Locomotion control interface for a remote robot (Avatar)

Thijs Wittendorp
S1739085

University of Twente
BSc Creative Technology

Supervised by
Dr. Ir. Douwe Dresscher and Prof. Dr. Ir Jan van Erp

Abstract

This project aims to find the best locomotion interface for operating a remote robot. An intuitive interface is needed for operating the i-Botics robot. With this robot, i-Botics is competing in the ANA Avatar XPRIZE. The grand challenge of this competition is to make the operator feel like he is in a different location. The challenge of this locomotion interface is that it has to be used without hands. It has to be used without hands because the operator's hands are occupied by the controls of the robot's manipulator. Literature research is done on how interfaces could be made intuitive and what interfaces are currently available. Locomotion interface concepts are made using this background information. A selection of four concepts is made, and prototypes of these concepts are built. The prototypes are evaluated in a user test and compared to each other to find which prototype performs best. The user tests showed that interfaces that have a literal relation between input and output performed best. Interfaces controlled with body-leaning are faster to learn than those controlled with feet. However, these two methods perform the same after learning. Although leaning based interfaces are faster to learn, the interface operated by feet has a higher usability score than the leaning based interfaces. This is why an interface operated by feet that has a one-to-one relation between input and output is the best interface for operating a remote robot.

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1. Introduction

1.1 Context

Robots are an essential part of contemporary life. They operate in many industries, such as the manufacturing industry, military, or fire brigade. Robots that are remotely controlled allow the operator to perform tasks from another location that he is.

The ANA Avatar XPRIZE is a competition with a grand challenge to create a robot that makes you feel like you are in a different location, can interact with people as if you are in the other location and bring your skills to this different location. The operator should be able to move the robot in a way that is not harmful to the people around the robotic avatar.

i-Botics is one of the participants in the ANA Avatar XPRIZE competition. It is an open Innovation hub for research, development, and implementation for interaction robotics. This research center has been founded by TNO and University of Twente. It aims at developing knowledge and technology for robotic solutions. There are two research lines i-Botics is currently working on; tele-robotics and exoskeletons.

1.2 Problem definition

One of the challenges in iBotics' XPRIZE project is the control of the movement of the remote robot. The control interface has to work with both a differential drive an omnidirectional platform. While controlling the movement of the robot, the hands of the operator are occupied with the control of the manipulator. Control of the movement, therefore, needs to be done through a different interface. The operator is restricted to a small space called the 'cockpit' and he or she is sitting or leaning position while operating. The goal of the controller is that the operator is 'embodied' in the remote robot and the operator does not have to think about how to control the platform in order not to break the embodiment.

1.3 Research question

The following research question will be answered: What is the most intuitive way to control the locomotion of a differential drive or omnidirectional robot without using hands? The learnability, efficiency, and effectiveness will be used to evaluate the intuitiveness.

1.4 Approach

There are many possibilities for the realization of this project. A selection of four existing or prototype interfaces will be made and user-tested to evaluate what the most suitable interface is. This user test will focus on what locomotion interface is preferred by users. The test participants of the controller will not operate a physical robot, but a robot in virtual reality. This will give the same effect since the real robot is also controlled from elsewhere with vision through a video feed.

1.5 Report structure

The structure of this report will follow the design process of creative technology, which consists of four phases: ideation, specification, realization, and evaluation. The ideation phase will focus on concept generation. To get insight in the subject background research will be done before the ideation phase. This insight will be used in the concept generation. In the specification phase and realization phase, one concept will be chosen, and a prototype will be made. The specifications of the prototype can change along the way. In the evaluation phase, the prototype will be evaluated with the help of user tests.

2. Background research

The background research consists of two parts. The first part is a literature review where research on intuition, immersive teleoperation and VR locomotion interfaces will be reviewed. The second part is the state of the art, which focuses on commercial available VR locomotion controllers. The existing locomotion interfaces will be compared and evaluated if they fit for controlling robotic avatars locomotion. The results of the literature will help to evaluate the existing interfaces or can give guidance if a new interface has to be designed.

2.1 Literature review

At the moment, it is not clear what the best way for locomotion control is without using hands. Research is needed on what the best way is to operate locomotion without using hands. In this literature review, it will be discussed what makes an interface intuitive, how teleoperation can be made immersive and what locomotion control interfaces are used in VR. The results of this literature review will be used to evaluate different locomotion interfaces.

2.1.1 intuitive interfaces

Intuition first has to be defined in order to develop an intuitive interface. At this moment, there is not one clear definition of intuition. Abernathy and Hamm identified 20 different definitions of intuition [1]. Some of these definitions describe intuition by what it is not, while other definitions describe it by an unconscious process. Epstein [1], on the other hand, describes intuition using cognitive-experiential self-theory (CEST). CEST is a dual-process theory of personality according to which people process information with two systems. In contrast to other descriptions, CEST is explicit about what intuition is. The first system of CEST is an experiential/ intuitive system, which is an associative learning system that humans share with animals. The second system is the human uniquely verbal reasoning system. The operating principles and attributes of both systems can be seen in table 1.

Table 1 Comparison of the Operating Principles and Attributes of the Experiential/Intuitive and Rational/Analytic Systems [1]

Experiential/Intuitive System	Rational/Analytic System
1. Operates by automatically learning from experience	1. Operates by conscious reasoning
2. Emotional	2. Affect-free
3. Motivated by hedonic principle to maximize pleasure & minimize pain	3. Motivated by reality principle to construct a realistic, coherent model of the world
4. Associative connections between stimuli, responses, & outcomes	4. Cause-&-effect relations between stimuli, responses, & outcomes
5. Behavior mediated by automatic appraisal of events & "vibes" from past relevant experience	5. Behavior mediated by conscious appraisal of events & of potential responses
6. Nonverbal: encodes information in images, metaphors, scenaros, & narratives	6. Verbal: encodes information in abstract symbols, words, & numbers
7. Holistic	7. Analytic
8. Effortless & minimally demanding of cognitive resources	8. Relatively effortful and demanding of cognitive resources
9. More rapid processing: oriented toward immediate action	9. Slower processing: oriented also toward delayed action
10. Resistant to change: changes with repetitive or intense experience	10. Changes more readily: changes with speed of thought
11. More crudely differentiated: broad generalization gradient; categorical thinking	11. More highly differentiated; dimensional & nuanced
12. More crudely integrated: context specific; organized by cognitive-affective networks	12. More highly integrated; organized by context-general principles
13. Experienced passively and we are seized preconsciously: by our emotions & have uncontrolled spontaneous thoughts	13. Experienced actively and consciously: we believe we are in control of our reasoning
14. Self-evidently valid: experiencing is believing	14. Requires justification via logic & evidence

Intuition is considered to be a subsystem of the experiential/intuitive system. Intuition operates by the same principles and attributes but has narrower boundary conditions than the experiential/intuitive system. The primary function of intuition is to learn automatically from experience outside awareness. This learned experience can be used to react quickly in present situations without reasoning.

Mappings can be used to implement previously learned experiences in an interface to make it intuitive. In [2], three different mappings are discussed; Metaphoric mappings, isomorphic mappings, and conventional mappings.

- Metaphoric mappings base input actions on everyday experiences. An example is the slider lock that was used on iOS, where the metaphor is a physical sliding lock.
- Isomorphic mappings are one-to-one literal relations between input actions and resulting system effects. The most common form is physical-physical mapping. An example of this is a racing game where the movement of a player's body is mapped to the car's movement. An advantage of physical-physical isomorphic mapping is that it is easy to learn.
- Conventional mappings are those adapted from previous practice and commonly found in product interfaces. When conventional matings are found across multiple interfaces, they become familiar. An example is the arrangement of letters on a qwerty keyboard.

The three mappings perform differently. In terms of intuitiveness, there is no difference between the three mappings. However, while using metaphoric mapping, the interface does not meet the expectations as much as with the other two mappings [2]. Another important note about metaphoric mappings, made by Still et al.[3], is that if the user gains experience with a system, the interaction can become more intuitive without the user of a metaphor. Besides mappings, using affordances is another method to make an interface intuitive [3]. Affordances are properties of an interface that show the possible actions a user can take and guide user interactions immediately and effortlessly. This guidance may make affordances the most intuitive type of interaction. Affordances have one-to-one relations and have this in common with isomorphic mappings. The combination of using affordances and isomorphic mappings seem to be the best way to make an intuitive locomotion interface.

Although intuitive interfaces are fast to learn, they are not always the best interfaces. For an interface to be intuitive, it has to be familiar, but a familiar interface is not always the best interface. An example of this is that the computer mouse was not intuitive for some people because they were not familiar with it. These people were familiar with an MS-DOS like interface which was more intuitive for them [4]. Thus an intuitive interface can be excellent for the first interactions, but Raskin [4, p. 18] stated that “a new interface paradigm that is commonly titled ‘intuitive’ may well turn out to be one of the worst qualities it can have.”

2.1.2 Immersive teleoperation

The level of immersion while teleoperating the robot is essential to focus on the task entirely. Immersion will give the operator the feel that he is present at the robot’s location. A key aspect of teleoperation is having visuals of the robot. A vehicle or robot can be remotely controlled while having visuals from cameras attached to the vehicle (inside-out control) or through observations of the vehicle (outside-in control). Outside-in-control only performs well if the vehicle is close to the operator and if there are no obscurations. There are several difficulties with both methods when remotely operating a vehicle according to paper [5].

- Outside-in-control can be disorienting if the vehicle is driving towards the operator because left and right are reversed, and problems with depth perception can occur.
- When using inside-out control, the field of view is essential. A narrow field of field performs worse than a wider field of view.
- Distance estimation is also a problem during both inside-out-control and outside-in-control. Operators using a head-mounted display have the feeling obstacles are further away than they are.
- Negative obstacles such as ditches, holes, and drop-offs are challenging to see on a screen. Stereo vision could help since depths can be seen better.
- Vehicle rollovers are a significant problem when driving over ramps and banks. The operator has no indication that a vehicle is in a dangerous situation, and the rollover comes as a surprise.
- Overcontrol is a typical characteristic of novice operators. The operator applies a steering input, but he does not immediately see the result. The operator increases the steering input until he sees a result. This increased input leads to more steering than intended. After some minutes, the operator steers slower, which results in less overcontrol.

