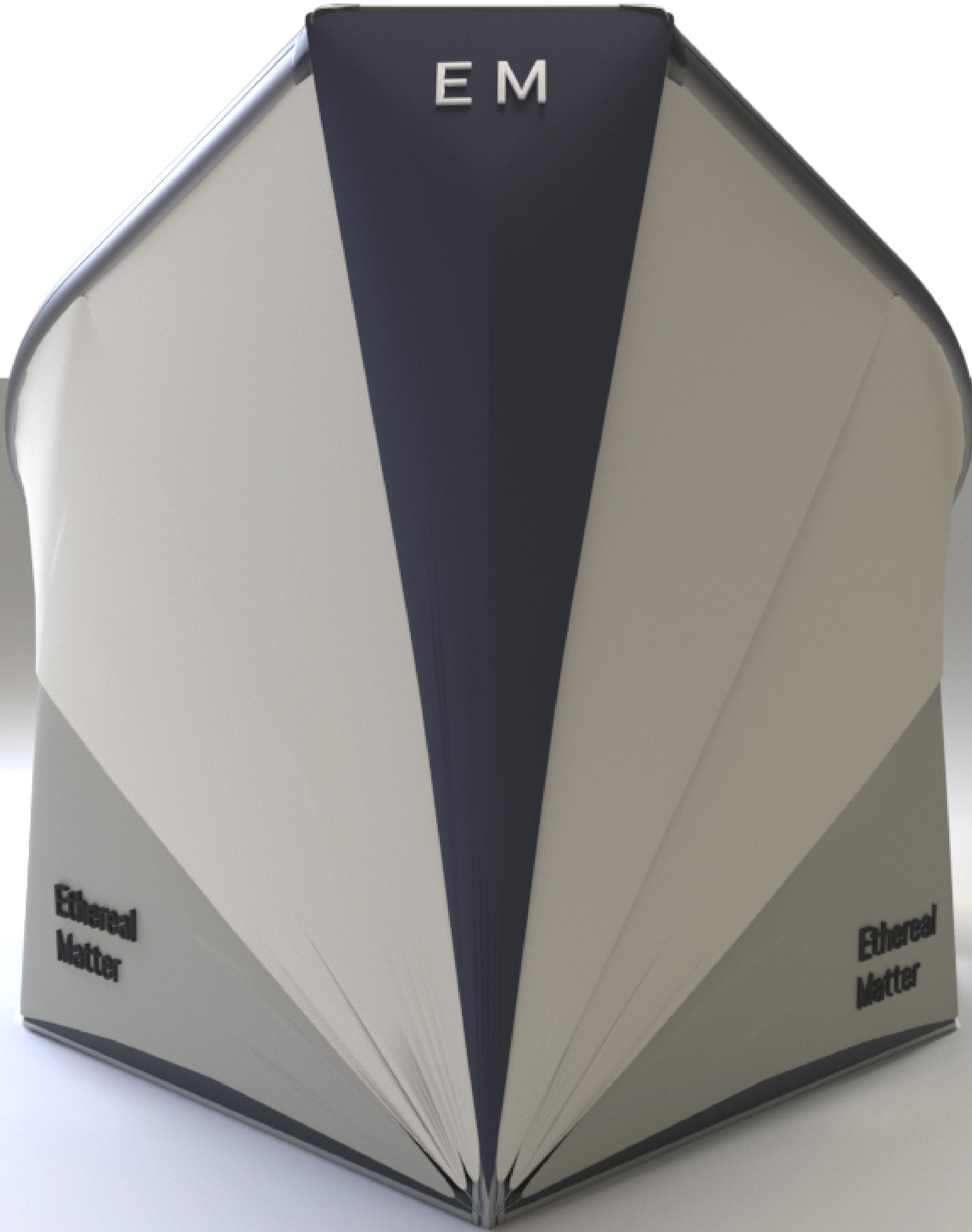
Fitness 2.0

Design of a physical virtual reality engine with real-time force feedback



Master Graduation Report

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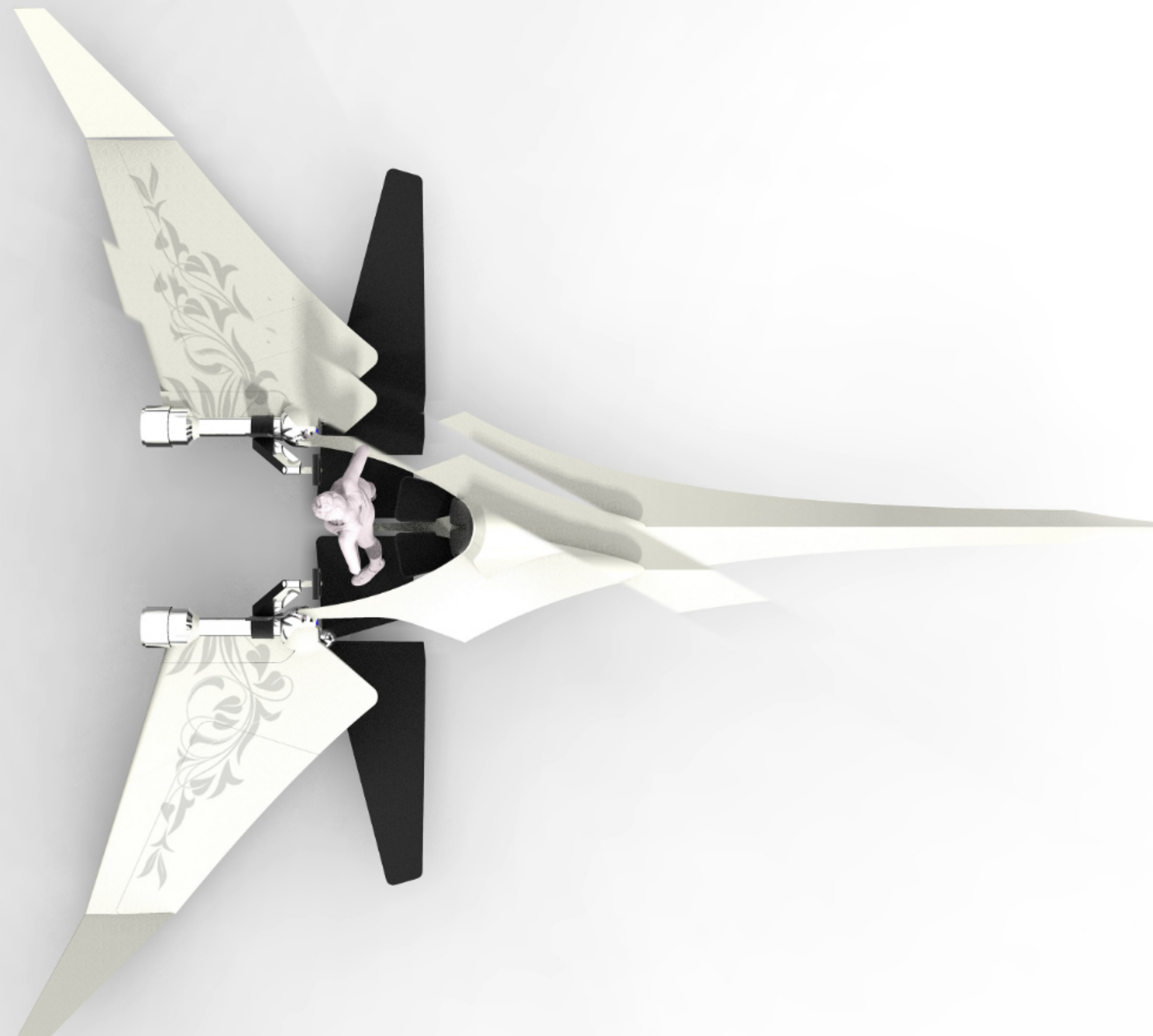
TU Delft



Master thesis

Programme

MSc in Integrated Product Design
Technical University of Delft

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The soft, warm rays hit her face as she turns her head towards the sun. She knows this feeling all too well. The excitement of total freedom, cruising through the clouds over her favourite landscape makes her stomach tingle. A slight shift to the right and the ornithopter goes into an elegant right-hand turn in between the two glowing clouds ahead of her. As she dives into the cloud's shadow, she takes a deep breath of the refreshing air that rushes through her hair and makes her shiver for a moment.

As she slowly descends towards the ground, she flexes her legs, pulls her arms inwards and tenses her whole body, anticipating what is about to come. The ornithopter approaches the canopy of the trees of the peaceful forest below her. With all her strength she straightens her legs and yanks the wings of the ornithopter with both her arms downwards, sending her into a gut-twisting ascend towards the endless sky. It's a good day. All the stress of the past week turns into physical exhaustion during her flying session. She likes being here. She loves the ecstatic feeling of the moment and the relaxation that she feeds on throughout the rest of the day. Her next session is already reserved.

Contents

1 Executive Summary

The Ethereal Engine combines fitness with gaming and VR. By using two actuated armatures and foot platforms, the machine can provide users with force feedback while they enjoy a multitude of simulations that do not feel like a workout at all.

Regular physical exercise is very difficult for many people. This can lead to poor health and increased associated risks for the body and the mind.

The Ethereal Engine offers a solution: With exhilarating and exhausting experiences, users can fly with an ornithopter through magical landscapes or paddle through alien waters on foreign planets.

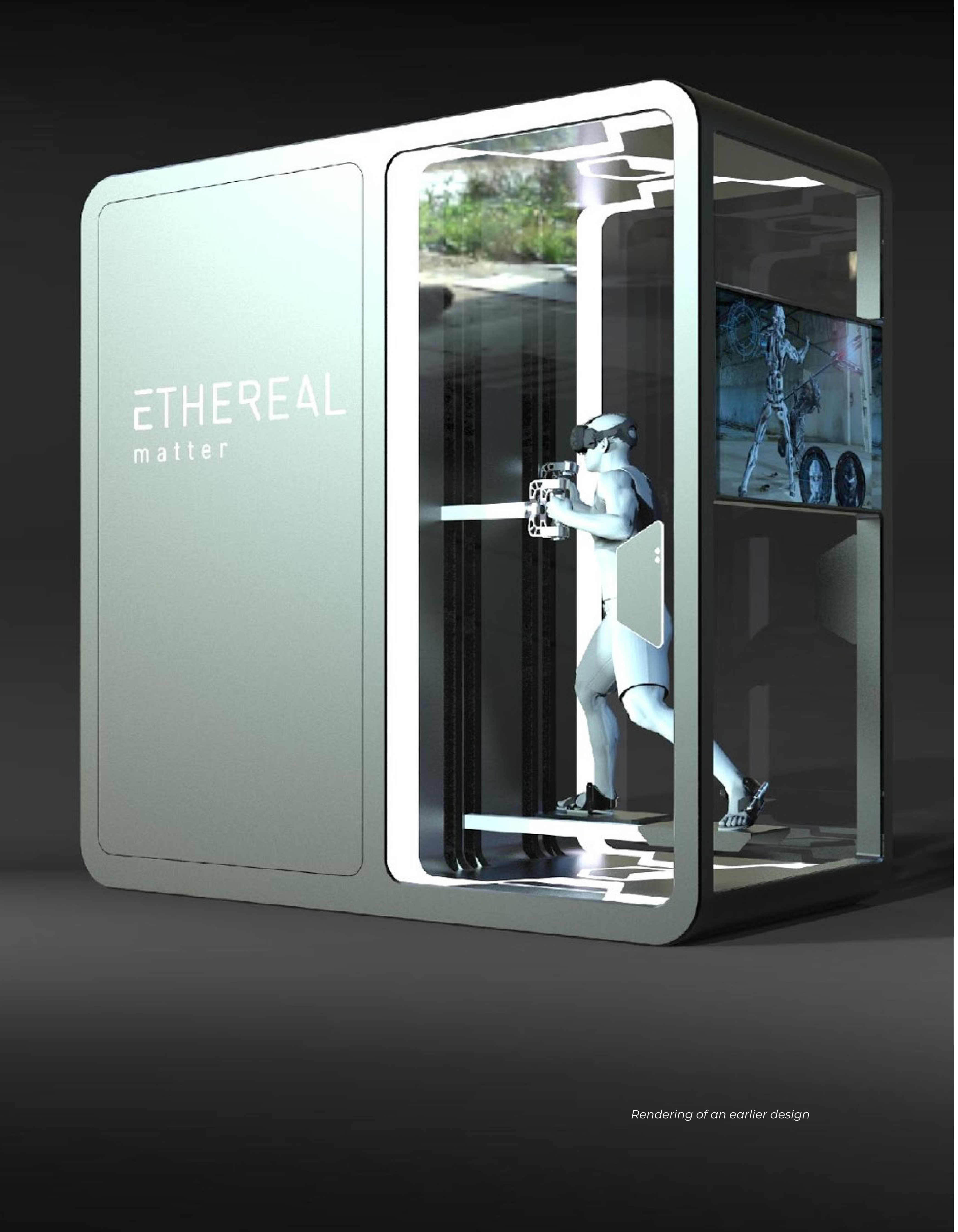
Invented and under development by the company Ethereal Matter in the US, the project spans multiple countries, TU Delft faculties and student projects.

In this graduation project, the next design of the frame for this very machine is proposed, with a special focus on user perception on the one hand, and engineering-related topics on the other.
The project commences with user research into spatial perception emotion and the experience of transitioning from and to VR.
Practical limitations such as maximum carrying weights, door and truck dimensions, and intended use cases result in manufacturability, transport, assembly and durability requirements.

By using and adapting generative design tools (McNeel's Rhino, Grasshopper and the plugin Karamba3D) for structural spaceframe design, a satisfying solution is found for the main structure. This basic structure is then designed around and iterated upon using VR reality tools like Gravity Sketch to create frame layouts that feel comfortable and safe. Constant iteration and testing in VR leads to a modular frame layout that allows multiple machines to be connected, but also up or downgraded to more or less extensive versions. Features like a mirror, a space to safely store personal belongings, and integrated lighting are proposed. The machine has fabric for the outside covering which is customizable, affordable and easy to transport.

The final design includes a seat in the back with an attached screen for outside viewers to see what is happening in VR. Added interactive elements could lead to whole new interactions between people in the real world with the people in VR.

Accompanying the project was the construction and assembly of a partial prototype of the frame and one armature in the Dreamhall of the TU Delft.
It is upon the next students to finalise the second Ethereal Engine in the world and perform the (first?) intercontinental handshake through VR.



Rendering of an earlier design

2 Introduction

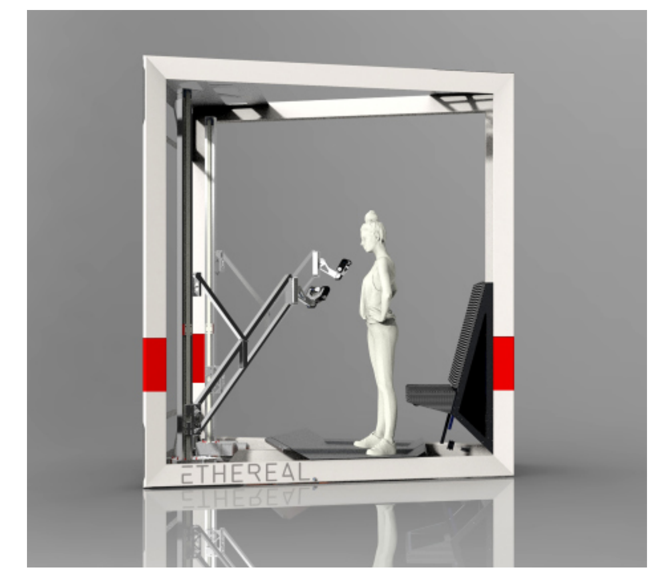
Today's world is interesting, exciting and scary as ever. In the everchanging circumstances, people cling on to simplifying narratives, wish back the good old times, or flee into social bubbles where they are surrounded by comfortable opinions. The rise of virtual reality and the influence of large, profit-oriented companies defining the worlds within these artificial realities will likely increase those problems and extrapolate them inside this parallel, digital world. This dystopian cyberpunk future is not fixed, however. On the contrary, projects like the Ethereal Engine envision a future, where responsible use of Virtual Reality technology fosters the increasing trend of physical fitness and provides thrilling workout experiences, that can be enjoyed in solitude or in company – real as well as remote. The Ethereal Engine allows one to visit and exercise in places that are unreachable for many people or even non-existent, fantastical worlds.

What this project is about

This Graduation project is based on the brainchild of the American designer and entrepreneur Scott Summit: A fitness apparatus that uses virtual reality to offer new types of simulation that are enhanced with force feedback. In this chapter, a brief explanation of the machine will be followed by an explanation of why it is highly relevant, how it differs from existing products and what future possibilities it offers. In the end, an overview will be given of what my contribution to this project is, how this thesis came to be and what to expect from this report.

The Ethereal Engine

The 'Ethereal Engine' is a new type of 'virtual reality' (VR) experience using a mechanical apparatus to provide haptic force feedback. The device consists of two actuated arms with grips at their respective end which users hold with their hands while they stand on two separately actuated platforms with their feet. (See image to the right). The user wears a VR headset and is tracked by a motion-capture (mocap) system that translates the posture data to the VR environment continuously so that a digital avatar can be rendered in real-time allowing for complex interactions and increased immersion. All these systems are held in place by the overall frame, which houses the necessary electronics, actuators and additional sensors, including cameras for the mocap system.



Above: Rendering of the current design
Below: Envisioned ornithopter simulation

Upon using the engine, the user can move the handgrips and feet platforms, which then provide varying resistance to the performed motions to add as real as possible force feedback to the simulated experience.
For example, a user could be flying in a bird-like wingsuit through a simulated mountain world (see page 7 bottom), where every wing flap needs an actual force to be exerted physically by the user which is generated through the precise control of the actuators (e.g. stepper motors) of the arm assembly. With this machine, a multitude of simulations can be envisioned, from conventional (outdoor) sports to contemporary computer games, up to futuristic experiences in space.

Why this project matters

The Ethereal Engine unites at least three major topics that are ubiquitous worldwide phenomena: fitness, gaming, and VR.
With this combination, the unique new way of 'exergaming' takes the best aspects of gaming and exercising and blends them into exiting, wholesome VR experiences that are as fun as gaming but potentially as demanding as a full workout session at the gym. In the following, the question of why this makes the Ethereal Engine a highly relevant product will be answered from the perspectives of these three topics.

Fitness

As the world is coming out of a pandemic, self-awareness and a healthy lifestyle are of ever-increasing importance to people around the globe. Yet, the sudden lockdown of public places like sports clubs and gyms has left many people unable or unmotivated to keep up a healthy workout routine. According to a survey of the IHRSA, every second person that had been active in a sports club in the previous year declared to be less active (International Health, Racquet & Sportsclub Association [IHRSA], 2021). Out of these, 1 out of 10 admits to having stopped exercising altogether.
On the other end, even though a healthy diet and regular exercise are heavily sermonized and commonly known to benefit overall well-being and health, the prevalence of obesity is increasing in various countries (Rakhra et al., 2020).

At the same time, the fitness and well-being industry has seen a steady increase in demand over the last decade which clearly shows how people are changing towards a more active and healthier lifestyle: The wellness and fitness market is growing at a steady annual rate of 5 – 10 per cent (Falardeau et al., 2021). This development will most likely even speed up with the pandemic easing up and allowing for more and more sports facilities to open up again.

Gaming

Another activity, practised worldwide and crossing national borders, cultures and gender, is gaming. Ever since the rise of digital gaming devices like computers and consoles, many people spend a considerable time of their day sitting in front of a computer screen or TV, solely moving their hands and eyes. This behaviour is known to be problematic for overall physical health as too little exercise and activity as a result of increased video gaming can lead to musculoskeletal, visual and other health-related problems (Ayenigbara, 2018).
In middle-school children, research has revealed an inversely proportional correlation between moderate and vigorous physical activity (MVPA) and gaming (Hygen et al., 2022). It is expected that the effects last into adolescence with major implications regarding people's physical health throughout adulthood.
Common examples of popular games are EA Sports' 'FIFA' and Mojang's 'Minecraft', where a player runs around the football field or open world while sitting still in reality.

Here is where the Ethereal Engine can bring fitness and physical activity back into gaming: Disguised as a fun simulation experience, or game, users eventually need to use their whole body to control e.g. a flying machine. Coupled with an effort-based reward system, users can easily be motivated to give all they can to reach for example maximum altitude or speed.
It is easy to imagine a new era of e-sports where contestants not only excel with fast reaction times and advanced strategies but being physically fit as a necessity to maximise results.

VR

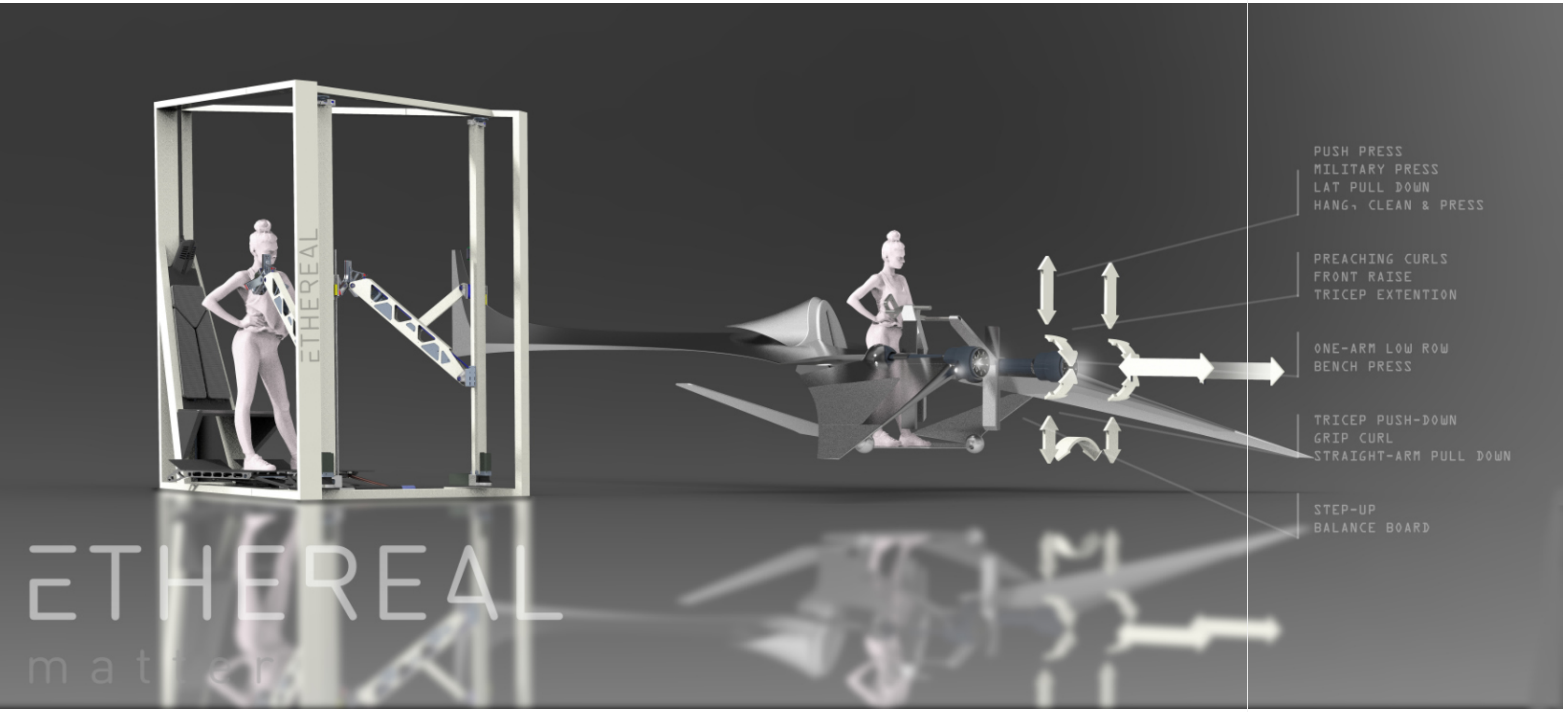
Virtual reality is not a new concept, one might conclude with the recent popularity gains of companies such as Meta.
Early research into VR already concluded, that the success of virtual reality environments – similar to films and video games – comes from their "arousing, even exhilarating experience […]" (Lombard & Ditton, 1997).

Lombard and Ditton inferred as early as 1997 that

> *"Perhaps the most prominent psychological impact of presence is enjoyment and delight. Technologies that provide a strong sense of presence, including simulation rides, IMAX theaters, and virtual reality entertainment, are increasingly popular with the public and financially lucrative for those who design and market them. (Lombard & Ditton, 1997).*

They already predicted that such experiences are not just trend-based developments and popular because of their novelty, but "simply put, fun." (Lombard & Ditton, 1997).

The most widespread VR devices are limited to the use of an HMD with speakers and two hand-held controllers with joysticks, triggers and buttons. These satisfy only the visual and aural senses, as the controllers are used for control input and can only vibrate at best. A popular example is the VR game 'Beatsaber', where a player has to smash boxes with light sabres to the rhythm of the music.
However, in reality, humans rely on many more senses and as Lombard and Ditton conclude, next to olfactory output and tactile stimuli, the sensory experience of body movement – called 'proprioception' – and force feedback can add to the overall experience of feeling 'being inside the virtual environment' (Lombard & Ditton, 1997).



Possible workout exercises

Differences to existing VR devices

Most VR products' input is limited to two controllers (e.g. Oculus Quest, HTC Vive, Valve Index, Sony Playstation VR, HP Reverb) but the Ethereal Engine is a machine that adds the possibility of performing physical work through the arms and legs, exercising the upper and lower body at the same time. Just as everything in real life is subject to gravitational pull and inertia (on planet earth at least): With this machine, virtual objects have weight, wind and water impose resistance and walls are impenetrable.

Benefits & Possibilities

This physical resistance to movements, generated through force-feedback, opens up many new possibilities for various applications: Through the Ethereal Engine, gaming becomes physically demanding, therefore promoting physical fitness for people usually sitting behind a screen; fitness turns into a thrilling experience that feels little like a workout and more like an adventure, possibly increasing the chance for people to exercise regularly and eventually reduce modern world obesity. Next to games and fitness, new ways of instructional training and research (e.g., human movement studies) are possible, where the engine could be used to educate and train people or do research about performing physically demanding tasks most ergonomically.
Finally, the engine allows for tailored rehabilitation after disease or injury. Being able to precisely control the range and path of motion, while adding the desired amount of resistance to a patient's exercise provides physiotherapists with a powerful tool to reduce recovery time and possibly increase the success rate.
All in all, the Ethereal Engine provides a platform for positive future use of virtual reality by providing force feedback and therefore potentially making fitness, gaming and rehabilitation fun experiences.

How this thesis contributes to the overall development

This report specifically shows the development steps leading up to a modular design of the frame for the Ethereal Engine. It gives the first indication for a free-standing structure that can be added upon to create multiple variations of the machine with more or fewer features and exposure. Engineering and user-related research and aspects give a wholesome idea of what the future design of the machine should pay attention to or could improve. Among these are manufacturing, transport and assembly considerations, along with material choices for durability and customization, in addition to new ways of transitioning and interacting between reality and virtual reality.

How this thesis came to be

This graduation thesis is a continuation of a 'Joint Interdisciplinary Project' (JIP) that consisted of TU Delft students of various faculties, who worked together with Ethereal Matter on designing and improving the machine, especially the armature and hand grip.
I was personally not part of the JIP team but joined the overall project with this thesis without hesitation when I got introduced by Erik Tempelman.

What the reader can expect from this report

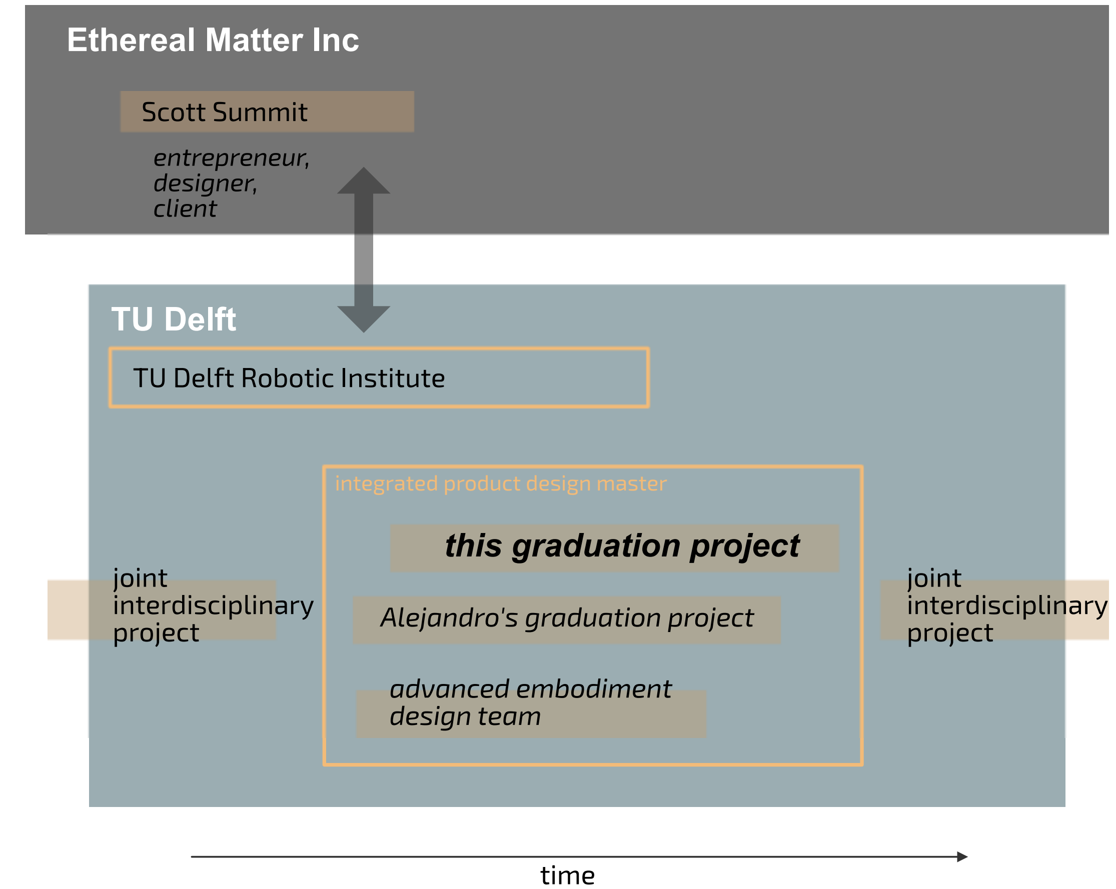
This graduation report summarises the design engineering process that went into creating the design of a frame for the Ethereal Engine. It will show how user focussed research, combined with generative design tools, state-of-the-art virtual reality sketching tools and physical prototyping resulted in valuable and tangible insights that influenced the overall design. Despite the linear structure of this report, the design process is usually iterative, involving many loops in multiple stages throughout, which can occur multiple times. Especially for a project like the Ethereal Engine, where the requirements and developments at the company constantly evolve and demand the designer to adapt new insights constantly.
The report condenses these iteration loops into graspable stages, starting with the early exploration and analysis through desk and user research, converging to a list of requirements and a vision, followed by a diverging generation, ideation and conceptualisation phase. Eventually, after a lot of collaboration with and feedback from the client, the report presents the prototyping results and the final design of the Ethereal Engine including the envisioned embodiment.
Concluding the report are the recommendations and a reflection that follow the overall summary and discussion of the proposed design. The reader will be guided through most of the decision-making and designing process that led to the final result.
To understand the project, however, quite a bit of background information is necessary to comprehend the context in which this graduation project finds itself.

3 Context

This chapter gives a brief overview of the main stakeholders, responsible for and involved in the process, as well as how this project came to be, and in which stage I joined with my graduation thesis. It furthermore illustrates what kind of similar products exist and what sets the Ethereal Engine apart.

Stakeholders

Multiple stakeholders are involved in this project. Their relation to each other and their involvement over time can be seen in the diagram to the right. A brief introduction of the main stakeholders 'Ethereal Matter Inc' and the 'TU Delft Robotics Institute' will be given in the following.



Stakeholder diagram

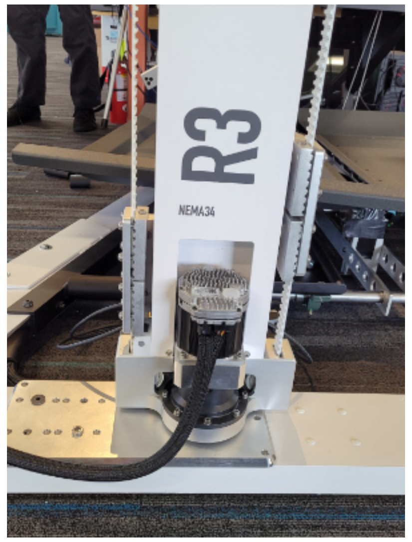
Ethereal Matter Inc

The project was initiated by Scott Summit who founded the California-based company 'Ethereal Matter Inc' with the intent to bring a working VR fitness engine to the market. A goal is to create a viable business based on the Ethereal Engine as a platform that will open up new possibilities for the future use and development of VR applications. With the increased interest for mixed reality (MR) – VR, augmented reality (AR) and a mix thereof – technological developments by companies such as Meta and software developments by companies including Unity and Unreal, the Ethereal Engine poses an invention in the middle of an ever-increasing market (Alsop, 2022).

Due to a registered patent, all IP rights are owned by Scott and Ethereal Matter Inc. With the constant increase in competition, the aim is to make use of the first-mover advantage to stay at the forefront of innovation in VR by providing the first platform for force feedback enhanced VR simulations with which to gain and hold a profitable market position.

TU Delft Robotics Institute

On the other end, the TU Delft Robotics Institute is the collaborating partner interested in utilizing this undertaking to teach students from various disciplines (Industrial Design Engineering, Mechanical Engineering, Robotics, Computer Sciences, etc.) about developing such a complex machine. Next to the advancements and prototypes developed in California, a prototype will be built, tested and improved in the Netherlands and multiple interdisciplinary projects and master theses (including this one) will be working on various aspects of the project simultaneously and consecutively. The collaboration of Ethereal Matter and the TU Delft Robotics Institute started with the JIP in the autumn of 2021 with various students from various engineering studies improving several parts of the Ethereal Engine and making a start in building a functional prototype in Delft.

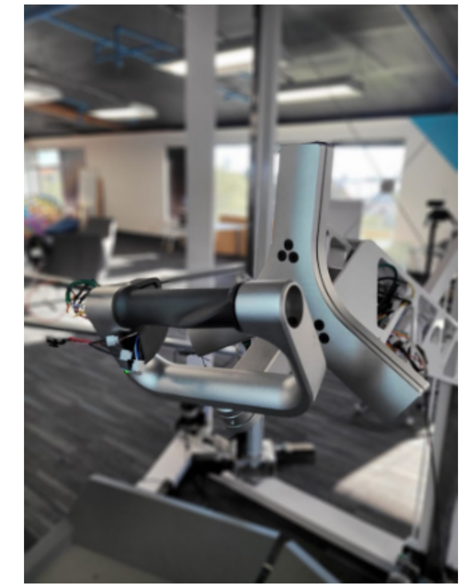


The actuated vertical mast

Current state

When starting my graduation, a working prototype was constantly under development and testing in the US. It consisted of a frame, two actuated hand armatures (one newer than the other), two moving foot platforms as well as a seat. The system uses a Kinect camera to track the user's position to generate a matching avatar in the virtual environment (VE).

