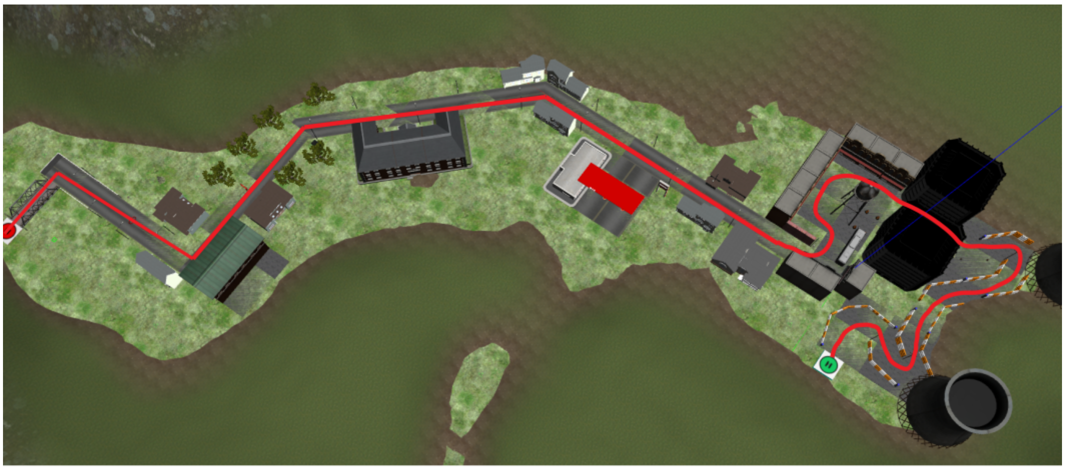

Figure 4.1: Course used in pilot test

to 5 (strongly agree) and was used to collect quantitative data about the experience of haptic feedback. The second part of the questionnaire consisted of a set of open questions aimed at gathering qualitative data about the vibrotactile patterns and the information encoded in them. The questionnaire used can be seen in Appendix A. The participants each received both iterations of the patterns, V1 and V2, for the purpose of investigating which one is more useful.

4.2 Pilot test results

The pilot test was done with four volunteering participants, all male students at the University, of which three had no prior experience with drones, with a setup as described in the previous section. Some important findings have been made about the usability of the test setup, the vibrotactile patterns and what cues should be encoded in them, thus having achieved the goal of the pilot test. However, due to the small sample group and the number of different conditions, the results are not sufficient to give any significant insight of the benefits of using the vest as a vibrotactile display to provide haptic feedback to drone operators. Nonetheless, the participants have reported that from a subjective experience the feedback provided made them more aware of the drone behaviour. One recurring issue, that manifested throughout the experiments with different severity, was a delay between the simulated time and the real time. The simulated time is the internal clock of the simulation that coordinates all the nodes and the communication between them. The rate at which the latency increased was proportional with the amount of time spent in the simulation. This issue rendered the conditions in the simulation very unrealistic and the control of the drone almost impossible if a certain amount of time was spent on the course. The issue was mediated eventually by decreasing the quality of the image sent from the simulated camera on board of the drone. Thus the quality of the visual feedback was decreased until a point where the environment was still easily recognizable, but the performance of the simulation was greatly increased.

Additional nodes, which were not vital to the core of the simulation were also removed from the simulation. These changes implemented after the pilot test brought the latency issue of the simulation to a point where it became negligible and did not severely impact the control of the drone or the physics of the simulation

Another issue arose from the amount and intensity of actuation of the tactors. During certain maneuvers in which the direction of motion of the drone was opposite to its tilt, with components on both x and y axes, more than half of the tactors on the vest were actuated all at the same time and all around the body, leading to confusion and increased workload reported by the participants. This caused them to disregard the information received through the vibrotactile cues. Moreover, the intensity of the vibration was too strong and over long periods of time it became distracting from the task of flying the drone. While users, reported that the cues about the yaw of the drone encoded in the shoulder tactors in V1 was more intuitive and gave a better feeling of immersion than the information encoded in V2, the cues of V2 gave them more valuable information about the direction in which the drone was moving. In addition, they found the cues on the x and y axes about the direction of movement of the drone, regardless of its attitude, very useful for a better control of the drone, since the behaviour of the drone was better understood. Compiling the feedback given by the participants regarding the way haptic feedback was provided led to the V3 iteration of the vibrotactile patterns. Thus the information about the attitude of the drone was disregarded since it was redundant and less useful for the operator, being replaced with cues about the velocity of the drone, while also the intensity of the vibrations was decreased.

The number of conditions in the experiment was too large, and in order to achieve significant statistical power, a rather large sample size would be required. In addition, having two course which each needed to be flown twice, resulted in a long time needed for the each participant to complete the experiment. Due to time constraints this was not desirable. For this purpose, the number of conditions and the scenarios were adjusted. The first flight scenario was eliminated, while the second one was adjusted to make the path required to be taken by participants more visible.

4.3 User test

Based on the insight gathered during the pilot test, both the setup for the experiments as well as the haptic feedback provided were adjusted to address the problems that were encountered in the first phase of the testing. In this section, the procedure adopted for the user test is described, as well as the setup.

Prior to the start of the experimental session, the participants are told what the experiment consists of and are asked to fill out a consent form and to fill out a questionnaire form with basic details such as their name, age, sex and whether they had any previous experience with flying drones, devices with haptic feedback, virtual reality or gamepad controllers. Afterwards, participants are given an explanation of the basic commands of the drone and their resulting movement of the drone, and their mapping to the joystick used to fly the drone. Next to that, participants get a verbal explanation of the vibrotactile patterns on the vest and what type of information is encoded in these. The third iteration of the haptic feedback patterns, V3 was used for this user test.

Each participant only had to fly in one scenario, where the course was adapted based on the pilot test feedback. The course can be seen in Figure 4.2 and a close-up of part of the course can be seen in Figure 4.3. The course was flown in total twice, once with haptic feedback and once without. The course is made such that it has section with tight and sudden changes of direction as well as sections that are more open and allow for flight with a higher velocity. In addition, the course had a few obstacles, such as hoops or a bridge, which needed to be approached or bypassed. The order of which mode was first, as well as the start and end points of the course were altered in order to eliminate the learning effect of the course which would impact the end results. Thus, the participants could have been divided into four groups, however since they were required to perform exactly the same task with the same conditions, while only the order was alternating, this study has a within-subject design. Due to this choice, less participants are required for sufficient statistical power, in comparison with the larger number of users required for the type of study initially adopted for the pilot test to have statistically significant results.

Figure 4.2: Course used in user test

Before the participants could start with the course, they were allowed to have a short practice session in which they could control the drone without having to perform a specific task, in order to get more familiar with the control. While they could only practice for a maximum of 5 minutes, they were allowed to stop the practice session at any time before that if they felt ready. Participants who flew the first course while receiving the haptic feedback were also provided with haptic feedback during the practice session. After the practice session, the participants receive explanation on the experimental procedure. The task is verbally described and participants are shown a top-down image of the flight course which can be seen in Figure 4.2. They are instructed to fly at a height of the light poles present in the simulated environment, with the exception of a few obstacles which require to be approached at a lower height.