These difficulties should be taken into account when developing an immersive locomotion interface. Many difficulties are due to bad vision or lack of depth information. These difficulties can be solved by using a virtual reality headset because this provides the user with depth information and has a wide field of view.

One difficulty that is not due to bad vision is overcontrol. The addition of kinesthetic feedback (simulator platform motion) can reduce overcontrol. The response time drops from an average of 0.56 to an average of 0.44 seconds when reacting to sudden changes with addition of kinesthetic feedback. The addition of steering wheel torque feedback can provide a 'feel of the road'. Without feedback, it feels like operating with a time delay in the control system [5][6]. The decrease in response time is of great importance because, according to [7], a time delay is the main problem in teleoperation control. Ideally, all forces in a telerobot are reflected to the operator without any time delay. However, in most cases, the impedance of the telerobot is much higher, and there is a physical distance to travel from the robot to the operator. Therefore, a time delay is an inevitable factor in teleoperation. This time delay is even more when communication is done over the internet. If this time delay is untreated, small delays may lead to instability of the telerobot.

2.1.3 Control interfaces in Virtual Reality

There are multiple ways to control locomotion in virtual reality games without the use of hands. This locomotion control in VR games has many similarities with teleoperating a robot while having visuals through a virtual reality headset. One aspect of a control interface in VR is controlling the camera angle; this can be done using a joystick or by head orientation. Paper [8] shows that controlling the camera orientation using head-tilt, present advantages for novice users because it is easy to learn. However, for trained users, there is no reason to prefer head-tilt control over a classical joystick control, since a joystick is faster than head-tilt for experienced users.

The second aspect of a VR input interface is locomotion control. Besides controlling the camera orientation with the user's head, locomotion can also be done using head-tilt. The VR character will move in the same way the user's head is leaning. Using head-tilt to control movement performs better, in terms of task completion, than navigation with controller or walk-in-place [9]. This method is easy to use and less demanding than using a keyboard and mouse for navigation, especially for less experienced users [10]. Leaning can be quicker and feels natural because people tend to lean in the direction they are walking. Besides smooth movement with controller, walk-in-place, or by leaning, locomotion can also be done in the form of teleportation. With this teleportation method, the user can point where he or she wants to go with his VR character. This method is faster than using a controller of walk-in-place, but because of the jumps, it is not immersive [11] [12]. Walk-in-place is more immersive than teleportation, but the disadvantage is that this method can be tiresome after a while. It seems that novice users prefer both the camera control and locomotion with head orientation. However, experienced users prefer methods without head orientation.

2.1.4 Conclusion

The goal of this literature review is to understand how a controller can be made intuitive, immersive, and easy to use. To make the controller of a robot intuitive, the user has to be familiar with it. The controls of the robot should look like controls that are common for most people. An intuitive interface might be beneficial for novice users but does not have to be the best interface for experienced users. Teleoperation can be made immersive by having good visuals, preferable stereo, and time delays as low as possible. For existing control interfaces, locomotion and camera angle controlled with the head is the easiest and quickest interface to learn for novice users. However, this is not the preferred interface for experienced users. Experienced users are faster with a controller or keyboard. The user has to be identified to design a locomotion controller for i-Botics. The most suitable controller for novice users is not the same controller as for experienced users.

2.2 State of the Art

There are already a number of VR controllers that allow for locomotion control without using your hand. These controllers can be controlled while staying in the same spot and with no movement of the hands. The controllers will be compared on five different criteria; the number of axis, operation position, speed control, feedback, and availability. The criteria will be listed in a table to get an overview of the controllers.

2.2.1 3dRudder: Foot Motion Controller For VR

The 3DRudder is a controller that enables you to control VR games with your feet. This leaves your hands free for other controls. The device can be used by placing both your feet on the controller. This can only be done while sitting because the controller does not support full body weight. The 3DRudder can be used by tilting, spinning, or pressing the device, which results in four controllable axis. A disadvantage is that the controller does not have haptic feedback. Another disadvantage of the controller is that it can slide on the floor when using it due to the sphere bottom.

Figure 1: 3DRudder

2.2.2 Ground control

Ground control is a VR accessory designed to support hands-free locomotion. Although the crowdfunding campaign was unsuccessful is still is an interesting concept. There are two separate controllers, one for each foot. These 4-axis controllers can move forward and backward, left and right, rotate and tilt. Both controllers control the same movement, but the values are added up for more precision. So if one controller is moved all the way forward, the in-game character moves at 50% speed. If both controllers are all the way forward, the character moves at 100% speed. Although both controllers have the same function, it can still be confusing for the users to have four controllable axis per foot.

Figure 2: Ground control

2.2.3 VRGO

The VRGO chair and VRGO mini are VR controllers that can be used without hand or feet. The VRGO is designed to sit on. To move the in game character in-game, you lean in the direction you want the character to go. The in-game character will rotate 1:1 with the rotation of the chair. The VRGO chair is an egg-shaped stand-alone chair while the VRGO mini is a controller that you place on your office chair. The egg shape of the VRGO makes it hard for users to balance and return to the neutral position to stop moving.

Figure 3: VRGO chair (left) and VRGO mini (right)

2.2.4 Stinky

The Stinky board does not allow for speed control, like the three controllers mentioned above. The controller consists of 4 buttons that can be clicked by tilting the pad in one of the four directions with your feet. The controller is not meant as a stand alone controller but as a complementary controller. The controller does not have speed control because it has buttons and not a step-less input.

Figure 4: Stinky board

2.2.5 Alto 100

The alto100 is a plate where you can stand on and move to the edges of the controller to move in that direction. It is not clear if the controller can detect how far the user is from the edge in order to control the speed. The controller features haptic feedback that makes you feel the VR world move underneath you. This is done with a flexible top surface of the controller. Alto states that this controller has an intuitive experience and has few cases of people with nausea using this controller.

Figure 5: Alto100

2.2.6 Comparison of controllers

An overview of the different interfaces and the different criteria can be seen in table 2.

Table 2: VR controllers with their criteria

	3DRudder	Ground control	VRGO	Stinky	Alto100
Number of Axis	4	4	3	4	2
Operating Position	Sitting	Sitting	Sitting	Sitting	Standing
Speed control	Yes	Yes	Yes	No	Unclear
Haptic feedback	No	No	VRGO chair: No VRGO mini: Yes	No	Yes
Control input	Feet	Feet	Body leaning	Feet	Body position
One-to-one relation	Yes	Yes	Yes	Yes	Yes
Available for sale	Yes	No	VRGO chair: Yes VRGO mini: NO	No	Yes (developer kit)

2.2.7 Conclusion

From the literature, it is learned that a locomotion interface that uses leaning is more intuitive for novice users. The VRGO is the only interface that uses this technique. Although the 3DRudder does not use a leaning technique, users report a learning time of 15 minutes, which is the same as the learning time of the VRGO. Feedback in the interface can reduce the response time of the operator, and this feedback is used in the VRGo and Alto100. The alto100 is used by standing on the edge of the device in the direction you want to go. To look in the direction you are moving, the user has to turn his body so his face is towards the edge of the device. This movement is not possible in the cockpit and the alto100 is therefor not suitable. The Stinky and possibly the Alto100 do not have speed control which can make it difficult to control a robot precisely. The Ground Control is expected to be difficult to use because each foot has 4 axis to control. Overall the 3DRudder and VRGO seem to be the best solution although they have some disadvantages.

The 3DRudder and the VRGO are promising interfaces because users report that is intuitive to use and are able to control an omnidirectional robot. However, they have both have disadvantages. Both interfaces currently have no haptic or force feedback. The VRGO has the disadvantage that it is hard to find balance, and the 3DRudder can have the same problem because it does not automatically return to the center position. The 3DRudder has a problem that it can slide on slippery surfaces, there is however, a 'ground gripper' accessory that should fix this, but it is not released yet. These two interfaces are also not suitable for usage while the operator is in a leaning position. Besides these two interfaces, there are many more solutions possible for locomotion, which are not in a commercial product. Different concepts of an interface should be generated to see what else is possible. Some of these concepts can be based on the 3DRudder and the VRGO. These concepts can be evaluated, and a prototype of some of these will be made to test what interface works best.

3. Ideation

The ideation will focus on concept generation of locomotion control interfaces. The users of the interface will be identified to come up with concepts that fit the user's needs. Product requirements will be set to guide the design process. Based on the user needs and requirements, ten different concepts will be generated. The concepts will be evaluated, and the top three concepts of these ten concepts will be chosen to work out further in the specification and realization phase.

3.1 User identification

The control interface of the robot will be used by members of i-Botics. However, during the XPRIZE competition, the interface will be evaluated by a jury. This jury panel will have a limited time of one hour to learn the interface before evaluating it. The control interface has to be intuitive enough for the jury to learn it within one hour.

3.2 Context

To come up with the best method of a locomotion interface, the context in which it will be used has to be determined. When controlling the robot, the user is restricted to a small space called the cockpit. In this cockpit, the operator is in a sitting or leaning position. The operator’s hands are occupied by the control of the robot’s manipulator. The operator has stereoscopic visuals of the robot through a virtual reality headset, and he or she can rotate his head to look around. Head motion can therefore not be used for the control of locomotion.

3.3 Product requirements

- The interface has to work without the use of hands
- Head motion for locomotion can not be used
- Operators movement is restricted to the cockpit
- The interface has to work with both an omnidirectional and differential drive platform
- Can be used while sitting or leaning

3.4 Concepts

The ten different concepts are listed below. Despite the fact that it emerges from the literature review that force feedback can improve the experience, it is chosen not to implement force feedback. This leaves more time to make multiple prototypes. However, the concept will be evaluated on the possibility of adding haptic or force feedback in the future. This feedback can give the user a ‘feel of the road’ or get information about the proximity of obstacles.

3.4.1 Concept 1

In this first concept, the translational movement of the robot is controlled by the operator leaning in the desired direction. The operator’s body angle is measured by an inertial measurement unit attached to the operator’s chest. Rotation of the robot is done by the operator’s feet, and three different methods of this can be seen in figure 6. The three methods are: a rotating disk, a pressure plate and a small seesaw where both feet are placed on. This interface has a disadvantage that it can be hard to find the center where the robot is not moving. Feedback is hard to implement in the device attached to the operator, but it is possible to add in the feet part.