Picture of the US prototype




Detail images of the US prototype

Left: Image of the TU Delft prototype following the JIP

After the team of engineering and design students worked on the project throughout the JIP, a preliminary frame setup and a first version of the grip and handle were built in the 'Dreamhall' of the TU Delft. The frame consists of extruded aluminium profiles bolted together with custom CNC (short for 'computer numerical control') machined aluminium parts.

For more information on the parts and costs of these prototypes please refer to the chapter 'Main drivers' and the 'bill of materials' (BOM) in the Appendix.

What similar devices like the Ethereal engine exist?

Companies are currently developing dynamic and actuated products like gloves for precise movements (SenseGlove), haptic feedback controllers (Tactical Haptics), or omnidirectional treadmills (Virtuix Omni) for extended virtual realities.
For a brief overview of competitive products to the Ethereal Engine to grasp the amount of competition existing, online research into similar VR machines was conducted. Extracting already identified products from earlier reports, asking the client and searching the internet for VR-based technology. The search resulted in very different products that all enhance or allow the use of VR simulations. Most devices make use of additional sensory experiences, while some add the aspect of fitness, others rehabilitation, training, or a combination thereof. The identified devices were clustered into:

Vests

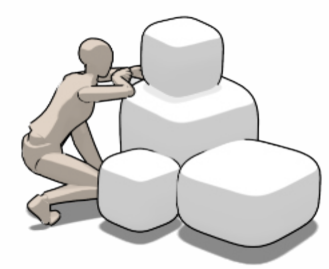
Vests can add the sensory experience of impact or temperature and are already used in VR gaming to simulate impact from being hit by objects, e.g. bullets ('bHaptics TactSuit', 'Atronika Skinetic', or 'OWO Sensations Technology'). With an increased quality of the simulated bodily interaction, they can add a significant amount of presence to a VE. Other suits are used to create precise full-body motion tracking for the film industry, but can also perform real-time health and performance analysis ('teslasuit')

Controllers

So far, controllers are used for tracking the user's hands (and sometimes fingers) to translate them into the VE ('SenseGlove', 'Tactical Haptics', 'Haptx gloves DK2'. This way, a matching representation of the user's hands and fingers can be used for input and helps link real movements to movements in the VE. Some controllers introduce additional friction feedback to give the user a sliding sensation when for example firing a bow and arrow.

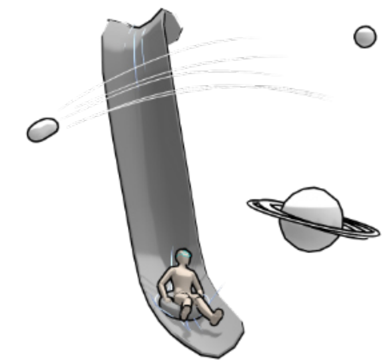
Locomotion

Moving around in an open VR world, while being in a confined space in reality, poses a challenge that has been overcome through powered ('Infinadeck'), or unpowered omnidirectional treadmills ('KAT VR', 'ACTVR' or Virtuix Omni') as well as locomotion shoes. Using these, the user can infinitely explore the VE on foot while staying in the same position in reality. Unpowered omnidirectional treadmills offer only a pseudo-real walking experience, as the user is basically sliding with special shoes over a curved surface. Locomotion shoes are still in their infancy and no commercially available product could be found.



Arenas

VR arenas allow for free movement in a limited amount of space, from room size to warehouse size. The VE has to be adapted to the available space of the arena, but the unlimited movement (walking, running, jumping, crouching, …) within it can create a very convincing and immersive VR experience (e.g. 'Hologate X'). These systems usually really on marker-based tracking, which involves special wearables, that need to be worn. The Ethereal Engine tries to avoid this with camera-based motion capture, to eliminate the need to change clothes and reduce the number of parts that are potential points of failure and need regular cleaning and disinfecting.

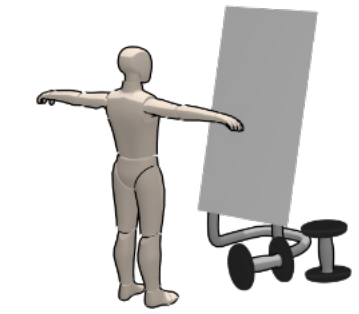


Specific

Some VR experiences mimic a specific sport or real-life experience or enhance them by adding visual information through an HMD. Riding through a fantastical VR world while sliding down a conventional water slide (e.g. 'VRSlide'), gliding through the alps while sitting in a parachute mock-up ('Paradrop VR') or going for a surf at Nazaré from the comfort and safety of an FEC ('family entertainment centre') all become possible with these specialised VR apparatuses. Unlike the Ethereal Engine, they mostly only allow for one particular simulation or activity to be enjoyed in VR, but the water slides for example, on the up side, convince all remaining human senses with only the visual input being simulated.

Robotic Arms

For fitness, rehabilitation, and research purposes, force control and force feedback are crucial. Most products are built similar to a multi-stage robotic arm and are either impedance or admittance controlled, depending on the intended use case. Available products are very limited in their range of motion or the movement that can be controlled or opposed. They make use of multiple ways of visual output, such as a screen, AR, or VR. The Ethereal Engine comprises two actuated armatures, which cover a wide range of motions compared to wire-based machines like 'Blackbox VR' or robotic arms like the 'Proteus Motion'.

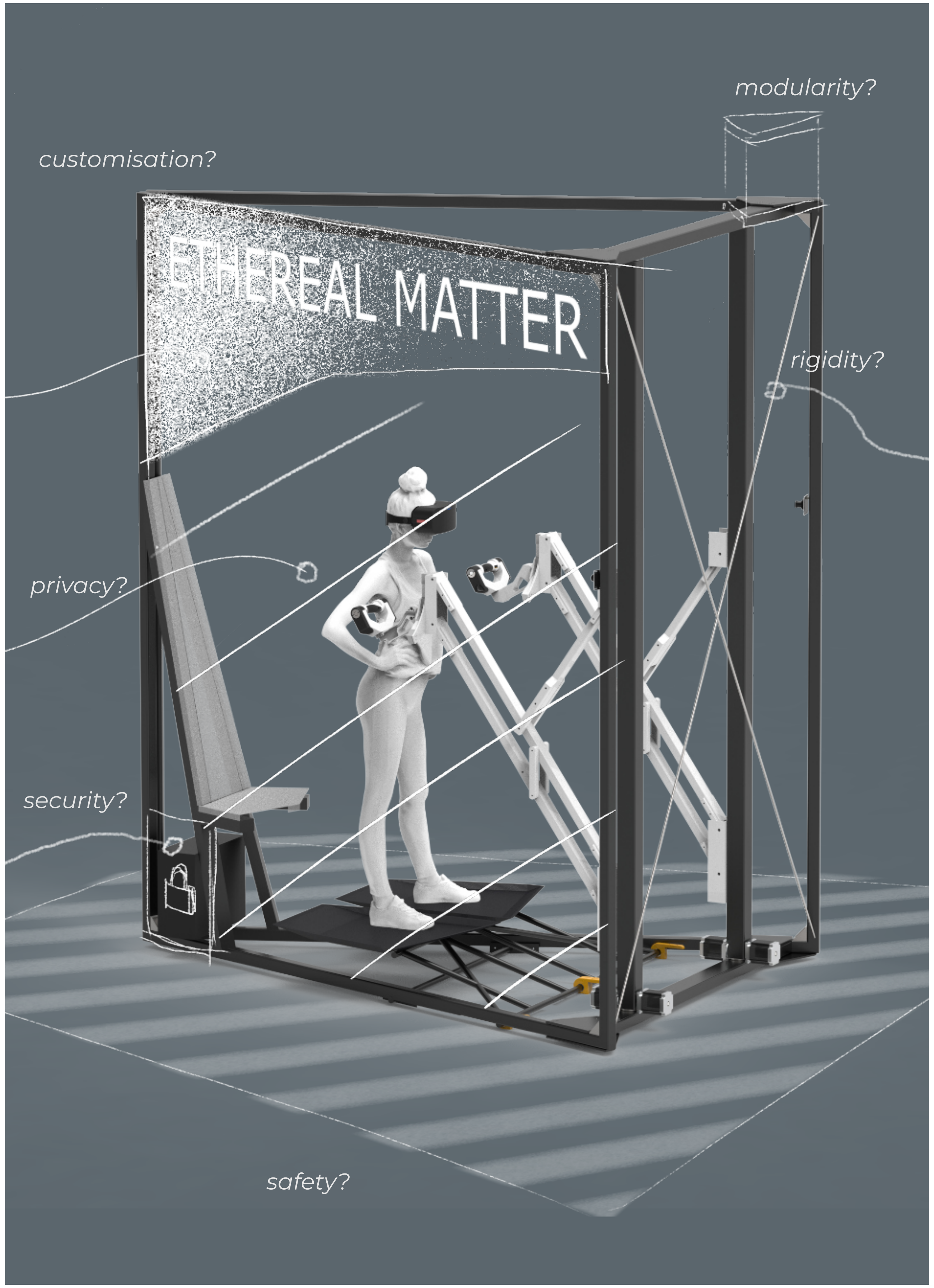


Non-VR fitness devices

Next to VR-based fitness devices, several products on the market allow for a multimedia-enhanced fitness experience without the use of an HMD. Some of these are large displays with additional resistance workout equipment, e.g. 'Tonal'. Others are simply smart mirrors with a screen and a camera-based mocap system embedded into them, just like the 'Tempo' or 'ProForm Vue'.
In general, the largest group of non-VR fitness devices contains regular full-body workout machines that can be found at home, but mostly in fitness centres and gyms all over the world.

How the Ethereal Engine is different

The Ethereal Engine uses the mechanisms of multiple of the described devices. The big advantage of the engine is the multitude of VR experiences that can be offered. The armatures and footplates cover a huge range of possible human motions, so many kinds of movement-based activities can be simulated. This makes the Ethereal Engine an attractive product for fitness centres, FECs, or venues in general and sets it apart from most of its competition.



4 Assignment

With the general overview and context of this project presented, in this chapter, the main challenges are identified and the goal of this thesis is explained.

Challenges

The Ethereal Matter engine is a complex product with a multitude of challenges to be solved, from the general construction, through sensing and user interfaces, up to the virtual experiences and their control by the user.
Ethereal Matter Inc has so far mostly worked on developing and testing the armature and foot platforms, but for attracting venture capital and a soon-to-come market entry it is crucial to have a design for the whole machine, including an overview of manufacturing costs and overall dimensions.
A large part of the machine – that underwent only a limited amount of development so far – is the frame. The frame will determine the overall final dimensions of the Ethereal Engine, it could contribute as a significant cost factor, and it holds all components in their intended place and orientation. Additionally, the frame will define the main appearance of the machine, hence it plays a crucial role in user perception and experience. Not only for the people using the machine but also for clients like fitness or entertainment centres which have to integrate it with existing devices at their locations.
This graduation project, therefore, focuses on creating a design for the overall frame, considering user-related aspects like spatial perception and comfort, as well as engineering aspects such as durability, manufacturing, transport and assembly.

Initial Requirements

The Ethereal engine needs to be comfortable to use for people with varying body shapes and sizes, so a good understanding of ergonomic aspects is crucial. Additionally, the perception of the machine and the ease of interaction with it will be important for the design. The aspect of safety during active use is mostly covered by a second IPD master graduate, Alejandro Lázaro Bilbao, but the safety of bystanders and when outside the simulation needs to be considered for the design of the frame as well.

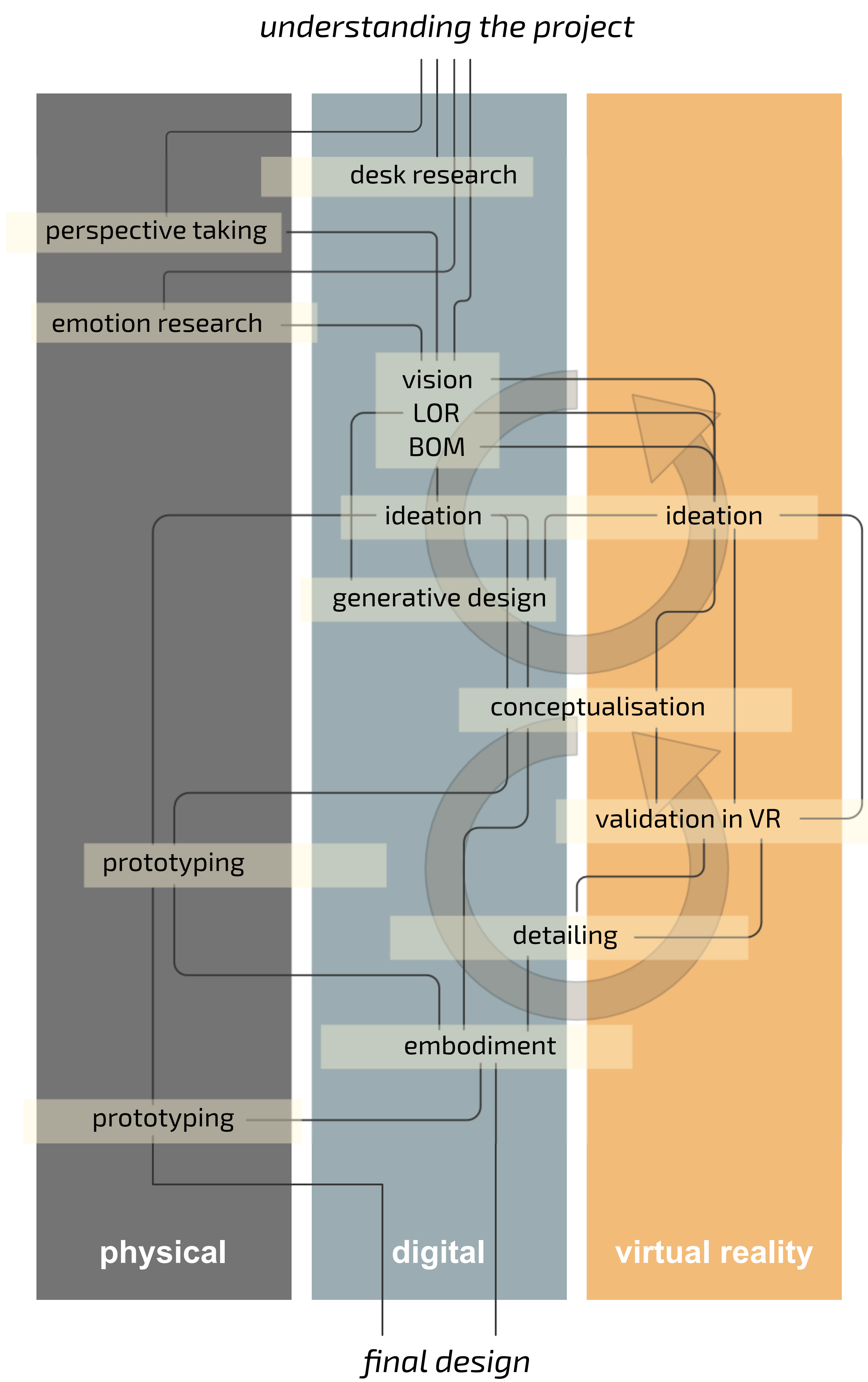
Assignment

After the initial exploration and research and in elaborate accordance with the company supervisor, Scott, the scope of the project was refined. The reasoning is described in this report and is based on bi-weekly (mostly online) meetings with the client.

The final goal of the project became:

> *"Creation of a frame design that sets the Ethereal Engine apart from traditional fitness devices: With enhanced interior lighting capabilities and adjustable exposure during use, the frame creates a comfortable, safe, yet exciting enclosure to enjoy a VR session in privacy or company."*

Considering the importance of the frame in managing the interference of events happening outside of the Ethereal Engine with the person immersed in a VR simulation, the focus lies on creating a good balance between being undisturbed, and yet being able to interact with people outside of the machine. Furthermore, the frame makes sure all components are connected in a sturdy, easy-to-transport and assemble manner. Naturally, a reasonable cost-price dependent on the expected units to be manufactured enables Ethereal Matter to create a long-term profitable business case.



5 Method

A methodical approach helps designers break down and grasp the complexity of a product like the Ethereal Engine and gives strategic guidance in uncovering interesting tangible and intangible aspects that need careful consideration from the research to the final design phase.

The general approach of the project

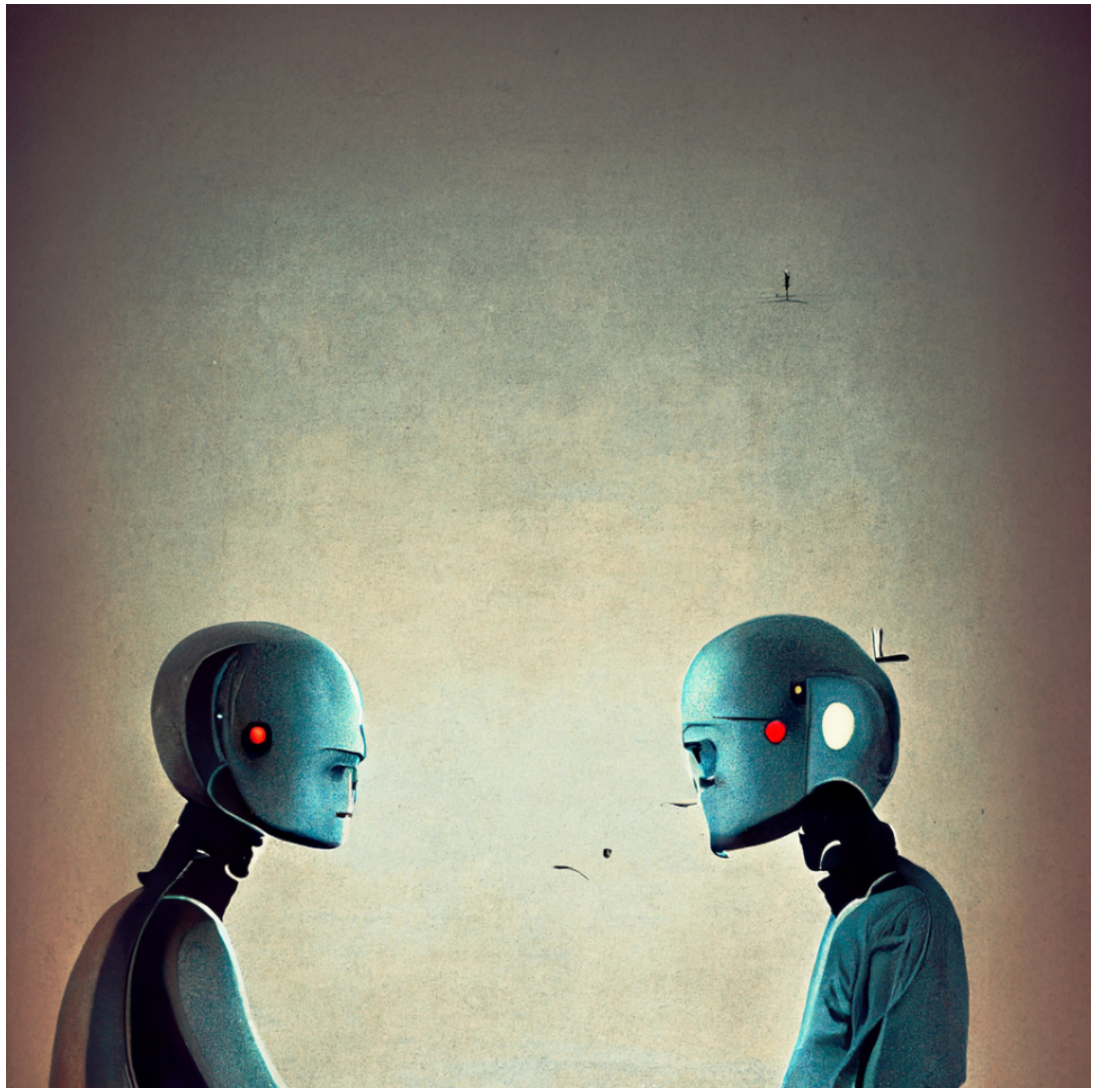
Initial research was conducted to understand the general concepts and terminology of VR experiences, probe the market for similar devices and identify important and interesting design opportunities and requirements.
Because of the 'HRI' (human-robot-interaction) nature of the project, the literature research was split into human- and robot-related research, the first focusing on human perception and experiencing VR, the latter more on the technical, product-focused engineering aspects. The research was performed based on initial research questions, which will be elaborated on in the following.

The exploratory desk research was initiated through 'Google Scholar' as well as 'ResearchGate', using keywords like 'VR', 'perception' and 'fitness' and appropriate results were selected based on their fit to the research questions or the assignment in general. From there, using the snowball sampling method, quoted literature was followed up upon and for specific research questions, more precise search terms were used or added.

Following the desk research, different methods of user research were used to identify intangible product qualities or possible inconveniences throughout a user journey.
First, a method 'perspective taking' was performed to get a good initial understanding of what aspects could influence a positive user experience. Based on those insights, a 'micro emotion scan' was conducted to uncover subtle, unexpected or underlying pain points and opportunities throughout a VR session inside the Ethereal Engine. With those, interesting design opportunities could be found and the results helped to make sensible design decisions with the end-user in mind.

What followed was an intense iterative design process consisting of generative design simulations, ideation and conceptualisation sessions with the client and fellow design students – in VR, as well as with physical prototyping.
The project was accompanied and concluded with physical prototyping sessions with the other graduate, Alejandro, building and testing the frame and first armature of the Ethereal Engine prototype in Delft.

Left: Method flow chart, read from top to bottom



Human-robot interaction as invisioned by Midjourney

6 Analysis

In this chapter, the results of the initial research phase are summarised and presented to create a clearer picture of the several aspects related to the Ethereal Engine. Important terms that are related to VR are explained, but more importantly, key insights are derived to, later on, dictate requirements or shape the vision for the design of the frame and user experience of the machine.

Literature research

The project commenced with the creation of research questions and subsequent literature research, both online and with printed literature. The results were split into two chapters depending on if they concerned mostly human and interaction-based aspects of the human-robot interaction or rather practical, engineering focussed aspects of the robotic part.

Human-related research

The human side of the HRI (i.e. 'human-robot interaction') concerns many subtle, subjective aspects of using the Ethereal Engine. Understanding these enables a careful consideration of negative consequences and identification of positive design possibilities for the frame and user journey in general.
The frame could potentially be an important factor for the engagement of the VR experience.

One of the most important questions regarding the design of a VR experience is:

What makes VR engaging and convincing?

To classify how convincing a virtual experience is, the underlying mechanisms and their aspects are commonly divided into two main categories: immersion and presence.

Immersion

Immersion describes physical aspects like frame rate, resolution, tracking etc. Note that these are all objective measures of how good a system is at portraying a virtual – or simulated version of – reality. Biocca and Levy describe immersion as how much of the perceptual system of a person is informed by the virtual reality experience. They conclude:

> *The more the system captivates the senses and blocks out stimuli from the physical world, the more the system is considered immersive. (Biocca & Levy, 1995a, p. 57)*

In their review, Diemer et al argue that a high immersion leads to an increased perception of presence (2015, p. 5). This does not mean that the faster the hardware and the better the HMD is, the more convincing the entire experience will be. On the contrary: a good hardware setup does not guarantee a high immersion, as a poorly designed virtual environment will not convince a person of being there. However, the significance of a good HMD comes to light when a very engaging, convincing VE is experienced: A slow, lagging HMD would not be able to convey the otherwise most convincing simulations.

Presence

Presence describes intangible qualities of the VR simulation, such as persuasion, believability and authenticity.
Opposite to immersion, presence is a subjective measure of the experience and can be defined as a person's "feeling of being there". Nevertheless, presence greatly depends on the immersive quality of a VR experience Diemer et al. (2015).

In 1997, Biocca made an interesting proposal, saying that a user can only be physically present in one of three places:

> *"[...] the physical environment, the virtual environment, or the imaginal environment. Presence oscillates among these three poles. (Biocca, 1997)*

In a virtual environment, "presence [...] develops from the construction of a spatial-functional mental model of the VE" (Schubert et al., 2001, p. 266). This means, that a person needs to process the multi-sensory stimuli to create an understanding of the VE. There are multiple ways in which to aid that process, the most important is adding or increasing the perceived "realness" of the basic human senses, such as vision (sight), audition (hearing), tactition (touch), olfaction (smell) or gustation (taste) (Humber Sensory Processing Hub, 2020).

Adding dimensional audio, for example, Lombard and Ditton (1997) predict an increase of presence in many circumstances. They further elaborate that next to quality, the spatial characteristics of sound are an important benefiting factor for a sense of presence (Lombard & Ditton, 1997). This creates implications for the choice of auditory input – headphones vs speakers – as well as the acoustic qualities of the Ethereal Engine's interior.

To further increase the feeling of presence, the sense of touch can be stimulated by adding a force feedback system that responds to user input and creates the sensation of physical resistance (Biocca & Levy, 1995b). This is exactly what the Ethereal Engine does with the two armatures and foot platforms.

According to Lipp et al. (2021) in between immersion and presence, 'simulation realism' describes how well virtual objects and worlds are perceived as real. In that sense, the high immersive qualities of a simulation lead to a realistic perception of virtual objects, which in turn can enhance a user's feeling of presence. The way in which for example inertia of objects and physical phenomena like gravitational pull are portrayed, can influence how 'real' a person thinks the simulation is. With the Ethereal Engine, this is possible to a degree that will take VR simulations to the next level.

Proprioception and the vestibular system

Additional to the aforementioned, commonly known senses, humans can make sense of their surroundings in more complex ways, which has implications for the design of the frame.
There is still debate among psychologists on how many senses in total humans possess, as the definition of a sense can vary substantially. However, the existence of the vestibular and proprioceptive sensory system is widely accepted. The former relates to balance and spatial awareness; it controls muscles and most reflexes and is stimulated when moving up, down, sideways, around or over. The latter senses the body's position and movement, so in turn creates a sense of body awareness (Humber Sensory Processing Hub, 2020). With the use of the actuated foot platforms, the Ethereal Engine adds sensory input to the proprioceptive and vestibular sensory system which makes the VR experience induce a stronger feeling of presence as more senses are stimulated. It is these systems that would also register undesired incidences like a sudden tilt of the whole machine, which can lead to a phenomenon called 'vection'.

Vection

If the whole machine was to suddenly tilt, the user inside it would detect an accelerating motion through the vestibular system, but it would contradict the visual inputs as the unintended tilt would not make the virtual horizon tilt accordingly. This mismatch of sensory inputs, called 'vection', is generally a major cause of motion- and cyber-sickness. A similar example is the strange sensation someone can experience when sitting on a stationary train at the station. If that person looks outside the window and only sees a second train that starts to accelerate, it can appear as if the person's train is starting to move. This mismatch of 'seeing' but not 'feeling' movement is called vection and can, among others, induce an unfamiliar sensation in the guts.

Flow

If the virtual simulation is highly immersive and no disturbances occur, a user can enter a state of high concentration, coined by psychologist Mihaly Csikszentmihalyi as 'Flow' (1990).
Flow describes the state of someone being fully involved in an activity and is strongly linked to enjoyment (Lipp et al., 2021). Weibel et al. (2008) state that "[...] flow mediates the relationship between presence and enjoyment". They also found a strong correlation between presence and enjoyment, which means that the more a user is immersed in a VR experience, the more fun the person could have. This circumstance is highly desirable for the Ethereal Engine, as aspects that contribute to the enjoyment of the VR experience will link the product to positive emotions.

The next important question to ask is:

What could interfere with this immersion?

To answer this question, anything that could disrupt the state of flow and the feeling of presence needs to be identified and understood to know how to mitigate it from occurring.
Lombard and Ditton (1997) point out how important the context of a media experience is, as a quiet room and a noisy arcade give very different environmental influences that need to be considered. The frame plays a major role in blocking out unwanted noise or, in contrast, allows for social interactions with bystanders that are not present in the VE.

Slater et al. (2002) identified the following factors that characterize a system regarding its immersive ability:

- *Inclusive: The extent to which sensory data from the real world is shut out.*
- *Surrounding: The extent to which sensory data can be delivered from any direction.*
- *Extensive: The range of sensory modalities accommodated.*
- *Vivid: The resolution, bandwidth and 'realism' of the displays.*
- *Matching: The degree of temporal and semantic correlation between changes to sensory data and kinesthetic proprioception.*
- *Eventful: The extent to which there are events in the VE that are independent of the volition of the participants, the extent to which the VE portrays a meaningful scenario.*

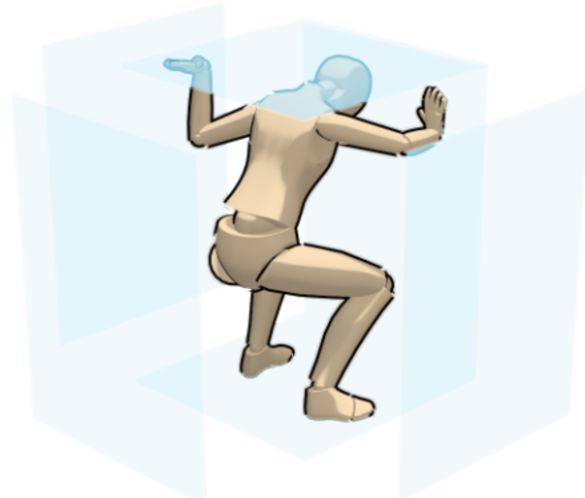
(Slater et al., 2002)

Especially the "inclusive" factor will depend on the design of the frame, as the better it shields from the surroundings, the more immersive and engaging the overall experience will be. The 'extensive' factor, so the range of sensory modalities, dictates requirements for the frame design, if, for example, a fan is added to simulate headwind for flying simulations.

Now that it has been discussed what it feels like to be inside a VE and what could interfere with a feeling of presence and immersion, the transition between reality and virtual reality will be discussed.

How does entering and exiting a VR simulation feel?

A very interesting aspect of VR experiences concerns the transition from the real world to the VE and back; simply speaking, the action of putting on the HMD and eventually removing it again. Most aspects related to entering are similar to exiting the VE, therefore the latter is discussed in the following. In an interesting paper called "The Dream is Collapsing", Knibbe et al. investigated the exit transition from VEs and give a first overview of the mechanisms and emotions involved in this transition. The researchers mention six recurrent themes related to this transition: space, time, control, sociality, sensory considerations and future opportunities (Knibbe et al., 2018, p. 5).



Space

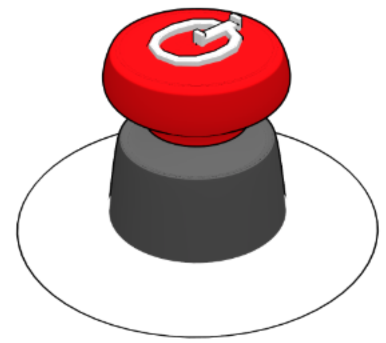
The study found that the perception of space varied a lot among the participants and the VE used per participant. Interestingly, the authors note, how

> *"[...] none of the participants noticed their own height change, but rather noticed the effect of this height change as it was manifest in their surrounding environment: (Knibbe et al., 2018, p. 5)*

This has implications regarding the feeling of being in an enclosed frame, as a sudden change of the space-to-self proportions – e.g. the transition from being small while in a wide-open virtual environment to being back to reality with a normal stature inside the Ethereal Engine – could lead to a sudden feeling of claustrophobia for the user.

Time

Participants described the virtual reality to end even before they took off the headset. It seems that the realisation to be in a fake environment ended the immersion even though the visual stimulation was still present. This creates certain expectations of what to expect when eventually sensing the real environment again. Such anticipation could result in surprise, disappointment, scaredness, over- and underwhelming, etc.



Control

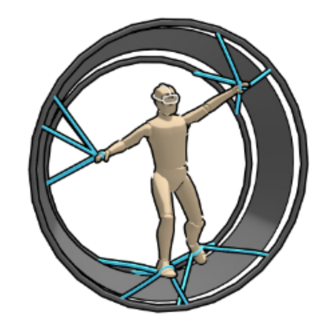
Participants of the study described the exit of the VE with analogies like exiting the 'Matrix' which could be continued upon with the design of the entry and exit user experience. Such analogies can serve as blueprints to ease or enhance the transition experience.

Sociality

Upon exiting the VE, the sudden realization that people have been watching without notice can lead to a feeling of embarrassment or shame, as one is completely unaware of the impression one made on bystanders while being in VR. This is a very important consideration for the design of the frame. The amount of privacy that the machine provides stands in stark contrast to the possibility to communicate and share the experience with people outside of the Ethereal Engine.

Sensory

The sudden change of stimuli – taking off the headset, headphones, letting go of the handles, etc. – can be overwhelming. Especially the more immersed – present – a person is in the VR experience, the more difficult it will be to readjust to being in reality again.
Participants of the study conducted by Knibbe et al. mostly mentioned the changes in lighting and texture. That makes sense, as the main stimulus of a VR experience is the HMD and human eyes need time to adjust to different light levels. The different colour spectrum and lighting quality created by the headset can also greatly differ from the illumination qualities of the room (ambient luminescence versus focal glow, different lighting direction, multiple light sources, etc.) and lead to this change of textures. Knibbe et al. further conclude that factors like disorientation and confusion related to the exit experience depend "on a combination of (a) how present the player is in VR, (b) the movement required within VR, and (c) the time spent in VR (participants commented that their experiences were bound by their length of participation in VR)." (2018, p. 9).



Future opportunities

Knibbe et al. lastly mention future opportunities for the transition in and out of VR simulations. They mention the design of scary transitions to increase thrill, but also even the abrupt change from VR to reality by gradually exiting between these two realities.
For extending the VE beyond the headset, they mention adding haptic extensions which are already researched.

In the product presentation chapter of this report, a different future opportunity is discussed: Adding additional interactions for bystanders around the Ethereal Engine. This blending of a person in VR and the people, in reality, could add a great new interactive quality to the simulations of the machine, but potentially be implemented beyond the Ethereal Matter project.

Apart from disturbances that hinder a pleasant (transition) experience, there are several ways in which the Ethereal Engine could potentially facilitate a comfortable, or enhance a thrilling experience of entering and exiting the VE:

How can the transition to and from VR be made more comfortable or exciting?

There are multiple ways in which a transition into and out of a VE can be altered. The most obvious design factor concerns the user's vision. When switching from ambient lighting to the illumination of a display at a very close distance to the eyes, the contrast can be uncomfortable. Easing the transition would mean adapting the surrounding ambient illumination levels and quality of such lighting to the capabilities of the HMD, and vice versa, adjusting the illumination levels of the headset to the ambient light before placing it over the head and eyes.
Vasylevska et al. (2019) state how that is necessary to enable immediate use of the headset.

Another problem is the disorientation that a user can feel upon exiting the VE. Menin et al. (2022) link that to "the user's unawareness of their surroundings" (Menin et al., 2022, p. 410) which means that the design of the Ethereal Engine's frame interior plays a major role in reducing or enhancing this disorientation.

Light levels

As mentioned in the previous section, light levels pose a crucial role in the transition of VR experiences. Interestingly, Knibbe et al. (2018) observed that participants suggested adaptations from within VR to ease the exit transition and adaptations to the real surroundings to heighten the exit experience, e.g. to make it more thrilling. They propose to make

> *"[...] users mentally aware of specific features of their physical environment (such as the sound) for a period of time before they remove their headset (and complete their transition back to the physical environment)." (Knibbe et al., 2018, p. 7).*

In a comparative study on HDMs, Mehrfard et al. (2019) measured the brightness (cd/m²) and colour accuracy (Δe) of several products ranging from 44.4 to 190.5 cd/m² and 6.5 to 28.6 Δe*, respectively. These lighting levels need to be taken into account for the amount of light that needs to be present in the machine during entering and exiting the VE. Matching these will allow for an eased transition experience, deviating from them could make a thrilling exit experience by creating disorientation (sudden darkness) or blindness (extreme brightness) on purpose. For the latter, extreme cases have to be designed with care as they could induce major discomfort, paranoia or even seizures.