After completing the task of flying the drone, participants were asked to fill out a questionnaire, which was structured similarly to the pilot test. Thus the questionnaire had a section of questions with answer on a scale from 1 to 5 aiming to gather quantitative data, and a section of open questions aiming to gather qualitative data. The questionnaire the users were required to fill can be seen in Appendix A.

During the experiment, their flight performance was recorded. The x, y and z coordinates of the drone were recorded and stored automatically, while the number of crashes and obstacles

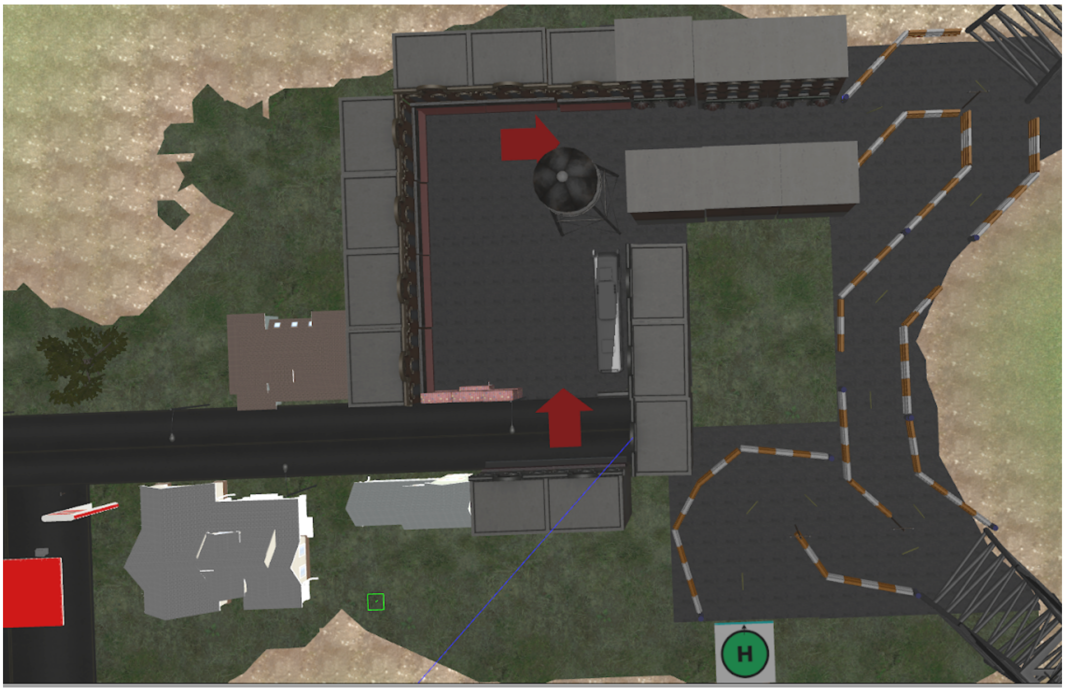

Figure 4.3: Close up image of the course used in the user test. Red arrows indicate which path the user is required to take

circumvented were noted down in a table. The main parameters used to analyze the data are the completion time of the course and the deviation from the indicated flight path. In addition, the number of crashes and obstacles circumvented are also used as additional parameters to analyze the performance. The results obtained are presented and analyzed in the next chapter of the report and should give an indication of the effects of haptic feedback for the task of drone teleoperation.

Chapter 5

Main Results

In this chapter, the method used to analyze the data recorded during the user studies is described and the results are presented and discussed. These results should give an indication of the effect of the vibrotactile display and the haptic feedback provided on a drone teleoperation task and, together with the literature research, should provide an answer to the research questions formulated. First, the data obtained from the task of controlling the drone will be analyzed and the findings presented, followed by the results of the questionnaire and the subjective experiences of the participants. The user test included 15 subjects of which 10 males and 5 females who participated voluntarily. They were selected by a process of convenience sampling due to time related constraints and were not required to fulfill any particular requirements. From the participants, 8 have said that they have no previous experience with drone flight, while 7 have had some experience either flying a drone in a simulator or in reality. Out of the 8 subjects with no prior drone experience, 2 were not able to fly the course in its entirety and within the designated area. The flight paths of the 2 participants will not be considered for the first part of the analysis since they did not complete the task and were not able to follow the course as indicated, however their experience will be included in the analysis of the questionnaires. Most of the participants had previous experience with game-pad controllers that were used in the current setup to control the drone, and a majority of them had some experience with games in virtual reality, however only 6 participants were somewhat familiar with the use of haptic feedback.

5.1 Drone control task

A number of parameters have been recorded for each course flight session and for each participant, as mentioned in the user test section. Therefore, there were two sets of parameters per participant, one corresponding to the condition of haptic feedback provided while the other corresponding to the condition of drone operation without the vibrotactile display. Looking at the mean and the standard deviation of these parameters grouped for all participants per condition, a comparison can be made between the performance of the participants while they recieve haptic and visual cues, and their performance while they only receive visual cues.

For each flight session, the x, y and z coordinates of the drone were being recorded at a frequency of 100 Hz and saved in a JSON format, together with the flight condition of haptic feedback. This data was used to compile a flight path of the drone controlled by the user and compare it against the desired flight path. The desired flight path was represented by a path that would pass through the center points of the visual cues placed on the course to guide the participants in the virtual environment. This comparison was achieved through the analysis of area-based deviation between the two paths. An algorithm called ALCAMP [25] was used to find the least-cost area mapping between the two paths, and plot this mapping. The advantages of this algorithm is that it works for paths of varying lengths and number of datapoints and that it is robust to potential issues of path crossovers and loops which could cause errors in the computation of the areas. However, the algorithm does have the drawback of only being able to consider 2-dimensional paths. To overcome this, two separate analysis have been made, one which only considered the path composed of x and y coordinate points, the XY-plane, while the other only considered the z coordinate points for the path, the Z-plane. The paths and area value of all participants can be seen in Appendix B for the XY-plane group and Appendix C for the Z-plane groups.