Figure 6: Concept 1

3.4.2 Concept 2

The second concept is like concept 1, also controlled by the operator leaning in the desired direction. However, the leaning direction is not measured with an imu but with a pressure plate mounted on the seat. Rotation is done with the feet like in concept 1. In this concept, it can also be challenging to find the center position where the robot is not moving. However, in contrast to concept 1, this concept allows haptic feedback in the chair.

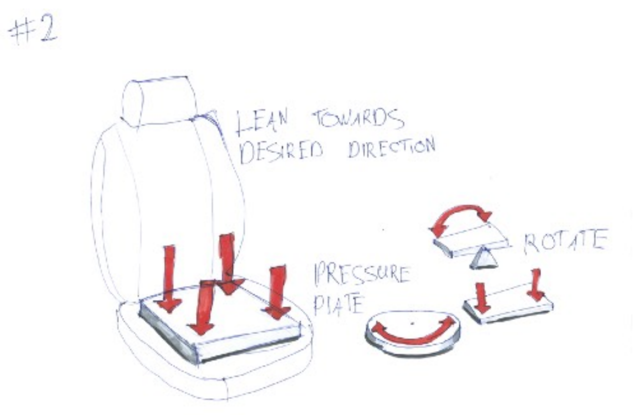

Figure 7: Concept 2

3.4.3. Concept 3

Concept 3 is another interface based on leaning. This interface is a chair that can bend in any direction and is able to rotate. A spring in the leg allows the bending of the chair, as seen in figure 3. The movement of the chair is one-to-one linked with the movement of the robot. The spring should not be too stiff otherwise it will be tiresome to move the chair. Rotating while the chair is bend can be difficult. Haptic feedback can be implemented in the chair, but force feedback hardly possible.

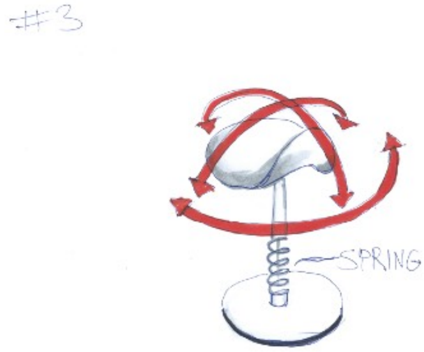

Figure 8: Concept 3

3.4.4 Concept 4

This fourth concept is controlled by only using your feet. A rotating disk can move in x and y-direction. An advantage of this concept is that the operator's feet do not have to rotate with the translational movement. This is a more one to one movement with to feet and the robot. Springs can be added to automatically return to the center position. Moving the disk towards the operator can be hard when springs are added. It is possible to add motors for force feedback, but it will become a complex system.

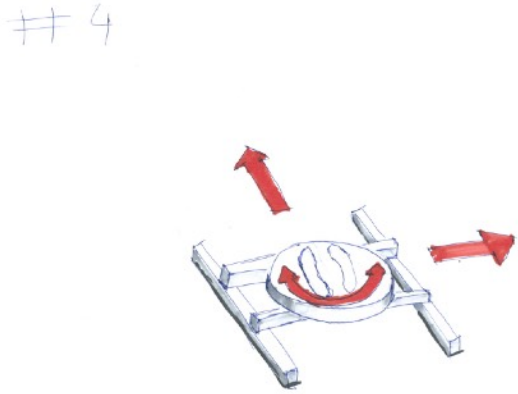

Figure 9: Concept 4

3.4.5 Concept 5

Concept 5 is heavily based on the 3DRudder. The controller is used by placing your feet on the half sphere and tilting it in the direction the robot has to go. To rotate, the robot the controller can be rotated. A sketch can be seen in figure 10. This system has the same advantages and disadvantages as the 3DRudder.

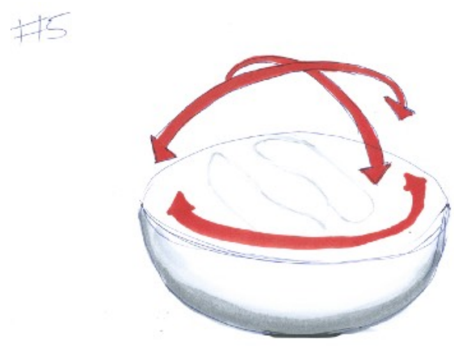

Figure 10: Concept 5

3.4.6 Concept 6

Concept 6 is a concept that does not use a one-to-one relation between the controls and robot movement. X and Y movement is done with two separate pedals where the feet should be placed on. The pedals are mounted on a rotating disk. The rotation of this disk controls the rotation of the robot. The two pedals are not a one-to-one motion with the robot. This can make it confusing and harder to learn.

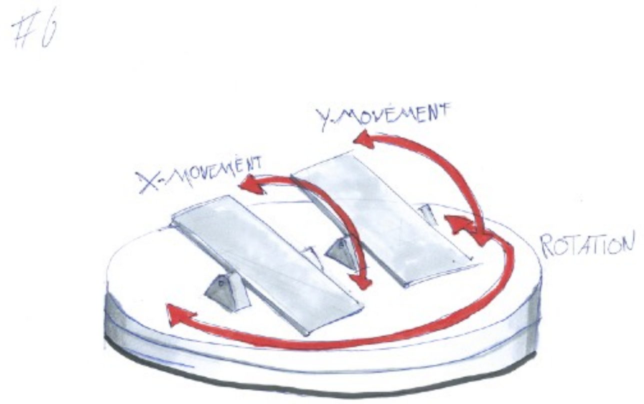

Figure 11: Concept 6

3.4.7 Concept 7

Concept 7 uses differential pedals ,which are controlled by using your feet. If both pedals are in the forwards position, the robot will go forward. However, if the pedals are in opposite direction, the robot will rotate. To move sideways, both pedals can be moved to the left or right. This design might take some time to learn because both feet have to move independently.

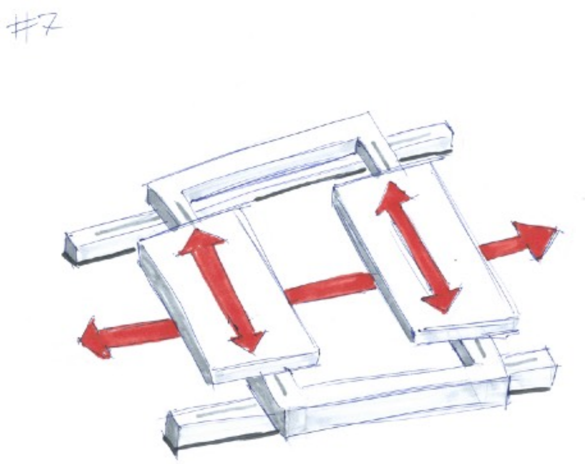

Figure 12: Concept 7

3.4.8 Concept 8

Concept 8 uses a rudder system to control the rotation of the robot. This rudder system is a parallelogram, so the pedals attached at the end will not rotate but only move back and forth as depicted in figure 8. The x and y-movement of the robot are controlled with the pedals. An advantage of the parallelogram is that your feet do not have to turn, which makes it more comfortable. The x and y movement can be confusing.

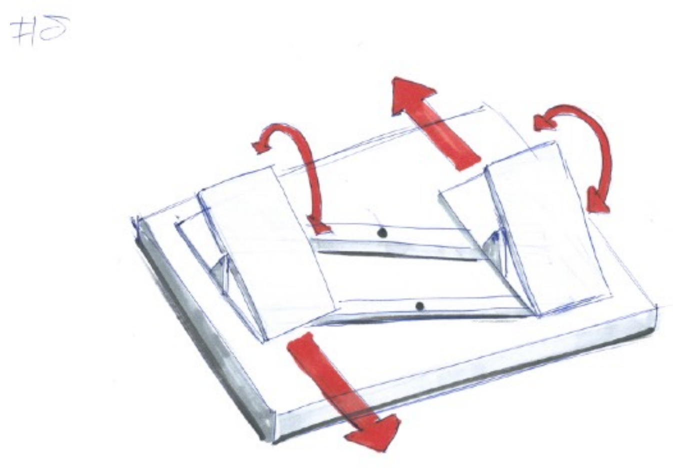

Figure 13: Concept 8

3.4.9 Concept 9

Concept 9 consists of a rotation disk for rotation with a pressure plate on top. The pressure plate controls the x and y movement of the robot. The operator has to apply pressure in the desired direction. An advantage of this concept is that it is a simple design with few moving parts. Haptic feedback can be added in the pressure plate. It can be hard for the operator to precisely feel how much pressure he applied and how fast the robot will move.

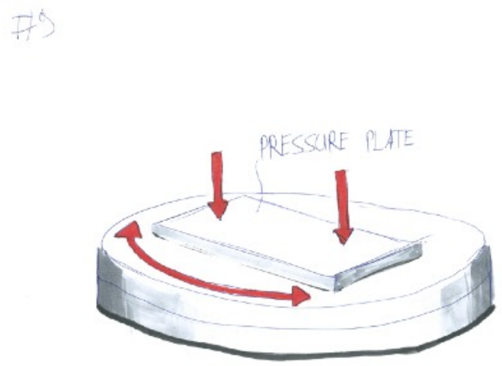

Figure 14: Concept 9

3.4.10 Concept 10

The last concept is a complex design. Two rings can rotate independently from each other. These two rings control the x and y movement of the robot. On top of the second ring is a rotating disk that operates the rotation of the robot. Because all axis

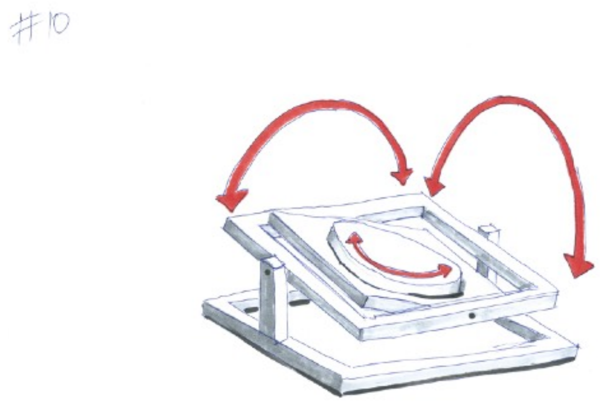

Figure 15: Concept 10

rotate, force feedback can be implemented by adding motors to each axis. A disadvantage of this design is that it is complex to build, which can result in an interface that is not working or can break easily.