Headset	Brightness (cd/m²)	Color accuracy* (Δe)
HTC Vive Pro	133.3	6.5
Oculus Rift S	80.5	11.7
Primax 5k	44.4	8.1
HTC Vive	190.5	8.9
Samsung Odyssey	126.5	7.1
Lenovo Explorer	88.7	15.5
Dell Visor	76.2	7.7
Acer WMR	76.6	28.6
HP WMR	101	16.6

Light levels and colour accuracy of selected HMDs (Mehrfard et al., 2019)

The perception of small, enclosed spaces

The Ethereal Engine comprises a certain closed-off volume when a fully enclosed frame is chosen. That raises an important question regarding the interaction of the user with the machine: How does the user feel when being inside this enclosed space?

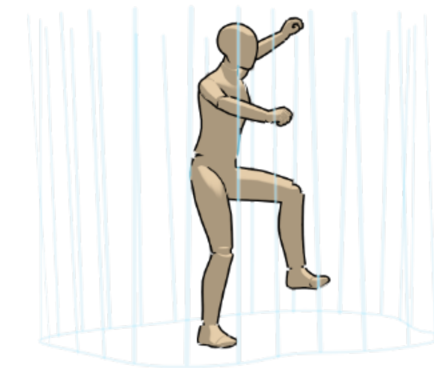
To get a preliminary answer to this question, it has to be understood how humans perceive space in general. In the "Handbook of perception", Carterette & Friedman mention an experiment conducted by Hayward and Franklin in 1971, which "showed that the perception of open and enclosed spaces was not a function of the relative sizes of the dimensions of these spaces, as had been suggested by Garling (1969), but was rather a function of the relation of boundary height and viewing distance." (Carterette & Friedman, 1978, p. 161; Hayward & Franklin, 1974).
This means that simply increasing the volume inside the machine is not the best option to produce a comfortably large space. Carefully designing and testing the interior will be important to prevent the user from feeling for example claustrophobic.
Another research question that was explored is:

How can people trust the Ethereal Engine?

An important fundamental human need is security (Desmet & Fokkinga, 2021, p. 10). People using the Ethereal Engine should feel comfortable trusting the apparatus but also their immediate surroundings. VR headsets usually already include safety features like a 'Guardian boundary' that give visual cues when a person leaves a predefined area in reality. On approach, a virtual wall appears in the VE and when crossing this boundary, the video from the tracking cameras is used to show the actual surroundings in a way that is similar to AR. Entering the guardian boundary again switches the display back to showing the VE exclusively.

This temporary switch can be a useful way to reassure the user that no one entered the machine, and additionally, it could be utilised for the transition creating a smooth shift from being in reality to being in VR.

**colour accuracy was measured as the deviation from the results of a display colour calibration device. Therefore, a lower value is better, as it means colours are displayed closer to the true colour.*



However, Knibbe et al. (2018) point out that such blending of the real with the virtual world potentially violates the sense of security, as the reassurance of being able to take off the VR headset at any time is challenged.

Conclusion

With the knowledge acquired from researching the qualities of VR, several things can be concluded and taken into consideration for the design of the frame. Blocking out senses from the real environment on the one hand and adding multi-sensory stimuli, that are linked to the VE, on the other hand, will help the user feel present and immersed inside the VE.
Improving immersive factors, like the resolution of the HMD, frame rate and so forth, increase the quality of a VR simulation and help create an engaging and convincing experience, but they are bound to the VR headset used, so will not be followed upon in this project.
The light levels of common HMDs give a first indication of how much light needs to be available inside the Ethereal Engine. It also plays an important role in how the interior space of the machine is perceived. In combination with the present colours materials and surface finishes, the frame could be perceived as inviting and secure, or uncomfortable and claustrophobic.
In addition to aspects such as space and sensory input, it will be important for Ethereal Matter to make good recommendations to customers of the Ethereal Engine regarding the time participants spend inside. The frame will provide the most control over the social dimension but control for the user in general needs good consideration for the entire machine in future developments.

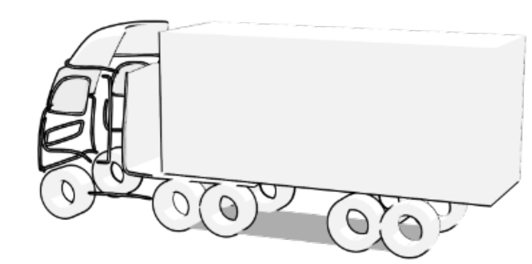
Robot-related research

The second major part of the research is concerned with the practical aspects of designing the frame of the Ethereal Engine. It will touch upon physical dimensions and aspects that need to be considered for manufacturing, transport and assembly, as well as other important features or practicalities that concern the machine.

For a large machine like this, a valid question is:

What are the maximum transporting dimensions for the whole machine?

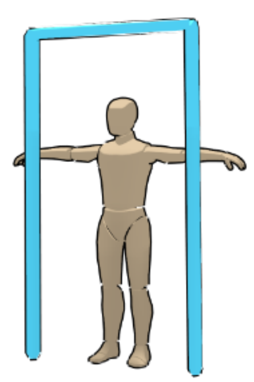
After manufacturing, the Ethereal Engine needs to be shipped and transported to its final destination. The limiting factor here is the road transport by truck. Standard American Trucks can carry objects up to a width of 100 inches (2,54 m), while European Trucks are limited to an internal width of 2,45 m (external width of 2,55 m (COUNCIL DIRECTIVE 96/5 3/EC, 1996). The latter will therefore be the limiting width for individual frame parts and assemblies, as using oversize trucks and other ways of transport would prove unreasonably costly.



For the overall ease of transport, it would be beneficial if parts fit onto standard Euro palettes with dimensions of 1,2 x 0,8 m (European Pallet Association e.V [EPAL], 2020). Nevertheless, parts of the machine can exceed the aforementioned dimensions, but one dimension needs to lay inside these boundaries to make the transport feasible from an ergonomic and economical perspective. Said parts could be laid on their side for instance.
After the transport on the road, the next step is to research:

What are common building dimensions to take into consideration?

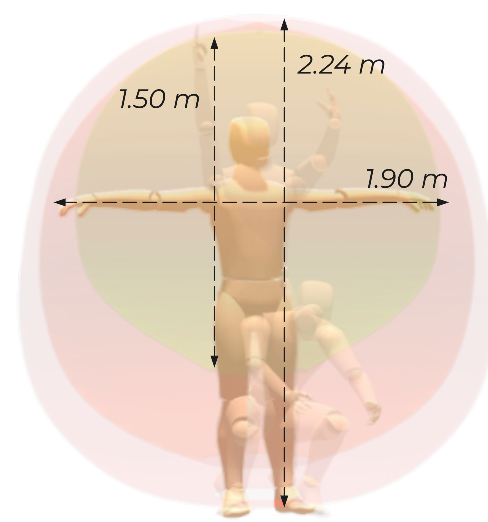
Just like the truck dimensions, building dimensions need to be considered mostly for the transport of frame parts and the final assembly of the machine. Individual parts need to be carried from the truck used for transport through various doors and hallways to the final space where the Ethereal engine will be erected and installed.
Most public buildings like fairs or entertainment centres are conceived to accommodate large objects, so the main places to worry about sufficient space are gyms and conventional places like office buildings.
Of interest are the dimensions of doors, hallways and the presence of elevators and narrow passages that could limit the amount of clearance provided when moving individual frame parts around.



Of course, components could be disassembled to the smallest bits and parts, but that would come at an unreasonable high price for manual labour reassembling everything in the right way without damage.
Moving forward, a hallway width of 1,5 m is regarded as commonly available, as it is recommended in the Manual of Standard Building Specifications (2019) by the European Union. This width allows parts to be transported with a manual pallet jack if needed.
The manual furthermore recommends a minimum ceiling clearance of 2,6 m for office floors and 3,5 m for ground floors. Therefore limiting the overall frame to a height of 2,6 m would allow the machine to be placed in a wide range of buildings, but that depends on the ongoing development of the armatures and foot platforms, as their motion combined with the maximum height of a user will determine the vertical clearance that needs to be accommodated.

What is the maximum range of motion (in 3D) that needs to be housed?

In an experiment, the range of motion for a P95 male (the author, 1900 mm) – based on measures for the international stature of mixed gender, according to the online anthropometry tool DINED – was conducted and resulted in the following maximum dimensions (Molenbroek & Huysmans, 2022):



What are the maximum carrying weights and dimensions for frame parts?

The NIOSH (National Institute of Occupational Safety and Health) guidelines give a comprehensive overview of lifting and carrying limits that were used for this project. The lifting equation for the recommended weight limit (RWL) gives a good indication of the maximum weight individual frame parts can have to be transported by one, two or more people.
23 kg is given as the absolute minimum for lifting objects most ergonomically (Applications Manual for the Revised NIOSH Lifting Equation, 1994).
Frame parts should therefore not exceed 46 kg if they should be movable with two people at once.

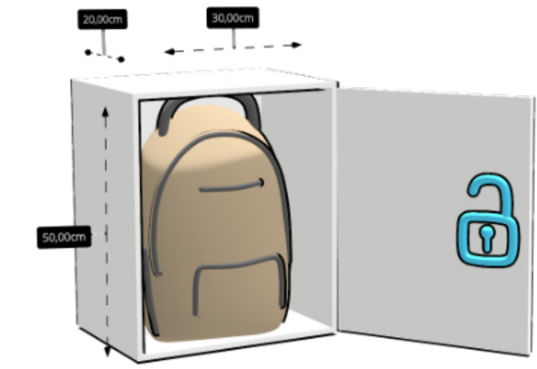
Additional aspects related to the whole machine will be discussed in the following.

What other features are needed to include in a VR fitness machine?

Hygiene

A concern regarding the shared use of a VR fitness device is hygiene. Eventually, users could bring their personal headset, but all other interaction points of the machine are shared and will be susceptive to sweat and other potentially unhygienic substances. Therefore, the Ethereal Engine should be easy to clean and sensitive components should be closed off.
Furthermore, with the COVID-19 pandemic, disinfection is another important concern that should be considered in the design of the machine. It would make the use of the Ethereal Engine a lot safer if the risk of infection with viruses or bacteria is kept to a minimum. This can be done through manual cleaning, but systems that use for example UV-C light can do the task in minutes without the need for aggressive chemicals.

If the VR headset is provided with the Ethereal Engine, one can easily imagine how the headset will need regular cleaning, especially after intensive workouts. Cleanability is considered an important property of VR headsets and could determine which headsets to recommend for use in the Ethereal Engine (Mehrfard et al., 2019).



Storage

When someone wants to use the Ethereal Engine for a workout while fully immersed in VR, storing (potentially valuable) personal belongings is necessary. The frame could house such an option, such as a small locker. For that, the size of a small backpack of approximately 300 x 200 x 500 mm will likely be sufficient for most users to store valuables and spare clothes (these are around the same dimensions granted for carry-on cabin bags on aeroplanes).

Tether

For continuous experiences where the same VR headset is used, the internal batteries will eventually run empty. A tethered connection to a power supply will enable unlimited use of the HMD of choice. Such a cable will need to run from the head of the user to a place in the machine where it is connected to the power supply while not interfering with the user's motion and avoiding the risk of accidentally being pulled out or wrapping around the user. In general, guiding the cable away over the head of the user appears the most secure and practical as chosen for most tethered VR headsets like the HTC Vive.

General fitness machines and equipment

In general, the Ethereal Engine can be classified in two ways: The machine can be considered as a fitness device with additional VR, as well as a VR experience with the added fitness component. When viewing it as a fitness device, research suggests five tangible quality parameters, that can be used to analyse the possible success of such a product (Addolorato et al., 2020):

Attractiveness

Efficiency

High quality and experienced design control

Functional and practical linearity

Specialty and cost

Addolorato et al. mention three additional, intangible aspects, which are 'beneficial', 'engagement' and 'magic moments' that occur during the use of the fitness apparatus.
While the tangible parameters need to be considered for the design of the frame by default, a 'magic moment' could add a unique and convincing aspect to spark curiosity about using the Ethereal Engine, see 'interaction for bystanders' in the product presentation chapter. Additionally, such a moment would set the machine apart from usual fitness equipment and leave a lasting impact on people's memory after leaving.

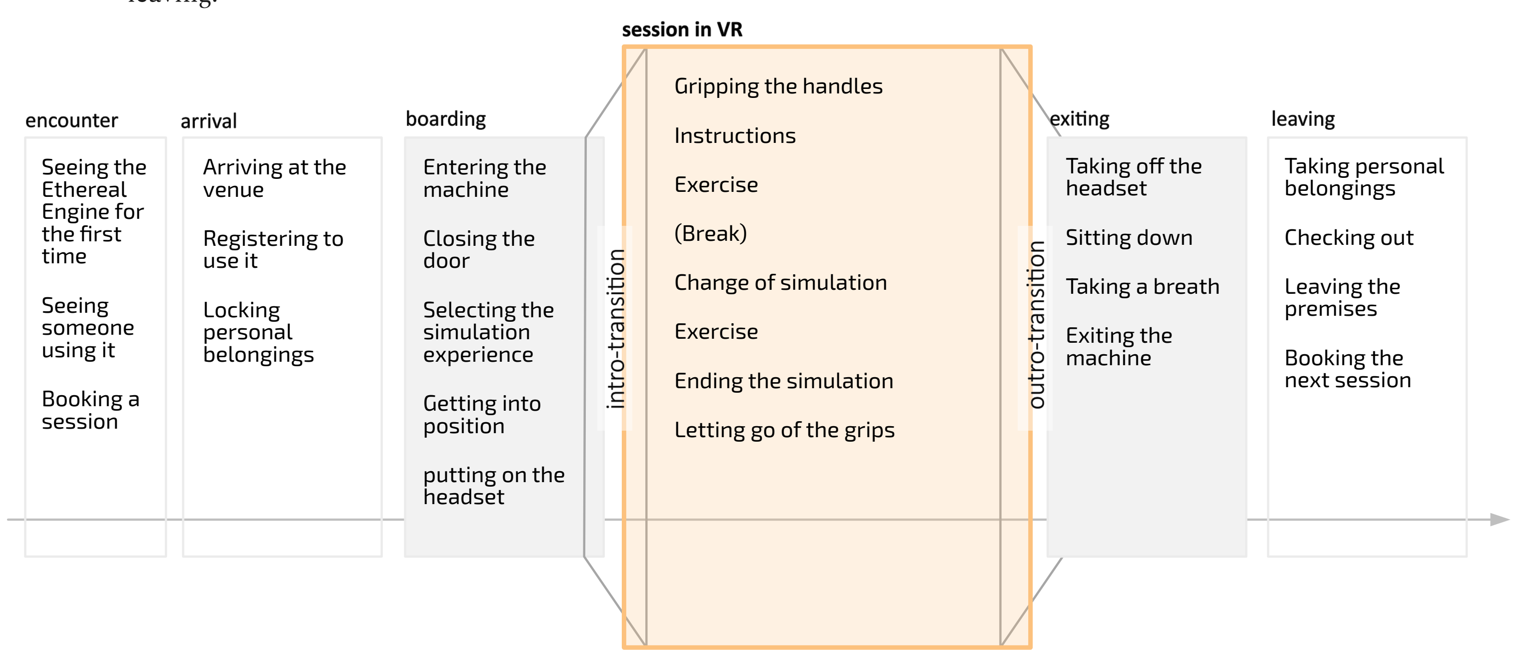
User research

Next to the desk research, user research approaches were used to uncover new insights that have not been identified by the client as beneficial or potentially obstructive to a positive and rememberable user experience. As a start, an ideal user journey gave interesting clues on how what to probe for during the following user research.

What should the user journey ideally look like?

A general timeline of the user journey can be seen in figure below. Research suggests taking breaks of 10 – 15 minutes after being in VR for 15 – 30 minutes, but effects over the long term when exceeding these limits have not been studied enough yet (Department for Business, Energy and Industrial Strategy). From my own experience, it can be said, that especially for people new to VR, these recommendations should definitely be followed, but after some time, longer sessions are easily possible without problems.

Evidence furthermore suggests, that a user could experience balance and coordination issues following VR use, therefore, a possibility to take a rest nearby is highly recommended (Department for Business, Energy and Industrial Strategy). This design for the Ethereal Engine, therefore, includes a seat just behind the user.



Taking perspective

Envisioning the use of a complex product like the Ethereal Engine is difficult without some kind of (working) prototype. For a start, taking the perspective of a possible end-user can be very insightful.

Method

The method used for this project is loosely based on the 'perspective taking' approach proposed by Prandelli et al. (2016) which goal is to discover entrepreneurial opportunities by taking perspective from the user's point of view. The method was adapted to identify opportunities and threats for a desirable user journey of the Ethereal Engine. For this method, I tried to think and act like a first-time user while I approached the prototype frame envisioning how it would feel like to go through a whole VR fitness experience. I went through all the possible steps someone would go through when using the machine, including a workout in VR and the steps preceding and following that. To test the spatial properties of the enclosure, I used a large piece of acoustic fabric to simulate different ways in which the user could be sealed off from the surroundings.

Results

The outcome of this research was some concrete ideas that needed consideration, as well as intangible aspects which could affect the perception of the user journey, the Ethereal Engine in general as well as the space within the machine.

Two main scenarios crystallised: Scenario A, which has a user use the machine for a solitary (workout) session for instance at the gym. Here, it is necessary to cover most of the user to outside bystanders, as it will create a private experience without the chance of being stared at or even photographed without notice and especially consent. Especially the back of a person would be most vulnerable, as the small gap between the nose and VR headset makes it impossible to see further than left and right. I noticed, that a too-low barrier can lead to the fear of falling out of the machine, more so when standing on elevated foot platforms. In general, it creates a very unfair situation, in that the person being active in the simulation is not able to see their real surroundings, while everyone else can easily stare at them without being noticed at all.
Adding some shielding to the surrounding frame could also positively enhance the chance of sparking curiosity in people who encounter the Ethereal Engine for the first time.

Scenario B is a group of people going to an entertainment centre for instance, where they want to have a good time and fun with each other. Here, the interaction with bystanders is crucial. The client described multiple occasions, where people were cheering with the person trying out the US prototype. This added interaction created a collective feeling, which can lead to the same positive effect a workout buddy can have on one's motivation to exercise.
A further finding was the large impact exterior lighting can have on perceived comfort inside the machine, especially when entering and exiting the VE.
In general, the chance of hurting oneself when accidentally letting go of the handles during an intense movement, as well as simply losing balance and falling, lead to the importance of padding the frame inside where the user could get in unwanted contact with it.

Lastly, a place to store the headset would be very convenient and the access in and out of the machine should be as inclusive as possible, especially when considering the use of the Ethereal Engine for rehabilitation, or simply providing enjoyable experiences to people with disabilities.

Capturing Emotions

Emotions are fundamentally connected to human existence, they govern our decisions and influence our experiences, may they be good or bad, or anything in between (Desmet, 2021).

A second conducted user research method is concerned with the user's emotions. This method is called 'Micro Emotion Scan' and aims to uncover the whole range of micro emotions a person experiences when interacting with a product, in this case, the Ethereal Engine (Desmet, 2021).

According to this model, the process of eliciting an emotion constitutes of several parameters and their interplay as can be seen in the figure to the right (Desmet, 2002). The emotion depends on the appraisal of the product which in turn is made up of a person's motive and an immediate stimulus. Motives can be explained simply as needs, goals and values that a person has or adheres to, e.g. needing a sense of security when being inside the Ethereal Engine. The stimulus is the actual event, which in this case could be entering the Ethereal Engine. Combined, they will determine how the person automatically, subconsciously judges the product, evaluating if the event of entering is good or bad. Consequently, the person could feel anticipation towards what is about to happen inside the virtual simulation. This would be an example of a – undoubtedly desirable – positive emotion. On the other hand, the person could feel anxiety if the space he or she is standing within is uncomfortable, claustrophobic even.

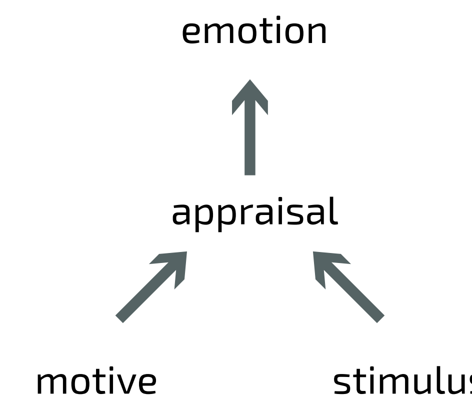


Figure of the basic model of product emotion

Therefore, the design of a frame for a VR fitness machine creates several concerns and possibilities regarding user interaction and experience. Desmet et al. state that

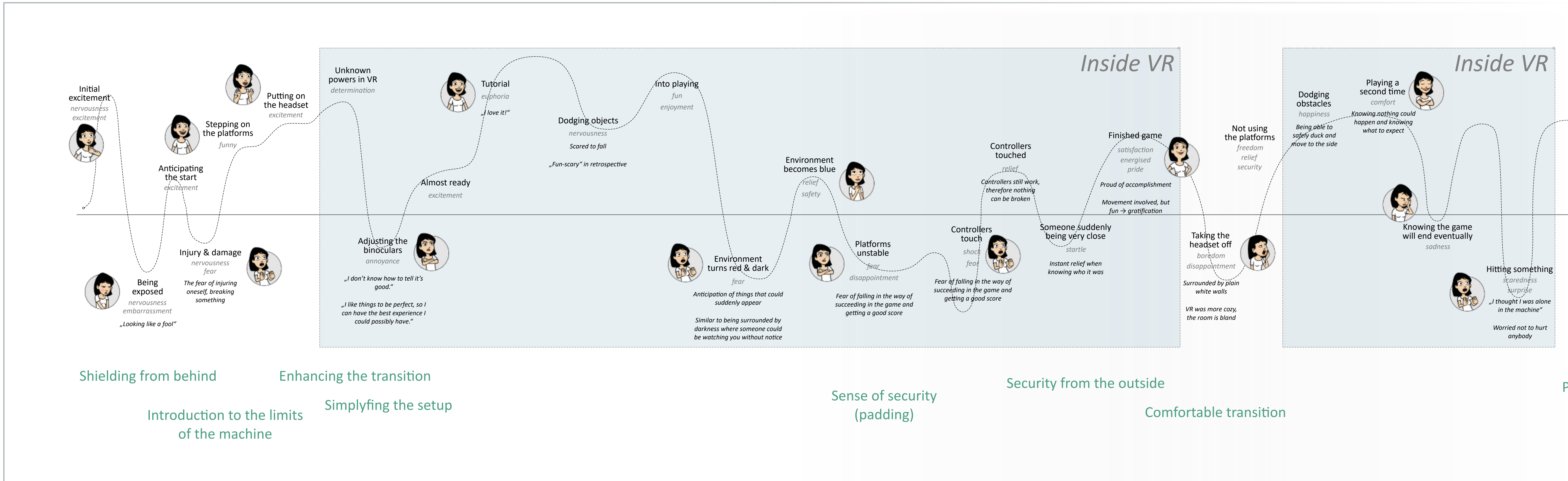
> *"[...] emotional experiences are reliable entry points to uncover underlying concerns." (Desmet et al., 2021)*

Figuring out possible concerns by capturing micro-emotions can be a helpful tool to make sure the frame of the Ethereal Engine adds to an overall positive user experience that is one to be remembered.

Method

The research was conducted with a female participant that had only a little experience using a VR system. The setup consisted of the prototype frame and the VR headset and an informed consent form was prepared, discussed and signed before the experiment.

First, the participant was introduced to the project, the VR headset and what was about to happen. Then the participant stepped inside the frame, onto the



The emotional journey of the participant, first half

slightly unstable foot platforms, put on the VR headset and went into VR 3 times, doing several activities each time. The first was to play a very active game called 'Beatsaber', where boxes have to be split with two light sabres to the rhythm of the music. The second time, the participant played the game standing on the floor and during the third phase, the participant experienced a non-interactive 360° video of a dinosaur in the forest that wakes up, approaches and leaves again. During the VR sessions, the interviewer occasionally interfered by, for example, unexpectedly touching the controllers of the participant, to trigger emotions that would happen during real-world scenarios, such as when someone simply reaches into the Ethereal Engine to scare the user of the machine.

After the experiment, the participant mentally went through the whole experience again using the emotion capture cards as guidance to remember the events that triggered corresponding micro-emotions. Using the laddering technique based on Jonathan Gutman's Means-End theory (1984) as adapted by Desmet (2021), I tried to identify the underlying reasons the participant experienced these emotions. The goal was to uncover motive hierarchies and understand the properties of the experience that corresponded to these fundamental motives.

The order in which these were uncovered looks like this:

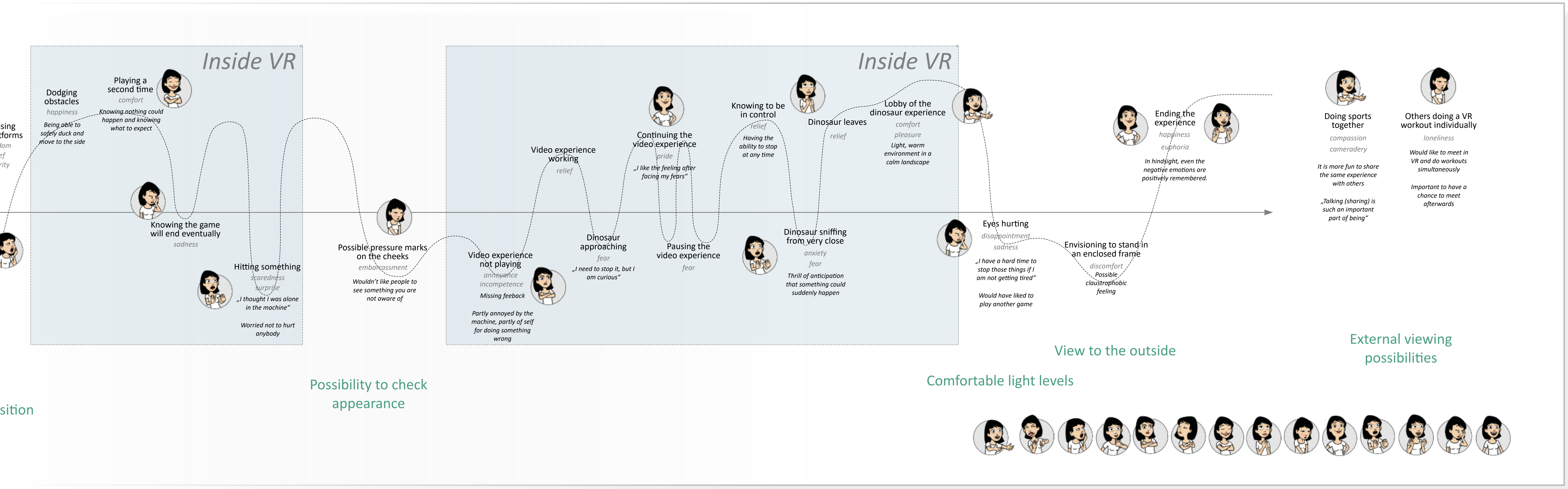
1. *Emotion*
2. *Stimulus event of that emotion*
3. *Underlying motive (goal, need, value, expectation that was harmed/reinforced)*
4. *Fundamental motive*

Asking questions like "Why is that important to you?" helped to ladder up to more abstract motives.

Summary

Throughout the experience, the participant described a multitude of micro-emotions. From the anticipation of the experience to start, to the fear of hitting something, several positive and negative emotions were evoked. Interestingly, the user journey was dominated by a lot of sudden ups and downs, but the participant described the overall experience as positive and even most of the negative emotions as remembered positively.

The main takeaways from this research can be seen in the figure above, continuing on the next page.



The emotional journey of the participant, second half

Discussion

The fact that the participant remembered negative micro emotions positively is a phenomenon called 'rich experience' and the reason for the success of many common activities or products like rollercoasters, puzzles, climbing, film and so on. What these have in common is that the negative emotions they elicit – fear, frustration, sadness, disgust, terror, etc. – are perceived positively because they are consequence-free (rollercoasters and climbing are generally safe), detached (movies create real-looking events by staging and faking), or serve a greater good (the boredom of exercising or the annoyance of completing a complicated puzzle are rewarded with a healthy body or pride)

Due to the limited number of participants, the results of this research were used not to evaluate a design but to inspire and discover important aspects for the frame to take into consideration further on in the design process.

Having the possibility to check one's appearance after a session in VR could be very important to many potential users of the Ethereal Engine. The fundamental need for beauty can be satisfied easily when a user can check their appearance e.g. for pressure marks from the HMD, sweat, or other visual disturbances after an intense workout session.

7 Main drivers

From the insights gained throughout the research phase, five main drivers, a vision, a list of requirements and a package were derived. This resulted in a better-defined scope of the project which was described in the assignment chapter. This chapter will give an overview of the design boundary conditions and the aspired vision for the design of the Ethereal Engine's frame.

Main drivers

Main drivers provide a focus for the choices and sacrifices that need to be made further in the design. The perfect product doesn't exist, but choosing the right alternatives during the development makes sure the most important properties adhere to the overall vision.

Based on the literature and user research, as well as discussions with the client, the main drivers were chosen to be that the frame of the Ethereal Engine shall:

1 be **safe** to use, with no chance of getting injured.
2 provide a **comfortable transition** in and out of the machine and VR.
3 have an **exciting, engaging appearance** that reminds of an unforgettable experience, less of a workout.
4 provide **good interior lighting and a clear background** for the camera-based mocap.
5 be **modular** to easily up- or downgrade the setup to a minimal or full-fledged configuration.

The goal of this project is to develop a lightweight, cost-efficient and easy-to-manufacture and assemble frame, which constitutes the main structural basis for the engine; a frame that gives the user a comfortable perception of the engine before, while and after being in a VR simulation.
In addition to the main drivers, a vision was created that served as a mental construct to keep the focus not only on practical engineering aspects but also on the anticipated experience for end-users.

Vision

The vision also created a focus for many decisions that could not be based on hard facts or requirements. The vision is mainly concerned with the Gestalt of the overall machine which demands an iterative design process with a lot of trial and error. The vision became the following:

"Creation of a **frame design** that sets the Ethereal Engine apart from traditional fitness devices: With enhanced **interior lighting** capabilities and **adjustable exposure** during use, the frame creates a **comfortable, safe, yet exciting** enclosure to enjoy a memorable VR session in **privacy or company**."

Compared to common fitness devices which are generally simple, dark powder-coated metal constructions, the frame shall try to avoid this aesthetic wherever possible to set itself apart from the negative associations people have with fitness equipment and gyms.
A major aspect is the distinction between doing a workout session in the Ethereal Engine on your own and going to an entertainment centre with friends or family to have a joyful experience in company. Serving these rather opposite needs proved to be a big challenge throughout further development.
Finally, as the user is basically wrestling with two robotic arms, a friendly appeal makes sure that users are curious rather than afraid of stepping into the machine.

Accompanying the vision, a set of requirements was derived from the research, but mostly in collaboration and discussions with the client.

List of requirements

These requirements were divided into hard requirements: depending on if exact conclusions could be drawn when they were met, and soft requirements: when a verifiable value was not yet or impossible to be determined. The frame connects all necessary components and keeps them oriented in the right position relative to each other.

A few notable requirements are listed below, please refer to the appendix for the complete overview:

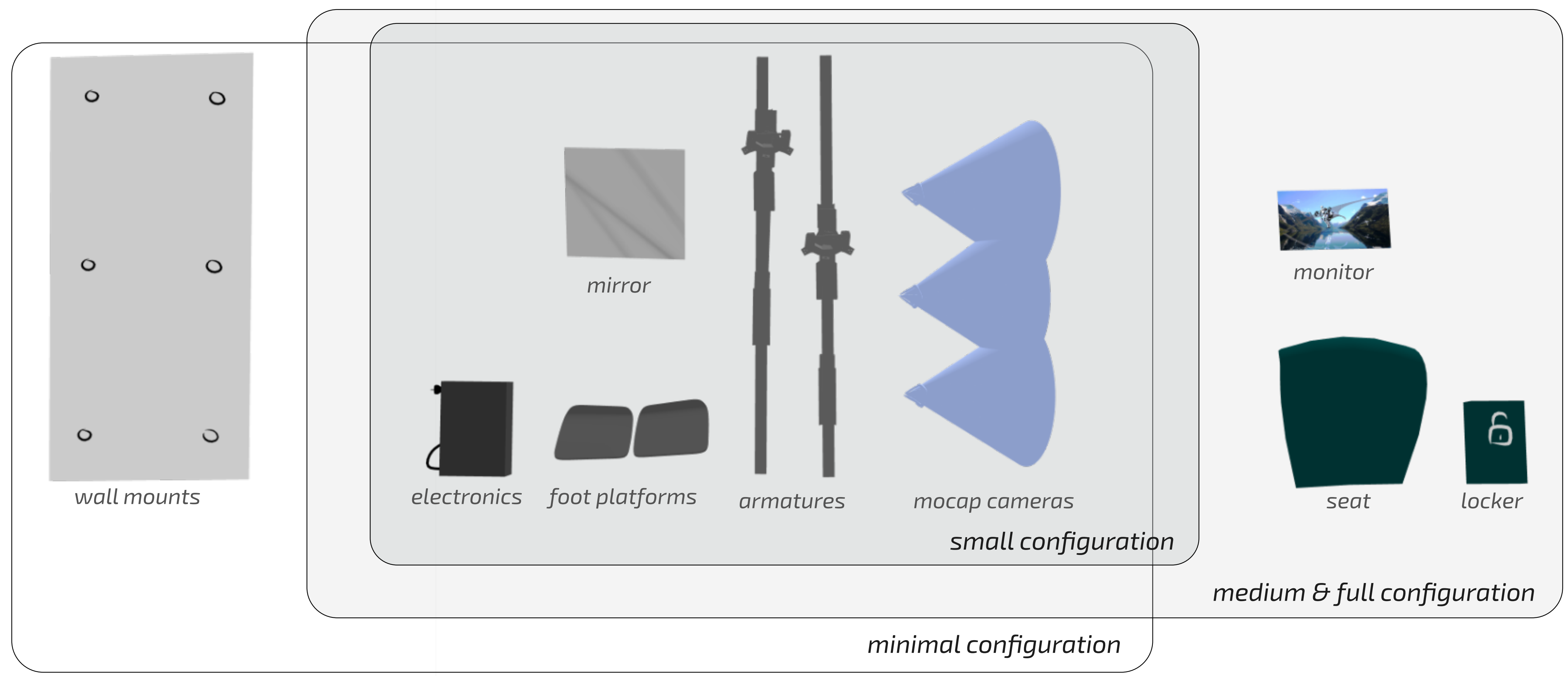
- Individual frame parts maximum weight: 50 kg
- Storage for personal belongings with the following dimensions: 300 x 200 x 500 mm
- Broken parts can be easily accessed and replaced
- Users can see what is happening outside the machine
- Users should be able to take a rest by sitting down exactly where they are
- Creating a maximum load of 4.5 to 5 kN/m^2 on the floor. As stated for "C4: Areas with possible physical activities, e.g. dance halls, gymnastic rooms, stages." (EN 1991-1-1:2002 (E), 2002)

It has to be noted that the requirements in this project were ever-changing. For an elaborate explanation please refer to the recommendations chapter.