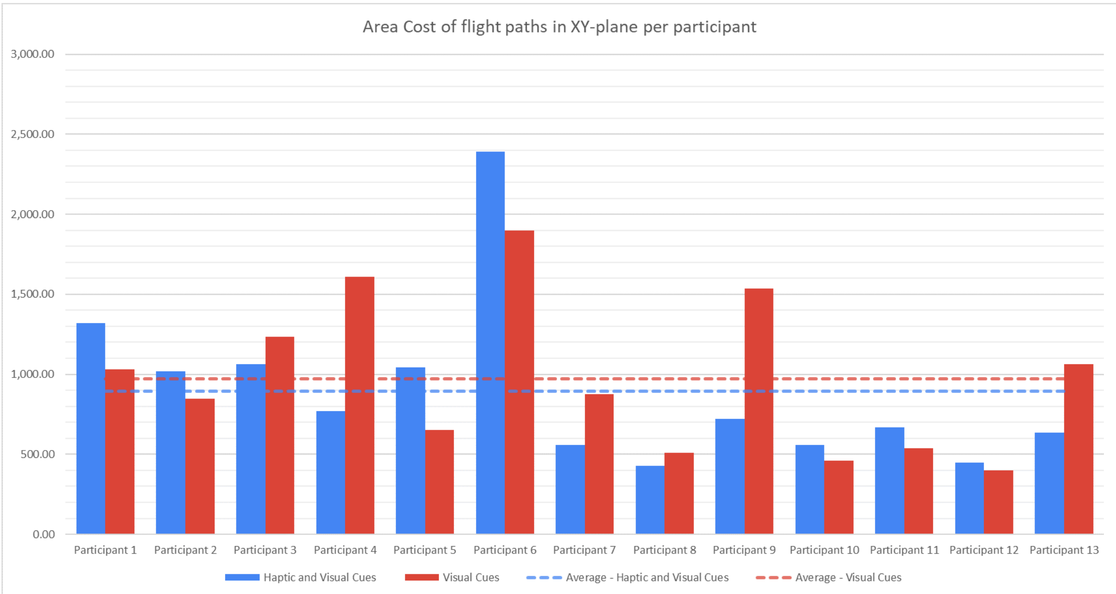

Figure 5.1: Area Cost of flight path in the XY-plane per participant. Blue corresponds to the condition where haptic and visual cues were provided, while red corresponds to the condition where only visual cues were provided. Dotted lines indicate the mean value over the participants, per condition

In Figure 5.1 and Figure 5.2, a comparison of the area values is presented for both XY-plane and, respectively, Z-plane, for each participant, depending on whether the haptic feedback was present or not. The blue lines correspond to the course where haptic and visual cues were provided to the participant, while the red lines correspond to the course where the user had to control the drone based only on the visual feedback. Participants 1 through 6 in each graph declared that they have no previous drone experience, while participants 7 through 13 were somewhat familiar with drones. For the XY-plane, it can be seen from the graph that only 6 participants had better results while the haptic cues were provided, in contrast to the situation when relying only on visual cues. The same figure drops to 4 only participants for the Z-plane. However these two figures are not fully relevant for making a correct appreciation of the effects of haptic feedback. Because of the within-design type of study, theres a potential for a learning effect bias when comparing the different performances

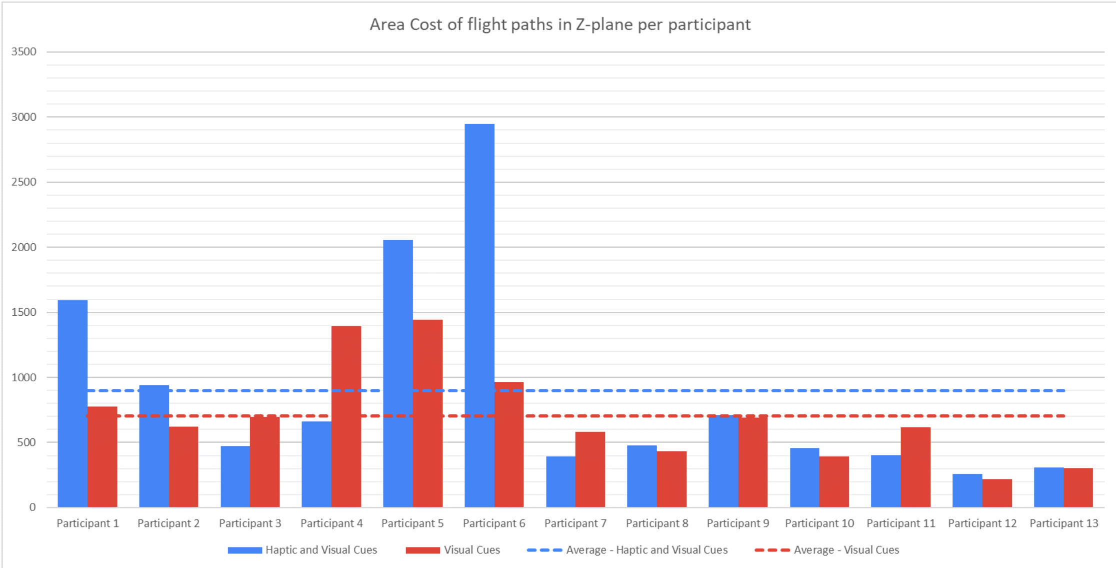

Figure 5.2: Area Cost of flight path in the Z-plane per participant. Blue corresponds to the condition where haptic and visual cues were provided, while red corresponds to the condition where only visual cues were provided. Dotted lines indicate the mean value over the participants, per condition

Mean value	**Feedback**	**No Feedback**
XY-plane	894.26	973.46
Z-plane	898.40	702.90
Completion Time (seconds)	222	191
Number of crashes	4.15	6.07
Number of obstacles bypassed	2.15	3.23

Table 5.1: Mean values over all the participants, per haptic feedback condition

of a single participant. For this purpose, the mean and standard deviation over the haptic feedback condition will be considered since it mediates the effects of learning and transferring from one condition to the other.

In addition to the average area cost for the XY- and Z-planes, the completion time of the courses, the number of crashes and the number of obstacles circumvented were also averaged according to the haptic feedback condition. A crash is considered when the users crashes the drone into an object in the simulated world, such as a house or a tree, but also when the drone drops on the ground, outside the start and finish area. A number of obstacles which needed to be tackled were also present in the simulated environment, such as poles, hoops or bridges. If the user avoided the obstacle by circumventing it, instead of tackling it, this instance was recorded.

In tables 5.1 and 5.2, the values for the mean and the standard deviation for the parameters mentioned can be seen. From the mean values, it can be observed that the haptic feedback provided in the XY-plane appears to have a benefic effect on the flight performance, however it degrades the flight performance in the Z-plane. One thing that can be noticed is that the values for the haptic feedback in the Z-plane are distributed over a large range, given

Mean value	Feedback	No Feedback
XY-plane	530.74	502.07
Z-plane	820.24	390.75
Completion Time (seconds)	88.3	65.8
Number of crashes	2.86	5.83
Number of obstacles bypassed	3.12	2.44

Table 5.2: Standard deviation values of parameters, per haptic feedback condition

the high value for the standard deviation. After doing a paired-samples t-test with 12 DF and $\alpha = 0.05$, in which the null hypothesis is that there is no significant differences in the haptic feedback condition and the no haptic feedback condition for the XY-plane, we obtain a p-value of $p = 0.512$ and since $p \geq 0.05$, it can be concluded that the null hypothesis is not rejected. Thus, there is no statistically significant difference between the means of the conditions. Doing the same t-test for the Z-plane yields a p-value of $p = 0.3075 \geq 0.05$, also resulting in not rejecting the null hypothesis. Therefore, there is not enough evidence to claim that the average value for the course performance in which feedback cues were provided is different than the average value for the situation in which only visual cues are provided, with a 0.05 significance level, despite a difference in the mean values. Haptic cues appear to have an impact on the completion time for the course, participants requiring on average more time to complete the course when these cues are complementing the visual feedback. However, haptic feedback appears to lead to an increased safety factor since the average number of crashes has decreased from 6 to 4, together with a smaller value for the standard deviation compared to the no haptic cues condition. Lastly, the number of obstacles circumvented by the participants, decreased on average, pointing to a better ability to control the drone. The relative improvements between the haptic cues condition and the visual cues only condition are shown as percentages in Figure 5.3. A positive percentage value is correlated with a positive effect.