3.5 Concept Evaluation

The evaluation of the ten different concepts will be done using a multi-criteria analysis. It is chosen because it offers a good comparison of the criteria. Each concept is given a score or value for the different criteria, as seen in table 3. The priority of each criterion is calculated using a pairwise comparison using an online comparison tool. These priorities are shown in table 4. The scores are normalized and multiplied by the priority to get a ranking for each concept which can be seen in table 5.

The result of the multi-criteria analysis shows that concept 3 has the highest score, followed by concepts 2 and 1. Concept 9 and 1 have a nearly identical score, but concept 9 is the only one of the top four that uses feet as input. It will be interesting to see how this compares to leaning as input. Concept 5 also has a high score and should also be considered using.

Initially only three prototypes would be chosen to use as a concept. After prototypes were made for the three chosen concepts, there was time left for another prototype. All three prototypes have a one-to-one relation. It would be interesting to compare the one-to-one to a prototype that does not have this one-to-one relation. A concept that has two independent pressure plates is chosen as well. This concept steers by applying pressure on the front with one foot and on the back with the other foot. An illustration can be seen in figure 16.

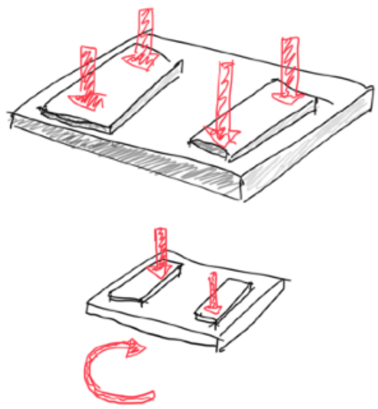

Figure 16: Concept with alternative steering

Table 3: Input MCA

	1	2	3	4	5	6	7	8	9	10
Complexity	4	6	4	7	4	8	8	8	5	9
One-to-one	yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
Possibility haptic feedback	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Possibility spring loaded	No	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes
Control input	Lean ing	Lean ing	Lean ing	Feet	Feet	Feet	Feet	Feet	Feet	Feet
Predicted comfort	7	7	6	5	6	5	6	6	7	5
Predicted easy of use	6	6	6	5	6	4	5	4	6	4

Table 4: Priority

Criteria	Weight
Complexity	2,5
One-to-one	30
Possibility haptic feedback	8
Possibility spring loaded	11
Control input	8
Predicted comfort	14
Predicted easy of use	13

Table 5: Concept ranking

Concept	Rank
1	67,5
2	74,5
3	79,5
4	56,5
5	60,5
6	19,5
7	33,5
8	18,5
9	67
10	49

4. Specification & Realization

In this chapter, the design decisions of each prototype will be explained, and it will be explained how this is realized in a working concept. These prototypes will be tested in a virtual reality environment created in the Unity engine. The specification and realization of this VR environment will be elaborated as well.

4.2 Concept 9 realization - Pressure plate on a rotating disk

As described in the previous chapter, this concept consists of a pressure plate on a rotating disk. The operator applies pressure on the plate in the direction he wants to robot to move. The rotating disk controls the rotation of the robot. A sketch of the prototype can be seen in figure 14.

4.2.1 Specification

- Must be able to measure x and y direction and rotation.
- Must not break when large amounts of force are applied
- Must have the accuracy and precision to control 10 different speed levels
- Must communicate with the Unity program
- Should automatically calibrate
- Should have error handling
- Could have a beautiful design

4.2.2 Pressure plate

There are several ways to measure pressure. The most common way to do this is by using a load cell or a force-sensing capacitor. Force-sensing capacitors can provide improved sensitivity and repeatability compared to load-cells. However, because this interface is operated by using your feet which can apply relatively large amounts of force, the sensitivity of a load cell is high enough. The costs of load cells are lower than that of a force-sensing capacitor, and load cells are much more common in everyday products like weight scales. Because the sensitivity of a load cell is high enough, and these sensors can be found in old weight scales, these sensors are chosen to measure the applied force.

Loadcells are usually made of strain gauges in a Wheatstone bridge configuration, as seen in figure 17. These strain gauges are made of thin wires that have a change in resistance if they are stretches. A downside is that the resistance will also change if the temperature changes. There are multiple strain gauges in the Wheatstone bridge configurations to have the same resistance in different environment conditions. This solves the problem of different resistance in different environment conditions

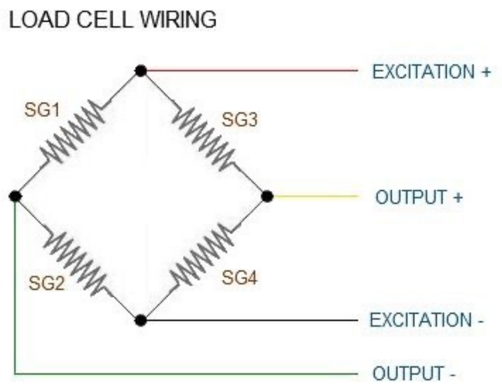

Figure 17: Wheatstone bridge

The load cells that will be used in this prototype are from an old weight scale. These load cells have only three wires, which indicates they are made from only half a Wheatstone bridge. In the weight, scale two load cells are used to create a full bridge. This is however not possible in this prototype because the force on each corner of the plate should be measured independently. To still have a full bridge, two resistors of the same value as the strain gauges, 1 Kohm, are added. The electrical schematic of the prototype can be seen in figure 18.

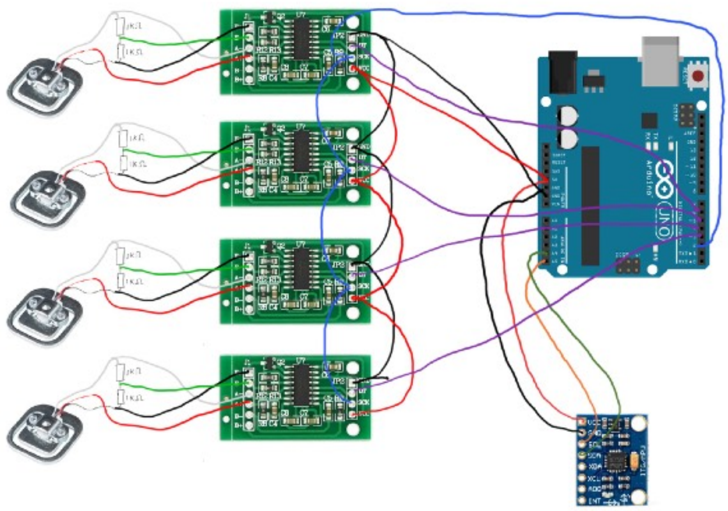

Figure 18: Schematic of pressure plate

The signal from the load cells is amplified using an HX711 breakout board. This board amplifies the signal and has a 24-bit analog to digital converter. For each load cell, an HX711 board is used. The four boards share a serial clock input, but each board's digital data output is connected to a different input pin of the Arduino. A library called HX711-multi is used to read the values of the four HX711 boards. This library is a modification of the HX711 library and allows to connect multiple HX711 boards to the Arduino. The HX711 has a refresh rate of 10Hz or 80Hz depending on the input of pin 15 of the HX711. The default rate is 10Hz which was, unfortunately, found after user test were done. This refresh rate of 10Hz is much lower than the frame rate of the virtual reality headset which is at least 90fps for smooth usage. This low refresh rate of the HX711 could make the prototype feel unresponsive.

The direction can be measured by calculating the difference between the center of the pressure plate and the center of pressure. An illustration can be seen in figure 19 to clarify this method.

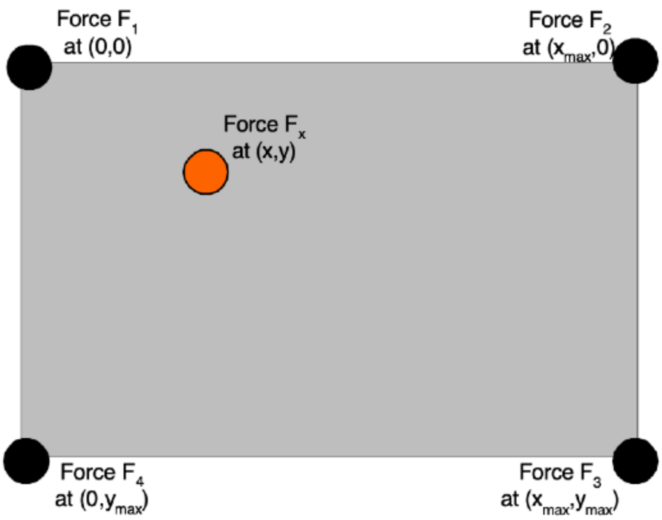

Figure 19: Determining the position using 4 load cells [14]

A load cell is placed at each corner of the pressure plate. Each load cell will measure a different force depending on where the pressure is applied. The center of pressure can be calculated using the following formulas [14].

$$F_x = F_1 + F_2 + F_3 + F_4 \quad (1)$$

$$x = (F_2 + F_3)\frac{x_{max}}{F_x} \quad (2)$$

$$y = (F_3 + F_4)\frac{y_{max}}{F_x} \quad (3)$$

The values of each load cell can be used in the formulas without converting the values, to for example kilograms, because the difference between them is used to calculate the position.

4.2.3 Rotation measurement

The pressure plate is mounted on a rotating disk. This rotation can be measured multiple ways, for example by using a potentiometer, rotary encoder, or an inertial measurement unit (IMU). The pressure plate will also be used in concept 2, where the pressure plate is placed on a rotating chair. Connecting a potentiometer or rotary encoder to a chair requires modifying the chair or a complicated hardware design to make this work. If an IMU is used in the pressure plate, the rotation can still be measured without having to modify a chair. When used correctly, an IMU is precise and accurate enough to measure the rotation of the pressure plate.

The IMU used in this prototype is the MPU6050, which has a 3-axis accelerometer and a 3-axis gyroscope. The data of both sensors is combined by the MPU6050's digital motion processor to compute the pitch yaw and roll of the IMU. Using the digital motion processor of the MPU6050 gives a high accuracy and precision, however the Arduino code to use the digital motion processor is complex. Instead a library that reads the raw values of the MPU6050 and calculates angels is used in this prototypes. This library, called MPU6050_tockn, is much simpler to use but still has enough accuracy and precision for this prototype. The refresh rate of the IMU in combination with the Arduino is 100Hz which is much higher than the HX711's refresh rate.