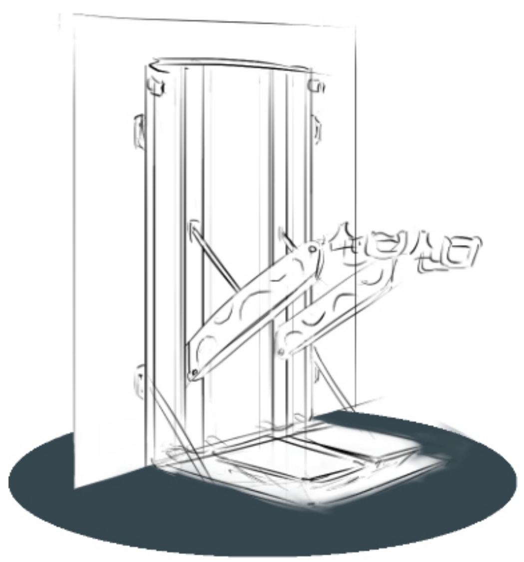
Determined by the fifth of the main drivers and supported by several requirements, the modularity approach became an important aspect of the design of the frame. To better conceptualise what that means, a set of packages was defined:

Packages

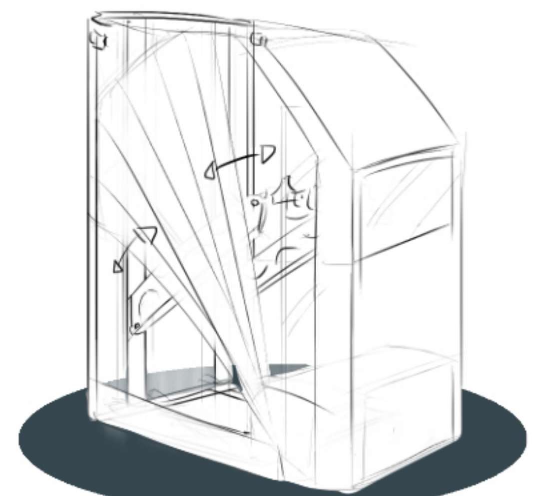
As the Ethereal Engine has several use cases and the possibility to be extended or reduced in functions, it is very helpful to determine those components as packages. Arranging them allowed me to sketch around them and design for their mechanical, electrical or optical connection as well as their respective positioning.
The illustration below shows all of the components that the Ethereal Engine consists of:



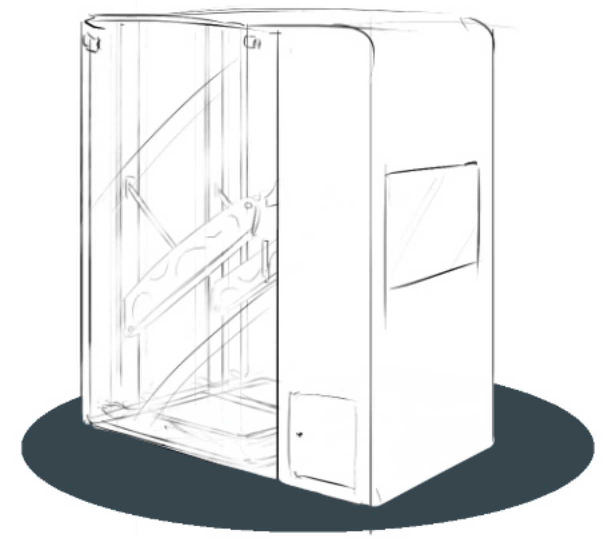
Visualisation of all components side-by-side



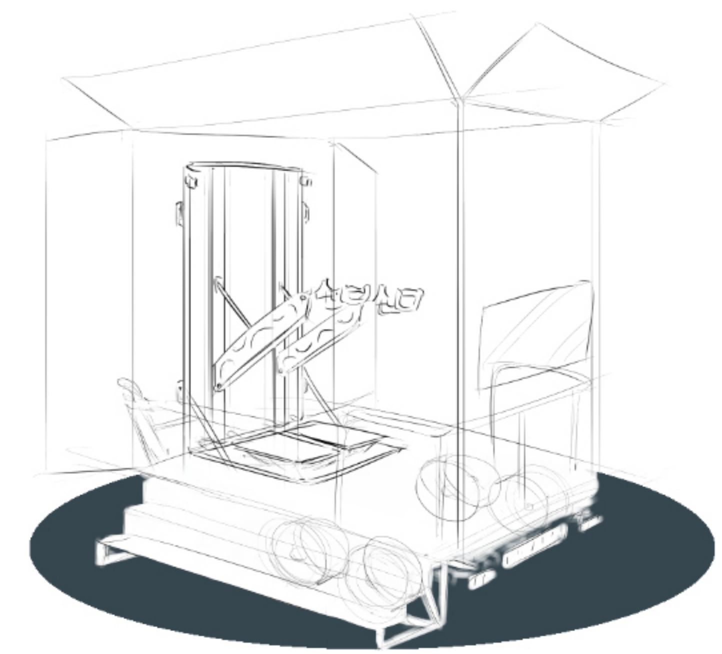
minimal configuration



medium configuration



full configuration



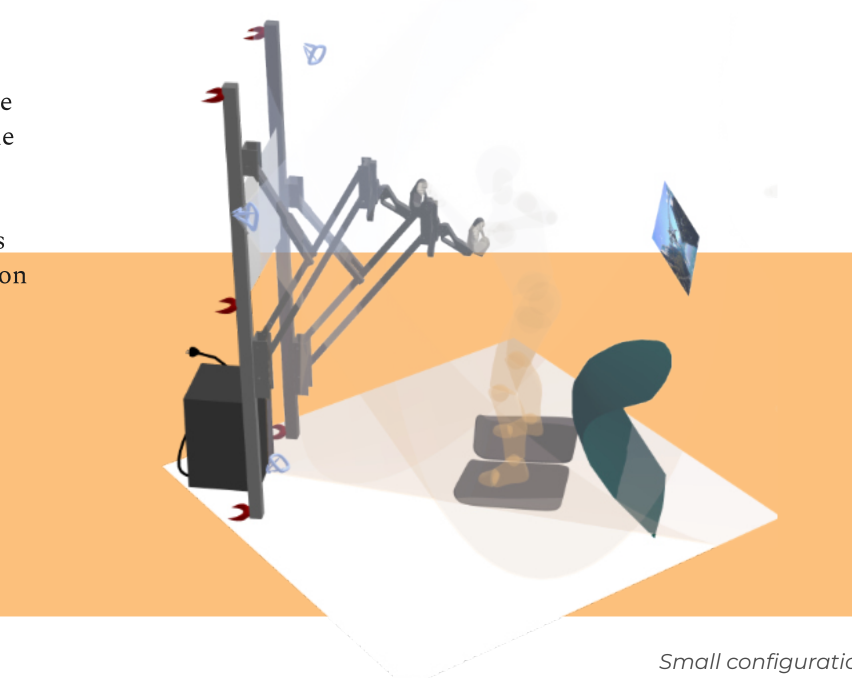
minimal mobile configuration

The minimal required components of the Ethereal Engine are the two armatures and foot platforms, the electronics consisting of motor controllers and computing units, at least two cameras for the mocap system and a mirror to check one's appearance, but also to quickly see what is going on behind the back.

The resulting **minimal version** can be seen on the right. It can be noted, that the space for the electronics should be housed as close to the actuators and sensors as possible so it is therefore located at or beside the base of the two armatures. The armatures themselves need at least two, possibly three rotating connection points each to make sure they stay upright, experience little deformations and hence only tilt minimally during heavy use.
For the mocap system, a thorough analysis of where to place the cameras has been defined as out of the scope of this project, they are therefore assumed in front, as well as to the side of the user where they can obtain a clear view of the entire body. By arranging them in a stereoscopic way on the horizontal plane, occlusion of the arms and hands that is caused by the armatures can be limited. Additional cameras could be used for more reliable, accurate full-body tracking.
Lastly, the foot platform's position is determined by the average size of a human body to accommodate most users comfortably. A distance determined by the client has been used.

Minimal configuration

For the **small configuration**, a few components are added for increased comfort and possibilities of the Ethereal Engine. These are a seat and an external monitor. The seat allows for simulations where sitting workouts are included. It furthermore gives the user a good point of reference about the position and it acts as a safe place to quickly sit down on when feeling cybersick or simply exhausted.
The monitor allows spectators to enjoy a view of what the person inside the machine is currently seeing. This greatly increases sociality and engagement, as bystanders can be supportive and e.g. cheer for the user. The screen can also serve trouble-shooting purposes or maintenance tasks.



Small configuration

The **medium configuration** is the first version that can be considered public and stand-alone, as opposed to the minimal and small configuration, it not necessarily needs a closed-off room or area to be operated safely. It features a surrounding structure that ensures only one person can use the Ethereal Engine at any given time. The structure keeps people from reaching far inside the machine to disturb the person by touching, or even get injured when getting stuck in the robotic arms for example.
The medium version features an appealing interior lighting setup which can not only add additional thrill to the transition in and out of the machine but will greatly increase the quality and reliability of the camera-based mocap system.
The medium configuration features a small locker that can house small items or a bag with the user's valuables.

Medium configuration

Full configuration

For the **full configuration**, an entire enclosure is added for maximum privacy and the possibility of ventilation and disinfection. This version limits exposure to a minimum and can be imagined for fitness centres where workouts in solitude with maximum privacy are desired. By enclosing the whole space, the incoming and outgoing air can be controlled and filtered. For extensive cleanliness, UV-C disinfection could be added. For that, no light leaks may occur as most UV-C radiation is dangerous to the naked human eye.

The focus of this master thesis lies on the medium configuration, but as the modularity approach needs to consider the whole bandwidth of configurations, the other versions can easily be derived from the final design by adding or removing components. This gives the Ethereal Engine a huge benefit regarding market entry and long-term economic viability.

Mobile version

For a mobile version as shown in the overview of page 44–45 above, the minimal configuration of two armatures and two foot platforms could be mounted inside a regular-sized trailer. The trailer walls could then open or fold away, opening access to and good visibility of the Ethereal Engine. This is especially interesting to promote the product during market launch as it can be quickly transported and used at different locations, but also provides an interesting opportunity for temporary events like fairs which could rent an Ethereal Engine for a limited amount of time.
Once the event is over, the trailer can be closed, locked and stored away space-efficiently until the next event takes place.

Additional components

Next to the components addressed in the several packages, the following components can be added for an enhanced experience:

Fans

Adding fans for all kinds of simulations where rapid forward motion is involved, such as flying, running or riding, increases the sensory stimulation and can therefore enhance the feeling of presence. Sensing fast-moving air brushing against one's skin and hair will help reproduce the real experience of head-wind while one is sailing over the water at high speeds. This increased simulation realism will most likely greatly increase the fun during use. It will also help to keep the user cool during sweat-inducing exercises.

Speakers

Added speakers can act as another sensory stimulus further convincing the realism of the user experience. Especially if these speakers are distributed like a modern surround sound system (e.g. a 7.1 setup), they can add spatial information and help portray the spatial dimensions of the VE. VR headsets usually already feature built-in speakers, so an additional sound system is optional, but not necessary to offer auditive input.

Bill of materials

Many of the components discussed for the packages were already determined or developed by the client and the foregoing JIP team. A collection of these components was summarized in a bill of materials (i.e. 'BOM') to get an overview of the price individual components add to the cost of the Ethereal Engine as a product. It could also be used as a benchmark for the following design process and help projects following thereafter to focus on the improvement of certain components. Most importantly, it gives the client and possible investors a convincing indication of the final price for the machine in its respective configurations.

The client stated, that "As a result, bill of materials become the central data point for the business model." (S. Summit, personal communication, 2022) He furthermore mentioned the following manufacturing quantities:

Year 1: Assume 10 pilot sites for the first year.
Year 2: Scale toward 100 sites.
Year 3: Ramping into production with potential for 500 sites/year onward.

The accumulated costs of the US prototype so far are 11.500 €. This includes everything that could be obtained from the client and includes labour costs only for already assembled parts like the frame. These costs refer to the prototype that can be seen in the context chapter.

The prototype at the TU Delft, as purchased and assembled by the JIP team only accounts for 1.500 € as it consists of a mere version of a frame and the grip assembly only. Furthermore, all CNC machining was done in-house free of charge, so only material and component costs constitute the small price in comparison.

In general, it can be expected that the assembly of the Ethereal Engine will provide a major cost point, so reducing the complexity as much as possible helps make the product a viable undertaking.

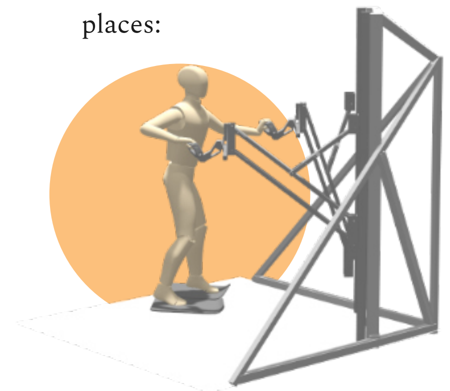
8 Optimisation

Throughout the process of understanding the project and envisioning a designed frame past the prototype stage, a large emphasis emerged on the structural aspect. As the frame holds heavy and powerful robotic components in place, all while ensuring a safe and comfortable user experience, the importance of a stable structure can not be underestimated. In opposition to that, cost, weight, part count and part dimensions are crucial for the economic success and market adoption of the Ethereal Engine. Finding the right balance of a lightweight, but sturdy frame proved to be a very complex undertaking, but expert knowledge and advanced generative design tools made this possible and will be described in this chapter.

Load Cases

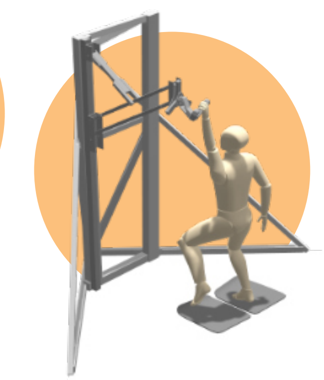
Important for the structural design and especially when generative design comes into play, are the loads the frame has to withstand.

It was distinguished between 3 different load cases, where various loads act in different places:



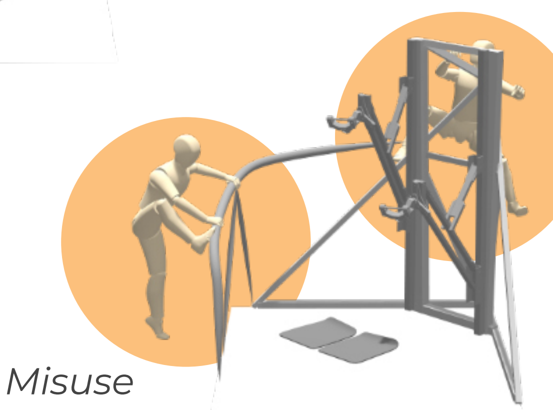
1 Regular use

These load cases describe the maximum loads that will occur regularly during normal use of the Ethereal Engine. Full effort vertical climbing, as well as a full forward push, are movements that can be expected regularly and should be sustained by the machine easily. Interesting here are the resulting deflections and vibrations, as they could interfere with the mocap system, create an undependable feeling for the user, or simply generate unwanted, distracting noise.



2 Heavy use

In this load case, the maximum loads that the machine needs to endure are defined. This means for example a physically strong and heavy person exerting the maximum possible force in a certain direction or by simply hanging from one arm. If this exertion happens in an unfavourable position, e.g. with the armature fully extended, the loads reach maximum levels, but the structure of the Ethereal Engine must not yield (i.e., permanently deform).



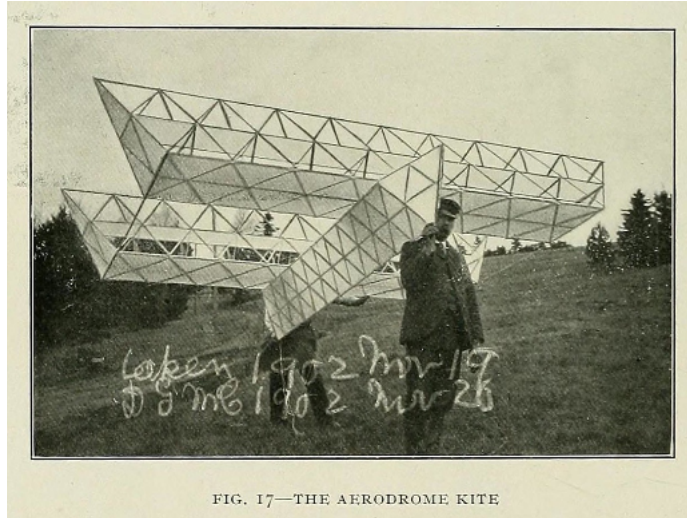
3 Misuse

The last of the load cases is concerned with malicious or false use of the machine. One could imagine someone climbing over the frame, hanging from it or testing the physical limits of the structure in alternative ways. Even though the mounted mocap cameras would serve as a good video surveillance system – privacy issues need to be considered – people could still challenge the machine when the cameras are off, for example. When that happens, minimizing damage to the machine and limiting bodily harm to the vandal should be the aim.

In the table below, an overview of the main loads used for the initial design process is given. Values from load case 2, the heavy use, was the baseline for these calculations. The complete overview of definitions for the three load cases can be found in the appendix:

Heavy use	load
Vertical hang	1300 N
Horizontal push	500 N
Horizontal pull	500 N
Side hang	750 N

Table with loads during heavy use



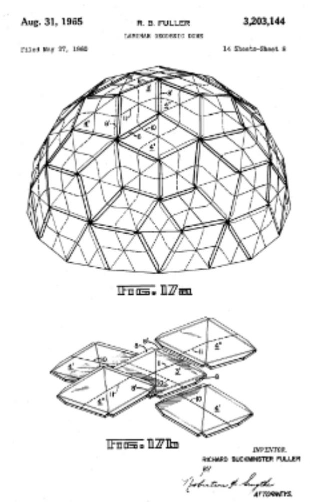
Tetrahedral kite by A. Graham Bell

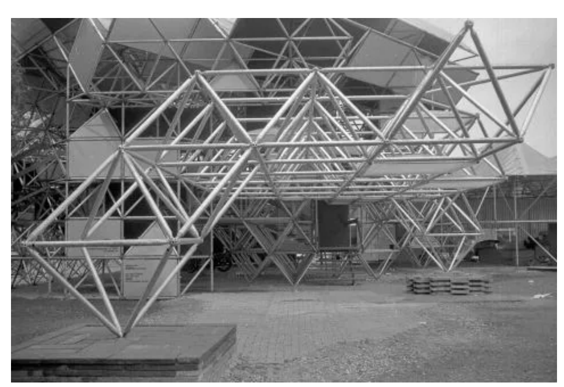
Spaceframes

To create cost-efficient yet sturdy structures, the concept of spaceframes proved to be very useful for the main structural basis of the frame.

Spaceframes extend tetrahedral geometry to the third dimension. Alexander Graham Bell experimenting with tetrahedral kites in 1898, Max Mengeringhausen developing the MERO space grid system in the late 1930s, and Richard Buckminster Fuller promoting the use of Geodesic domes for efficient shelters, are prominent examples of the early inventors of spaceframe structures (Buckminster Fuller Institute; Green, 2017; MERO-TSK International GmbH & Co. KG).

The reason spaceframe designs can be this efficient comes from the general properties of many metal-based materials such as steel and aluminium, but also fibre-based materials like wood, carbon fibre or glass fibre composites.
Materials, especially metals, are a lot stronger in tension and compression than in bending or torsion. If loads are only applied on hinged nodes that do not transfer moments, there is no bending or torsion involved. The resulting deformations from tension and compression are therefore a lot smaller as well when compared to bending and torsion (Tempelman, 2020). This has important implications for the Ethereal Engine, as any large deformations of the frame will be exaggerated by the armatures complicating the positional sensing of the end effectors, or intercept with the camera-based mocap system.


Geodesic domes by R. B. Fuller


Space grid system by M. Mengeringhausen

What remains a crucial consideration when designing spaceframes is the critical buckling load of individual members that are in compression. Especially when a load would act on a member elsewhere than on a node on either end, e.g. when someone leans onto the frame, chances for this member to buckle and deform plastically are increased. The relevant formula for the critical buckling load is

$$F_c = \frac{\pi^2 E I}{(k L)^2}$$

with E as the material's modulus, I as the cross-sectional area moment of inertia, k as the hinge factor (for a hinged node k = 1, a (realistic) rigid node k = 0.7) and L as the length of the member. As can be easily seen, the hinge factor and length of the member have a large influential factor in creating a maximum critical buckling load. With hinged nodes, the critical buckling load increases by a factor of around 2, so halving the length of individual members results in a fourfold increase in resistance to buckling (Tempelman, 2020).

In summary, simple two-dimensional members, made from e.g. steel tubes, or extruded aluminium profiles can be a cost-effective solution to build large structures like the Eiffel Tower, bridges, or the frame of the Ethereal Engine. The challenge is to keep individual member lengths short, without considerably increasing the part count and assembly difficulty, as well as choosing weight-efficient materials and cross-sections for ease of transport and low material costs.

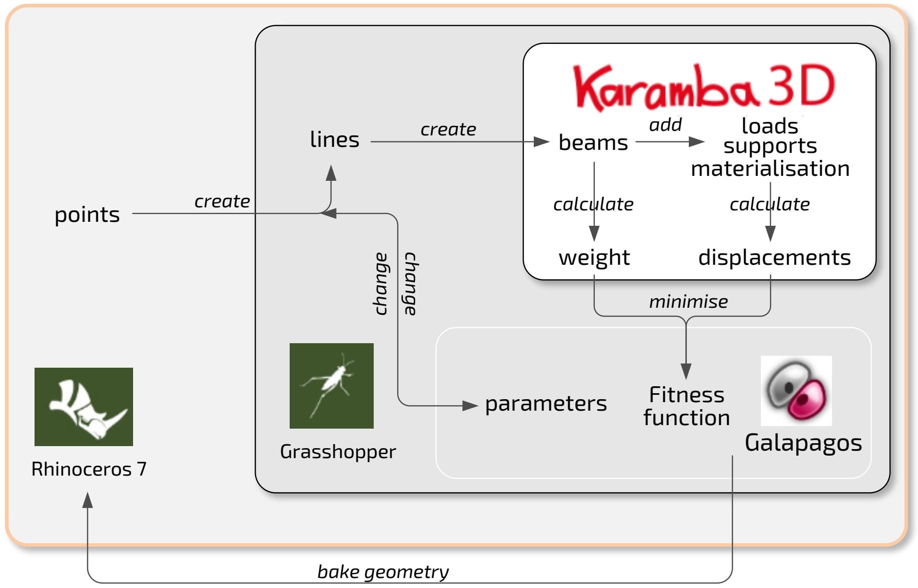
Generative Design

A great tool to explore a broad spectrum of options without the necessary effort to create a digital model for all of them is the use of generative design tools.

Expert interviews with Martijn van de Ruitenbeek – inventor of 2D engineering apps like FrameDesigns – and Turlif Vilbrandt – owner and founder of Uform Co. – were very helpful in determining the right combination of software to reach a working generative design model quickly.
The tool of choice for this project was the built-in node-based programming language Grasshopper as part of the CAD modelling software Rhinoceros 7, offered by McNeel. An additional plug-in ‘Karamba3D’, developed by Clemens Preisinger, was obtained, as it proved to be a suitable tool for Finite-Element-Analysis (FEA) using only linear components, which in turn sped up the calculations immensely compared to common triangulated, volumetric FEA’s.
Martijn furthermore stressed the importance of fatigue and recommended – as a rule of thumb – adding a safety factor of 3 to the yield strength of the structure in question (M. van de Ruitenbeek, personal communication, 2022).

Goal

The goal of using generative tools from the start of the design process was to explore the design space of possible geometries, quickly iterate a large set of options and converge to an optimised, lightweight, cost-efficient frame construction.
With the chosen setup, different materials could easily be tested for their suitability as well.



Generative design model flowchart

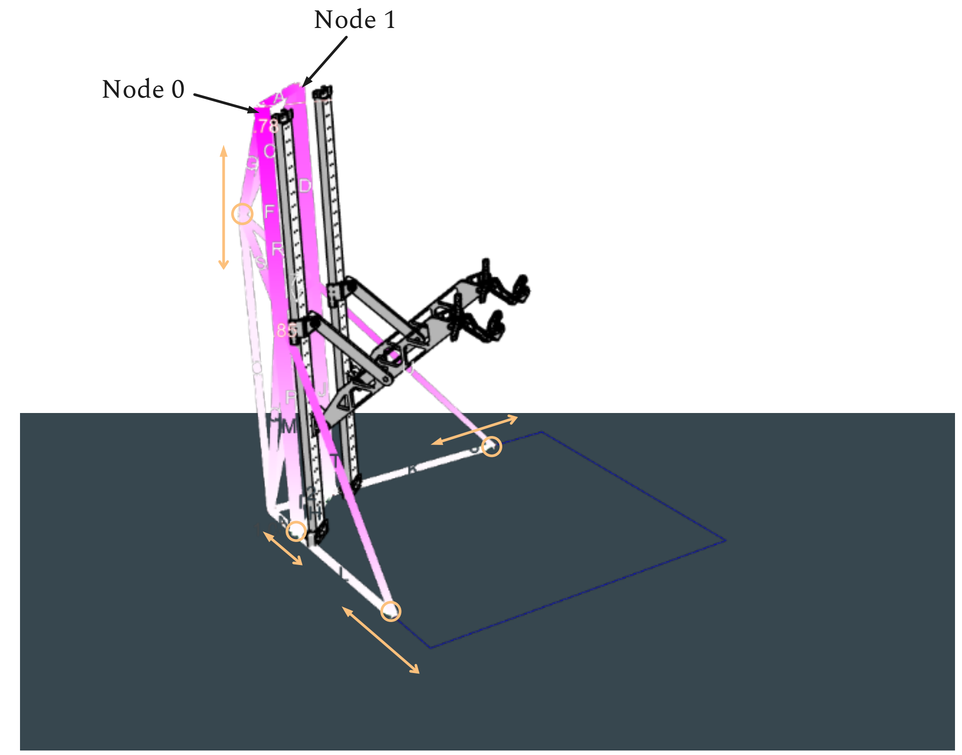
Method

The above diagram shows how the digital representation of the simplified frame model was built and how information flows through the model and affects changeable parameters. These parameters were:

- Choice of material
- Choice of cross-sectional areas for member groups
- Z-position of the upper central node
- Length – or outward extension – of the main diagonal beams on either side
- Distance of the vertical beams from each other and from the central vertical beam

Determining the forces that act upon the frame structure as a result of the forces exerted at the end-effector – the grip – were determined with an adapted Matlab model from the JIP team. Calculations can be found in the Appendix.

The digital generative design model was constructed by placing points in three-dimensional space in Rhinoceros 7 where individual nodes are needed or expected to be.
These points were referenced in Grasshopper and posed the start and end points of lines, that represented the individual spaceframe members. They were then materialised with the Karamba3D plugin and eventually analysed for the resulting mass and deflections for each load case.
The result of the overall material mass and beam deflections was combined into a fitness value which fed into the Galapagos evolutionary solver. The solver was allowed to change the location and properties of the aforementioned parameters and by minimizing the fitness function with the linear descent method converged on a few optimal solutions.



Setup of the basic structure to optimise

Material	Displacement at Node 0 & 1	Mass of the structure in kg	Profile dimensions
Aluminium 6061 T6	~ 10 mm	~ 50 kg	50x50x4 mm
Steel	~6 mm	~ 110 kg	40x40x2 mm

Table of generative results

Results

The resulting deflections depending on the material, cross-sectional area and node position can be seen in the table above.

In general, the algorithm minimised the overall footprint of the structure to decrease overall mass and member lengths. It also balanced the length of individual members to even out strain peaks and distribute forces evenly among all members. It did so by for example moving the upper central node down and keeping the diagonal beams short.
This made manual tweaking of the input boundaries necessary, resulting in an iterative process of adjusting and running the optimization. Eventually, the algorithm converged on a satisfactory geometry which was then baked – converted to geometries that can be used and manipulated further in the modelling process – and used to create beams with the appropriate cross-sections.

Discussion

The generative design process was characterized by many adjustments to the model. Balancing the mass of the structure with the desired maximum deflections was more difficult than expected. The results showed that the generative algorithm could only indicate some values for the positioning of nodes for example. Other factors like usability, manufacturability or assembly pose hard and soft limitations to the optimal lightweight, yet strong, spaceframe structure and had to be added manually.
In many cases, this meant adding practical limits to keep the algorithm from e.g. moving the vertical beams impractically close together.
Despite these limitations, a satisfactory space frame design was created, that resulted in the properties discussed above and deemed satisfactory.

9 Ideation

The ideation phase consisted of many iteration loops between a VR-based sketching software called 'gravity sketch', intermediary sketches on paper, and discussions involving the client and fellow design students. A client visit led to quick progress by rebuilding the existing frame prototype and visualising ideas in VR inside it. A creative session complemented this stage with interesting new aspects and perspectives.

Gravity Sketch

'Gravity Sketch is an intuitive 3D design platform for cross-disciplinary teams to create, collaborate, and review in an entirely new way.' (Gravity Sketch, 2022, ADDME)
This very accurate self-description already highlights the benefits of Gravity Sketch for the design process of this graduation project: The software is quick to learn and the possibility to experience frame designs in full scale in three dimensions cannot be matched with design sketches or renderings of CAD models.

How it works

Gravity Sketch is to be used with a tethered or standalone VR headset, such as the Oculus Quest 2. The core idea is the ability to generate geometry in three-dimensional space by literally drawing in mid-air. One needs to use the two controllers of the VR set to manipulate the view and use the various pen, stroke, surface and volume tools available to create lines, NURBS and polygon surfaces. These can be further repositioned, refined and coloured with total freedom in terms of size and complexity with the computing power of the headset or computer being the ultimate limit.
On top of that, a lot of customizations and additional tools allow design possibilities beyond imagination, which are not further discussed here. Instead, trying out the software yourself is highly recommended.
One last feature to mention is the pre-defined mannequins that can be loaded into the workspace. Their posture can be manipulated at will, by intuitively grabbing and repositioning their limbs around the joints.

Image of Gravity Sketch in use

Benefits for this project

The aforementioned benefits became especially apparent during this graduation project as the design in question is concerned with a space that encompasses a human being. As mentioned earlier, spatial perception is something hard to design for as it needs careful consideration not only of the space's volume, but of its shape, size of the parts it is composed of, the lighting, the colours, or the possibility to view outside.
Therefore, it was immensely valuable to be able to 'step into' the designs at a very early stage – basically from the initial sketching phase on – to experience the created spaces on a 1:1 scale. This had an even greater effect when collaborating with one or more people joining the same room full of sketched ideas. It was then possible to discuss designs while looking at them in three dimensions, make changes and experience the consequences of those changes immediately.

Why it matters

Even though analogue and digital sketching on a two-dimensional canvas will always have their place in the design process, the intuitiveness that VR combined with tools like Gravity Sketch can offer is astonishing. It combines the advantages of abstract two-dimensional drawing – efficient, minimal tools needed – with those of for example clay-modelling – intuitive, three-dimensional – while already generating digital, 3D geometry that can immediately be continued upon with modern CAD software to reach the necessary precision for manufacturing.
With affordable AR glasses steering towards a market entry, the success of three-dimensional sketching will likely increase even further (Future Market Insights, 2022). With AR glasses, designers can view their designs in any context which is a huge advantage as it accelerates the overall process because there is no need to make prototypes first. Gravity Sketch offers such a possibility as an experimental feature called 'pass-through', where the 3D model is placed on top of the image coming from the black and white cameras of the Oculus Quest headset. This rudimental version of an MR allowed me to step into the prototype of the Ethereal Engine and sketch in the actual positions and dimensions of it, see page 55 bottom.

Creative session

Besides the first generation of ideas and concepts in Gravity Sketch and on paper, a creative session was scheduled to generate surprising input that helped to quickly explore the design space.
For this session, the relatively new VR zone located in the library of the TU Delft was used, as there is a sufficient supply of VR headsets.

Goal

The goal of the session was two-fold: first, to generate unexpected, interesting and inspiring ideas through a brainwriting-like sketching session. Introducing external people to the project and having them give input from an outside perspective helps to broaden the view on the project. The participants were prompted with the following topics for which to design the frame of the Ethereal Engine: comfortable, minimal, all-in.
Second, the goal of this session was to evaluate how a group of designers can effectively collaborate in the same virtual space with little to no experience in VR and especially with Gravity Sketch.

Method

Three fellow design students were recruited for this creative session and quickly briefed about the project, the Ethereal Engine, the goal of the session and the possibility to take a break or even leave the session altogether. Each of them got provided with an HTC Vive VR headset (tethered to a computer) and two controllers to use Gravity Sketch. It was deemed sufficient to limit the tools the participants should use to the stroke tool which allows them to draw free-form lines in space with varying thickness, much like a brush stroke, but in three-dimensional space.
The session was prepared with a schedule and by placing a CAD model of the package of the Ethereal Engine inside the collaboration room of Gravity Sketch together with respective prompts and sample images for each setup located above. This can be seen on page 57 above. By utilising layers, it was possible to show and hide certain geometries to move through the schedule one by one.

Procedure

The session started with an introduction to VR and Gravity Sketch after everyone had joined the collaboration room in VR. A tutorial on how to use the stroke tool and how to move around the virtual room was followed by a brief, free tryout of the program.
Next up was the initial free-sketching phase, in which participants were distributed among the three packages with the three prompts displayed above, which they should try to incorporate into their design. A fourth package was added, where a completely unprompted design was made, to stimulate the creative thinking of participants.
After a break outside of VR, results were discussed and in a second round, participants moved on to a different prompt, either adding to the previously made design or starting from scratch.
For time and exhaustion reasons, a third round was cancelled and we collectively discussed previously prepared designs. Participants were encouraged to simply sketch their ideas onto the design and experience the frame designs by standing inside them on a 1:1 scale.

Picture of participants

Summary

Following the session, eight very distinct designs emerged, each with distinct details or ideas that gave interesting ideas for the further design process.