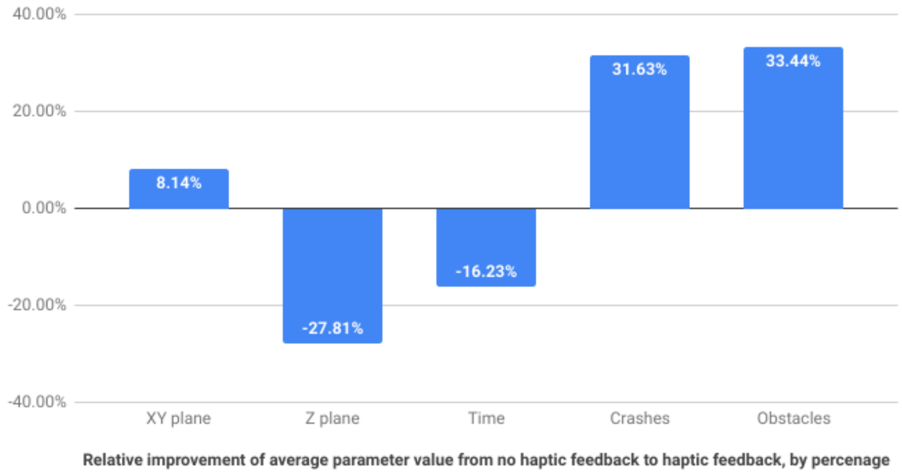

Figure 5.3: Relative improvement of average parameter value, from visual cues only condition to haptic and visual cues condition

No previous experience	Feedback	No Feedback
XY-plane	1267.47	1212.17
Z-plane	1444.32	982.53
Number of crashes	6	8.33
Number of obstacles bypassed	3.66	4.83

Table 5.3: Mean values over participants with no previous drone experience, per haptic feedback condition

Previous experience	Feedback	No Feedback
XY-plane	574.37	768.75
Z-plane	430.48	463.22
Number of crashes	2.57	4.14
Number of obstacles bypassed	0.85	1.85

Table 5.4: Mean values over participants with some level of prior drone experience, per haptic feedback condition

An interesting comparison between the effects of the haptic feedback on the participants who already had previous experiences with drones and the users who did not can be made. Using the same parameters, new averages have been computed depending on the previous experience of the participants. This values can be seen in table 5.3 and 5.4. Additionally, the relative improvement of each parameter has been computed, in percentage value, between the haptic feedback condition and the no haptic feedback condition and can be seen in Figure 5.4. The blue line corresponds to participants with no previous experience while the red one is for users with some familiarity with drones. It can be noticed that the effect of haptic feedback seems to be more significant for users with previous experience. For the deviation from the designated flight path, it can be observed that the haptic feedback had positive effects only for the users who already had some interaction with drones prior to the experiment. For the participants who were not familiar with the control of drones, the haptic feedback provided actually led to a degradation of their performance. Nonetheless, for both groups of participants there appear to be improvements in the safety factor and the number of obstacles successfully tackled. Similarly, the effect is more significant for more experimented users.

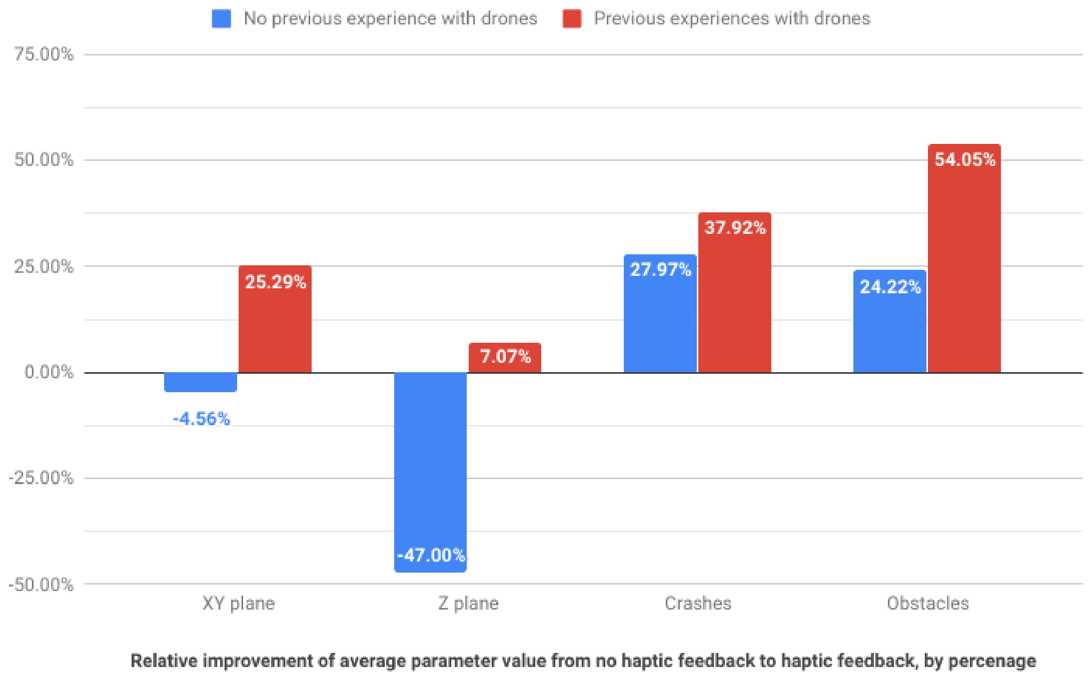

Figure 5.4: Relative improvement of average parameter value, from visual cues only condition to haptic and visual cues condition. Blue corresponds to the values from the users with no previous experience with drones, while red corresponds to the values from users which had some level of familiarity with drones

5.2 Subjective experience of the participants

The results of the quantitative part of the questionnaire filled in by the participants at the end of the experiment session can be seen in table 5.5. The answers to the questions were in the form of a scale from 1 to 5. The value 1 corresponds to the statement Strongly Disagree and the value of 5 corresponds to the statement Strongly Agree, while the middle value 3 corresponds to the answer Undecided. As it can be seen from the table, participants agree that they could clearly perceive the haptic cues during flight and that the haptic feedback made them more aware of the behaviour and motion of the drone during flight. Both these answers have a small variance, indicating that most of their experiences are similar, regarding these two aspects.

On average, participants were able to identify the information encoded in the vibration patterns, and reported that the sensation of vibrotactile feedback was pleasant and the vest comfortable to wear. However, these values have a high degree of variance, with a standard deviation of about 1. This means that while most of the users agreed with the statements, some were undecided regarding this aspect, however, one of the participants which was not able to complete the course reported that the sensation of haptic feedback was very unpleasant and the information encoded in the vibrotactile patterns was not clearly identifiable. Moreover, most of the participants disagreed with the statement that the feedback provided was leading to confusion, however a high variance of the answers makes this finding less significant.