The range of motion used for rotating is from -30 and 30 degrees. These angels are comfortable to use which is concluded after trial and error. If the pressure plate is rotated more, the robot will rotate faster in that direction.

4.2.4 Physical design

The pressure plate is made from a wooden plate that is 30cm by 40cm. These dimensions are such that two feet can be placed on them comfortably. On each corner of the wooden plate a load cell is glued as described before. The four load cells are connected to the amplifier boards, which are also placed on the bottom of the pressure plate. A cable connects the four amplifier board to an Arduino that is near the computer. The IMU is placed on the bottom of the pressure plate as well. A picture of the bottom of the pressure plate can be seen in figure 20.

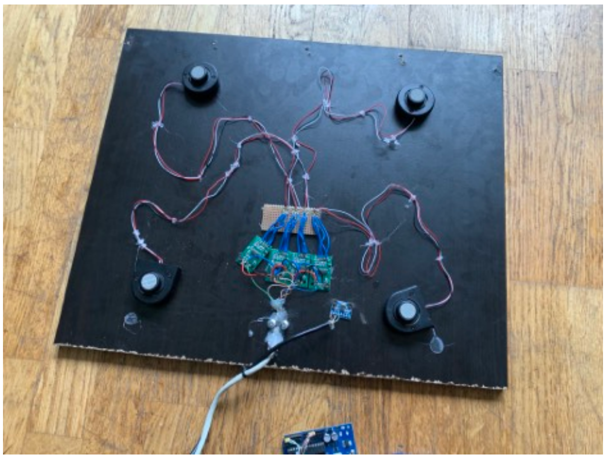

Figure 20: bottom of pressure plate

The pressure plate is placed on a rotating disk. This disk is made from a turntable sold by Ikea. This turntable is designed to place food on, so it is not stable enough to place your feet on and apply pressure. There is much play between the bearing and the wooden plate when placing feet on the disk. This is fixed by making the connection between the bearing and wooden plate stronger with two-component adhesive. The bottom plate of the turntable is replaced with a larger plate, so it does not tip over. Last, rubber bands are attached between the top and bottom plate to make it automatically return to the center position. An image of the bearing and pressure plate can be seen in figure 21.

Figure 21: rotating disk

4.2.5 Evaluation of prototype

The prototype does fulfill most requirements. It is possible to move the robot in VR in all directions. The ten different speed levels can be controlled. This is tested using a simple program created in Processing in which a circle can be controlled with the prototype. The screen in devices into a raster of 20 by 20 squares. The circle moves over the squares and can be moved, so it fits in the square. A screenshot of the program can be seen in figure 22. During testing, it is possible to move the circle to the desired position and keep it there. This proofs that the concept has the precision and accuracy to control the robot with 10 different speed levels. The prototypes automatically calibrate on startup, which is a function of the libraries used. There is some sort of error handling where really large values are ignored but other types of errors are not handled. The physical design of the prototype is durable and robust since it is possible to stand on it. The design of the prototype is not very beautiful and looks like a rough hacked prototype.

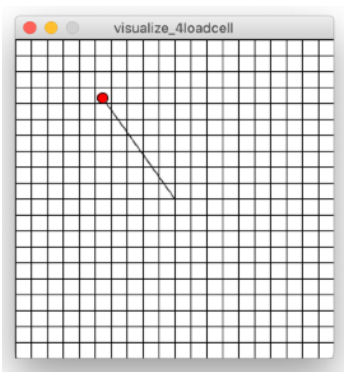

Figure 22: Precision and accuracy test program

4.3 Concept 2 realization - Pressure plate on chair

Concept 2 is using a pressure plate on a chair. To move in a specific direction, the operator has to lean in the direction he wants to go. A change in the concept is that rotation is not done by feet, but by rotating the chair. This is done so all controls are done by the body, and the feet are free to help to lean in a certain direction. A sketch can be seen in figure 7.

4.3.1 Specification

- Must be able to measure x and y direction and rotation.
- Must not break when large amounts of force are applied
- Must have the accuracy and precision to control 10 different speed levels
- Must communicate with the Unity program
- Should automatically calibrate
- Should have error handling
- Could have a beautiful design

The pressure plate of the previous concept will be used in this concept as well. An additional plate of wood is placed between the seat of the chair and the pressure plate, to make the pressure plate work on a chair,.

4.3.2 Evaluation prototype

Since this prototype is almost the same as the previous, most requirements are fulfilled. It is a bit more challenging to control the 10 different speed levels since the seat of the chair that is used can compress a bit. Even with a wooden plate beneath the pressure plate. This could be solved by using a wooden chair that can rotate. This prototype does look better than the previous because the rotating disk is not necessary and is, therefore, less bulky.

4.4 Concept 11 realization - Pressure plate alternative steering

This concept is the only one that has a non one-to-one relation. This concept has another method of steering compared to the other three prototypes. To steer, pressure is applied on the front with one foot and on the back with the other foot. The sketch of this prototype can be seen in figure 16.

4.4.1 Specification

- Must be able to measure x and y direction and rotation.
- Must not break when large amounts of force are applied
- Must have the accuracy and precision to control 10 different speed levels
- Must communicate with the Unity program
- Should automatically calibrate
- Should have error handling
- Could have a beautiful design

4.4.2 Physical design

Again the pressure plate is used in this prototype. This time the pressure plate is used upside down, with the load cells pointing upwards. On each set of two load cells a wooden plate is glued and secured with duct-tape. This is certainly not the best way to attach the wooden plates. This concept was chosen to build after the pressure plate was finished, so the pressure plate was not designed with this prototype in mind. A picture of the prototype can be seen in figure 23.

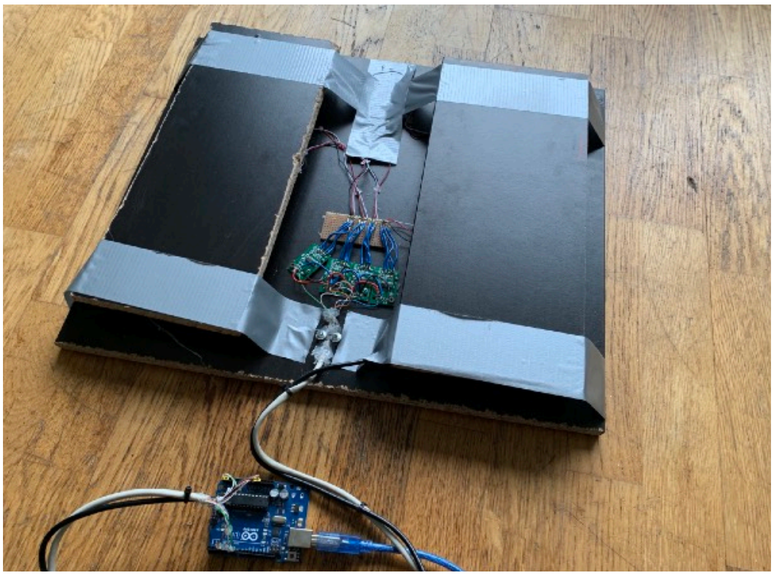

Figure 23: prototype with alternative steering

Rotation measurement

For calculating the rotation, the center of mass is calculated for each of the two plates. This is done using the same formulas as for calculating the y position as describes in the pressure plate section, but this time the y position is calculated for each plate. Adding the the y value of the first plate and the negative y value of the second plate will give a value for rotation. If on both plates the same pressure is applied on the front or back, the rotation values will cancel each other out, which results in no rotation.

For moving forward, backward and sideways nothing has changed compared to the pressure plate on rotating disk concept. The calculations of the rotation and translation do not seem to interfere with each other. It is possible to move forwards and rotate at the same time.

4.4.3 Evaluation of prototype

This prototype is an altered version of the pressure plate concepts. The two plated are not secured very well and the physical design is not very good. The duct tape also does not add to the esthetics of the prototype. While the build quality is not that great, the prototype does function well. Like with the other prototype based on the pressure plate, all 10 speeds could be reached. This can be done while applying a steering action. It is however difficult to do, but this is a limitation of the user, not the prototype.

4.5 Concept 3 realization - Spring chair

The spring chair is a concept that is based on leaning. A spring in the leg of the chair allows it to bend in the direction the operator wants to go.

4.5.1 Specification

- Must be able to measure x and y direction and rotation.
- Must not break when large amounts of force are applied
- Must have the accuracy and precision to control 10 different speed levels
- Spring must be stiff enough to not compress while sitting on
- Must communicate with the Unity program
- Should automatically calibrate
- Should have error handling
- Could have a beautiful design

4.5.2 Physical design

The spring used for the chair is from an old spring rider, an outdoor playing device found in most playgrounds. This spring is stiff enough that it does not compress when sitting on it, but is still flexible enough that it can bend quite easily when sitting on it. Spring riders usually are dug into the ground to make it stable. This prototype has to be used indoors so it can not be dug into the ground. A wooden frame is attached to the bottom of the spring to make it stable when using. A picture of the spring and frame can be seen in figure 24. On top of the spring, there is a wooden plate on which a bearing is placed.

Figure 24: Prototype spring chair

This is the same bearing like the one used in the first prototype. It is glued on the wooden plate with two-component adhesive, so there is no play. On top of the bearing, a wooden plate is mounted as the seat of the interface. This concept was designed with a saddle-like chair, but since the spring is high, it would not be possible to reach the ground with your feet. This is why a low profile bearing and a wooden plate is chosen.

4.5.3 Angle measurements

A spring is used in this concept which means that there is not a pivot point where a potentiometer or rotary encoder could be mounted on. An IMU is used to measure the angle of the seat compared to the floor. The rotation of the seat could be measured with another sensor, but since there already is an IMU it is more convenient to use this as well for the rotation measurement.

The MPU6050 library used in the previous two prototypes performs well if only one axis is changed at a time, but if multiple axes are changed at a time the measurements are inconsistent. The measurements will drift quite fast, and after a while, it is no longer possible to control a robot. To solve this problem, a library which uses the digital motion processor of the MPU6050 is used. The code is more complicated than the library used in the previous prototypes, but this does solve the problem of drift when moving along multiple axes. This library also is much more precise and accurate than the library used for the previous prototypes.

The range of motion that is measured for the x and y-axis is from -10 to 10 degrees. This angle can be reached without too much force. For angles more than 10 degrees, it is required to hold yourself to the seat, otherwise you will slide off. The range of motion for rotation is from -30 to 30 degrees, like in the previous prototypes.