The following aspects emerged from the creative session

- One participant suggested covering portions of the user's face similar to how office glass doors do it
- Another participant mentioned how it was weird to display what happens inside the machine to the outside when full privacy is desired
→ the user should hence be able to choose if a broadcast of their visuals is desired
- Opening up space of adjacent machines allows people to talk to each other during the exercise
- Shielding for sound is crucial for solitary workouts, but could easily be done with e.g. headphones

"I think that these arms always look super mechanical. So if you do not want it to be a gym experience, I think you're gonna have to hide them in some way." (participant 3)

- One participant suggested the arms could be in a resting position when boarding the machine. Only once the headset is put on would they come down, so the user only sees them moving inside VR, where they could look less mechanical and therefore dangerous

"You can also project onto fabric, like instead of a screen, then people can see what's around you." (participant 1)

- The presence of an instructor (caregiver, gaming coach, physician, etc.) would mean the necessity to be able to easily communicate to the outside of the Ethereal Engine
- One participant mentioned the frame could create a certain associated feeling of entering the machine: Like entering an elevator, becoming Superman, etc.
- How and in what direction the doors open was discussed as an important point

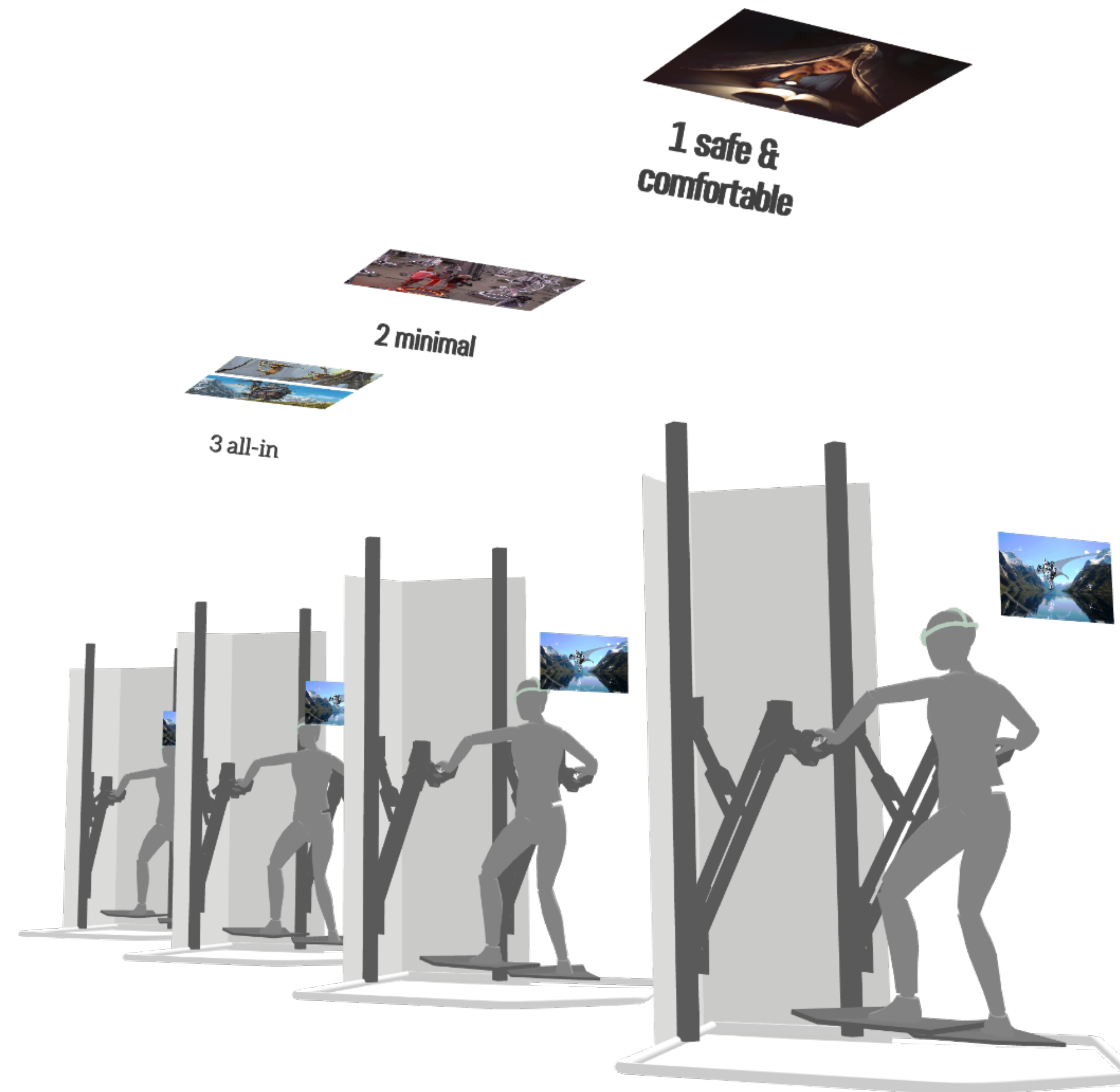
Discussion

The results of the creative session revealed interesting aspects that were incorporated in the following design process and could be the basis for further development of subsequent projects related to the Ethereal Engine.
All in all, the creative session was very helpful to uncover new perspectives and identify aspects that had not been considered yet, but it also showed some limitations.
Placing a screen in a certain position already limited the design freedom, as some participants wanted to move it to different places. An interesting discussion arose from that problem, but it showed how even small pre-determinations can decrease the explorative space.

Additionally, explaining and understanding a large and complex project as the Ethereal Engine in a short amount of time was quite challenging. Teaching the basics of Gravity Sketch was easier, which showed the intuitiveness of a VR sketching tool and the complexity of the project.

For future VR sessions with (first-time) users, it is crucial to plan regular breaks. Cybersickness can occur quickly and participants described that they only noticed it when taking off the headset.

Additional to the creative session, a client visit took place halfway through the project.

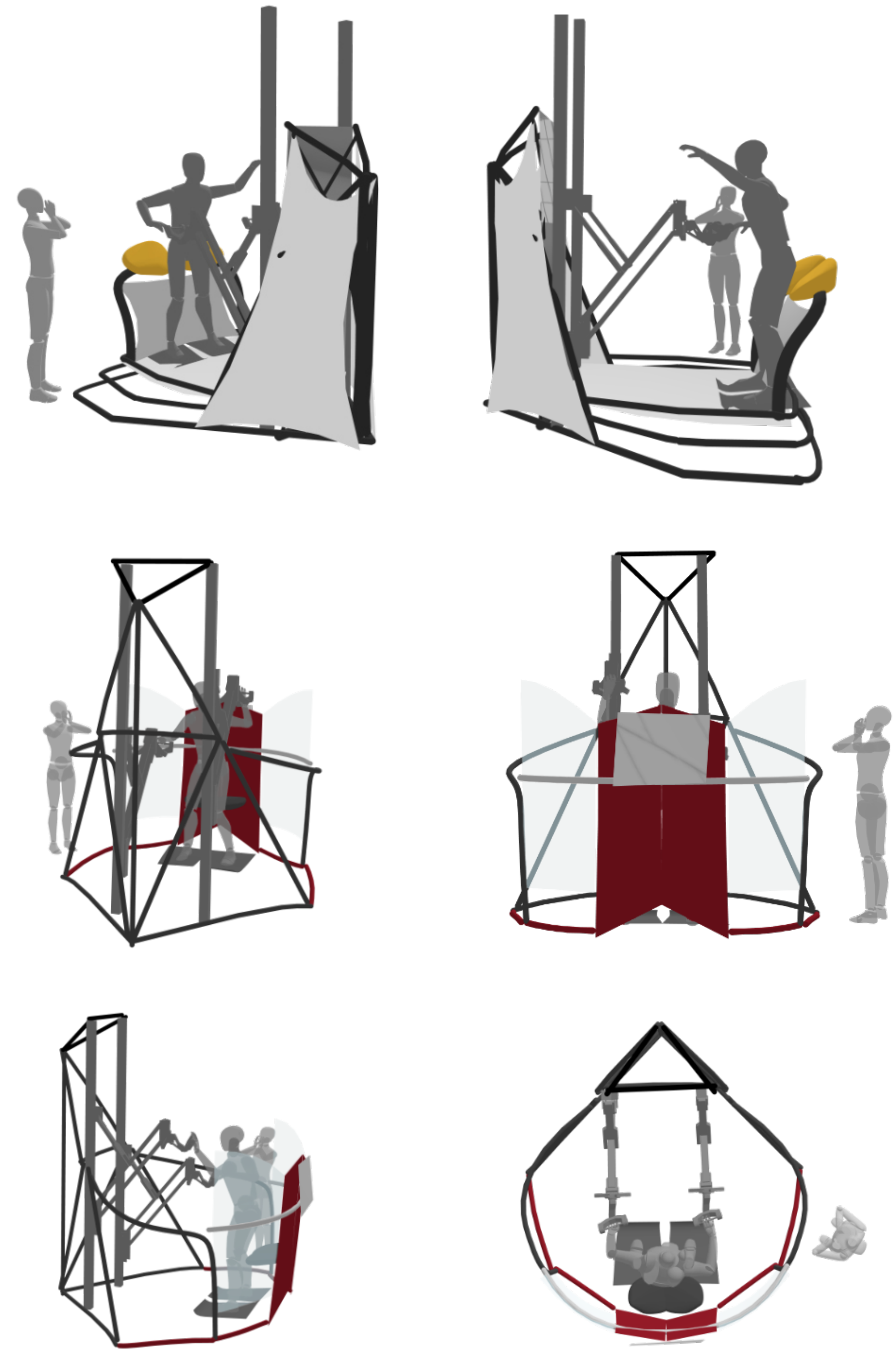


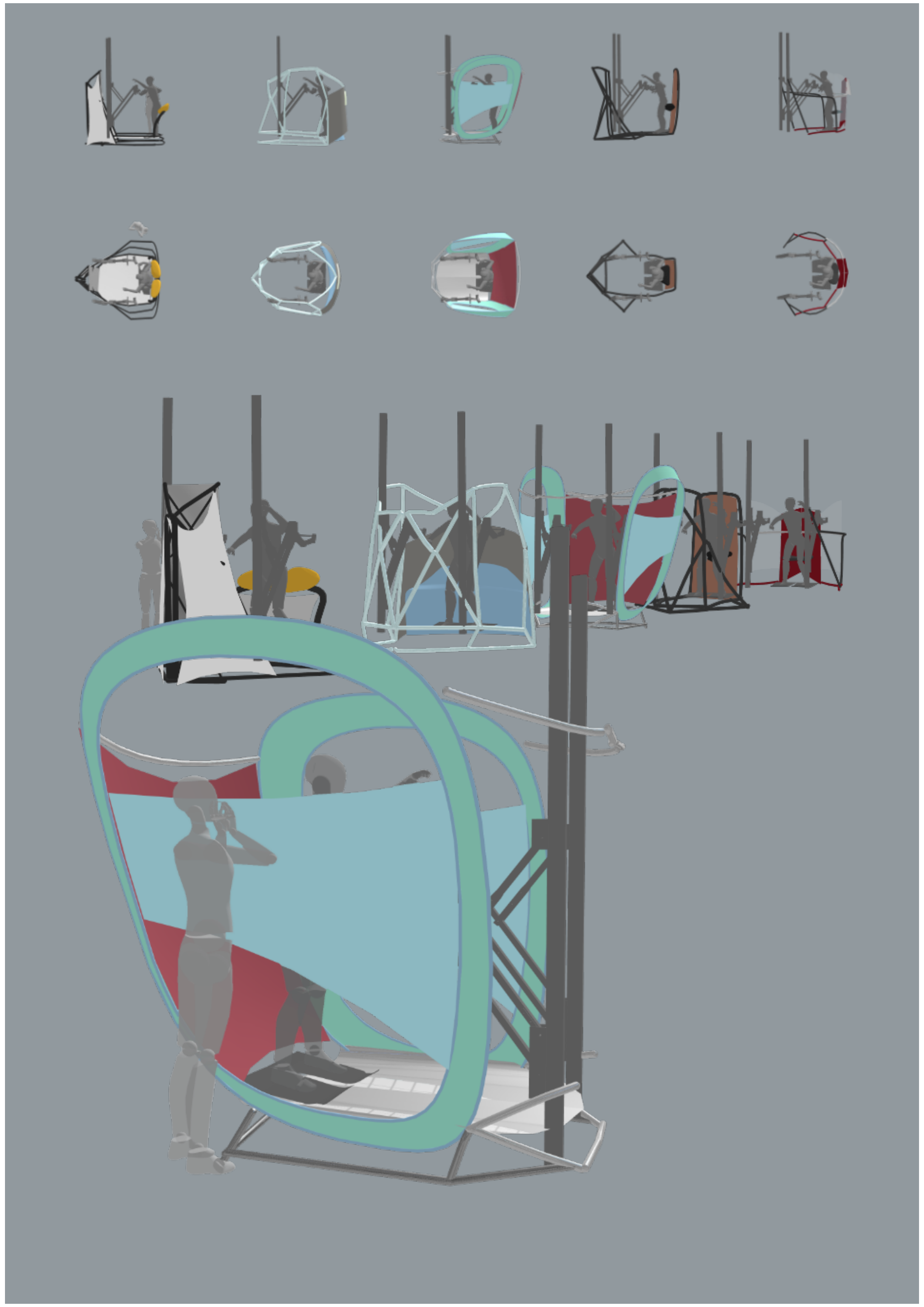
Setup of the creative session

Client visit

Next to the regular online client meetings with Scott, he flew over to the Netherlands for a week, in which a lot of progress was achieved with the frame design.
The existing frame was taken apart and completely re-assembled to better suit a modular approach and a cost-effective design.
With the extensive experience of the client from building a prototype in California for the last two years and the acquired knowledge from the research phase of this graduation project, quick iterations led to a new overall layout and basic structure.

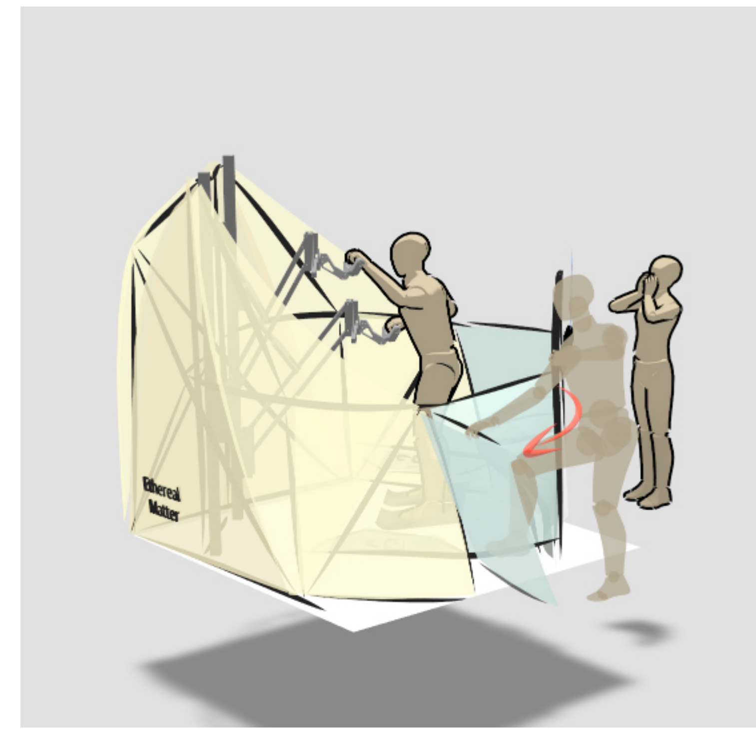
The benefits of VR-based designing became even more apparent: After brainstorming over the construction of the prototype, I could quickly sketch the changes in Gravity Sketch and using the pass-through feature overlay them with the prototype. This way, Scott and I were able to experience, discuss and revise changes to the design almost immediately.





10 Concepts

The generated concepts summarise the main ideas of the ideation phase and they represent the main decisions that needed to be made with the client. The discussion of the aspect of modularity is then followed by the concept decision which concludes this chapter.

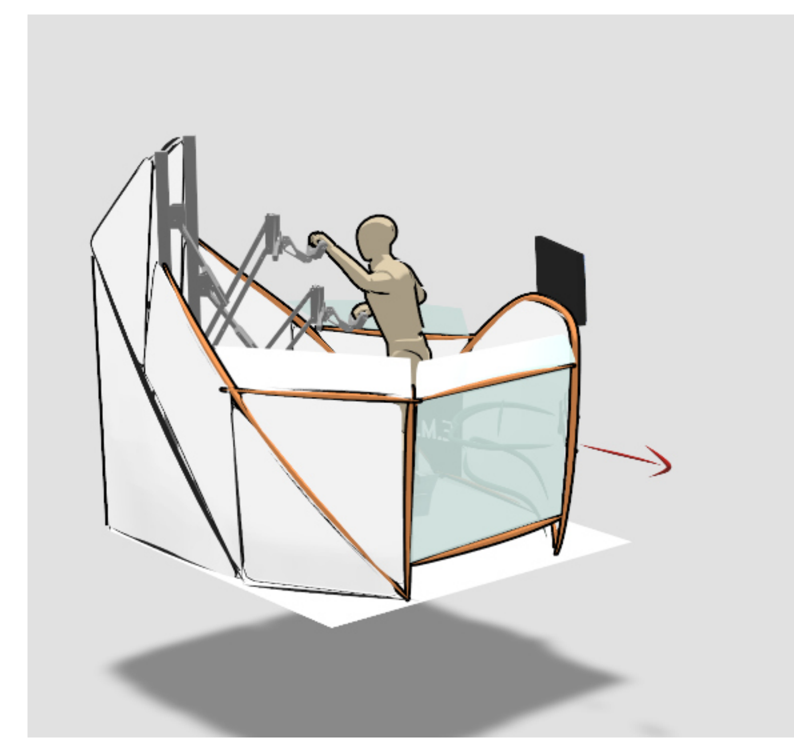


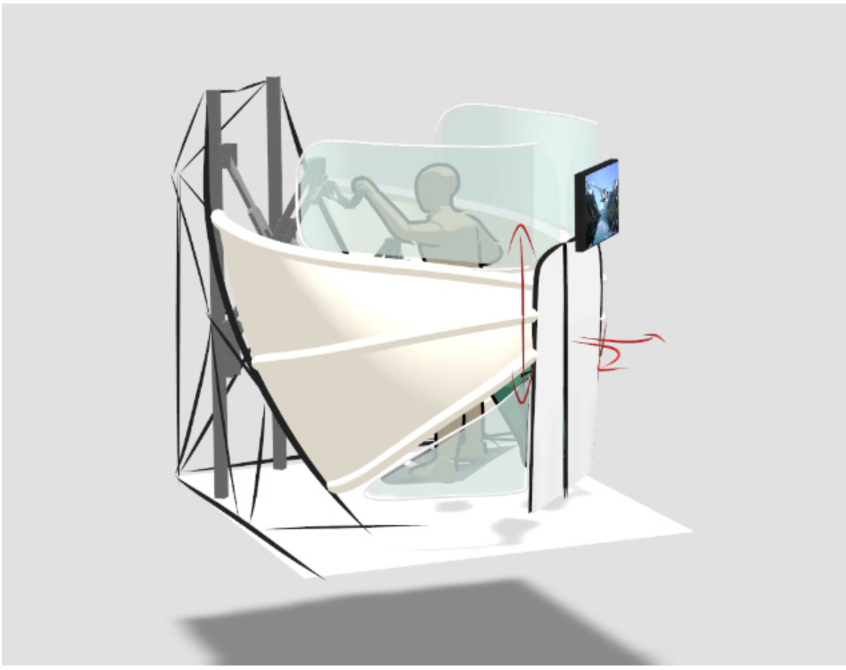
Concept 1

Concept 1 consists of large fabrics that cover the main structure. This makes for a soft, comforting look and creates a large branding surface. Choosing fabric makes the design relatively affordable, as no special tools or moulds are needed. It is furthermore very versatile as it is easy to install due to the fabric's forgiving large tolerances and easy to clean. A beneficial effect of the fabric is the dampening of sound coming from the machine itself or the outside. In theory, the fabric could also be used to project the visuals instead of a dedicated external screen.
The overall design is symmetric with two possible entry doors that open to the outside.

Concept 2

Concept 2 is asymmetric to reduce the number of parts necessary, as only one entry is present. Added panels made from plastic or wood, create a sturdy appearance and give the machine a robust look. Adapting the frame geometries as much as possible allows for the same panel geometry to be used in several places, reducing the number of unique parts. The panels could be made from transparent or translucent material, to play with light and the partial coverage of the user.





Concept 3

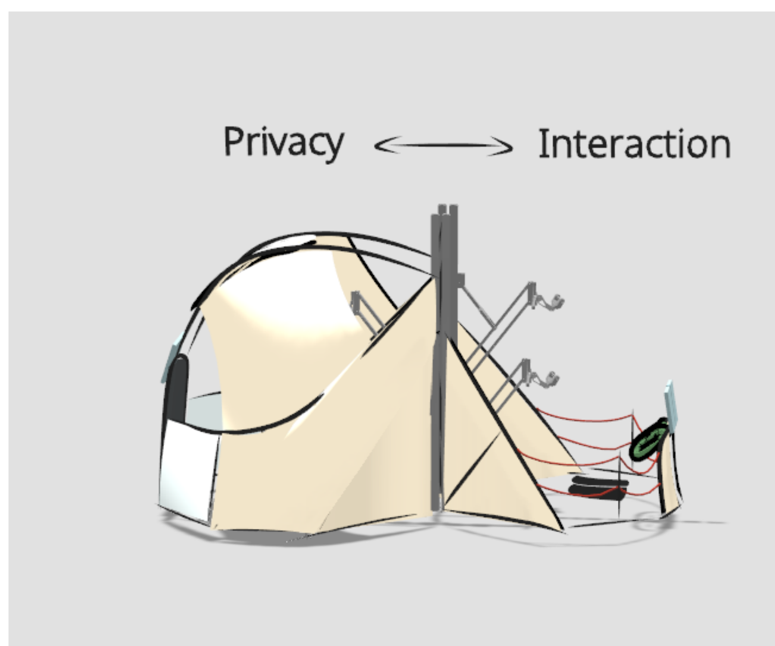
Concept 3 is unique as it uses inflated fabric similar to large kites. These inflated parts give the frame rigidity, yet are soft enough to provide a cushioning effect. An advantage of this design is the possibility for the user inside the machine to alter the amount of exposure to the surroundings. A disadvantage on the other hand could be the durability of the fabric structure and the difficulty to control the shape through all possible adjustments by the user.
The design is symmetric again, but the central door is made up of the backrest and seat. They separate to let the user in and out. This provides a very central entry to the Ethereal Engine and the user is directly in the right place after entering.

Decisions

Based on the three designs, three important decisions regarding the general setup of the Ethereal Engine arose:

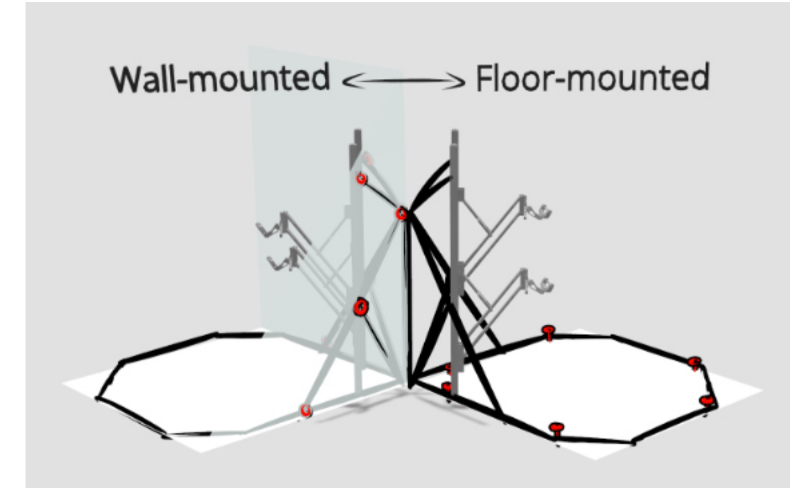
Private vs interactive

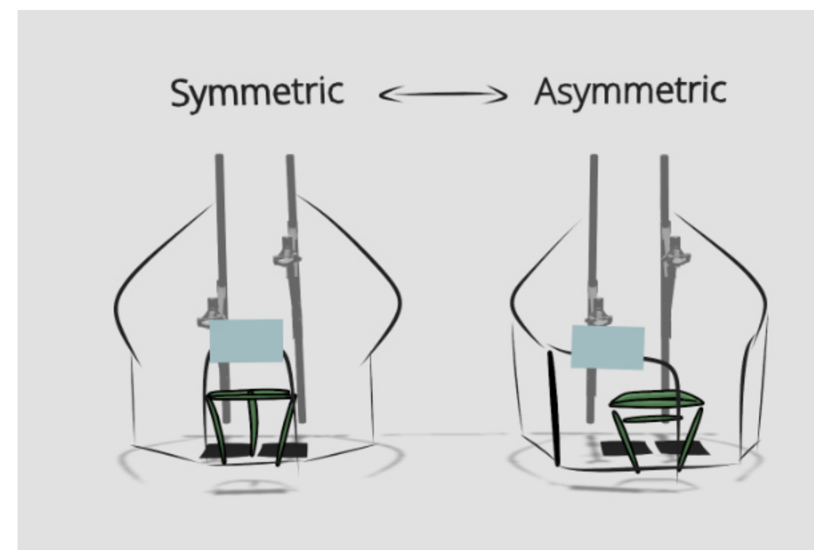
A trade-off needs to be made between the two scenarios mentioned in the perspective-taking research of the analysis chapter. Ensuring that no external viewer can interfere with the experience or even get hurt requires a design that closes the machine off almost entirely. This comes at the cost of sacrificing engaging interactions with bystanders or people in adjacent Ethereal Engines. Together with the client it was determined, that an open, more interactive version would be the way to go for the first market product.



Wall-mount vs Floor-mount

A wall-mount was favoured by the client all along, but the generative design simulations and calculations showed that a free-standing machine is possible, especially if it was bolted to the floor. A wall mount would only be necessary for the minimal version, where no supporting structure for the vertical beams is present. An expert of the client with plenty of experience in the fitness industry confirmed that large fitness devices like the Ethereal Engine are regularly screwed into the floor of such venues.



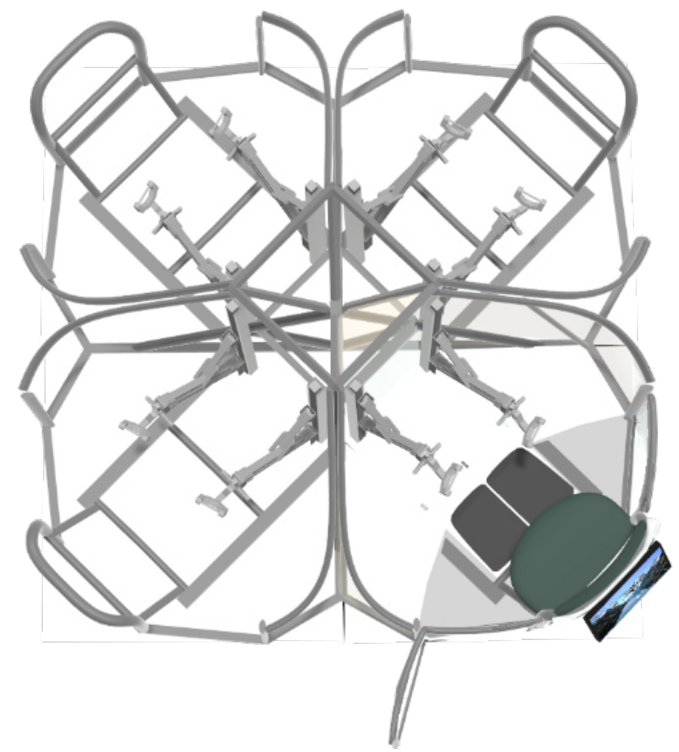


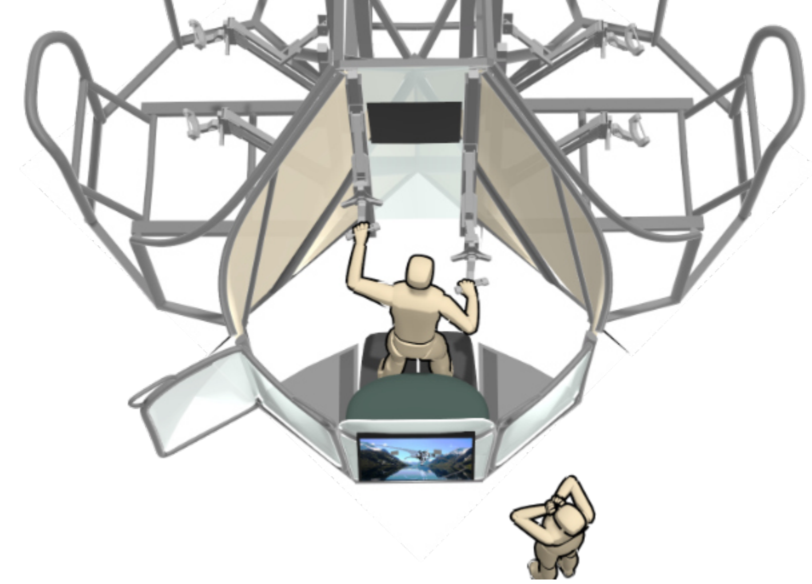
Symmetric vs Asymmetric

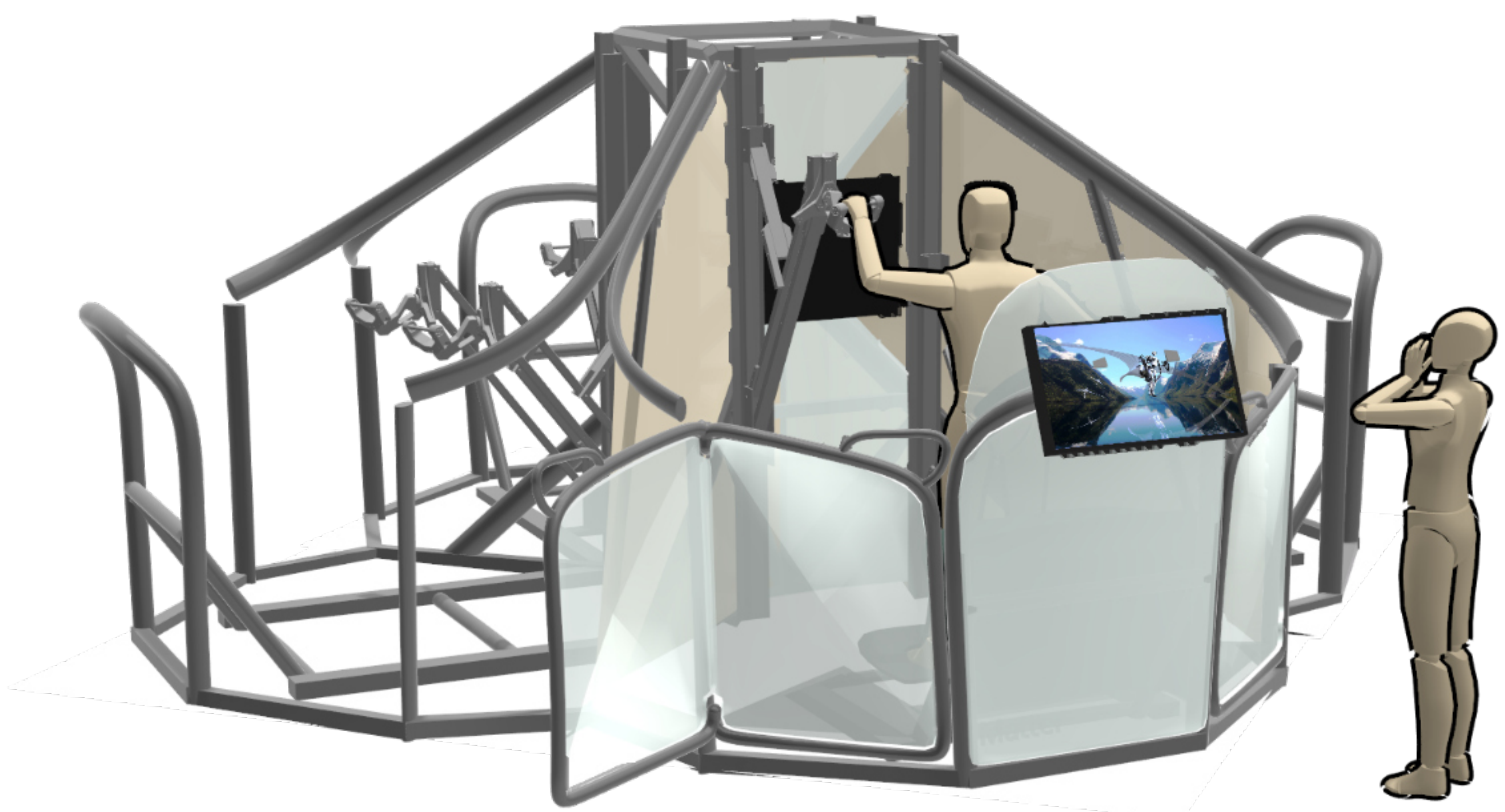
As already mentioned in the descriptions of the concepts, an asymmetric frame means a reduced part count, as only one entry point needs to be created. However, a symmetric design benefits from the possibility to use parts twice for both sides if they are symmetric by themselves; hence do not need to be mirrored to fit on the other side of the machine. It furthermore serves the modularity idea as it is irrelevant on which side of the machine another engine is added. When the Ethereal Engine is placed next to a wall, one entry and exit are right next to it, making boarding and leaving the engine more difficult. With entry points on either side of the seat, access becomes more comfortable, as one point will always be on the opposite side with respect to the wall.
The decision, therefore, fell in favour of an overall symmetric frame.

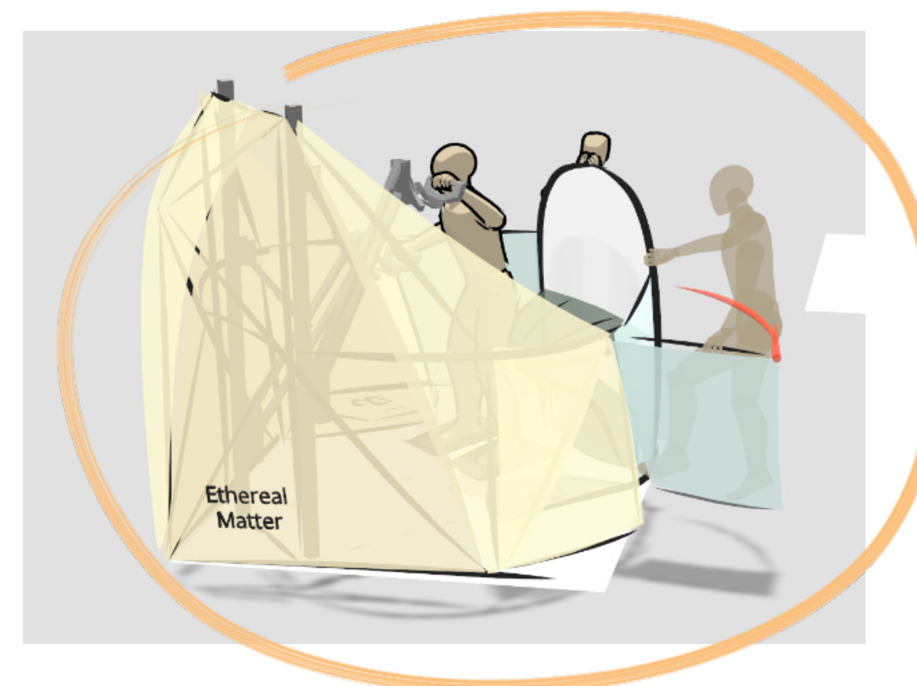
Modularity

The modularity of the structure was considered and ideated in different stages of the ideation phase. The benefits are apparent: When more than one machine is placed in a location, they can be connected on either side. This ensures additional stability and the possibility for users to interact. The most prominent advantage however is that a customer buying the Ethereal Engine saves on the purchase of any additional machines. If the Ethereal Engine is constructed in a way that it can share similar parts with adjacent machines, adding one, two or three machines to an existing one becomes considerably cheaper. The resulting requirements dictate that members shared with adjacent engines need to be symmetrical in two and many times all four directions as well as not be mounted from the outside of the frame.









Concept choice

From the presented concepts, in accordance with the client, concept 1 was chosen because of the overall symmetry, versatility of the fabric and the benefits of modularity.
The described process of designing, discussing and choosing was very fluid. Every client meeting revealed more insights from experience with the US prototype and general everyday business as well as advancements with the design in Delft. The just-described process consisted of many more in-between iterations and revisions than it appears. Nevertheless, the main decisions and considerations were mentioned and described in this chapter.

After settling on one concept, geometries and materials need to be defined and refined. The following chapter elaborates on the materialisation, embodiment and detailing of the Ethereal Engine frame.

11 Embodiment

An increased emphasis on manufacturing and assembly is present in the embodiment phase of the design process. This chapter explains material choices and considerable aspects of using a custom aluminium extrusion profile for the prominent side rail and potentially the vertical mast. Additional features like lighting, vibrations and a tether are discussed as well. The chapter concludes with the main insights generated from the expected BOM of this design.