According to the participants, controlling the drone was difficult. Only three users have reported that they could control the drone with relative ease, while most of them were having difficulties or were undecided regarding this aspect. Regarding the mental workload of the participants during the task of drone operation, little can be said. With a value of 3, participants were on average undecided whether the use of haptic feedback led to an increase in their concentration workload.

Question	**Average of Answers**	**Standard Deviation of Answers**
I could clearly perceive the vibro-tactile feedback during the flight	4.70	0.45
I could clearly identify which information was encoded in the vibration pattern	3.60	0.98
I would describe the sensation of feedback as being pleasant	3.60	1.04
I could control the drone with little difficulty (regardless of feedback mode)	2.53	0.91
I would describe the vest as being comfortable to wear	3.80	1.08
I would describe the sensation of feedback as being confusing	2.60	1.05
I would say that feedback helped fly the course more easily	3.20	0.96
I would say that feedback made me more aware of the behaviour in flight	4.06	0.88
I would say that having feedback did not lead to an increase in my concentration workload	2.93	0.96

Table 5.5: Questionnaire results

Based on the open questions, more insight was generated. Participants were asked about which mode of flight they would prefer and why. Of the subjects, 11 have reported that they prefer the operation mode in which haptic feedback is provided next to the visual cues, giving as arguments that they became more aware of the behaviour of the drone during the flight, or that the experience was more immersive due to the haptic cues. Only 4 users have reported that they prefer controlling the drone without receiving haptic feedback, because it was either confusing or distracting and could not use the additional information provided through the vest to control the drone better.

Participants were asked whether they would have liked to receive information about other parameters regarding the control of the drone. Most users declared that they were satisfied with the information encoded, however 3 participants wanted to receive additional information about the objects situated in the proximity of the drone and the distance to those objects. Also, a large number of participants have declared that the course in which they flew the drone was rather difficult.

The subjects also agreed that the feedback provided in the XY-plane was very intuitive, while the haptic cues provided on the shoulder tactors was less intuitive but very valuable. One of the users argued that the mode of actuation of the tactors placed on the XY-plane was very tiring, since most of the time they would fly forward and always feel a constant vibration on the front part of the body which eventually became obnoxious and distracting from the task of controlling the drone.

Despite recognizing the usefulness of the cues provided by the tactors on the shoulders, participants had a hard time using that additional information since it was not provided intuitively. They had to actively think of which shoulder corresponded to which direction, contributing to a lessening of the effect of the haptic feedback. In some situation, the cues received in the Z-plane, made users confused about the direction of the thrust. This can be seen in the plots for the Z-plane paths, where there are really high spikes.

Some of the participants said that they found the effects of the haptic feedback provided most useful at low velocities and when controlling the drone in the proximity of building. They reported that the haptic cues made them realize in which direction they were drifting and allowed them to avoid collisions with the objects in the environment. Nonetheless, it was generally agreed upon by users that more training with the haptic feedback would have been more useful and perhaps would have led to better results. The same can be said about the training time in which they were able to get used to the control of the drones.

Chapter 6

Conclusions

Based on the findings of the literature review and the results gathered in the user study a conclusion can be drawn and the research question at the foundation of this research can be answered. The goal of the graduation project has been achieved since a system which is able to provide haptic feedback to a drone operator has been designed and its effects have been investigated. The haptic feedback was provided through a wearable vibrotactile display which encodes information about the behaviour of the drone. Taken into account the data obtained from the experiments, it can be said that, on average, haptic feedback has mostly beneficial effects for the task of drone teleoperation.

The first research question aimed to find out the extent to which haptic feedback would lead to a more accurate control of the drone. Based on the results obtained, users were able to bypass less of obstacles intended to be tackled while flying with the vest, pointing towards a better awareness of the drone behaviour and a better control. In the XY-plane, an improvement can be seen in the deviation from the designated path, due to the haptic cues, however in the Z-plane the effect is negative. The separation of results depending on the previous drone experience of the participants gives better insight. The haptic feedback provided has positive effects for the subjects who were somewhat familiar with drones, leading to an increase in performance in both XY-plane and Z-plane. The results are more significant in the XY-plane where the feedback provided was more intuitive, compared to the Z-plane where the encoding of the information was less intuitive and sometimes led to confusion. However, due to the haptic cues provided, subjects with no prior drone experience saw a degradation of performance, despite being able to tackle more obstacles. From the subjective experiences of the participants, a majority of them preferred to control the drone while wearing the vibrotactile display, and they agreed that the haptic cues enable them to become more aware of the movement and behaviour of the drone. Therefore it can be said that haptic feedback does lead to a more accurate control of the drone, particularly for drone operators with previous experience, but the extent of this improvement is not completely clear. No significant beneficial effects were found for subjects with no drone flying experience since the objective parameters are indicating different outcomes.

The second research question aimed to investigate to which degree does haptic feedback lead to an increased safety factor in the operation of the drones. Based on the results, the number of crashes, on average, decreases by almost a third. This holds true for both groups of participants, regardless of their prior experience, however, it can be seen that the improvement is more significant for the subjects that were somewhat familiar with drones.

An average increase in the completion time of about 30 seconds can be observed for the participants and can potentially be correlated to flying the drone at lower velocities, since they are more aware of the drone behaviour. Being more aware of the movements of the drone, as reported by participants, can lead to an increase of the safety factor. An increase in the mental workload of the participants for the duration of the task could have negative effects regarding the safety. However, based on the questionnaire, no clear differences in the cognitive effort required to control the drone while wearing the vibrotactile display can be found. Therefore it can be said that haptic feedback enables a safer operation of a drone, observing a relative improvement of more than 30% when compared to the visual feedback only condition.

The last research question tries to look at what type of information relevant for the behaviour of the drone should be encoded in the haptic cues provided to the operator. Based on the literature review performed, it was discovered that encoding information about the velocity and direction of movement of a helicopter was valuable for pilots and improved the issue of spatial disorientation. This finding was extrapolated to drones, since they have similar flight capabilities and dynamics as helicopters, and the same type of information could help the drone operators which are deprived of a lot of sensory information compared to the pilot of a manned aircraft. Based on the feedback gathered during the pilot test, and the experience of the participants, it can be argued that information about the velocity and direction of movement of the drone during flight is very useful information which can be encoded in the vibrotactile patterns of the haptic display. Additionally, information about the objects in the proximity of the drone was also deemed potentially useful by participants, and confirmed by existing works in the field, however the feedback is provided through kinesthetic cues instead of cutaneous cues.