4.5.4 Prototype evaluation

The physical build is robust since it is made of a spring designed for much more movement, and the wooden bottom frame is sturdy and substantial. It is not expected that this prototype would brake with regular use or even non-normal use. The weakest point of this prototype is bearing because it is not designed to sit on. However, the bearing can hold it quite well, and a little play is not a problem because the seat can rest on the carriage bolts beneath it. The interface can be used with high precision and accuracy, and the ten different speed levels can be reached easily. It calibrates before startup, and error handling is done the same way as in the previous prototypes.

4.1 VR Environment

The four locomotion interface prototypes will be tested in a virtual reality environment because this way, the actual tele robot does not have to be used to evaluate the interfaces. It is possible to use the prototypes without a VR headset, however, since the tele robot will also be used with a VR headset, it is closer to the real situation when a VR headset is used. It can be that some prototypes are causing more motion sickness than others. This can only be tested when using a VR headset.

An HTC Vive headset will be used to view the VR environment. This headset is powered by steamVR, which is a tool to run VR-content on a VR headset. VR-content can be created in the Unity game engine. There is a steamVR plugin available in Unity to play the content on the headset. Unity and the steamVR plugin will be used to create the VR environment.

4.1.1 Environment

The real-world robotic system will have to operate indoors. It has to maneuver in open areas, in tight spots, and look at things or interact with the environment. To replicate such an environment in VR a room where the robot has to navigate in both tight and open spots. The VR environment is a large room with obstacles to make a sort of labyrinth. The top view of this labyrinth can be seen in figure 25. It is possible to look over the obstacles so the whole room can be seen. This way, there is less chance of VR motion sickness which is learned from personal experience. As said before, the VR environment will be created in Unity. To build the room and the obstacles, a plugin called ProBuilder will be used. This plugin allows to quickly building simple geometry.

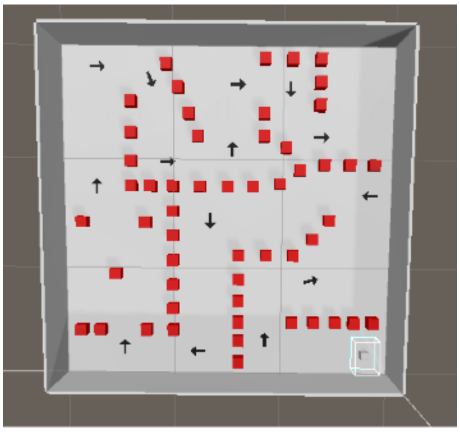

Figure 25: Top view of VR environment

The robot is represented by a simple cube that can move in x and y direction and can rotate. This movement is done with a CharacterController, which allows for easy movement and collision constraints. The CharacterController uses an input values between -1 and 1 to control the velocity of the character.

4.1.2 Motion sickness

Motion sickness became a problem during the development of the VR environment. The first issue that caused this was a too low frame rate. This was because the computer used, a MacBook Pro, was not capable of handling the VR headset. Switching to a computer with a GTX1060 video card solved this problem, and frame rates are above 90fps and motion sickness is a lot less. However, when changing direction and especially when rotating motion sickness still occurred sometimes. One way to reduce motion sickness while moving, is by fading out peripheral vision. This is subconsciously interpreted as motion without significant information loss [13]. To achieve the loss of peripheral vision, a unity plugin called VR Tunneling Pro is used. With this plugin a color vignette can be applied when moving or accelerating fast. In figure 26, a screenshot of the color vignette can be seen. Last, a fan pointed at the user is used to reduce motion sickness. The cold breeze is very nice during use of the VR headset.

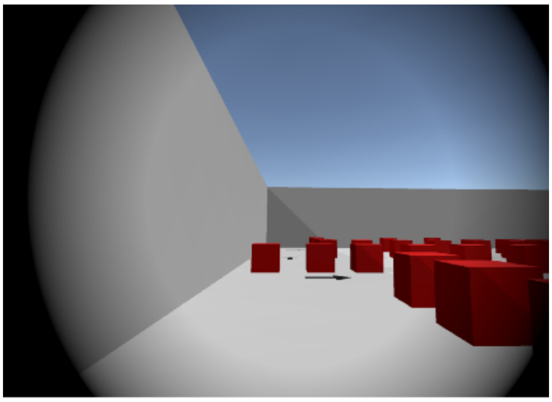

Figure 26: Point of view with vignette

4.1.3 Interface communication

Communication with the interfaces is done using serial communication. The microcontroller of the interface will send the direction values to the computer, and unity will read these values. The reading of the serial data can be done by reading the serial port of the computer every frame. However, this slows the game down to frame rates under 90 frames per second, which is not optimal for VR applications. A plugin called Ardity is used to solve this problem. This creates a communication between the microcontroller and Unity on another thread, which does not influence the frame rate of the application.

An Arduino will be used on the three different prototypes. To make all three prototypes compatible with the VR application, all three Arduinos send information the same way to the computer. The Arduino measures and calculates the x and y velocity and rotation velocity. The x and y values are values between 0 and 300, and the rotation is a value between -100 and 100. There ranges are chosen to be integers, because Arduino handles integers better than float. The x and y values are chosen to be between 0 to 300 because this is the distance between the load cells in millimeters. As described in the previous section, the pressure plate calculates the position of center of mass. Having the values is millimeters was convenient for testing and it is never changed since 0 to 300 has enough values for controlling the robot's speed in Unity. The rotation value is chosen so that there are more values per degree than the precision of the MPU6050.

These values from the Arduino are read in Unity and converted to value between -1 and 1, which are used to move the robot. The mapping is done using equation 4. A diagram of the communication between the Arduino and Unity program can be seen in figure 27.

$$new = (old - old_{min}) * (new_{max} - new_{min}) / (old_{max} - old_{min}) + new_{min} \quad (4)$$

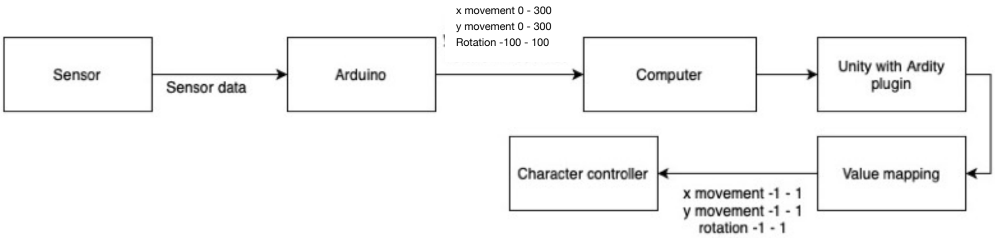

Figure 27: Communication between Arduino and Unity program

4.6 Conclusion

The four prototypes perform as planned and fulfill the most requirements. During testing while building the prototypes, a few things were noticed. The prototypes based on leaning are quite fast to learn. The prototype with the spring feels like you have more control over the robot compared to the prototype with the pressure plate seat. The pressure plate-controlled-by-foot prototype is at first a bit hard, but after a while, this prototype is easy to use. The prototype with the 'alternative steering' is hard to learn. After learning it is usable, but it is hard to move in a certain direction and rotate at the same time. There is no difference noticed in responsiveness between the pressure plate based prototype and the spring prototype, although there is a big difference in refresh rate. A problem with all four prototypes is that rotation sometimes causes a bit of motion sickness because your body is not moving while VR robot keeps rotating. The learning based prototype do cause more motion sickness than those operated by feet. A way to solve this is by mapping rotation to rotation, instead of mapping rotation to rotation speed. This is, however, not possible because of the cockpit restrictions. User testing has to be done to really test which way of locomotion performs the best in terms of first time usage, learning times, and performance.

6. Evaluation

User tests will be done to evaluate the four prototypes. The user test will help to answer what the best method is for locomotion control. The performance of the four prototypes will be measured with the learnability, efficiency, usability and number of hits.

6.1 User Test

Six family members will be asked to participate in the user test. It would have been ideal if more people participated in the user test, but due to the COVID-19 regulations, this is not possible. Family members are also not the best participants since they can be biased. For this user test, a within-subject study is chosen, so that every participant will test all four prototypes. A within-subject study is chosen because this gives more results than a between-subject study. It is not expected that there is a learning effect since the 'labyrinth' has arrows indicating the way.

6.1.1 Test Method

The participants are informed about the test and are given a consent form. Before the test starts, it is explicitly mentioned that using a VR headset can cause motion sickness for some people and that they can quit at any time. The test can begin after the participants are ready, and the content forms are signed.

The participants are asked to put the VR headset on and look around to get familiar with the environment. The prototypes have to calibrate on the startup of the Unity application. After calibration is done, the participants are asked to sit on the interface or plate their feet on it depending on the prototype. They are asked to navigate through the parkour following the arrows as fast as possible without hitting objects. It is not explained how the interface works. It should take approximately 1 minute to complete the parkour. Completion time and the number of objects hit are recorded during the task. After the parkour is finished, the participants can take off the headset and can take a break if they want it. If the participants are ready again, they are asked to navigate through the parkour again for a total number of 5 runs. It is done five times to measure the learnability [15]. After the five runs, a system usability questionnaire is given. Each participant uses all four prototypes five times. All participants started with the pressure plate with feet prototype, after that the spring chair, then the pressure plate on seat, and last the prototype with 'alternative steering'. After each prototype the user is asked if they want to take a break or continue with the next prototype. At the end of the user test, the participants are thanked, and as a compensation for their time they can play a VR game.

6.2 Learnability

The learnability considers how easy it is for users to accomplish a task the first time they use the interface and how many repetitions it takes to become efficient at the task. In the learnability study, a learning curve will be produced, which reveals the changes in task completion time after several trials. There are three aspects of learnability that is important for different kind of users [15]. The three aspects are:

- First-use learnability: This aspect is of interest for users who only use the interface one time. It tells something about how easy it is to use the first time you try
- Steepness of the learning curve: This aspect tells how quickly people get better at a task after repeating the task. The steepness of the learning curve is essential for users who use the interface multiple times. If people feel that they are progressing quickly, they will be motivated to stick with it.
- Efficiency of the plateau: What is the productivity after the users have fully learned to use it. This aspect is important for users who frequent and long-lasting need to use the interface.