Materialisation

Below, the materials chosen for the main components, the structural spaceframe, the custom extrusion for the side beams and the fabric covers will be elaborated.

Structural Spaceframe

The material of choice for the structural spaceframe is aluminium 6061 T6, which is commonly available and used for many applications (Matmatch GmbH). It is easy to machine and a T6 tempering treatment process increases its high strength-to-weight ratio. This heat treatment furthermore provides an improved anodizing response compared to other 6061 variations all the while aluminium itself already surpasses most steels which are susceptive to rusting.
With this alloy, many manufacturing processes like extrusion are possible, which allows for great customization at a reasonable cost prize.

These reasons likely contributed to the development of 'item' profiles in the 1980s. Instead of using steel profiles, two engineers from Germany patented their invention of a square aluminium extrusion with slots along either of the four sides, where special t-nuts can be placed inside to connect other profiles or parts to (item Industrietechnik GmbH). Quickly, this modular system was adopted far beyond factories and can be seen in various daily applications in the original form of 40 by 40 mm and in extremely advanced, more complex geometries and dimensions.

Aluminium can be recycled and large aluminium extrusion companies like 'Hydro' are already progressing with reducing the amount of virgin material necessary to create their extrusions, using post-consumer waste for example (van den Oever, 2022). This will make aluminium an increasingly sustainable material choice for the main structure of the Ethereal Engine. This advantage extends to the manufacturing process, as the possibility to slide the fasteners along the profile reduces the need for very tight tolerances, which in turn reduces the number of rejects of custom-made parts.

Additionally, modular systems like the item profiles allow for easy replacement of broken parts, which makes repair a more viable option compared to welded steel structures for instance.

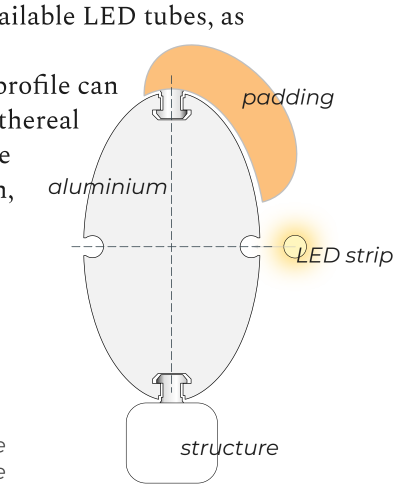
Finally, the use of a profile with standard dimensions allows for it to be easily substituted with profiles of differing internal cross-sections, mechanical properties or surface treatments without the need to change any connection pieces.

Custom aluminium extrusion

A prominent feature of this design of the Ethereal Engine is the two large beams that come down both sides of the structural spaceframe and encompass most of the users' visual field while providing a clear safety boundary for bystanders.

For these beams, a custom aluminium extrusion is envisioned, as this will offer multiple advantages for mounting of parts and general appearance.

The cross-section of the profile is symmetrical in two orthogonal planes and features two slots for t-nuts and two for commonly available LED tubes, as can be seen below.
Because of the symmetry, the profile can be used for both sides of the Ethereal Engine and does not need to be produced in a mirrored version, needing another extrusion die.



Cross-section of the custom aluminium profile

After extrusion, the profile is bent with a large radius of more than 1000 mm. Of course, tolerances and the internal geometry of the extrusion need to be adapted to this bending process, but deformations of for example the slots pose no major problems to mounting the fabric or the light strip.

Choosing the large cross-section of the profile was intentional, to provide the Ethereal Engine with a sturdy and trust-worthy appearance, and also to create a visual appearance of acceleration from the user forward and upward. The idea is to strengthen the feeling of excitement and generate a visual connection to the dynamic, uplifting experience – e.g. flying – the person is about to board.

Slots

With the aforementioned slots, connecting the outside fabric – or rigid panels instead – becomes very easy. Additionally, custom add-ons can be easily attached to the frame in many places, lending the Ethereal Engine good customizability: potential buyers of the machine might decide to add extra padding for security or fans for increased immersion and presence of their users.

Lighting

As discussed in chapter 7, lighting the interior of the Ethereal Engine can not only provide a more comfortable or enhanced transition experience for the users, but it also ensures a good quality motion capture. The cameras mounted in front and to the side of the user need consistent light levels to reliably detect the person's position and orientation of limbs. Changing ambient light, such as infalling sunlight, can easily overwhelm the mocap system, leading to unwanted consequences, even injuries. The Ethereal Engine, therefore, features multiple LED light strips that are placed inside the custom aluminium extrusion. Using individually addressable RGB diodes, matching light animations can b envisioned for the simulations that can experienced.

Limitations

Besides the advantage of adding custom accessories like fans, using a custom aluminium extrusion has its limitations. The bending process could be a deciding cost factor, as a custom template would need to be made. On top of that, the geometry would need to be optimised for the bending to not cause undesired deformations or internal stresses that reduce the safety or life span of the Ethereal Engine.

Enclosure

Another major cost factor of a machine this size is the enclosure. For the Ethereal Engine to provide a safe space for the person exercising inside and bystanders not being able to reach into any moving mechanisms, a lot of surface needs to be covered. For this, fabric was the cost-efficient choice of material.
Fabric has many benefits over other stiff solutions, like plastic panels or sheet metal: Fabric is lightweight and flexible, so it can be easily transported in a folded-up state. It can be customised by simply dyeing it in different colours, or in a more advanced fashion with custom imprints. The choice of fabric can give a different overall appeal, with a more translucent fabric eliciting curiosity about what is happening inside the machine and a thick fabric improving privacy and adding a comfortable acoustic dampening effect.

Close-up of LED strip in extrusion

The multi-layered design does not only have aesthetic reasons, but the gaps between the fabric ensure good air circulation in and out of the machine, to keep the person inside it cool during exhaustive sessions.
Lastly, the fabric covers can be added or removed with ease and do not require tight tolerances either.

Tether

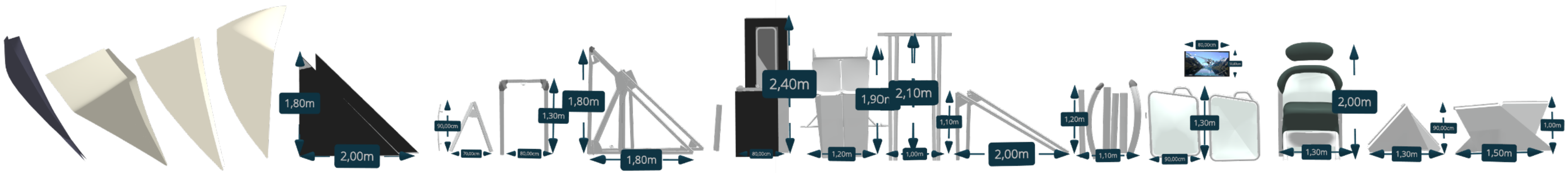
A feature already mentioned in the analysis chapter is also related to the privacy of users: the tether. The former prototype of the Ethereal Engine did not comprise a dedicated place to connect the VR headset to a charger. If the machine is intended to be used with private VR headsets, or when less than two headsets are available at any moment, it is important that a person can still utilise their booked session with an empty battery. The design, therefore, factors in the possibility to attach a tether next to the headrest that charges the VR headset during the session.
It furthermore allows for the visual data to be streamed to the adjacent monitor, or even outsource the necessary computation from the VR headset to a dedicated graphics computer inside the Ethereal Engine. The headset would then only track the user's head and provide the visual input.

Other

For the remaining structural parts of the design, a mix of aluminium and steel profiles is envisioned. The bent and welded pipes of the seat and doors are made from stainless or coated carbon steel as they will experience most of the interaction with users. They need to be sturdy and scratch resistant as much as possible, but most importantly, the amount of bending and welding involved likely makes steel the better choice when it comes to part cost. As these parts constitute less of the overall geometry, weight and transport are less of an issue.

The floor beams that go all around and connect the spaceframe structure with the foot platforms, doors and the seat are made of aluminium for the benefits described earlier.

To house the electronics and cover parts that should be out of sight and reach for any unauthorized person, cut and bent metal sheets are used. Depending on the desired vandalism protection, they could be made from aluminium or steel. For the tread plates, which the user would stand and walk upon when boarding and exiting the machine, the choice depends on the availability and a potentially desired custom pattern that could be realised by stamping or hot rolling.



Exploded view of individual frame assemblies with dimensions

Assembly & Transport

After manufacturing and pre-assembling parts into larger sections, the machine Ethereal Engine needs to be transported to the desired location.
The resulting frame dimensions can be seen in the overview above.

Bill of materials

The table on the right indicates the overall price of parts needed for a single as well as multiple Ethereal Engines. Note, that these prices do not necessarily include transport and assembly and are very rough estimates. Also, the price for the different versions does not include the armatures and foot platforms, but for the seat. The former need to be added to the overall costs but were left out to distinguish frame costs more easily, the latter was included fully as it constitutes an important part of the design.
For comparison, the costs for the American prototype and the JIP purchases are shown as well.

version	cost	part count
Ethereal Matter	11,558 €	56
JIP	1,502 €	105
minimal	170 €	3
small	810 €	8
medium	4,376 €	72
full	5,626 €	9

Table of cost overview

The difference in part count comes from the varying detailed breakdown of the designs and prototypes, such as including bolts or not.

A closer look at the BOM in the appendix reveals, that adding one or more machines to the setup does not double, triple or quadruple the price exactly, but leaves every additional Ethereal Engine more affordable, as every added setup shares parts with the existing machine that can thus be left out.

When connecting multiple machines, whole new interactions can take place between users. Therefore, also the fabric covers can be reduced or left out altogether to foster vivid interaction from user to user in a motivating, fun and competitive way.

Overall, this setup of connecting multiple Ethereal Engines provides an attractive advantage next to the increased structural rigidity: The product comes with a built-in volume discount. That makes it potentially attractive for customers to purchase multiple machines, while Ethereal Matter could retain the redundant parts for every additional machine sold and use them for other customer orders.

Comparing the costs for the US prototype with the estimated price for the frame seems to suggest only a small significance for the total costs. This is not the case. This bill of materials merely serves as a starting point, a benchmark to evaluate future designs of the Ethereal Engine. As the American prototype has been built to a fully functional state, many unexpected costs have already been discovered, which is not true for the frame design. Especially the costs for manual labour for manufacturing and assembly should not be underestimated and need further evaluation.

12 Prototyping

Throughout the project, Alejandro and I were planning the advancement of the Delft prototype of the Ethereal Engine. For that, we needed to make a plan, order materials, plus machine and connect all the parts necessary to create the first assembled frame and armature outside of the US.

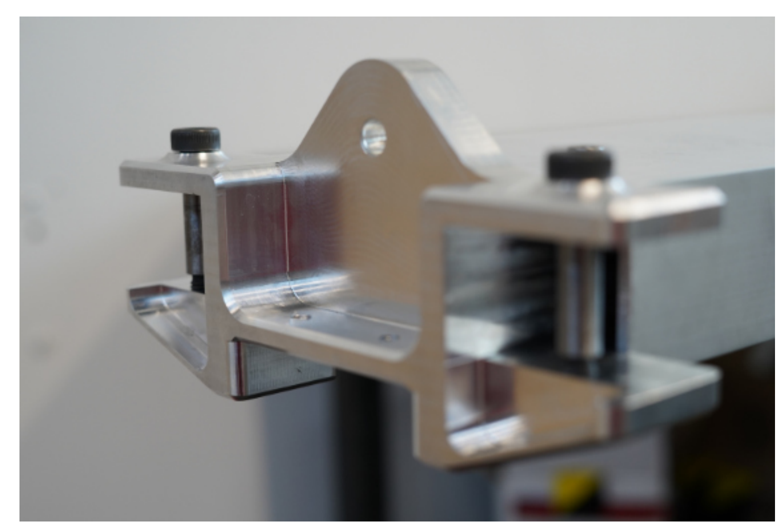
As described in chapter 9, during the client visit, Scott and I already rebuilt the frame that resulted from the JIP. In parallel, Alejandro and I modified the CAD files of Scott from imperial to metric dimensions, also adapting them to available standard profile dimensions available in the EU.

We ordered the appropriate materials, e.g. solid aluminium blocks for CNC machining the connection pieces, a linear rail, a square aluminium profile as the vertical mast to mount the rail on, as well as belts, pulleys and a wide variety of bolts and nuts.

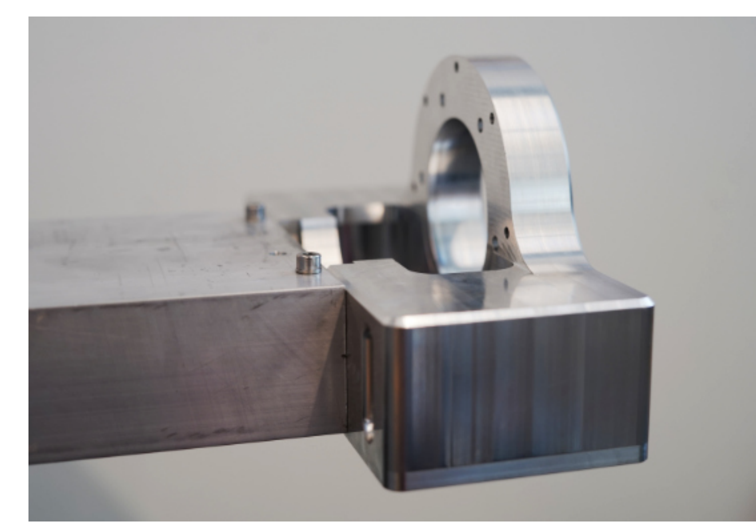
In close collaboration, we machined the parts with the help of the Dreamhall facilities and machines to eventually assemble one full armature and mount it to the frame. Unfortunately, some parts are still due to be delivered at the moment of writing, therefore it is up to the next JIP team or graduate students to add the actuators, belts and pulleys and complete the build of the working armature.

The images give an impression of the process of cutting, drilling, tapping and assembling all of the parts, which was overall very enjoyable. However, the prototyping process showed once more how important it is as part of the design process. The tolerances necessary to connect metal parts are very small and all the non-CNC actions need good planning and careful execution. Furthermore, the order in which parts are assembled and leaving enough clearance for operating wrenches and screwdrivers became apparent multiple times.

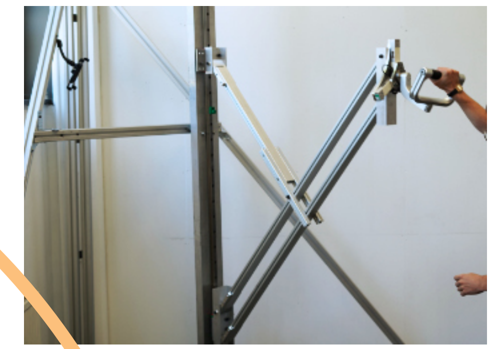
Top mounted CNC part

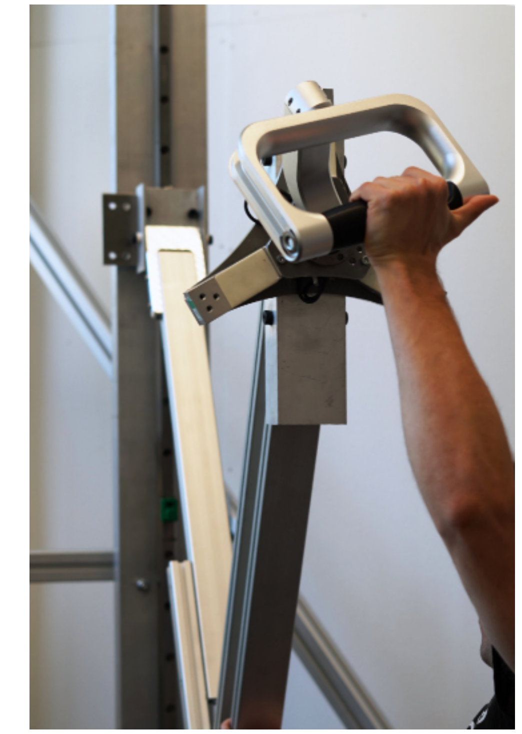


Bottom mounted CNC part



Old frame prototype at the start of my graduation project

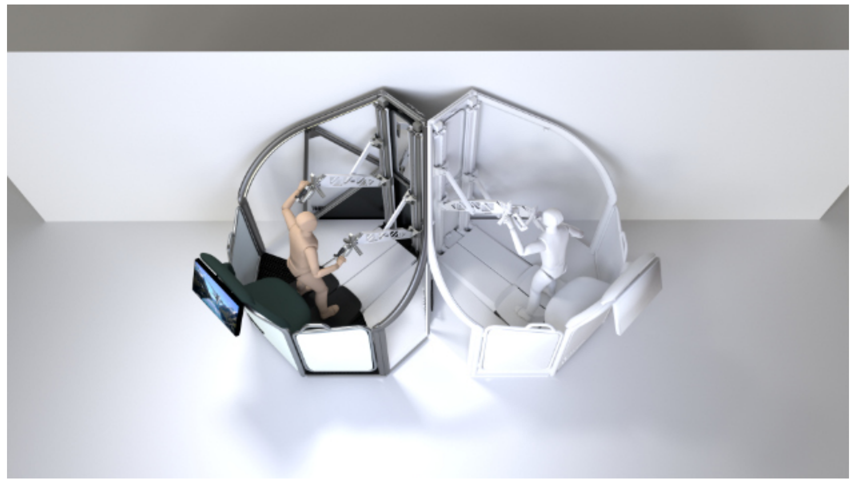




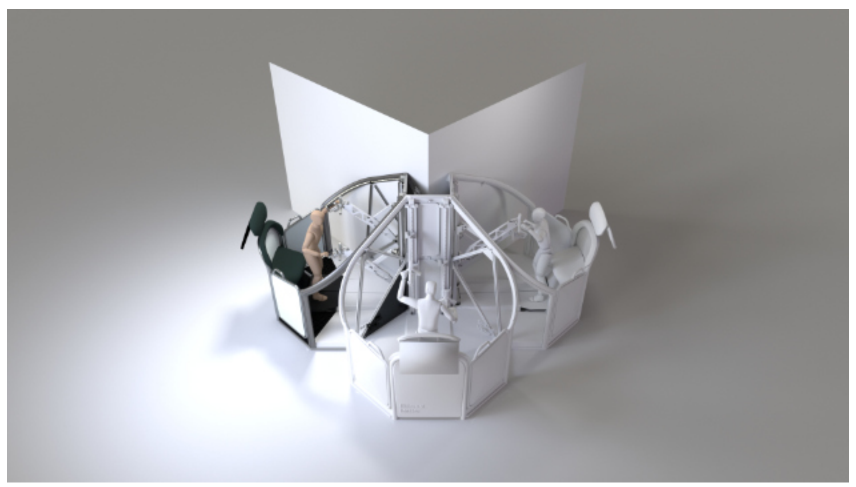
New Delft prototype of the Ethereal Engine

13 Product presentation

Finally, this chapter presents my proposed design for the Ethereal Engine and shows the different versions in the possible configurations and how it would look when placed in the context of a fitness centre (see page 86) on the conclusion chapter title page). As a final idea, I propose an added interaction for bystanders which is briefly described as well.



Two Ethereal Engines placed against the wall



Three Ethereal Engines placed against the a corner

Four Ethereal Engines in a free-standing clover arrangement

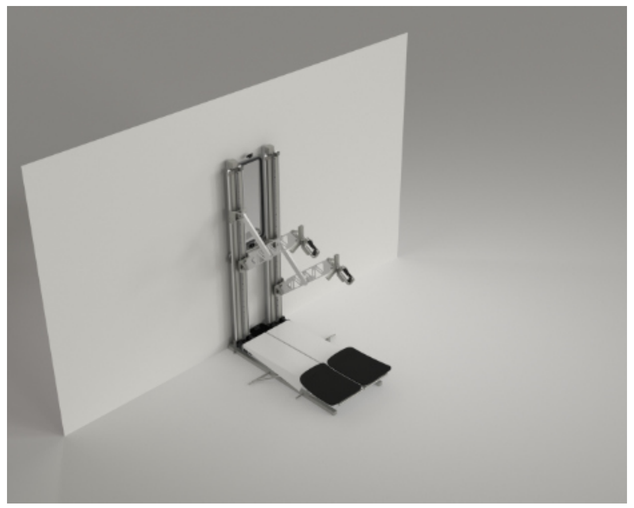
Interactive element for bystanders

Just as described in the analysis, a magic moment can add a memorable experience linked to the Ethereal Engine. An added interaction for bystanders could potentially increase participation and thus interest in using the machine. The idea is to add a mechanical interaction element, that would influence what is happening to the person in VR. The person flying with an ornithopter could for example receive an otherwise not possible to achieve boost, that helps reach new heights or add fun power-ups to the flight for a limited amount of time. This would not only decrease the boredom of people waiting for their turn but consecutively, create an engagement crossing the boundaries of virtual and non-virtual reality. As such, this kind of interaction could become an interesting research topic on its own and the Ethereal Engine could be a good way to test these. For a start, a simple interaction through the monitor could be conceived which later is replaced with a mechanical one consisting of e.g. levers, buttons, etc. to add physical engagement. This new way of cross-reality interactions could be transferred to general VR and AR research and developments in general and an interesting graduation project for interaction designers.

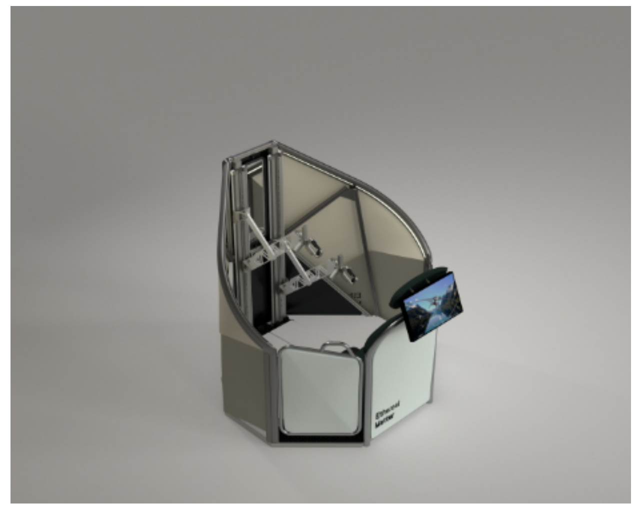
Exemplary added interaction for bystanders

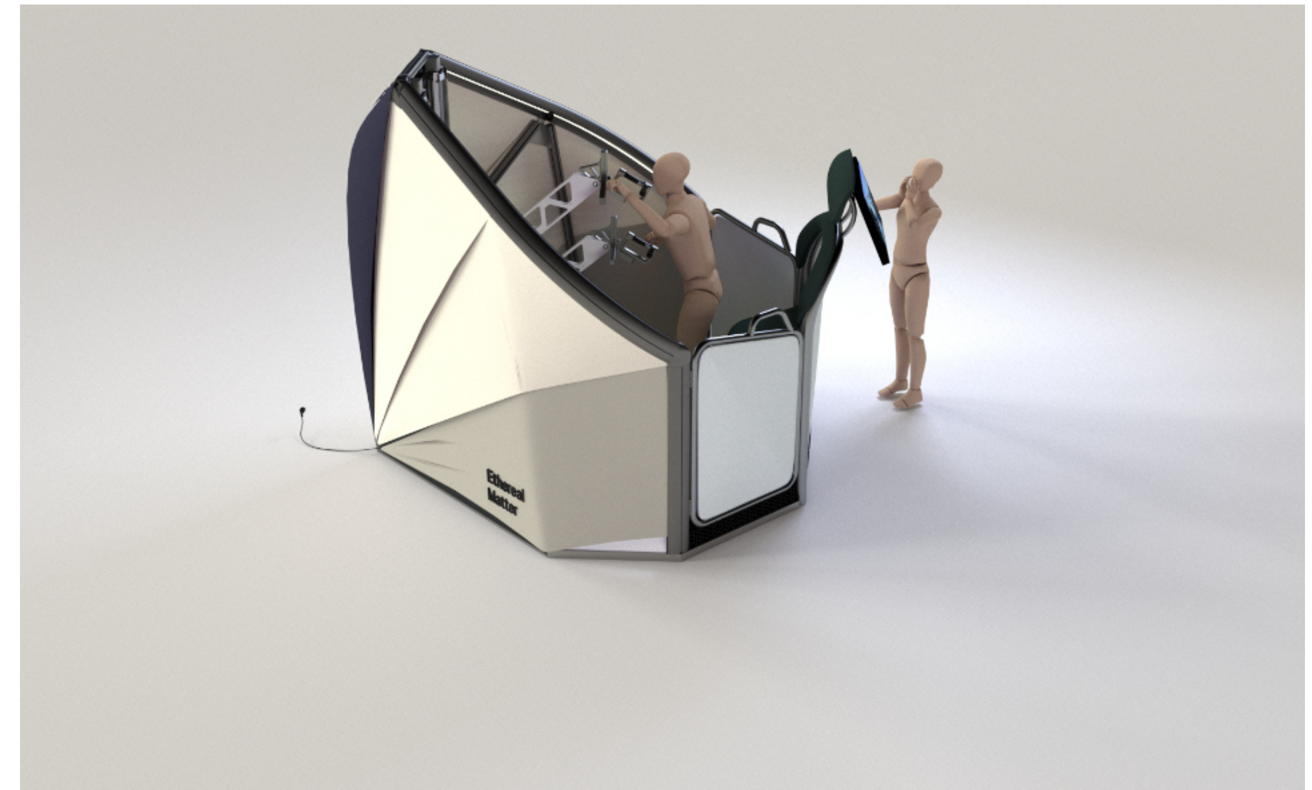
Section view revealing the locker underneath the seat

Minimal version

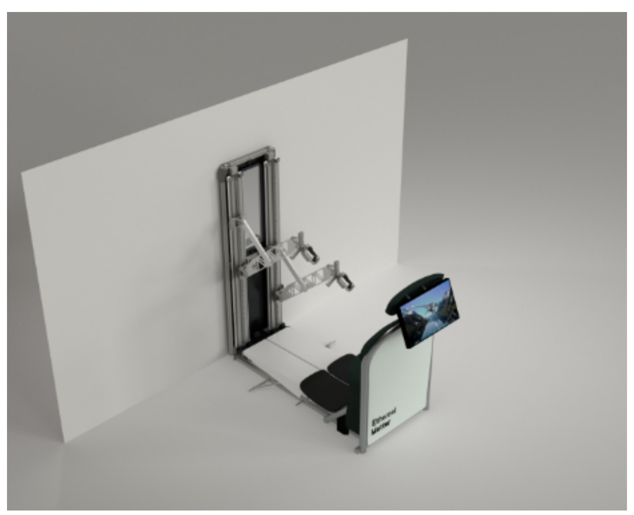


Medium version

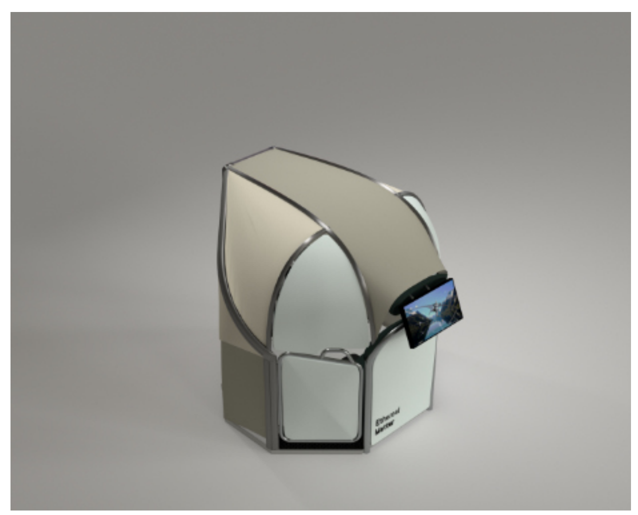


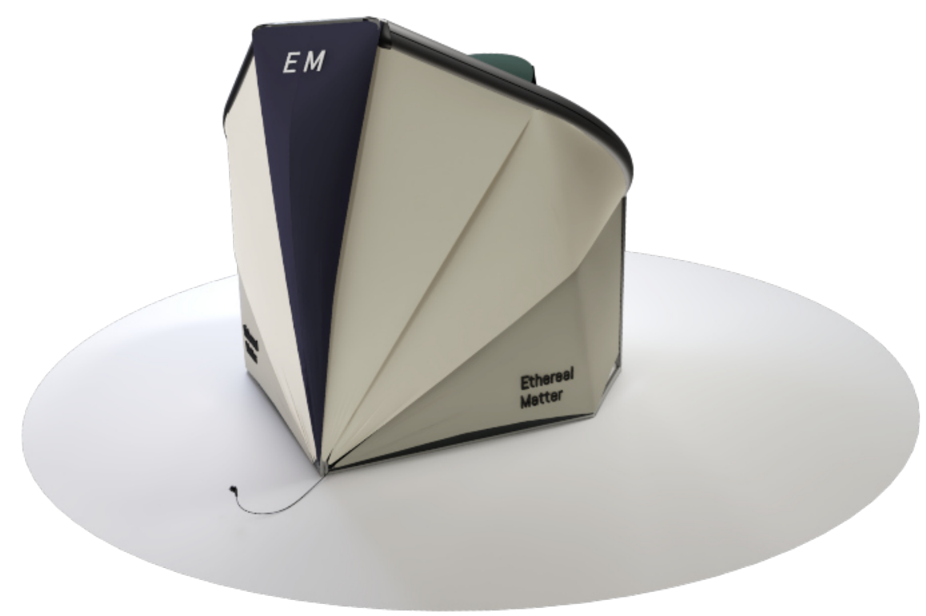


Small version

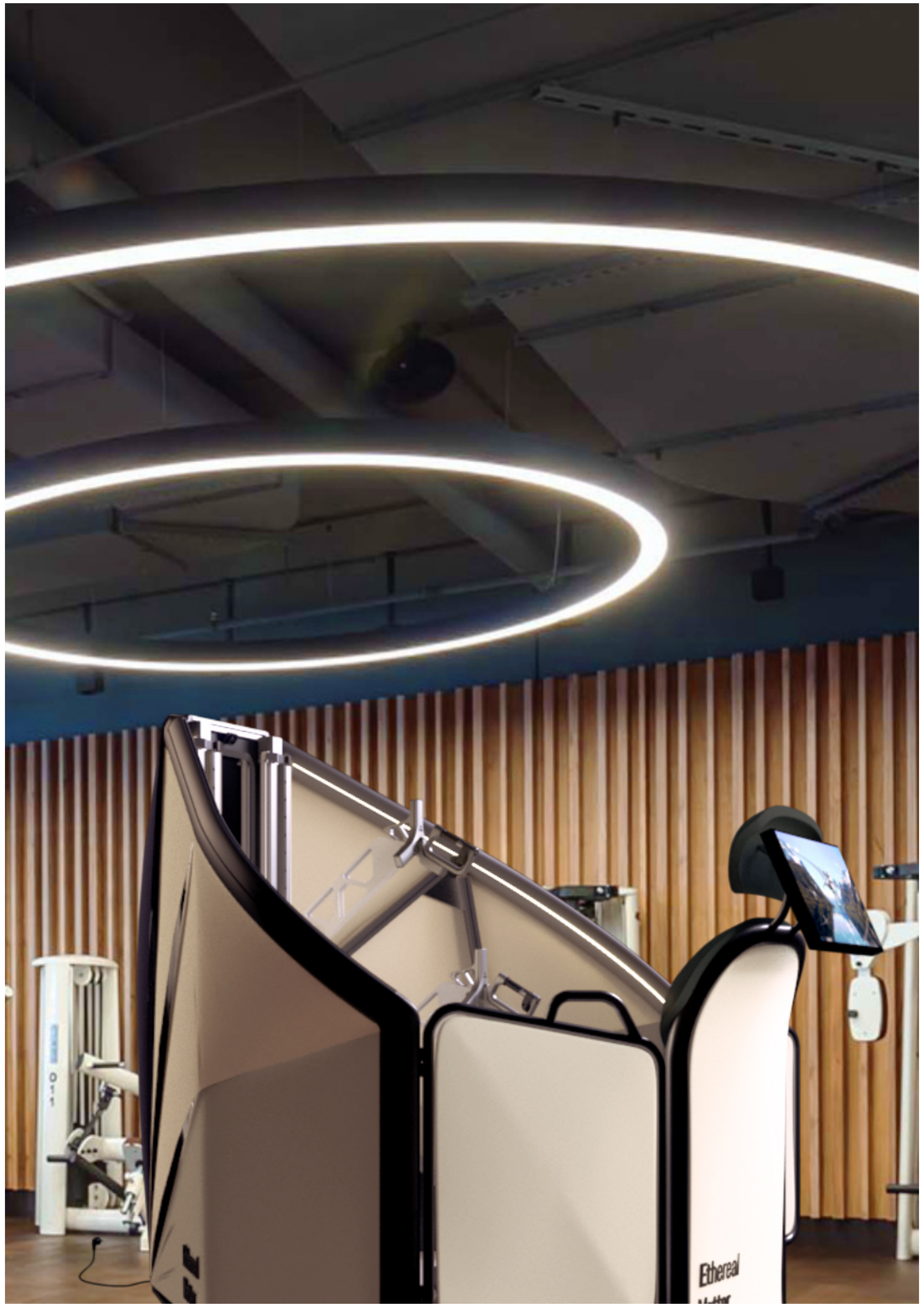


Full version





Exploded view of the medium version



14 Conclusion

Concluding this project is the summary explaining the necessity for a VR fitness machine like the Ethereal Engine and the proposed design of its frame. It is followed by the discussion which elaborates on the benefits, possible future use cases, how the design of the frame meets the defined main drivers from chapter 7, and to what extent the results of this thesis can be transferred to the future development of the Ethereal Engine.

Summary

As discussed in the introduction, keeping up with a regular workout routine is demanding for many people. A lack of regular physical exercise is known to cause a broad range of health issues, foremost physical but also mental. The effects of regular physical exercise, however, are well researched and known to benefit overall health and well-being.

A promising solution to solve this issue is the Ethereal Engine. It caters for the ever-increasing interest in video gaming, as well as the advent of virtual worlds, e.g., the Metaverse. By combining physical exercise with breath-taking VR simulations, the Ethereal Engine can create experiences that do not feel like a conventional workout. This could, in turn, motivate many people to enjoy a simulation inside the Ethereal Engine and thus regularly exercise.

At the beginning of this graduation project, there was a full prototype in development and operation in the US. A rudimentary frame was also constructed in Delft by a group of students throughout the JIP. However, current designs focus on a particular setup of the machine and can only be placed in public with added safety installations and modifications. The US prototype for example is still bolted to the ceiling to ensure proper rigidity during operation.

As a result of this graduation project, the overall frame design proposes solutions to a multitude of these shortcomings. Extensive user and literature research into the perception of space and interactions throughout a session inside the Ethereal Engine resulted in a list of drivers and requirements that set the basis for subsequent design iterations to create a version that shows how the Ethereal Engine could be manufactured, transported and assembled all why having the eventual user in mind.

With the help of generative design algorithms, a range of geometries and materials were explored, which generated a spaceframe structure that allows for the Ethereal Engine to be free-standing, only needing a good connection to the floor.

Another main feature of the design is the modular approach, which allows for the machine to be sold in different configurations that offer maximum flexibility: from a minimum, wall-mounted version – consisting of the armatures only – to a fully enclosed setup – offering maximum privacy, safety and possibilities for UVC-disinfection. The modular design furthermore eases sustainable practices like repair or upgrade of individual parts.