One very important aspect of how the information is transmitted through the haptic feedback is the level of intuitiveness. Despite providing the same type of information through the tactors that were placed on the vest in the shoulder area and due to their localization, the cues were less intuitive compared to the ones received on the area around the abdomen. This led to confusion for the operators and in most cases, a degradation of performance. This aspect points towards the fact that the effects of haptic feedback for teleoperation tasks are highly dependent on the method in which the cues are provided. While the number of participants in the user studies was low for achieving statistically significant results, the objective performance parameters combined with the users subjective experience of the vibrotactile display are pointing towards a positive effect of the haptic feedback. Nonetheless, the design of the haptic display can be greatly improved, especially regarding the method in which the information is encoded through the tactors. It can be concluded that the use of a vibrotactile display in the form of a vest has promising potential to improve the teleoperation of a drone, both from a safety aspect as well as a precision of control aspect.

6.1 Future work

Due to a number of constraints, certain decisions and compromises about the approach used to implement the haptic feedback and characterize it had to be made. These compromises had an effect on the outcome of this research and its findings. This brief section should give some indications on where additional work and research should be focused in order to improve the design of the haptic feedback provided to drone teleoperators.

The device used to provide the vibrotactile cues is a very crucial aspect of the haptic feedback. It can influence whether the information cues are delivered intuitively, thus restricting the amount of information that can be effectively encoded. Using the vest as a vibrotactile display was a good approach especially for the directional information on the X and Y axes due to the egocentric orientation of the drone teleoperating task, however it proved less appropriate for encoding the information regarding the Z axis. This was caused by the position of the tactors in the vest. Using different devices as vibrotactile displays, especially ones that can represent the three orthogonal axes in an intuitive way, like the HapticHead mentioned in section 3.1, could lead to better results since the information can be displayed more intuitively. Alternatively, the vest could be used in conjecture with other devices which provided vibrotactile cues in other areas of the body. Having vibrotactile devices on the hands or legs of the operator could lead to a better separation of the information encoded or a more intuitive encoding method. For instance a tactor on the lower part of the arm could encode the fact that the drone is losing altitude while one on the upper part of the arm could encode the altitude gain of the drone, leading to a more intuitive mapping. Thus the tactors on the vest in the shoulder area could encode a different type of information than altitude gain, for example the yaw of the drone. The overall effect would be a reduction in the confusion and distraction generated by cues provided in a non intuitive manner and also an increase in the resolution of haptic display and number of parameters encoded.

Another aspect which can be improved in the current setup is the method of encoding for the information. The vibrating patterns had only two parameters with which different information was encoded, namely the location of the vibration and the intensity. Investigating different vibrating patterns, particularly ones that make use of the frequency and rhythm of vibrations could prove beneficial. Also, continuous actuation of the tactors to display information can be tiring and distracting for the users, thus a different method of transmitting the same information over longer periods of time should be tested. A suggestion would be to use discrete vibrations, instead of continuous actuation of the tactors, to indicate a persistent cue, such as the drone moving forward. This would reduce the distracting aspect of the vibrations, reported by some participants, thus improving the effect of the haptic feedback.

The user test and its setup is another aspect that can be improved. Having more participants would be desirable as it would lead to a more statistically significant results and would allow for a different type of design for the user study in which the learning effect could be mitigated. Longer training times for users to get familiar with the controls of the drone as well as the haptic feedback would also be desirable for a better characterization of the haptic feedback. Lastly, testing of the haptic feedback should be performed in a real world environment as well, in order to gain a better insight.

This study can serve as a basis for future research in the area of haptic feedback and drones by considering different aspects of drone flight, opposed to the ones usually encountered in literature. The common approach is to provide feedback regarding the objects in the proximity of the drone for the purpose of collision avoidance using kinesthetic sensory cues. The present research focuses, however, on providing information regarding the behaviour of the drone, such as the direction of movement and the drone's velocity, using cutaneous sensory cues. Unlike manned aircrafts, this type of information about the flight of the drone is lost due to the physical separation between the drone and the user, inherent to teleoperation. By providing these types of cues, the task of teleoperation can become a task of telepresence, in which the operators feel more immersed. The feeling of immersion could ultimately lead to a more accurate and safer control of drones, however further research is required to confirm this.

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List of Figures

Appendix A

Questionnaire

A.1 Pilot Test

Questionnaire

	Strongly Disagree	*Disagree*	*Undecided*	*Agree*	*Strongly Agree*
I could clearly perceive the vibro-tactile feedback during the flight and identify which information was encoded in the pattern					
I would describe the sensation of feedback as being pleasant					
I would describe the first course as being too easy					
I would describe the second course as being too difficult					
I could control the drone with little difficulty (regardless of feedback mode)					
I would describe the vest as being comfortable to wear					
I would say that the experiment made me tired					
I would describe the sensation of feedback as being confusing					
I would say that feedback helped my fly the course more easily					
I would say that feedback made me more aware of the drone behaviour in flight					
I would say that having feedback did not lead to an increase in my concentration workload					

Open questions:

- Which mode of flying do you prefer and why?
- Is there an aspect of drone flying that you would like to receive feedback about and wasn't implemented in the current setup?
- How did you find the vibration patterns and the encoding method of flight parameters?
- Additional comments, remarks?