Ideally, the interfaces score high on all three aspects. This is not always possible, and sometimes trade-offs have to be made. As mentioned in the literature review: an intuitive interface is not always a good interface. It can be that an interface is really easy to use the first time and progression is made quick, but if the efficiency of the plateau is really low, it might not be the best interface.

The task completion times of the participants are plotted against the number of trials to produce the learning curve. The learning curves of the three prototypes can be seen in figures 28, 29, 30, and 31.

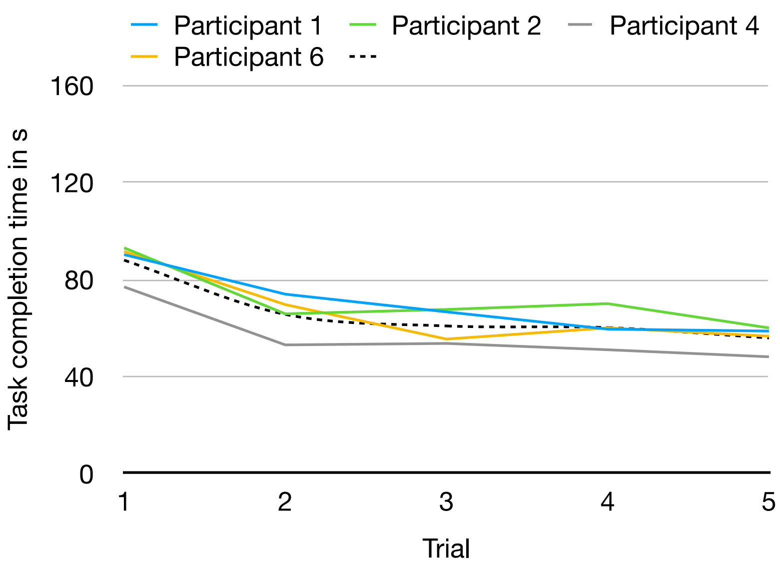

Figure 28: Learning curve of pressure plate on chair prototype (concept 2)

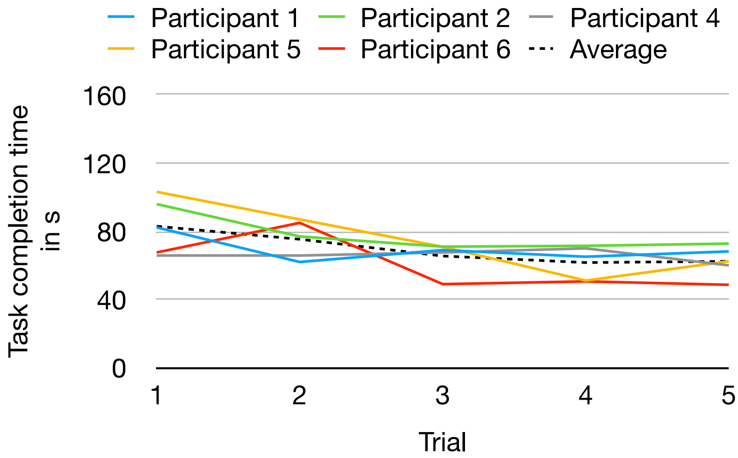

Figure 29: Learning curve of pressure plate feet prototype (concept 9)

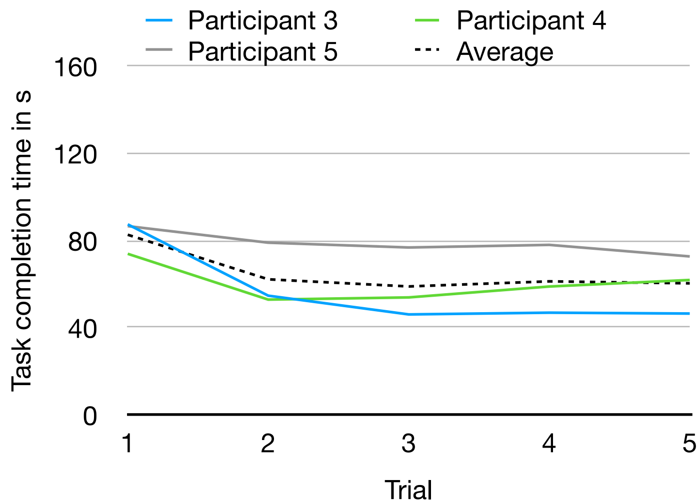

Figure 30: Learning curve of spring chair prototype (concept 3)

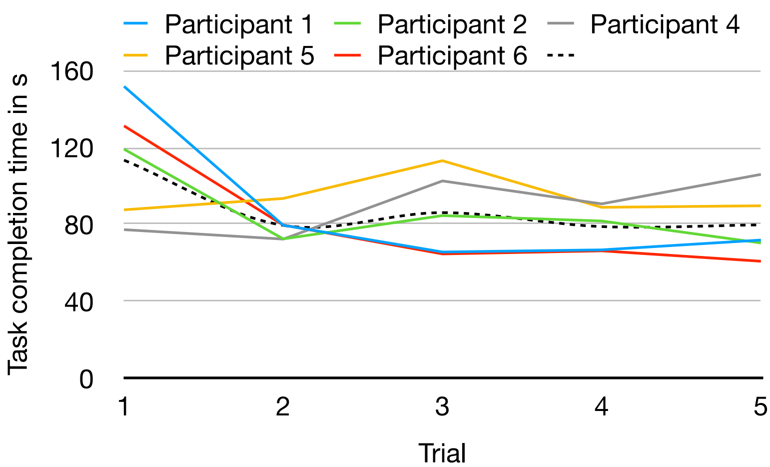

Figure 31: Learning curve of pressure plate 'alternative steering' prototype (concept 11)

6.2.1 First time use

The three one-to-one relation based prototypes all have a nearly identical first-time usage average, but the pressure plate with alternative steering has a much higher average. The first time usage times and averages can be seen in table 6. A one-way ANOVA test is performed to see whether there is statistical evidence to say that there is a difference in the first time usage times. However, there is not enough statistical evidence to say that there is a difference between the three concepts at a 5 percent confidence level.

Table 6: First time usage of each participant

	Pressure plate feet (concept 9)	Spring chair (concept 3)	Pressure plate on chair (concept 2)	Alternative steering' (concep t 11)
Participant 1	82,3		90,2	151,6
Participant 2	96,0		93,0	119
Participant 3		87,5		
Participant 4	103,2	74	76,9	77,3
Participant 5	65,8	86,7		131,1
Participant 6	67,6		91,5	87,5
Average	86,8	82,7	86,7	119,8

6.2.2 Steepness of learning curve

The task completion times seem to drop rapidly after the first time usage, and the learning curve is relatively steep. After two trials, which is in total approximately 3 minutes, the plateau seems to be reached. A one-way ANOVA test is performed to see whether there is a difference between each trial. At a 5 percent conference level, there is a difference in mean completion time between the five trials for the three one-to-one relation based prototypes. This indicates that the participants did learn to use the interfaces and improved their times over the five trials. For the pressure plate with ‘alternative steering’ prototype there is not enough statistical evidence to say that there is a learning effect in the five trials.

Carrying out a ‘post-hoc’ analysis of the means can show at which trial there is no learning curve anymore, and thus a plateau has been reached. For the spring chair concept and the pressure plate seat, the differences in the means of the last four trials are within the standard error. Only the first trial is largely different, indicating a plateau has been reached after the first trial. For the pressure plate with feet concept, the mean of the first two trials differ largely from the last three trials. The plateau of this concept seems to be reached after two trials.

6.2.3 Efficiency of plateau

The task completion times of the plateau are compared to compare how well the four concepts perform after learning. For the pressure plate operated with feet prototype, this is after the second trial and for the two leaning based prototypes after the first trial. Although there is no learning effect with the 'alternative steering' prototype, the task completion times after the second trial will be used. The mean completion times after learning of the pressure plate feet, spring chair and pressure plate seat are 63.2, 60.1 and 60.6, respectively. The mean completion time after the second trial of the 'alternative steering' prototype is 82.2 which is higher than the other three prototypes. The average times of the plateau can be seen in table 7. A one-way ANOVA is performed to see whether there is a statistical difference between the four groups. There is a statistical difference in the average time of the plateau between the four prototypes. A 'post-hoc' analysis shows that there is not a statistical difference between the three one-to-one relation prototypes. However there is a statistical difference between the 'alternative steering' prototype and the others.

Table 7: Average time completion times of plateau

	Pressure plate feet (concept 9)	Spring chair (concept 3)	Pressure plate on chair (concept 2)	Alternative steering' (concept 11)
Average	63,2	61,1	61,6	82,2

6.3 System usability scale

After the participant did five trials on a prototype, they were asked to fill in a system usability scale. It is a well-known questionnaire used in UX research and is used for measuring the perception of usability. The SUS questionnaire (appendix A) is a series of 10 Likert-scale questions that produce a score from 0-100. This score is not equivalent to a percentage score. The advantage of this scale is that there is large amounts of data is available that can help to benchmark the score of the prototypes. The average SUS score is 68 across 500 studies, and a score above 68 is considered a good score [16]. A SUS score above 80.3 is the top 10% of the scores.

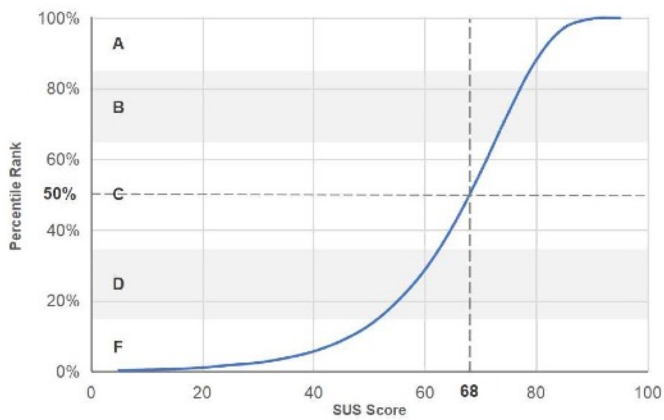

Figure 32: SUS score curve

These scores are not equal to a percentage or grade. In order to convert it to a grade, the scores have to be 'normalized'. The SUS score curve, which can be used to 'normalize' the SUS scores can be seen in figure 32.