Lastly, multiple features have been discovered and implemented, that make the Ethereal Engine a more enjoyable VR fitness machine. Among these are a storage compartment for personal belongings, a mirror to check one's appearance after an intense session as well as quickly see what is going on behind the person, a tether for charging and data transfer and lastly, integrated interior lighting that can be used to ease and enhance the transition experience in and out of the machine and the VR simulation.

A bill of materials gives an indication of the part count and price point for the different setups and shows how the possibility to connect multiple Ethereal Engines to each other saves parts and in turn costs.

Rendering of the Ethereal Engine in the context of a fitness centre

All in all, the Ethereal Engine is an exciting platform to create useful applications of virtual reality and it adds another powerful input to the experience of virtual simulations: force feedback. It enables more immersive games that could potentially get people to exercise regularly by playing these games.

Discussion

The possibilities of this machine however go beyond combining gaming, VR and fitness. Because of the precise control over the actuated armatures and foot platforms, the Ethereal Engine opens up new ways of tracking motion and underlying forces behind them. Being able to measure and control the input or output force at any point and in any direction gives the machine unprecedented abilities to better understand human motion and strength capabilities. It enables performance insights at a minute level and on the other hand, allows precise control of virtually any movement of the user's limbs. This is valuable for research, physical therapists and athletes alike. Beyond that, one can imagine using the Ethereal Engine for training and instruction of people on how to exert certain motions safely, i.e. construction workers. It could be adapted for the motion picture industry, where the machine could provide a broader range of motions and forces to place actors into more convincing scenarios, like wrestling with a large and strong creature. Eventually, the Ethereal Engine could be turned into a simulator for motion in extra-terrestrial places, e.g., space or planets with different gravity.

The presented design shows how the first generation of the Ethereal Engine entering the market could be conceived. The modularity of the enclosure offers an attractive option for venues like gyms, entertainment centres, or fairs to obtain multiple engines in configurations that fit their needs with the possibility to up or downgrade by adding or removing parts of the frame. Especially by purchasing multiple machines and arranging them together, compelling clusters can be created that enhance competition and interaction between up to four players.

As set out in chapter 7, main drivers, a surrounding frame with additional padding in the back offers a comforting feeling of being safe from people intruding on one's moving space as well as having a place to quickly take a seat when feeling nauseous or exhausted. The lighting makes the transition in and out of the VE more comfortable as it can match the light levels of the HMD and it can be utilised to create thrilling entry and exciting experiences.

The desired adjustable exposure that was described in the vision, however, was barely achieved as a user is limited to choosing if a live view shall be shared with bystanders on the monitor or not. Physical exposure solely depends on the configuration in which the Ethereal Engine is provided by the venue, i.e. the full version.
The same is the case for the clear background for the motion capture system. As the frame only partially separates the user from the surroundings, the cameras will need to be adjusted and the algorithm properly trained to ensure reliable identification of the user's limbs.

The overall appearance of the Ethereal Engine is dominated by diagonal visual lines, eliciting dynamic motion which could heighten the anticipation of what the user is about to do.

All in all, the design provides a full overview of how the Ethereal Engine could be conceived as a modular, engaging and safe product. Necessary developments and further research can be inferred from the decisions made while the presented design can serve as a benchmark to ultimately choose a design to enter the market with. The result generated new ground for discussion regarding the future combination of VR and fitness, while the graduation project itself showed the value of incorporating VR into the design process from an early point on.

Lastly, new cross-reality interactions as proposed in the product presentation chapter are exciting ways to use an innovative machine like the Ethereal Engine to research and develop novel ways of human communication and interaction.

15 Recommendations

This chapter contains the recommendations I inferred from this project. Specific suggestions for the client, succeeding students and their supervisors are followed by a vision that has accompanied this project all along and concluded with recommendations to the general public, specifically you: the reader.

For the Client

Multiple outcomes of this project have already been internalised by the client, such as the **addition of a locker**. However, I would like to point out a few things which I think could help make the Ethereal Engine a success.

Even though the client is now focussing on a minimal version for fitness centres, I think a wholesome strategy should entail the **aspect of modularity**. Offering an enclosure for safety and privacy could be crucial to quickly satisfy rising demand from public venues like entertainment centres or fairs in purchasing a customizable Ethereal Engine. Using materials like **fabric for the outer shell** could pose a great solution for customizability and would attract customers to later upgrade their machines to medium or fully enclosed configurations.
As part of the modularity, the **extrusion profiles used for this design could be easily substituted** by cheaper variants or different geometries and materials, better suiting very low production volumes during the first market entry. Using this advantage for the design should be considered in future developments.
The same is true for keeping a **spaceframe layout** for the main structural construction, which only loads members in tension and compression, as it will almost guarantee a lightweight yet strong design. At the same time, I recommend being mindful of the individual length of members to reduce the necessary buckling strength the profiles need to exhibit. This can be done by balancing out their length and reducing it to a minimum by dividing the geometry with additional members.
Furthermore, adapting the **approach of part sharing by connecting multiple Ethereal Engines** with each other could prove very valuable.
Nevertheless, more experimentation and design work need to be spent on this aspect, as by far not all questions regarding the embodiment and assembly have been answered.

In general, the possibility to bolt the engines to the floor of a venue and thus allowing them to be **free-standing** is something I recommend pursuing as an option as it allows for a lot more flexible and prominent placements. No load-bearing walls need to be available and the clover-like cluster of multiple Ethereal Engines creates an engaging, space-efficient setup that will gather crowds around them.

An important aspect that needs attention moving forward is how to place and attach the mocap cameras. They need to be unaffected by vibrations and deformations of the frame as much as possible. As the exploration is not done, if relying on a deep-learning mocap system – a system only using regular imaging cameras and a trained computational model – is a viable option, the cameras in this design have been placed by assuming little occlusion caused by the armatures and little influence from the loaded structure. To eventually reduce vibrations and movement of the cameras as much as possible, **spacers and mounts made from elastomer** can be used. Apart from that, **attachments made from magnesium** will greatly reduce the transmission of vibrations compared to other metals (Riehemann, 2000).

In any case, I hope the client can deduce some valuable insights from this contribution to the overall project and uses the design and the methods from this project as inspiration for the future development of a market-ready product; especially considering the end user of the machine.

I recommend keeping up the inspiring regular video calls with future students and teams, but especially to continue the in-person visits to Delft. I wish him and the company the best of luck moving forward and I am anticipating the first time I will be able to experience a simulation inside the Ethereal Engine with great excitement.

For the next students

The most important suggestion for future student teams is the importance of communication and collaboration for this project. As there will always be many stakeholders involved, clear communication and regular meetings, especially with Scott, make sure everyone involved is informed properly, but most importantly, valuable feedback can be given at an early stage.
Many questions have been answered before and can be found in the existing reports, but feedback from Scott has many times answered questions a lot faster than researching and exploring them yourself. A healthy mix of own research and questioning the people already involved in the project is recommended.
Adding to this is the urge to collect and build a project repository that will outlast your project. This will make it easier for the next students to grasp the project and start advancing with the actual developments a lot earlier.
A thing to keep in mind is the nature of any project, where a fast-moving start-up is involved. Whatever has been decided or developed is not set in stone. The following day, new insights or simply a talk with an expert can lead to completely new assumptions, specifications or requirements. These ever-changing circumstances can be dealt with best when at least a slightly different focus is chosen compared to what is under current development in the US. Be it an area that has not been explored or questioning an already made decision by experimenting with alternatives that have just recently become available.

The opposite is true for the prototyping part. Simply adapting the existing design from imperial to metric proved challenging enough, so rely on what has already been developed as much as possible. In that sense, keep the number of variables low, so improvements of what you are actually working on become clear in comparison.
For a successful prototyping experience, it is crucial to start thinking about necessary parts as early as possible and ordering them weeks, if not months in advance. Not only do some manufacturers have long lead times, but ordering through a large, public organisation like the TU Delft will lead to hick-ups and delays in many unforeseen ways.

Regarding the Delft build of the Ethereal Engine, two small pieces of advice are: keep the number of custom parts as small as possible, yet reduce the amount of manual labour as much as possible too. That means, you won't have to order many expensive, hard-to-get parts with long lead times, which could eventually make your proposal unusable for Ethereal Matter, but it also means relying on CNC-controlled machining, to reduce the amount of human error and realise the necessary tolerances. For any manual labour, follow a double-check procedure before machining anything that can not be undone or repeated easily.

My final remarks are simple: Enjoy working on a state-of-the-art, futuristic technology, that involves a very large amount of interesting research opportunities, a lot of prototyping and eventually an inspiring result of your project.

For their supervisors

The Ethereal Engine is a great opportunity as a project for enthusiastic students of all studies. The only three recommendations I want to give to their supervisors are the following:
First, enforce a good team collaboration with all parties involved, especially when multiple teams or student projects are involved. No matter how remote the individual topics might seem, a close collaboration can only benefit everyone.
Second, starting with prototyping as early as possible should be demanded. Even if students are still trying to understand the project, they can already order and assemble the recommended parts from previous teams. This will accelerate the grasping phase tremendously.
Third and finally, the complexity of the project and the different demands from different courses and electives like the JIP and the like make it almost impossible to have people from differing courses work on the same problem. Schedules, deadlines and deliverables will not align and make the overall collaboration difficult, if not impossible. It was tried at first for this graduation but quickly terminated to better suit the student team, as well as this graduation project.

For you, the reader

Solar Punk

Throughout my design process, an ever-present topic has been a concept called 'solar punk'. It is a way to envision the future of humanity opposite to common dystopian narratives such as 'cyber punk' and the like. Solar punk helps to channel the apathetic feelings of 'weltschmerz' (German, loosely translated as 'world pain') into motivation to be the change yourself.
The idea includes a sustainable use of available resources which influenced material choices and the overall aesthetic of the Ethereal Engine. Even though this project did not focus on sustainability, I focused on choosing recyclable materials – such as metals – preferred fastened connections over permanent welds and glue-ups, and chose fabric over plastics to cover large areas.

Finally, these recommendations belong to you, dear reader, representing the general public.
First of all: Thank you for taking the time to read this report. If you have made it all the way here, you now hopefully have a better understanding of what an integrated design engineering project could entail.

Second: VR is here to stay. No matter if you like it or not, VR will play a role in our future one way or another. This project already utilised VR applications to arrive at the final result.
I believe inventions like the Ethereal Engine provide positive use cases for VR and we should get excited about the possibilities, rather than paralysed by improbable dystopias. The best way to make sure, VR is put to good use, is to get involved yourself. That applies to almost anything, so if there is anything I would like you to take away from this report, it is that I challenge you to adopt a solar punk mindset and become part of shaping a better future.

Midjourney envisioning a futuristic gym with natural materials

16 Reflection

Being a reflective practitioner as described by Donald Schön is in my eyes a necessity that goes beyond designers and the like. In this chapter, I want to briefly reflect on what this project entailed and meant for me, what I learned and how I will channel my mistakes and shortcomings in my future career as an Industrial Design Engineer.

Why this project matters to me

Being part of the Ethereal Matter journey has been a great experience. From the start, I was hooked by the idea, as I have dreamed of a machine like that already during my teenage years. Meeting Scott for the first time was a positive encounter as well and the interactions and communications with him have always been fun, productive and inspiring.
Especially the week he visited meant full-time close collaboration which I enjoyed a lot.

How it contributes to Ethereal Matter

I am very grateful for having had this chance to provide Ethereal Matter with a proposal for a future frame design and I hope my discoveries and suggestions find at least partial consideration.

Nevertheless, I am aware of how much work still lies ahead getting from what I proposed to what the first available Ethereal Engine will eventually look like. I hope, however, that I was able to create a good foundation – and benchmarks – in many aspects; for the client as well as future teams working on the project. It would be great if said people could build upon my ideas and concepts in addition to the generative design and VR workflows, as well as the research opportunities that were identified through this project.

How I managed it

As all project have their shortcomings, so do graduation projects in particular, in my honest opinion.
I think this project is missing ergonomic considerations, which have been excluded due to focus and time issues, but they are very important for the future design of the Ethereal Engine. Of course, by using VR, I was able to evaluate spatial features very vividly and quickly, still, this introduced a bias that stems from my physique alone. Everything I evaluated was based on my perception.

I furthermore think, that the focus on a minimal version as Scott is working on right now, could have been an interesting focus, which would have allowed me to reach a more advanced state of a design, as the number of details and considerations could have been decreased.
When viewing the past months from a project management perspective, being forced to work by myself has been very tough. Even though I was lucky to have Alejandro to collaborate with on many aspects – especially prototyping and client communication – I struggled with the decision-making as I know it from myself already. I managed to organise myself a lot better than in previous projects, but especially towards the end, I dwell on decisions or get lost in unnecessary details for way too long.

A look in the mirror of the Ethereal Engine

That made reaching deadlines in a relaxed way impossible. I have to further improve how I structure my work and how I report it.

On the upside, I never imagined arriving at the results shown here. I am positively surprised how quickly VR sketching generative design using Grasshopper and the new rendering engine VRAY has become a natural part of my workflow. I learned a lot about materials and engineering and client communication overseas.
I was also not imagining that Alejandro and I would reach the prototype stage we eventually reached. I was glad we somewhat ignored the retention expressed by our mentors to spend too much time working on the physical prototype and it is with a very sad feeling, that we could not finish the assembly with belts and pulleys because of a delayed order.
The result is, that I am extremely curious about the next teams to connect the actuators, and drivers and finally hook the system up with a headset, so I have another good reason to visit the TU Delft again.

Where I see myself in the future

I will take a lot away from this project. Not just the mentioned work flows and prototyping experience. It is especially the way my supervisors and Scott have handled me and the overall project that inspired me for any future group work or supervision.
I like to be able to call myself a Design Engineer, but I will need to study engineering topics a lot more to even remotely achieve what other engineers do daily. Nevertheless, I will pursue this path and am curious about where I will end up working.

In any case, spreading the word about solar punk and the mentality behind it will be part of my career for sure.

Acknowledgements

I am very grateful to Erik, Gijs and Scott to mentor me during this whole time. I have felt welcomed, supported and inspired throughout the graduation and am sure that is due to your way of supervising and interacting with students and other people in general.

A special thank goes to Alejandro for the past months of uncounted hours in the Dreamhall double-checking each other before drilling an expensive CNC machined part. Working together with you has been very insightful and most of all fun.

I would like to thank Mart and Arjan for being motivating and perfectly critical sparring partners throughout the project. I thank Aslì for her expertise in emotion research, and especially Cristina for participating in it and sharing very personal feelings.

I would like to thank Anne for her support and general design discussions.
Lastly, a big and sincere thank you to Laura, my family and my friends who have endured, supported and cheered me up during the past half year.

Thank you!

References

Addolorato, S., García-Fernández, J., Gallardo, L., & García-Unanue, J. (2020). An Overview of the Origins and Effectiveness of Commercial Fitness Equipment and Sectoral Corporate Settings: A Critical Review of Literature. *Applied Sciences*, *10*(4), 1534. https://doi.org/10.3390/app10041534

Alsop, T. (2022). *Virtual reality (VR) - statistics & facts.* Statista. https://www.statista.com/topics/2532/virtual-reality-vr/

Ayenigbara, I. O. (2018). Gaming Disorder and Effects of Gaming on Health: An Overview. *Journal of Addiction Medicine and Therapeutic Science*, 1–3. https://doi.org/10.17352/2455-3484.000025

Biocca, F., & Levy, M. R. (1995a). *Communication in the Age of Virtual Reality*. *LEA's communication series*. L. Erlbaum Associates. https://books.google.nl/books?id=MzaMSbzcz6UC

Biocca, F. (1997). The Cyborg's Dilemma: Progressive Embodiment in Virtual Environments. *Journal of Computer-Mediated Communication*, *3*(2). https://doi.org/10.1111/j.1083-6101.1997.tb00070.x

Biocca, F., & Levy, M. R. (1995b). *Communication in the Age of Virtual Reality: Communication Applications of Virtual Reality* (1st Edition). https://doi.org/10.4324/9781410603128

Buckminster Fuller Institute. *Geodesic Domes*. https://www.bfi.org/about-fuller/geodesic-domes/

Carterette, E. C., & Friedman, M. P. (1978). *Handbook of perception: Perceptual Ecology*. Academic Press.

COUNCIL DIRECTIVE 96/5 3/EC, Official Journal of the European Communities (1996).

Csikszentmihalyi, M. (1990). Flow: the psychology of optimal experience. *Harper Perennial Modern Classics*.

Desmet, P.M.A. (2002). *Designing Emotions (unpublished doctoral dissertation).* TU Delft.

Desmet, P.M.A. (2021). *Design for Emotion (ID5564): Course Manual*. Delft. Delft University of Technology.

Desmet, P., & Fokkinga, S. (2021). *Human Experience Catalog: Six typologies of human experiences* (4th Edition).

Desmet, P. M.A., Fokkinga, S. F., Ozkaramanli, D., & Yoon, J. (2021). Emotion measurement: Emotion-Driven Product Design. In H.L. Meiselman (Ed.), *Emotion Measurement* (645th ed.). Woodhead Publishing.

Diemer, J., Alpers, G. W., Peperkorn, H. M., Shiban, Y., & Mühlberger, A. (2015). The impact of perception and presence on emotional reactions: A review of research in virtual reality. *Frontiers in Psychology*, *6*, 1–9. https://doi.org/10.3389/fpsyg.2015.00026

Manual of Standard Building Specifications, May 4, 2019.

EN 1991-1-1: Eurocode 1: Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings, April 2002. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.1.2002.pdf

European Pallet Association e.V. (2020). *EPAL Euro Pallet 800x1200mm product sheet* [Press release]. www.epal.eu

Falardeau, E., Glynn, J., & Ostromecka, O. (2021, June 21). Sweating for the fitness consumer. *McKinsey & Company*. https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/sweating-for-the-fitness-consumer

(2022). *Market Insights on Augmented Reality Glasses covering sales outlook, demand forecast & up-to-date key trends: Augmented Reality Glasses Market: Global Industry Analysis 2012 - 2016 and Opportunity Assessment; 2017 - 2027.* Future Market Insights. https://www.futuremarketinsights.com/reports/augmented-reality-glasses-market

Green, A. (2017). Alexander Graham Bell's Tetrahedral Kites (1903–9). https://publicdomainreview.org/collection/alexander-graham-bell-s-tetrahedral-kites-1903-9

Gutman, J. (1984). Analyzing consumer orientations toward beverages through means-end chain analysis. *Psychology & Marketing*, *1*(3-4), 23–43.

Hayward, S. C., & Franklin, S. S. (1974). Perceived Openness-Enclosure of Architectural Space. *Environment and Behavior*, *6*(1), 37–52. https://doi.org/10.1177/001391657400600102

Humber Sensory Processing Hub. (2020). *Introduction to 'The Senses'.* NHS UK.

Hygen, B. W., Belsky, J., Stenseng, F., Steinsbekk, S., Wichstrøm, L., & Skalicka, V. (2022). Longitudinal relations between gaming, physical activity, and athletic self-esteem. *Computers in Human Behavior*, *132*, 1–8. https://doi.org/10.1016/j.chb.2022.107252

International Health, Racquet & Sportsclub Association. (2021). *2021 IHRSA Media Report: HEALTH AND FITNESS CONSUMER DATA & INDUSTRY TRENDS BEFORE AND DURING THE COVID-19 PANDEMIC* [Press release].

item Industrietechnik GmbH. *item Chronik*. https://timeline.item24.com/index.php/de

Knibbe, J., Schjerlund, J., Petraeus, M., & Hornbæk, K. (2018). The Dream is Collapsing. In R. Mandryk, M. Hancock, M. Perry, & A. Cox (Eds.), *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (pp. 1–13). ACM. https://doi.org/10.1145/3173574.3174057

Lipp, N., Sterna, R., Dużmańska-Misiarczyk, N., Strojny, A., Poeschl-Guenther, S., & Strojny, P. (2021). Vr Realism Scale-Revalidation of contemporary VR headsets on a Polish sample. *PloS One*, *16*(12), e0261507. https://doi.org/10.1371/journal.pone.0261507

Lombard, M., & Ditton, T. (1997). At the Heart of It All: The Concept of Presence. *Journal of Computer-Mediated Communication*, *3*(2). https://doi.org/10.1111/j.1083-6101.1997.tb00072.x

Matmatch GmbH. *6061-T6 Aluminium – The Ultimate Guide*. https://matmatch.com/learn/material/6061-t6-aluminium

Mehrfard, A., Fotouhi, J., Taylor, G., Forster, T., Navab, N., & Fuerst, B. (2019, December 6). *A Comparative Analysis of Virtual Reality Head-Mounted Display Systems*. http://arxiv.org/pdf/1912.02913v1

Menin, A., Torchelsen, R., & Nedel, L. (2022). The effects of VR in training simulators: Exploring perception and knowledge gain. *Computers & Graphics*, *102*, 402–412. https://doi.org/10.1016/j.cag.2021.09.015

MERO-TSK International GmbH & Co. KG. *MERO: Company*. https://www.mero.de/en/company-en.html

Molenbroek, J. F.M., & Huysmans, T. (2022). *DINED - anthropometric database* [Computer software]. TU Delft. www.dined.nl/en

Prandelli, E., Pasquini, M., & Verona, G. (2016). In user's shoes: An experimental design on the role of perspective taking in discovering entrepreneurial opportunities. *Journal of Business Venturing*, *31*(3), 287–301. https://doi.org/10.1016/j.jbusvent.2016.02.001

Rakhra, V., Galappaththy, S. L., Bulchandani, S., & Cabandugama, P. K. (2020). Obesity and the Western Diet: How We Got Here. *Missouri Medicine*, *117*(6), 536–538. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7721435/

Riehemann, W. (2000). *Damping in Magnesium and Magnesium Alloys.* https://doi.org/10.1002/3527607552.ch104

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The Experience of Presence: Factor Analytic Insights. *Presence*, *10*(3), 266–281.

Slater, M., Steed, A., McCarthy, J., & Marinelli, F. (2002). The Virtual Ante-Room:: Assessing Presence through Expectation and Surprise.

Tempelman, E. (2020). *NSFD: engineering essays on structures & materials.*

Applications Manual for the Revised NIOSH Lifting Equation 1 (1994).

van den Oever, Y. (2022, June 8). Interview by M. von Seyfried. Hydro Extrusion Benelux.

Vasylevska, K., Yoo, H., Akhavan, T., & Kaufmann, H. (2019, March 23–27). Towards Eye-Friendly VR: How Bright Should It Be? In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 566–574). IEEE. https://doi.org/10.1109/VR.2019.8797752

Weibel, D., Wissmath, B., Habegger, S., Steiner, Y., & Groner, R. (2008). Playing online games against computer- vs. human-controlled opponents: Effects on presence, flow, and enjoyment. *Computers in Human Behavior*, *24*(5), 2274–2291. https://doi.org/10.1016/j.chb.2007.11.002

Image references

Page 8: https://img.freepik.com/free-photo/young-african-woman-running-isolated-white-studio-background-one-female-runner-jogger-silhouette-jogging-athlete_155003-34509.jpg?w=1380&t=st=1654266127~exp=1654266727~hmac=b96cdedeef78b431cb9e293ad74933c14ff6eb8a614f55c8c2f03f7ad7fe0595

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All other image sources were either created by the author, the client or the Midjourney application

Delft, 2022

TUDelft

Appendices

Appendix A

Initial assignment

How could the frame of the Ethereal Matter engine look like, with regards to optimal costs, structural rigidity, ease of transport and assembly, as well as user interaction and perception?

Project Brief

Personal Project Brief - IDE Master Graduation

TU Delft

Design of a physical virtual reality engine with real-time force feedback — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 23 - 02 - 2022 — 29 - 07 - 2022 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The project was created by Scott Summit, who, with his California-based company "Ethereal Matter Inc", is developing a next generation of virtual reality (VR) experience using a haptic system inside a mechanical apparatus (engine). He and his company aim at bringing a working engine to the market in order to create a viable business that will open up new possibilities for the future use and development of VR applications. With the increased interest for mixed reality (MR) – including VR, augmented reality (AR) and a mix there of – technology by companies such as Meta and developments by companies including Unity and Unreal, the engine poses an invention in the middle of an ever-increasing market. With a registered patent, all IP rights are owned by Scott and Ethereal Matter. At the constant increase of competition, the aim is to make use of the first mover advantage to stay at the forefront of future developments in VR in order to gain and hold a significant market share.

At the other end, the TU Delft Robotics Institute is the collaborating partner interested in utilizing this undertaking to teach students from various disciplines (Design, Engineering, Computer Sciences, etc.) in developing such a complex engine. Next to the advancements and prototypes developed in California, students will build, test and improve a prototype in the Netherlands and multiple interdisciplinary projects and graduation projects (including this one) will be working on the project simultaneously and consecutively.

The Ethereal engine is a fitness device consisting of two moving arm assemblies with grips at their respective end which users hold with their hands, while they stand on two separately moving platforms with their feet. (see figure 1). The user wears a VR headset and is tracked by a motion-capture system (MoCap) that translates positional data to the VR environment in real-time. All these systems are held in place by the overall frame, which houses the necessary electronics, actuators and additional sensors, including cameras for the MoCap system.
Upon using the engine, the user is able to move the hand grips and feet platforms, which then provide varying resistance to the performed motions in order to add a real as possible force feedback to the simulated experience. For example, a user could be flying in a bird-like wing-suit through a simulated mountain world (see figure 2), where every wing flap needs an actual force to be exerted physically by the user which is generated through the precise control of the actuators (e.g. stepper motors) of the arm assembly.

So far, VR experiences are limited to visual and auditory stimulation, as available VR sets only allow user input through hand-held controllers or hand gestures. Companies are currently developing dynamic and actuated products like gloves for precise movements (sense-glove), haptical feedback controllers (tactical haptics), or omni-directional treadmills (virtuix omni) for extended virtual realities, but the Ethereal engine is the first of it's kind to incorporate moving around and performing physical work through the arms and upper body at the same time.
This opens up many new possibilities for various applications: With such a machine, gaming becomes physically demanding, therefore promoting physical fitness for people usually sitting behind a screen; fitness turns into a thrilling experience that feels less like a workout and more like an adventure, increasing the chance for people to exercise regularly and eventually fight obesity. Next to games and fitness, new ways of instructional training and research (e.g. human movement studies) are possible, where the engine could be used to educate people or do research in performing physically demanding tasks in the most ergonomic way possible.
Finally, the engine allows for tailored rehabilitation after disease or injury. Being able to precisely control the range and path of motion, while adding the desired amount of resistance to a patients exercise provides physiotherapists with a powerful tool to reduce recovery time and possibly an increased success rate.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Conceptual rendering of the ethereal engine with a person actively engaged in the simulation

image / figure 2: Visualisation of what the virtual reality could look like with users flying around in winged suits.

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The Ethereal Matter engine is a complex product with a multitude of problems to be solved, from the general construction through sensing and user interfaces all the way to the virtual experiences and their control through the user.
To create a realistic undergoing, I will limit my Graduation Project to the overall frame, considering user related aspects like spacial perception and comfort, as well as engineering aspects such as stiffness, manufacturing and assembly.

The engine needs to be comfortable to use for people with varying body shapes and sizes, so a good understanding of ergonomic aspects will be crucial. Additionally, the perception of the machine and the ease of interaction with it will be important for my design. The aspect of safety during active use will be mostly covered by the second IPD graduate, Alejandro, but safety of bystanders and outside the simulation need to be considered for the design of the frame.

Next to that, Design for Manufacture and Assembly plays an important role in designing a working prototype in the Dream Hall of TU Delft. A cost-efficient design with high repairability and a few, easy manufacturing steps will make sure the engine becomes an affordable product for customers such as fitness centers or health institutions. The design needs to be validated with users and experiments, so improving and testing designs of frame parts on the Delft prototype will be part of this project.

Finally, there will be one AED team of the IPD master track, that will work on the engine simultaneously as well as another graduate student. For a successful use of the available work and skill force, lean management of the people involved will yield the best possible use of resources.
Creating a collection of all insights generated, as well as planning and aligning everyone's activities, is furthermore necessary.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

How could the frame of the Ethereal Matter engine look like, with regards to optimal costs, structural rigidity, ease of transport and assembly, as well as user interaction and perception? Test builds, simulations and scale models will be used to evaluate the design decisions. Additionally, a comprehensive collection of insights and materials will be created to help Ethereal Matter and successive students to quickly grasp the insights of the project.

Throughout my Graduation Project I aim to develop light-weight, cost-efficient and easy to manufacture and assemble parts, which will create the main structural basis for the engine. A frame that gives the user a comfortable perception of the engine before, while and after being in a VR simulation. The frame needs to house all the necessary components which, next to the grips and foot platforms, are the computing unit, the motion capture system, cables and a resting seat for the user. It furthermore makes for the overall visual perception of the engine in terms of safety or brand recognition, as well as privacy and physical safety when placed in public places like sport or entertainment centers.

Research into common building dimensions, spacial perception, safety regulations and ergonomic considerations will be followed by design and testing of different frame setups (wall-mounted, ceiling-mounted, free-standing, etc.) and subsequent DFMA optimization.
Simulations will be used in order to validate structural parts, while performing topology optimization for components that need to be strong, yet light-weight.

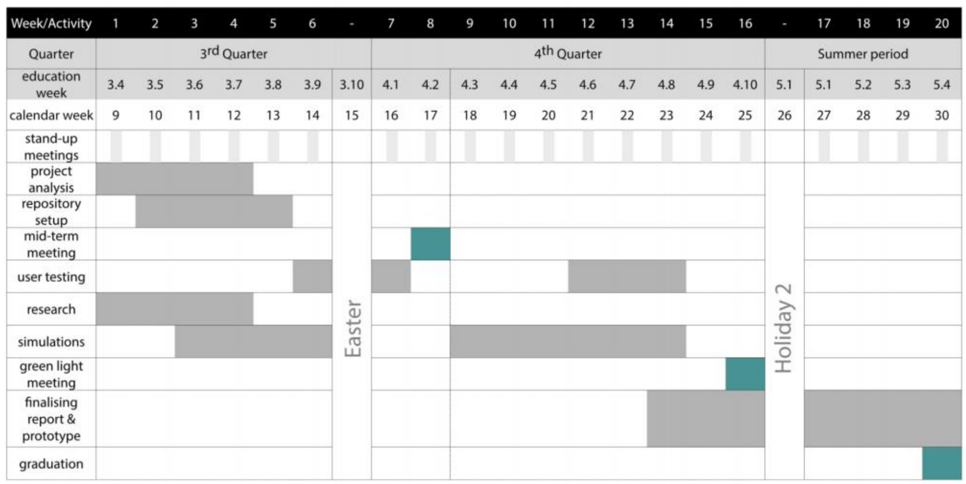
Besides the actual design work, I will be in close contact with the other graduate, Alejandro, the AED team, and ensure regular communication with all stakeholders involved to create a fruitful collaboration.
Finally, to make sure the project gains long-lasting momentum and speed, I will be in charge of creating a structured and comprehensible collection of insights, (CAD) files, BOM, etc. for Ethereal Matter and successive students.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 23 - 2 - 2022

29 - 7 - 2022 end date



I plan to work on my Graduation Project full time. So far, the only exception will be the Friday afternoons in Q3, during which I will be teaching assistant for the Modelling course given by Jun Wu.

The first weeks will be spent to get an overview of the entire project, update BOM's, acquire necessary parts to get the prototype running as much as possible while I simultaneously set up sensible infrastructure for building the project repository.

Creating first concepts, thinking about user interaction and journey will follow initial ergonomic literature and user research, but with the complex and iterative nature of the project, it is difficult to time these phases beforehand.

Throughout the project, weekly stand-ups will take place, to update all parties involved about the past developments, anticipated future actions and possible disruptions or road blocks. Additionally, regular meetings with Scott will be planned to exchange insights and receive feedback from him as the main client.

I plan two work-free periods to recharge my batteries:

Holiday 1: Easter (April 13th – April 19th)
Holiday 2: Summer (June 28th – July 5th), just after the Green Light Meeting.

Eventually, I aim to graduate at the end of July.

Initials & Name M.V. von Seyfried Student number 5366356

Title of Project Design of a physical virtual reality engine with real-time force feedback

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

The idea of a fitness machine, which the user is fully connected to, has been in my head for as long as I can remember. Therefore, it didn't need much thought to agree on the endeavor to design a VR based version for and with Ethereal Matter.
My background of working in the early stages of a start-up, funded by mechatronics engineering students who were developing a folding bicycle trailer, taught me a good deal of interdisciplinary work, communication and design engineering skills. The complexity of the trailer is somewhat surpassed by the additional electronics of the Ethereal engine alone, but I am certain, that my past experience in designing a product for an upcoming market entry will be very helpful.
The fact that this project requires a various amount of disciplines and skills – ergonomics, perception, aesthetics, mechanics, electronics, ... – makes it a very exciting undertaking for my final project at the TU Delft.

I look forward to applying project management skills that I gained through the AED project and several other team projects. Furthermore, I anticipate to enhance my generative and computational design skills to run simulations as well as to create light-weight, cost-efficient part geometry.

As the engine will be a first time (VR) experience for many users, I am additionally looking forward to collecting and generating insightful ergonomic and perceptual research data, in order to create a solid foundation for the future development of an enjoyable, safe product-user interaction.

Finally, I want to strengthen my ability of self-organizing such a long-lasting project; not losing my motivation when things don't work out as expected as well as keeping a good overview of deliverables and milestones. I want to use the graduation project to generate a reliable working habit that works for me and enables me to master lean management of projects.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix B

Informed consent form emotion research

You are being invited to participate in a research study as part of a master graduation project with the title "Design of a physical virtual reality engine with real-time force feedback". This study is being done by IPD graduate student Moritz von Seyfried from the TU Delft. Client of the graduation project is Ethereal Matter, represented by Scott Summit.

The purpose of this research study is to collect insights on the emotions that someone experiences when entering and exiting a VR fitness machine and the associated virtual environment, and will take you approximately 120 minutes to complete. The data will be used for identifying interesting design opportunities as well as pain points regarding the user experience of a VR fitness machine. The acquired data and insights will be used to generate insights to use for the master thesis (with the goal of designing such a VR fitness machine) and will be published within it. We will be asking you to pretend to be using a VR fitness machine while describing your experienced emotion at as many times as possible. The procedure is as follows:

- We will ask you to step into a prototype setup, put on the VR headset, step on a small platform and play a game in VR.
- After that, take the headset off and exit the machine.

During any of these activities, you will be asked if you are comfortable to proceed and encouraged to state at any time, if you are not, or if you need a break. Following these activities, an interview will be conducted to get further insights into the experienced emotions. The answers you provide will be noted on paper and manually transferred to and processed in a computer.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing the collected raw data only on the computer of the graduate student. All acquired data used for the documentation and to generate insights will be made anonymous. A documentation of the whole process with images and/or videos will only be conducted if you agree to it. Those media will be handled as described before, unless you give consent for using and publishing them in an identifiable way.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. You can ask for a removal or anonymization (should you have agreed to the identifiable use before) of all your personal data within the following month; please understand that a latter removable is not feasible considering the structure of the graduation project.