A.2 User Test

Questionnaire

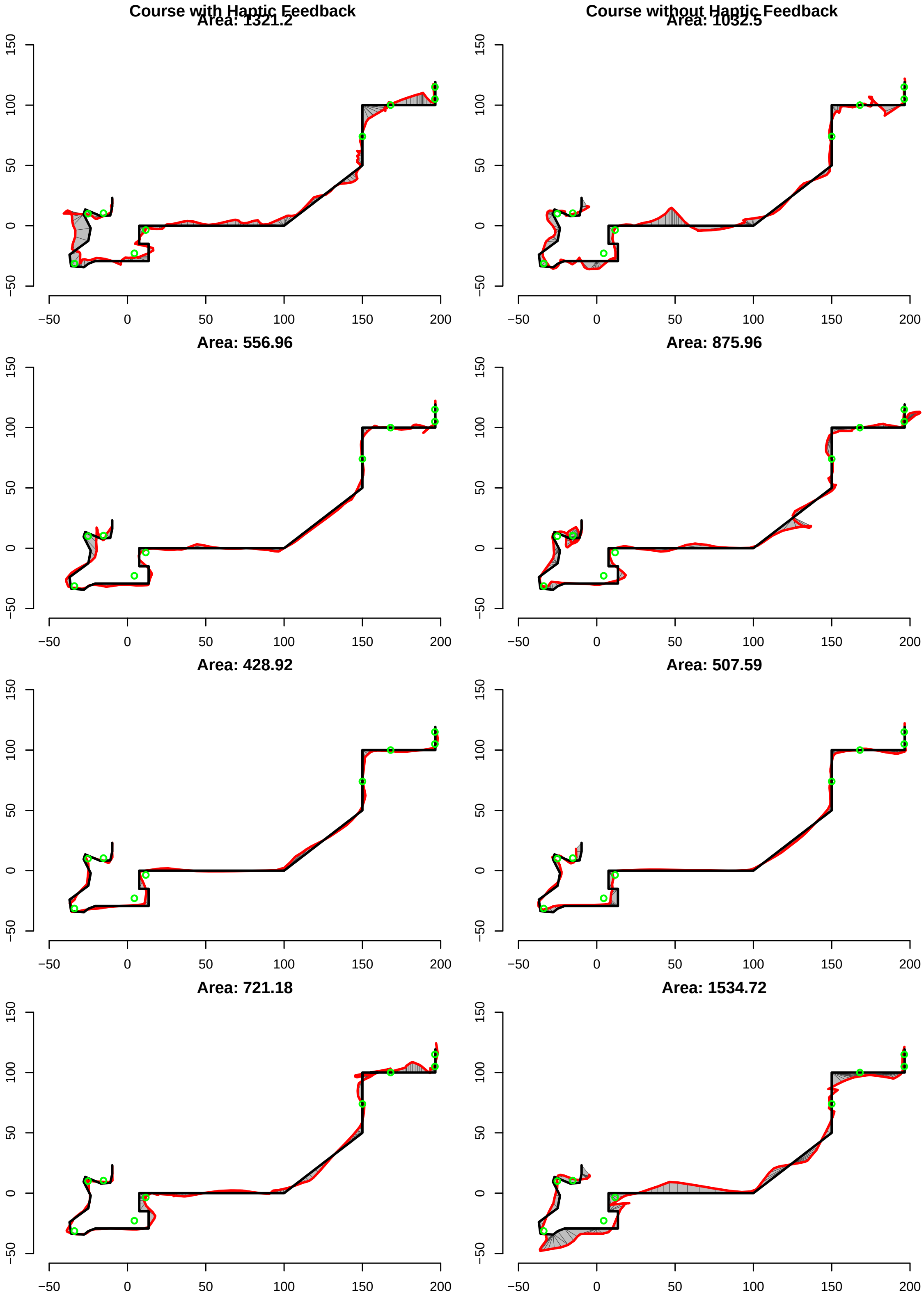
	Strongly Disagree	*Disagree*	*Undecided*	*Agree*	*Strongly Agree*
I could clearly perceive the vibro-tactile feedback during the flight					
I could clearly identify which information was encoded in the vibration pattern					
I would describe the sensation of feedback as being pleasant					
I could control the drone with little difficulty (regardless of feedback mode)					
I would describe the vest as being comfortable to wear					
I would describe the sensation of feedback as being confusing					
I would say that feedback helped fly the course more easily					
I would say that feedback made me more aware of the behaviour in flight					
I would say that having feedback did not lead to an increase in my concentration workload					

Open questions:

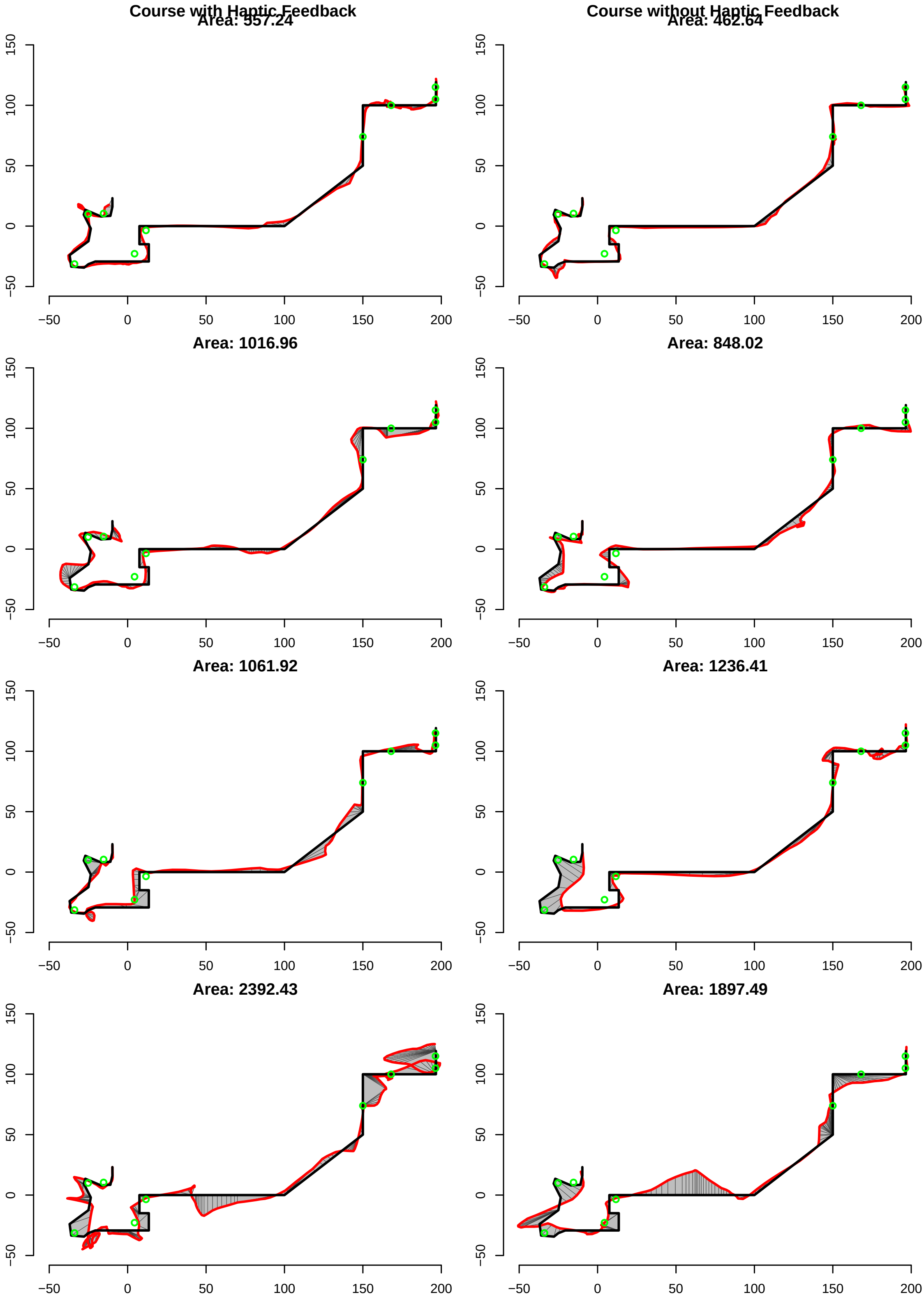
- Which mode of flying do you prefer and why?
- Is there an aspect of drone flying that you would like to receive feedback about and wasn't implemented in the current setup?
- How did you find the vibration patterns and the encoding method of flight parameters?
- How did you find the course, in terms of difficulty?
- What do you remember of the vibration patterns and what was the information encoded in them?
- Additional comments, remarks?