The three prototypes with a one-to-one relation scored much higher than the concept with ‘alternative steering’. The difference in the SUS score does not seem that much, but after normalizing it, the difference is much more. The scores can be seen in table 8. The SUS score of the one-to-one feet prototype scored the highest. After performing a one-way ANOVA test on the normalized scores, it can be said that there is enough statistical evidence to say that there is a difference in mean SUS score between the prototypes.

The controller operated by feet has the highest SUS score indicating that the feet controller clearly has the highest perception of usability. The concept with ‘alternative steering’ has the lowest usability score.

Table 8: SUS score per participant with averages

	Pressure plate feet (concept 9)	Spring chair (concept 3)	Pressure plate on chair (concept 2)	Alternative steering’ (conce pt 11)
Participant 1	87,5		77,5	7,5
Participant 2	85		60	75
Participant 3		65		
Participant 4	87,5	75	95	67,5
Participant 5	70	62,5		52,5
Participant 6	72,5		60	22,5
Average	82,5	67,5	77,5	50,625
Percentile Rank	82%	49%	68%	9%

6.4 Number of hits

During the user test, the number of obstacles hit was counted. This count gives a good indication when the participant does not have full control over the robot and unintentionally hits an object. A graph of the average number of hits per participant for each trial can be seen in figure 33. The number of hits for the ‘alternative steering’ prototype is relatively high for the first trial, but drops fast over the trials. Based on the number of hits, it does seem that there is a learning effect. The obstacle hit curve for the feet pressure plate seem to follow the same curve as the task completion times of this prototype. Almost no obstacle are hit anymore after the task completion time plateau has been reached. The average number of hits per participant for the pressure plate chair is quite high at the fifth trial. It is not clear why this is so high, but can maybe be because of boredom or tiredness of the participants after five trials. The number of hits for the two leaning based prototypes are low from the first trial and do fluctuate a bit in the trial after the first. The low number of hits can indicate that these two prototypes are easy to operate, the first time used.

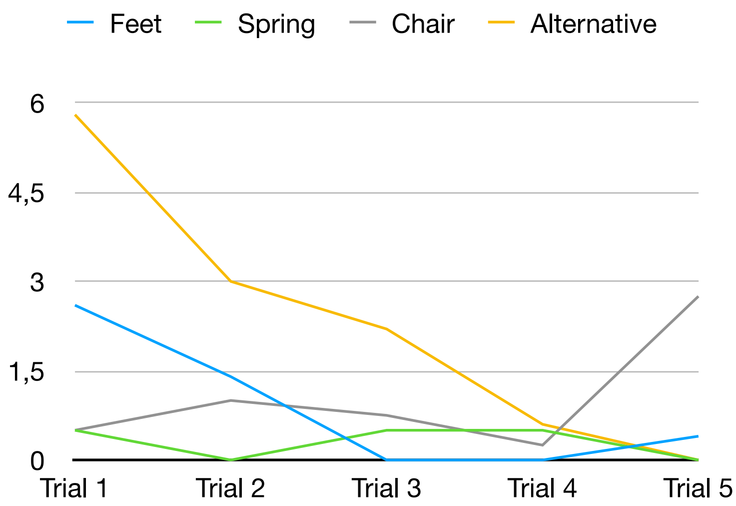

Figure 33: Average hits per participant for each trial

6.5 Feedback

The participants gave feedback during the use of the prototypes and while filling in the questionnaires. This feedback was not planned but was useful. Feedback about the feet controller concept was most about the position of the feet. One participant wanted the pressure plate to be tilted instead of being flat on the ground. This tilted position could improve the comfort of the prototype.

The prototype that received the most negative feedback was the spring chair concept. Participants said that it made them feel sick, more than the other concepts. One participant wanted to quit using the spring chair after 10 seconds of using it because of motion sickness. Participants also mentioned that it feels unstable and slippery, making the participants feel like they fall off the chair.

Rotating is causing motion sickness on the spring chair and pressure seat because at first, you rotate in reality, and the virtual robot follows, but after you stop rotating in reality, the robot will keep rotating. This is because the rotation of the chair is controlling the rotation speed. Some participants described to feeling as the feeling of being drunk.

6.6 Observations

Several interesting observations were done during the user test. These observations were not planned but are still useful. While using the prototypes based on leaning with the body, the participants moved their bodies way more than intended. It is possible to use both prototypes while keeping the body almost vertical, but the participants were leaning so much that their body was tilted more than 45 degrees when moving forward. It could be that this would be less after more extended usage, but at the fifth trial, this was still observed. It was not a problem during the user test, but if the user still has to operate a robotic arm with their hands, it could be difficult.

An observation with both prototypes operated by feet is that the participants wanted to apply much pressure going forward, more than needed. To apply the most pressure, the participant lifted their heels and only applied pressure with their toes or the other way around if moving backward. This does not influence the operation of the robot, but can be really uncomfortable after a while.

It took quite a while before the 'alternative steering' was discovered. Most participants discovered in the second or third trial. One participant did not discover this steering method. After the second trial he did not try anymore and decided to continue the remaining trials without steering. This resulted in the participant using the interface in weird positions in order to look in the direction he was moving.

6.7 Conclusion user test

The concept with the 'alternative steering' performed worse on all criteria. It is hard for users to figure out how to steer. After learning how to steer, it is still challenging to steer and move in the desired direction at the same time. This system is expected to be hard to figure out because it does not use a one-to-one relation between the input and output of the interface. This interface is not the most intuitive or best method for operating locomotion.

The two leaning based prototypes have the steepest learning curve and the least number of hits per participant in the first trial. Because of this, it seems that interfaces based on leaning are the most intuitive interfaces. The usability score of these two is not as high as for the concept operated by feet with a one-to-one relation. It is expected that the usability score is lower for the leaning based concept because participants mentioned that these two prototypes do cause motion sickness. This sickness is probably caused by the mapping of body rotation to rotation velocity of the robot. This is not the case when foot rotation is mapped to the rotation velocity of the robot. Participants also moved a lot with their body when using the prototypes. It is expected that it will be hard to, for example, operate the manipulator when using one of these prototypes. The low SUS score, motion sickness, and body movement make that this prototype may not be the best interface for operating locomotion.

The prototype operated by feet with a one-to-one relation does have a slightly steeper learning curve, but after learning it has the same task completion time as the leaning based prototypes. After learning, the number of hits is also low for this prototype. The SUS score of this prototype the highest score of the four prototypes. Little negative feedback was given, and during the observations, no major problems were seen. The fact that after learning it perform the same as the leaning methods, has less chance of causing motion sickness and body movement is very low makes this the best of these four interfaces for operating locomotion.

7. Conclusion

This project aimed to find the best locomotion interface for operating a remote robot. The literature showed that intuition is a system that learns from previous experiences. These experiences can be used in present situations. One way to implement these previously learned experiences in an interface is by using mappings. One-to-one mappings, combined with affordances, seem to be the best way to make an intuitive interface. This was seen in the results of the user test. The one-to-one relation prototypes performed better than the prototype that does not have this relation. Although intuitive interfaces are fast to learn, they are not always the best, as seen in the results of the user test. The leaning based prototypes are the fastest to learn; however, these are not the preferred method of locomotion of the participants. The interface operated with feet, and a one-to-one relation has a much higher usability score. The interface operated with feet using a one-to-one relation is the best method for operating the locomotion of a telerobot. Such an interface should be used for the i-Botics robot in the XPRIZE competition.

8. Discussion & Further work

There are some points of discussion in this project. The interface requires that it has to work while sitting or in a leaning position. During the project, the focus was shifted more towards an interface that performs well while sitting. Because of this shift in focus, concepts were chosen that are not suitable for usage while being in a leaning position. If the focus was on both methods, more prototypes were chosen that can be used both while sitting and in a leaning position. The prototypes that can be used while sitting are the two prototypes operated by feet. It is expected that the prototype with ‘alternative steering’ does not perform well while being in a leaning position since this prototype did not perform well while sitting. The pressure plate on a rotating disk prototype could be used while being in a leaning position. The rotating disk currently used is, however, not sturdy enough to stand on. The rubber bands used to make it return to the center position are also not stiff enough while standing on it, and this makes it hard to balance on it. Further work must be done to see how the current concepts perform while the user is in a leaning position. Concept with that are designed with usage while learning in mind should be tested as well.

Previous researched showed that feedback in the interface could improve teleoperation. This feedback can reflect the forces of the robot to the user or give information about nearby obstacles. In this project, it is chosen not to implement feedback in the interfaces to save time. Further research has to be done in how feedback can be implemented in an interface that is operated by feet and has a one-to-one relation.

The prototypes used only focussed on function and not on the ecstatics. The literature showed that affordances could make an interface more intuitive. These affordances guide the user on how a product can be used. The prototype that performed best, the pressure plate operated by feet, does not guide the user on how it can be used. It is not clear from the design that pressure has to be applied to move in the desired direction. If the interface's function is clear, even before using it, the interface can be made even more intuitive.

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Appendix

Appendix A. SUS questionnaire

1. Ik denk dat ik dit interface vaker wil gebruiken

Oneens ○-------------○-------------○-------------○-------------○ eens
1 2 3 4 5

2. Ik vind de interface onnodig complex

○-------------○-------------○-------------○-------------○
1 2 3 4 5

3. Ik vond de interface makkelijk te gebruiken

○-------------○-------------○-------------○-------------○
1 2 3 4 5

4. Ik denk dat ik technische support nodig heb om de interface te kunnen gebruiken

○-------------○-------------○-------------○-------------○
1 2 3 4 5

5. Ik vind de verschillende functies van de interace goed geïntegreerd

○-------------○-------------○-------------○-------------○
1 2 3 4 5

6. Ik vind dat er teveel inconsistentie in de interface zit.

○-------------○-------------○-------------○-------------○
1 2 3 4 5

7. Ik kan me voorstellen dat de meeste mensen snel door hebben hoe ze deze interface moeten gebruiken

○-------------○-------------○-------------○-------------○
1 2 3 4 5

8. Ik vond de interface omslachtig om te gebruiken

○--------------○--------------○--------------○--------------○
1 2 3 4 5

9. voelde me zelfverzekerd toen ik de interace gebruikte

○--------------○--------------○--------------○--------------○
1 2 3 4 5

10. Ik moet veel leren over de interface voordat ik het goed kan gebruiken

○--------------○--------------○--------------○--------------○
1 2 3 4 5

11. Hoe veel ervaring met een Virtual Reality Headset?

○ Geen

○ Wel is geprobeerd

○ Veel ervaring