Appendix B

XY-plane flight paths



Course with Haptic Feedback
Course without Haptic Feedback
Area: 1321.2
Area: 1032.5
Area: 556.96
Area: 875.96
Area: 428.92
Area: 507.59
Area: 721.18
Area: 1534.72
−50
0
50
100
150
200


Course with Haptic Feedback
Course without Haptic Feedback
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Area: 1016.96
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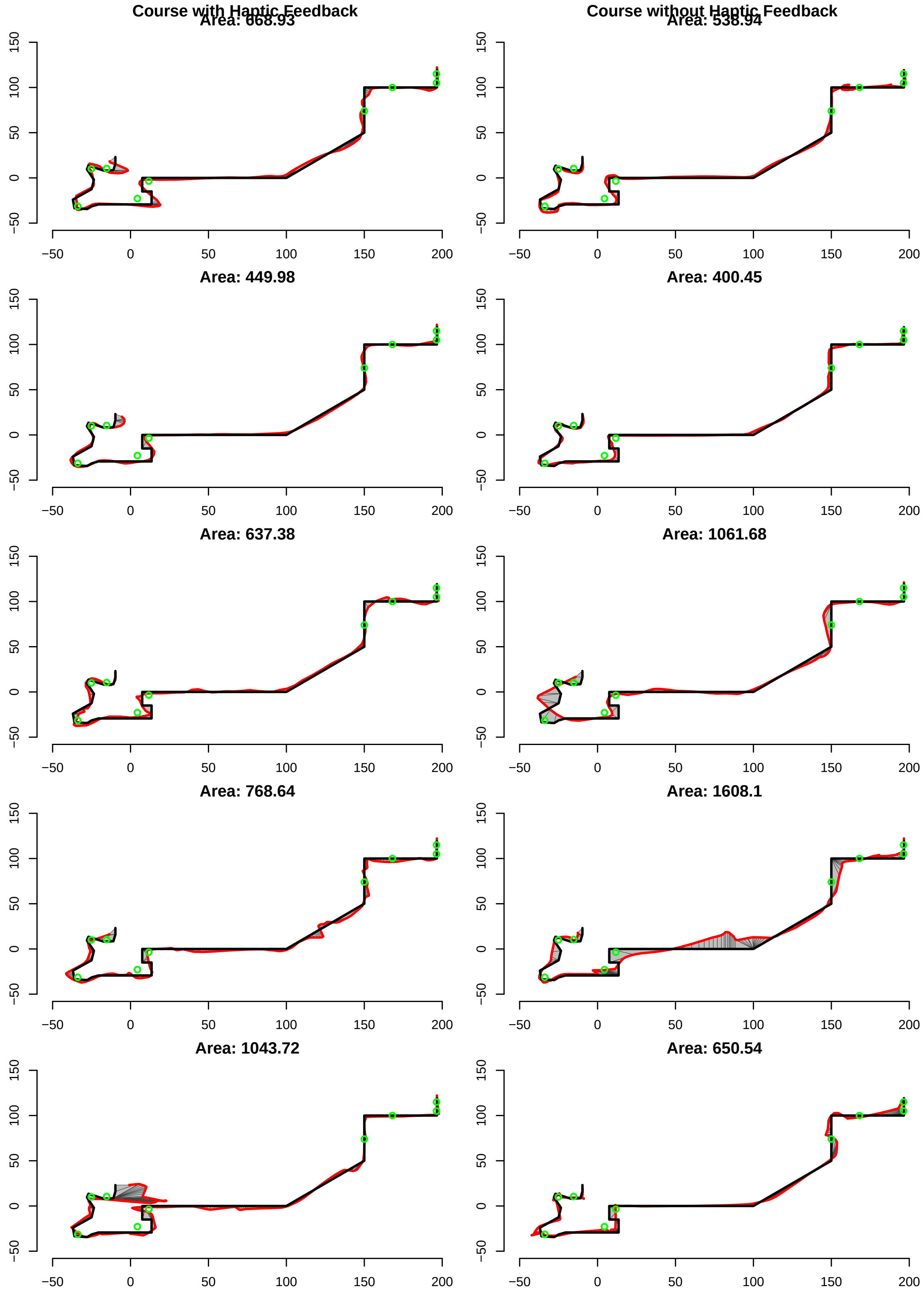
0
50
100
150
200


Course with Haptic Feedback
Course without Haptic Feedback
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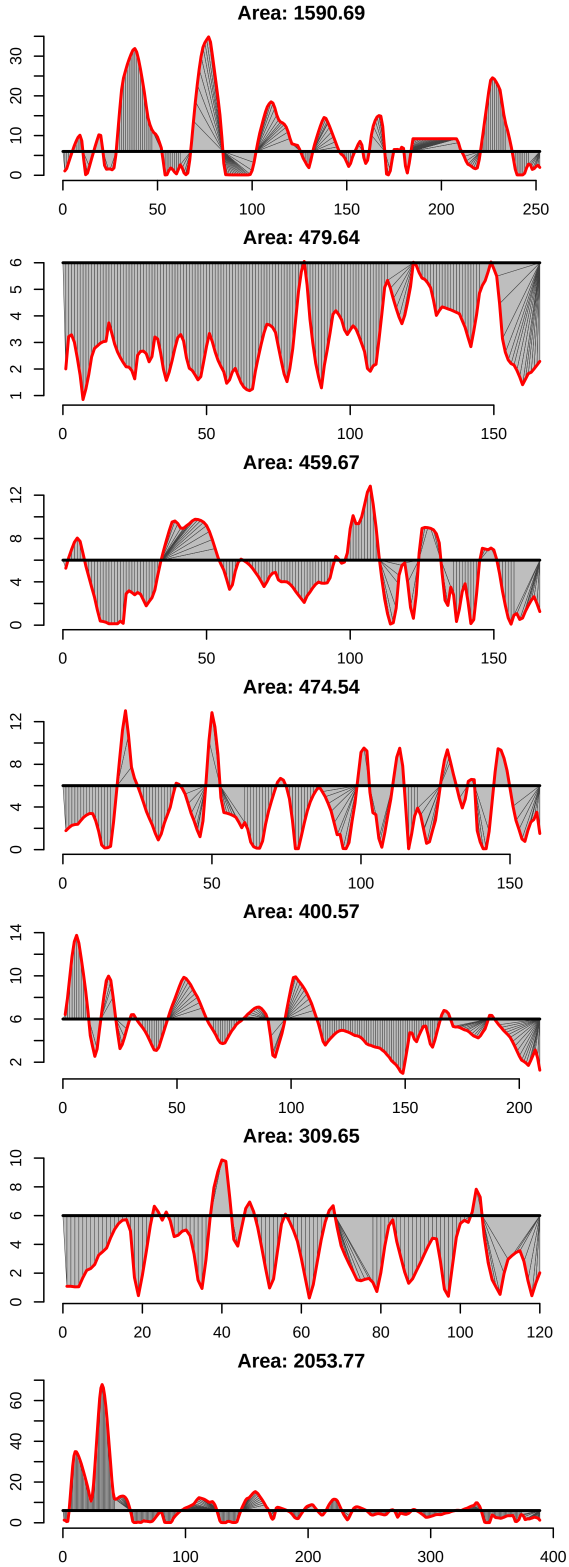
Area: 449.98
Area: 400.45
Area: 637.38
Area: 1061.68
Area: 768.64
Area: 1608.1
Area: 1043.72
Area: 650.54

Appendix C

Z-plane flight paths

C.1 Haptic feedback cues



C.2 No haptic feedback cues