Contact details:

…

Explicit Consent points

Please make sure that you select (and amend as necessary) any Explicit Consent points which are relevant to your study and exclude those which do not apply. You should also add further points and necessary to address your specific research situation.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated 06.08.2022, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: [*see points below*]	☐	☐
Provide briefly what is relevant from the following: • Using a VR headset and controllers in order to play a virtual reality game • Processing of your answers in written form and digitalization for processing • Being filmed/photographed during the activities		
4. I understand that I will be compensated for my participation by a tasty home-cooked meal and eternal gratitude	☐	☐
5. I understand that the study will end after approximately 120 minutes, or earlier, if the interview has finished		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks: • Risk of tripping/falling • Risk of hitting an object while in the VR environment • Feeling emotionally overwhelmed or discomfort in general I understand that these will be mitigated by • guidance and a walkthrough of the space before beginning of the study • clearing any objects in range, using the guardian feature of the VR headset and having a close eye on the participant at any times to intervene before anything happens • the possibility to stop or pause the activities at any moment	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable research data (PIRD) such as video and image material with the potential risk of my identity being identifiable from this material	☐	☐
8. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: Video and image material will be stored anonymously and made unidentifiable if desired	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
9. I agree for video and image material to be shared with the supervisory team of the graduate student and the company mentor.		
10. I understand that the (identifiable), non-published personal data I provide will be destroyed one month after the final graduation presentation.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
11. I understand that after the research study the de-identified information I provide will be used for and published in a • Graduation report • Video accompanying the graduation report	☐	☐
12. I understand that after the research study the identifiable images and videos are used for and published in a • Graduation report • Video accompanying the graduation report	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
14. I give permission for the identifiable images and videos that I provide to be archived in a protected google drive folder so it can be used for future research and learning.	☐	☐
15. I understand that access to this repository is restricted to people working on the research project.	☒	☒

Signatures

__________________________ _________________________ ________
Name of participant Signature Date

I, as legal representative, have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

__________________________ _________________________ _________
Name of witness Signature Date

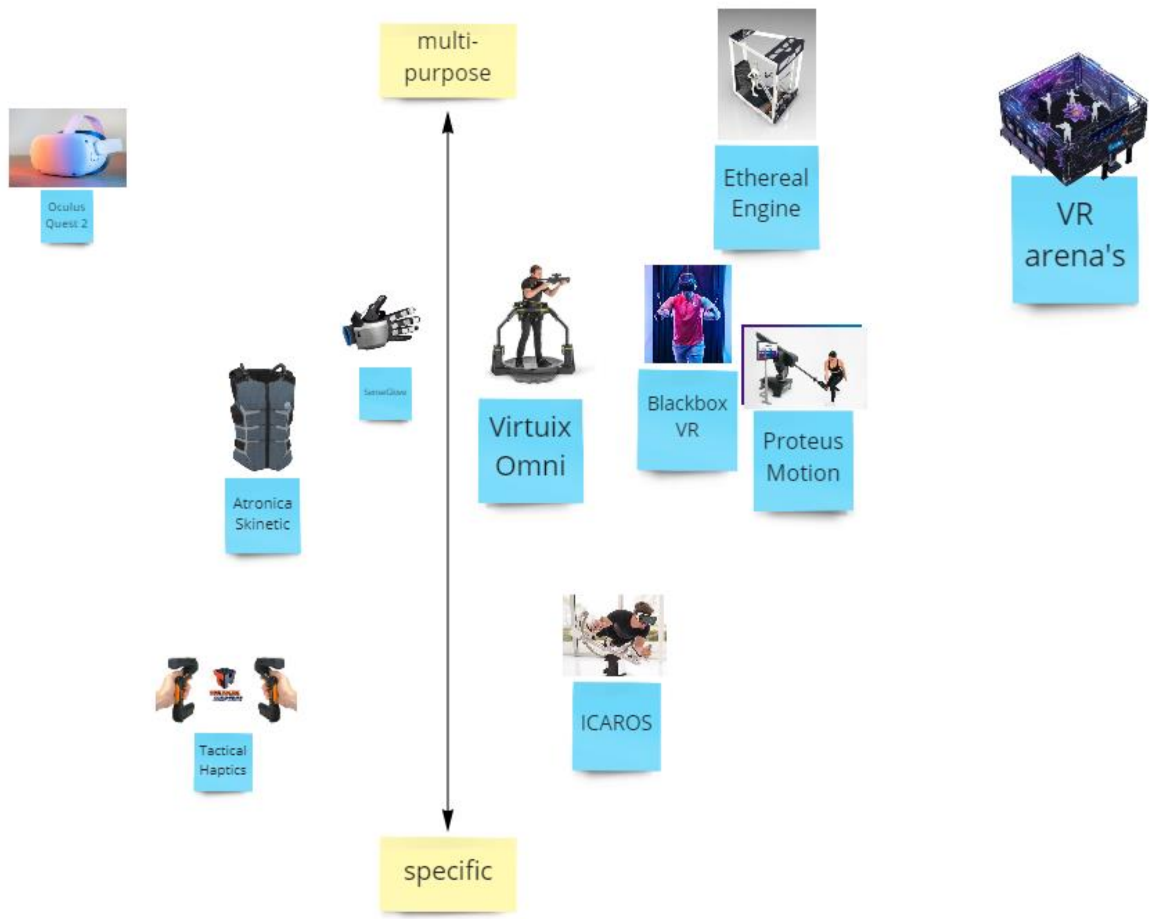
I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_________________________ ________________________ _ ________
Researcher name Signature Date

Study contact details for further information:
Moritz von Seyfried,

Appendix C

Similar products overview



Appendix D

Bill of materials

CONFIGURATION	Description	Part Count	Total Price
JIP		105	1.502,85 €
Scott		56	11.558,99 €
guess		0	0,00 €
Armature		0	7.363,04 €
min		3	170,00 €
small		8	810,00 €
medium		72	4.376,00 €
full		9	5.626,00 €
		0	0,00 €
Total		**253**	**31.406,87 €**

Assembly	Sub-Assembly	config	Part Number	Part Name	Description	standard part?	Quantity needed	Unit COST	Supplier/Manufacturer
Armature	Actuation	JIP	EL001	Gearbox	1-60 reduction gearbox		3	105,62 €	
Armature	Actuation	JIP	EL002	Servo Drivers			3	50,67 €	
Armature	Actuation	JIP	EL003	Servo Motors			3	58,00 €	
Armature	Arm	JIP	AR001	Main beam	Profile 6 60x30mm 4N180light 1630mm (Page 22 ITEM booklet) or Profile 6 60x30mm	yes	2	23,69 €	ITEM
Armature	Arm	JIP	AR002	Upper beam	Profile 6 60x30mm 4N180light 716mm (Page 22 ITEM	yes	1	20,81 €	ITEM

					booklet) or Profile 6 60x30mm				
Armature	Arm	JIP	AR003	Upper beam connection	Profile 6 30x30mm light 200+30mm (Page 21 ITEM booklet)	yes	2	- €	Applied Labs
Armature	Arm	JIP	AR004	Hinge mount	Costumized - Price estimation	no	3	- €	PMB,Dream Hall
Armature	Arm	JIP	AR005	Upper mount	Costumized - Price estimation	no	1	- €	PMB,Dream Hall
Armature	Arm	JIP	OT001	Sleeve Bearing		yes	6	1,67 €	MC Master US
Armature	Arm	JIP	OT002	Shaft collars		yes	2	2,50 €	MC Master US
Armature	Arm	JIP	OT003	Shoulder bolt arms	RS PRO M8 x 40mm Shoulder Bolt	yes	6	1,06 €	RS
Armature	Arm	JIP	OT004	Shoulder bolt carriage	RS PRO M8 x 12mm Shoulder Bolt	yes	10	0,24 €	RS
Armature	Carriage	JIP	CM001	Mount-Upper	U profile + drilling		1	17,90 €	DHZ store, Dream Hall
Armature	Carriage	JIP	CM002	Mount-Lower	U profile + drilling		1	15,56 €	DHZ store, Dream Hall
Armature	Grip	JIP	GR001	Body	3D printing - SLS	no	1	144,00 €	PMB, CDAM
Armature	Grip	JIP	GR002	Deadman	3D printing - SLS	no	1	- €	PMB, CDAM
Armature	Grip	JIP	GR003	Deadman	3D printing - SLS	no	1	- €	PMB, CDAM
Armature	Grip	JIP	GR004	End cap front	3D printing - FDM without support or SLS	no	1	- €	PMB, CDAM
Armature	Grip	JIP	GR005	End cap body left	3D printing - FDM without support or SLS	no	1	- €	PMB, CDAM
Armature	Grip	JIP	GR006	End cap body right	3D printing - FDM without support or SLS	no	1	- €	PMB, CDAM

Armature	Grip	JIP	GR007	U shape piece left	Costumized - 3 axis CNC milling	no	1	159,31 €	PMB, Dream Hall
Armature	Grip	JIP	GR008	U shape piece right	Costumized - 3 axis CNC milling	no	1	- €	PMB, Dream Hall
Armature	Sensorbox	JIP	GI001	Gimbal-Shell left	Costumized - 3 axis CNC milling	no	1	- €	PMB, Dream Hall
Armature	Sensorbox	JIP	GI002	Gimbal-Shell right	Costumized - 3 axis CNC milling	no	1	- €	PMB, Dream Hall
Armature	Sensorbox	JIP	SB001	Front plate	Costumized - 2.5 axis CNC milling	no	1	- €	PMB, Dream Hall
Armature	Sensorbox	JIP	SB002	Back plate	Costumized - 2.5 axis CNC milling	no	1	- €	PMB, Dream Hall
Armature	Sensorbox	JIP	SB003	Load cell	Sent by Scott	yes	3	4,98 €	Alibaba
Armature	Sensorbox	JIP	SB004	Bearing	Mounting Holed Roller Bearing 70 x20 mm 12mm thick	yes	1	218,00 €	RS (IKO NIPPON THOMPSOM)
Frame	Structure	JIP	FR001	Vertical Profile	Profile 5 50x50mm 2900 mm	yes	4	- €	
Frame	Structure	JIP	FR002	Horizontal Profile 1	Profile 5 50x50mm 900 mm	yes	4	- €	
Frame	Structure	JIP	FR003	Horizontal Profile 2	Profile 5 50x50mm 1800 mm	yes	4	- €	
Frame	Structure	JIP	FR004	Horizontal Profile 3	Profile 5 50x100mm 1500 mm	yes	2	- €	
Frame	Structure	JIP	FR005	Hinges	BLOCAN® Scharnier aluminium 2-delig	yes	5	3,50 €	
Frame	Structure	JIP	FR006	Angle joint	BLOCAN® Verstekverbinder 90°-270°	yes	8	2,42 €	

Frame	Structure	JIP	FR007	Extension connection	Customized to save costs		8	- €	
Armature	Vertical Beam	JIP	VB001	Extruded beam + Track	Simple calculations estimate the required I=23cm^4. Profile 80x80 light (Page 30 ITEM booklet)	yes	1	161,51 €	ITEM
Armature	Vertical Beam	JIP	VB002	Carriage	Costumized - Price estimation	no	2	- €	PMB, Dream Hall
Armature	Vertical Beam	JIP	VB003	Pulley	80 mm diameter		4	- €	
Armature	Vertical Beam	JIP	VB004	Belt	6251 mm length		2	- €	
Armature	Vertical Beam	JIP	VB005	Rail System	3000 mm lenght		1	- €	
Frame	Connections	**medium**		gusset plates	cut steel plates	no	3	13,33 €	
Frame	Connections	**medium**		bent gusset plates	cut and bent steel plates	no	7	21,43 €	
Frame	Connections	**medium**		tread plates	cut and bent steel or aluminium plates	no	2	40,00 €	
Frame	Connections	**medium**		CNC connections	machined and anodized	no	6	100,00 €	
Frame	Door	**medium**		door frame	bend and welded steel tubing	no	2	150,00 €	
Frame	Door	**medium**		door panel	made from PC, acrylic or similar	no	2	150,00 €	
Frame	Fabric	**medium**		custom fabrics		no	7	60,00 €	
Frame	Lighting	**medium**		LED strip		no	2	80,00 €	
Frame	Panel	**medium**		cover plates	cut and bent steel or	no	8	37,50 €	

				aluminium plates				
Frame	Structure	**medium**	standard extrusions	equal to 50x50x4 mm	yes	19	14,21 €	
Frame	Structure	**medium**	Floor beams around	square profiles	yes	5	20,00 €	
Frame	Structure	**medium**	custom extrusion	(bend) aluminium extrusion (note, no internal weight reduction has been done)	no	2	288,00 €	
Frame	Structure	**medium**	Side support beams	standard 50x50 extrusion	yes	6	20,00 €	
Frame	Structure	min	main two floor beams	connecting foot platforms and potentially seat with armature structure	yes	2	60,00 €	
Seating	Backrest	small	Headrest		no	1	60,00 €	
Armature	**Actuation**	**Scott**	**Gearbox**	**Motor Planetary Gearbox Nema34 Ratio 3, 86mm Flange 14mm Input 16mm Output**		**2**	**89,20 €**	**InGreat Store**
Armature	**Actuation**	**Scott**	**Belt**	**B25T10-MPK | 25T10 Open End Timing Belt Roll**		**4**	**72,19 €**	**Polybelt**
Armature	**Actuation**	**Scott**	**Pulley**	**P40T10/12-2A | 40T10/12-2 Aluminum 12 Tooth Timing Pulley**		**4**	**18,08 €**	**Polybelt**
Armature	**Actuation**	**Scott**	**Belt Clamp**	**CT10-25A | T10-25 Belt Clamp Plate Aluminum**		**4**	**16,86 €**	**Polybelt**

Armature	**Actuation**	**Scott**	**Gearbox**	**PLFE PLFE Economy planetary gearbox Ratio i=64 Frame size 090**		**1**	**850,08 €**	**Powermatic**
Digital	**Arduino**	**Scott**	**Arduino**		**yes**	**1**	**30,00 €**	
Armature	**Arm**	**Scott**	**Arm**	**ALUMINUM TUBE 6061 T6**		**2**	**311,95 €**	**Tube Service Co. 44**
Armature	**Carriage**	**Scott**		**Carriage & Track Assembly**		**1**	**1.555,43 €**	**Powermatic**
Digital	**Computer**	**Scott**	**Computer**		**yes**	**1**	**1.000,00 €**	
VirtualReality	**Controllers**	**Scott**	**VR controllers**		**yes**	**2**	**- €**	
Digital	**Graphic card**	**Scott**	**GPU (Graphic card)**		**yes**	**1**	**700,00 €**	
Armature	**Grip**	**Scott**	**Gimbal-I**	**CNC grip part**	**no**	**2**	**129,72 €**	**Shenzen Going Rapid Prototype Co., Limited**
Armature	**Grip**	**Scott**	**Gimbal-U**	**CNC grip part**	**no**	**2**	**200,56 €**	**Shenzen Going Rapid Prototype Co., Limited**
Armature	**Grip**	**Scott**	**Pass-through**	**CNC grip part**	**no**	**2**	**25,30 €**	**Shenzen Going Rapid Prototype Co., Limited**
Armature	**Grip**	**Scott**	**Sensor-Back**	**CNC grip part**	**no**	**2**	**121,44 €**	**Shenzen Going Rapid Prototype Co., Limited**
Armature	**Grip**	**Scott**	**Wrist**	**CNC grip part**	**no**	**2**	**100,74 €**	**Shenzen Going Rapid Prototype Co., Limited**
Armature	Grip	**Scott**	**Sensor-Front**	**CNC grip part**	**no**	**2**	**158,24 €**	**Shenzen Going Rapid Prototype Co., Limited**
VirtualReality	Headset	Scott	**VR headset**		**yes**	**1**	**- €**	
Platforms	Plate	Scott	Braces	Foot platform braces	no	4	$ 58,42	Shenzen Going Rapid Prototype Co., Limited
Platforms	Scissors	Scott	Chainring	7 Sprocket Chainring 1/2 X 1/8 44 teeth		1	$ 14,60	

Platforms	**Scissors**	**Scott**	**Pillow Block**	**Pillow Block Bearing 20 mm Bore 4 Bolt Square Flange Mounted Bearing**		**2**	**9,24 €**	
Platforms	**Scissors**	**Scott**	**Pressure Sensor**	**Thin Film Pressure Sensor SF15-54**		**1**	**8,27 €**	
Platforms	Scissors	Scott	Gas spring	Gas Prop Spring Strut 20inch 100lb		2	9,66 €	
Platforms	Scissors	Scott	Actuator	12V Linear Electric Actuator 18inch 600lbs		1	134,23 €	
Platforms	Scissors	Scott	Turntable Bearing	Turntable Ring Single-Row Ball Bearings 300lbs 8inch commercial		1	18,12 €	
Seating	Seat	Scott	Bench	Sheet metal bench	no	1	552,00 €	West Coast Fab Inc
Armature	Sensorbox	Scott	Load cell	100kg Load Cell, Electronics Load Cell Scale High Precision	yes	3	18,81 €	Amazon
Frame	Structure	Scott	Frame	Overall Frame		1	2.492,83 €	Bright Lights Welding and Manufacturing
Frame	Structure	**Scott**	Hanger	ALUMINUM TUBE 6061 T6		1	440,42 €	Tube Service Co. 44
Armature	Vertical Beam	**Scott**	Mast	ALUMINUM TUBE 6061 T6	no	2	366,11 €	Tube Service Co. 44
Seating	Backrest	small	cushioning		no	1	80,00 €	
Seating	Panel	**medium**	custom panel from PC, acrylic, or similar		no	1	150,00 €	
Seating	Seat	small	fabric cover	custom sewn	no	1	100,00 €	

Seating	Structure	small	Metal structure	bent steel pipes	no	4	62,50 €
Frame	Enclosure	full	Metal structure	bent aluminium pipes	yes	4	87,50 €
Frame	Fabric	full	fabric cover		no	3	166,67 €
Frame	Panel	full	panel above doors		no	2	200,00 €
Frame	Mirror	min	Mirror with frame		yes	1	50,00 €
Digital	Screen	small	Monitor for viewers		yes	1	150,00 €

Appendix E

List of requirements

Topic	Name	Descript
Engineering		
	weight	maximum machine weight of XX kg to conform to
	height	maximum machine height of 3,5 m to fit common b
	footprint	minimum footprint
	vibrations	vibrations limited to Z
	maximum displacement of mocap cameras	
	Replacing broken components	Individual frame parts should be replacable
	Upgrading to extended versions	The frame should be modular to allow for it to be e
	tamper proof electronics	no access to the electronics should be possible with
	load cases	safety factor normal load case: 1.5
	optics	limited field of view (&minimal shake), need to be ca
	MoCap	around 4 – 6 cameras
	Attaching	Attachment to the wall, or attachment to each othe
	free-standing	2 machines are able to stand together on their own
Manufacturing		
	Manufacturing numbers	The design should be optimised for a production ru
Assembly & Transport		
	dimension frame parts	maximum width of individual frame parts: 245 cm /
	weight frame parts	maximum weight of individual frame parts of 50 kg
	Power management	Power management is located in one place
Safety		
	Tamper proof connections	Power and data connections going outside the mach

	Letting go	User won't hurt themselves badly when suddenly le
	Falling	Users won't hurt themselves badly when losing bala
	Guardian	When switching to MR/AR view, features of the int
	Exit	Allow a quick evacuation of the machine in case of
	Bench	Bench sas a tactile orientation feature to be able to
Cost		
	Modularity	Frame parts can be added or taken away to up- or
Usability		
	Entry dimensions	Entry opening dimensions of: X x Y x Z
	Shielding	Users are shielded from behind
	Exposure vs privacy	User can adjust the level of exposure to their needs
	Cleanability	Surfaces can withstand common cleaning agents and
	Storing personal belongings	Personal belongings of 300 x 200 x 500 mm dimens
	Mirror	Users are able to view themselves before exiting th appearance
	Glimpse	Users are able to use the small gap between nose a
	Resting	The machine should allow for people to take a sittin
	Boarding	The machine should be easy to board and leave aga
	Status	People outside should see if someone is inside the r
	View outside	Users are able to view outside of the machine
Desirability		
	Branding surface	Have a customizable surface for branding
	Interaction player with bystanders	
VR experience		
	Immersion	The machine sufficiently blocks out XX
	Immersion	The machine allows communication to the outside
	Presence	The machine allows for added sensory stimuli
	Auditory qualities	The machine shall incorporate a spatial audio syster

Transition to VR	Thrill	The machine allows for a thrilling, exciting transitio
Transition from VR	Claustrophobia	The frame gives a non-claustrophobic feeling upon
Transition from VR	Light levels	The light levels within the machine are able to matc
Sustainability		
	Material	The frame uses recyclable materials whereever pos
	Repairability	Broken parts can be easily accessed and repaired

Appendix F

Load cases

Load cases | **coordinate system** | **life time of machine**

x,y,z

x=sideways | y=forward | z=upward

5 years

days used per year 300

hours used per day 7

total hours: 10500

Normal Load Cases

Load Case	Location	Direction	Force	Moment	matlab force input	resulting in m
Vertical pull	grip	-z	1000 N			
horizontal push	grip	y	89 N			
horizontal push	grip	y	318 N			
horizontal pull	grip	-y	427 N			250 N on mas
sideward push	grip	x	300 N	taken up by motor		
vibration	armature motors					

Maximum Load Cases

Load Case	Location	Direction	Force	Moment	matlab force input	resulting in m
vertical hang	grip	-z	1300 N		Wx=0; Wy=-1300 N	-741 N for Hx
horizontal push	grip	y	500 N		Wx=500 N; Wy=0	-1353 N for Ex
horizontal pull	grip	-y	500 N		Wx=-500 N; Wy=0	853 N for Ax,
side hang	grip	-z,zz	750 N	taken up by motor		1088 N for Hz
entering support	entry opening	x	1200 N			

Misuse Load Cases

Load Case	Location	Direction	Force	Moment	matlab force input	resulting in m
vertical yank	grip	-z				
entry opening hang	entry opening	-z				
climb	frame outside	-z				

Matlab to translate forces

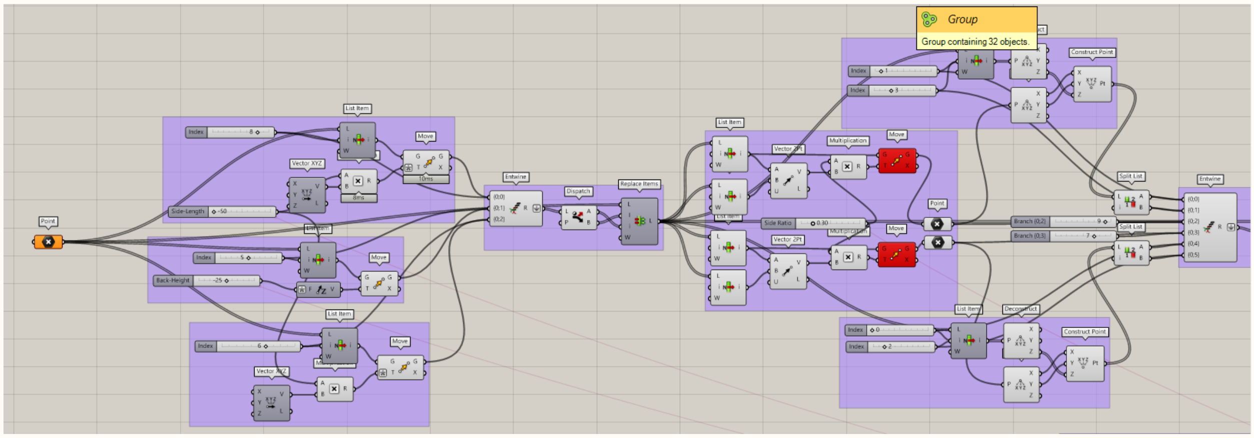
```
%% Ethereal Structural
%This script contains the arm mechanism structural analysis

l1= 0.6; %m
l2= 0.6; %m
l3= 0.6; %m

h1= 2; %m height of lower carriage
htot= 2.45; %m height of vertical mast

Wx= 0; %N
Wy= 1300; %N. Our lovely Texan :)
x= 0.272; %m. Distance between parallel bars
i=0;
j=0;
h= 1; %m. Height of the arm system from the lower carriage
MW=300; % Nm. Estimation of the moment generated on the grip

Fz = 750; %N horizontal force of someone hanging from arm to one side

global theta_1;
global alpha_1;

for theta_1= 0.15*pi/2:0.01:0.75*pi/2
    i=i+1;
    Theta_1(i)=theta_1 * 180/pi;
    Cx(i)=-Wx/2+MW/x; %N
    Fx(i)= -Cx(i)-Wx; %N
    Ex(i)= Fx(i); %N
    Dx(i)=((l1+l2)*cos(theta_1)*Wy-((l1+l2)*sin(theta_1)-x/2)*Wx+x*Ex(i)+MW)/...
    ((l1+l3)*sin(theta_1)); %N
    Bx(i)=Dx(i); %N
    Ax(i)=-Bx(i)+Cx(i); %N

    Fy(i)= Fx(i)*sin(theta_1)*(l1+l2)/(cos(theta_1)*(l1+l2)); %N
    Cy(i)= -Fy(i)-Wy; %N

    By(i)=(-
Cx(i)*(l1+l2)*sin(theta_1)+Cy(i)*(l1+l2)*cos(theta_1)+Bx(i)*l1*sin(theta_1))/...
    (l1*cos(theta_1)); %N
    Dy(i)=By(i); %N
    Ay(i)=-By(i)+Cy(i); %N
    Ey(i)=-Dy(i)-Wy-Ay(i); %N
  %Moment and shear in the bar ABC starting from A and noticing that B is
  %the maximum moment concentration point
    V_ABC(i)= Ay(i)*cos(theta_1)-Ax(i)*sin(theta_1); %N
    M_ABC(i)= Ay(i)*l1*cos(theta_1)-Ax(i)*l1*sin(theta_1); %Nm
  %Minimum moment of innertia
    sigma_al6082= 250E6; %Pa
http://www.matweb.com/search/datasheet_print.aspx?matguid=fad29be6e64d4e95a241690f1f6
e1eb7
    I_min(i)= M_ABC(i)*0.015/sigma_al6082*10^8; %cm^4
```

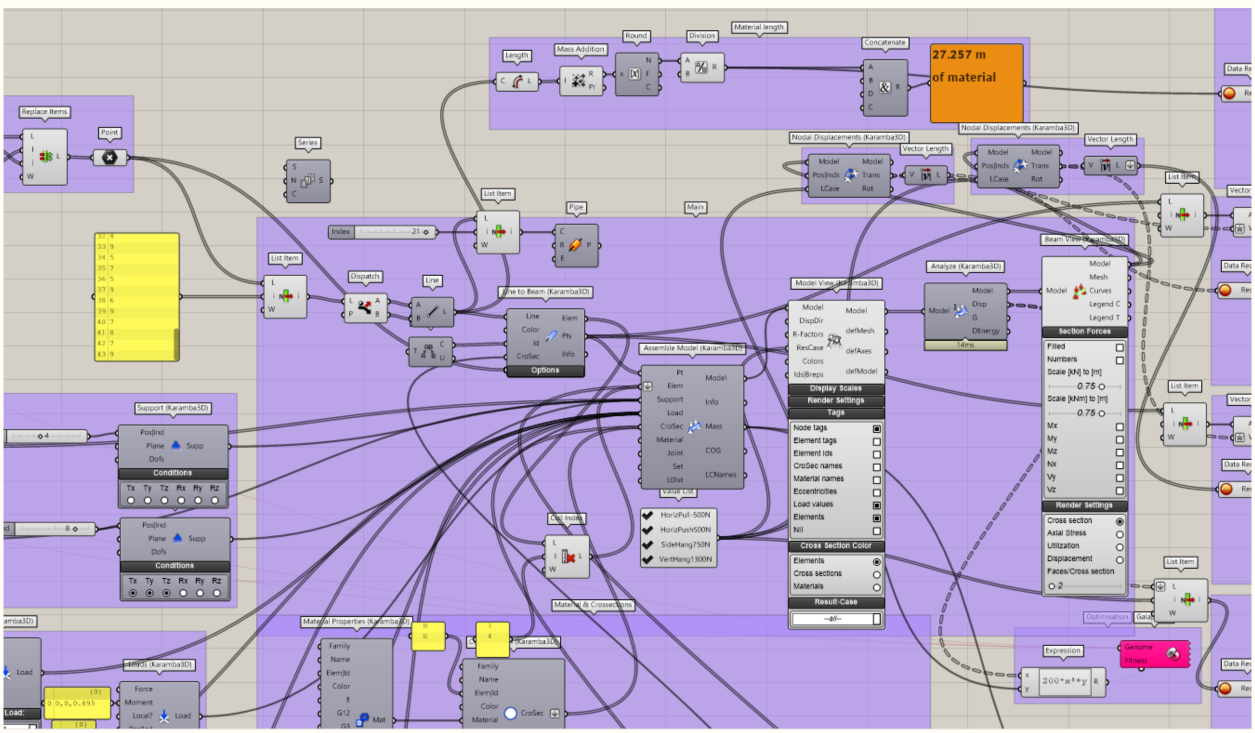
```
    sigma_shear_al6082= 220E6; %Pa https://www.makeitfrom.com/material-
properties/6082-T6-Aluminum
    A_min(i)= -V_ABC(i)/sigma_shear_al6082*10^4; %cm^2

    %sizing the 80x80 bar
    Blength = 2.45; %m length of vertical beam
    Hx(i)=(-Ex(i)*h-Ax(i)*(h+x)-Dx(i)*(h+x+(l1+l3)*sin(theta_1)))/Blength; %Nm
    Gx(i)= -Dx(i)-Ax(i)-Ex(i)-Hx(i); %N
    Gy(i)= -Dy(i)-Ay(i)-Ey(i); %N
    Hy(i)= 0;
    V_EADG(i)= -Dx(i)*sin(theta_1); %N
    %M_EADG(i)= MG(i); %Nm
    %I_min2(i)= M_EADG(i)*0.04/sigma_al6082*10^8; %cm^4
end

for alpha_1= 0.1:0.01:0.75*pi/2
    j=j+1;
    Alpha_1(j)=alpha_1*180/pi;
    L1(j)= (l2+l3)*cos(alpha_1);
    L2(j)= l2*cos(alpha_1);
    L3(j)= l3*cos(alpha_1);
    h2(j)= cos(90-alpha_1)*l1*2;

    Az(j)= Fz*L1(j)/L2(j);
    Bz(j)= Fz-Az(j);
    Cz(j)= Az(j);

    Hz(j)= (Bz(j)*h1+Cz(j)*(h1+h2(j)))/htot;
    Gz(j)= Bz(j) + Cz(j) - Hz(j);
    Mhz(j) = Fz*(l2+l3)*cos(alpha_1);
end
%     figure(1)
%     subplot(4,5,1)
%         plot(Theta_1,Dx,'Color', [0,0.7,0.9])
%         ylabel ('Dx Force in N')
%         xlabel ('Theta_1 in º')
%         hold on
%     subplot(4,5,2)
%         plot(Theta_1,Dy,'Color', [0.8500 0.3250 0.0980])
%         ylabel ('Dy Force in N')
%         xlabel ('Theta_1 in º')
%     subplot(4,5,3)
%         plot(Theta_1, Bx,'Color',[0,0.7,0.9])
%         ylabel ('Bx Force in N')
%         xlabel ('Theta_1 in º')
%         hold on
%     subplot(4,5,4)
%         plot(Theta_1,By,'Color', [0.8500 0.3250 0.0980])
%         ylabel ('By Force in N')
%         xlabel ('Theta_1 in º')
%         hold on
%     subplot(4,5,5)
%         plot(Theta_1, Ax,'Color',[0,0.7,0.9])
%         ylabel ('Ax Force in N')
%         xlabel ('Theta_1 in º')
```

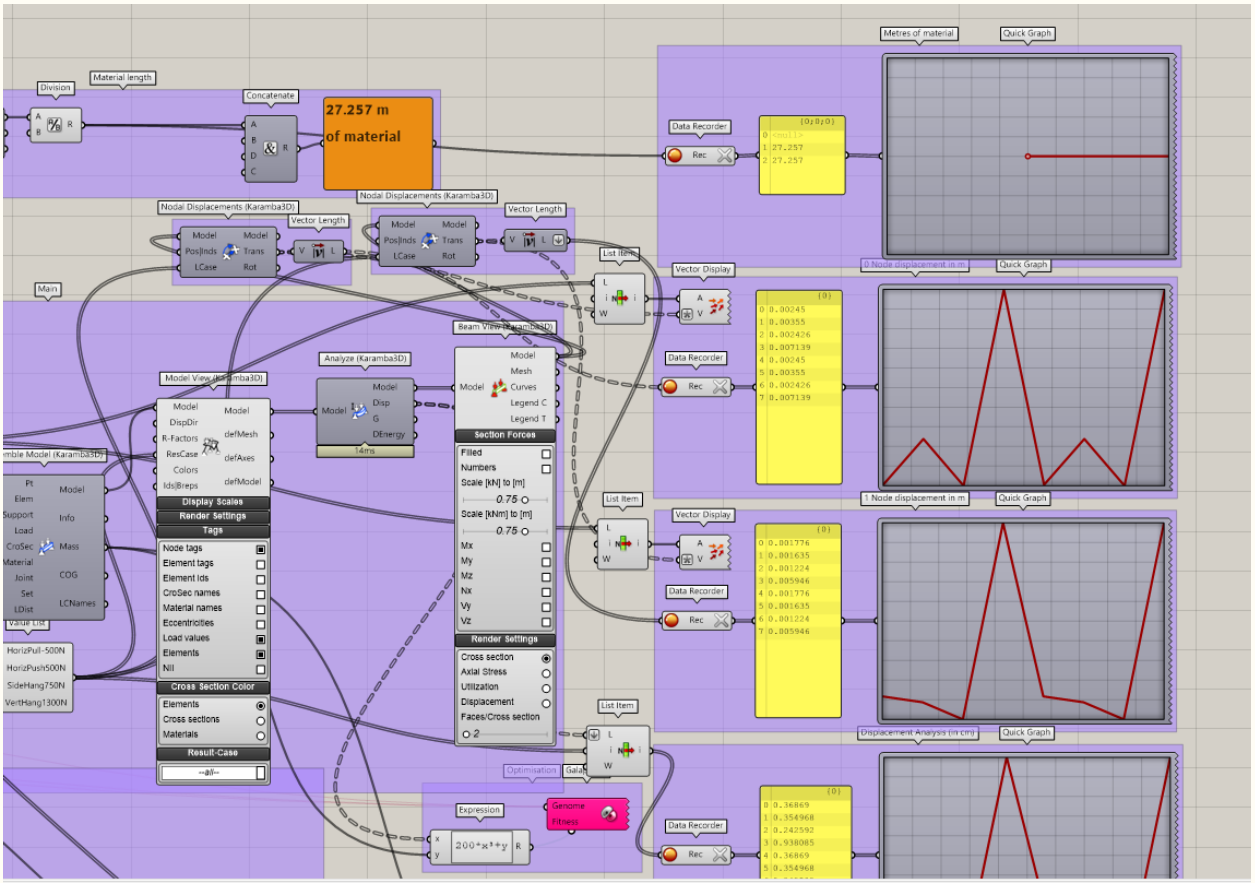
```
%          hold on
%      subplot(4,5,6)
%          plot(Theta_1, Ay,'Color',[0.8500 0.3250 0.0980])
%          ylabel ('Ay Force in N')
%          xlabel ('Theta_1 in º')
%          hold on
%      subplot(4,5,7)
%          plot(Theta_1,Ex,'Color', [0,0.7,0.9])
%          ylabel ('Ex Force in N')
%          xlabel ('Theta_1 in º')
%          hold on
%      subplot(4,5,8)
%          plot(Theta_1,Ey,'Color', [0.8500 0.3250 0.0980])
%          ylabel ('Ey Force in N')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,9)
%          plot(Theta_1,Fx,'Color', [0,0.7,0.9])
%          ylabel ('Fx Force in N')
%          xlabel ('Theta_1 in º')
%          hold on
%      subplot(4,5,10)
%          plot(Theta_1,Fy,'Color', [0.8500 0.3250 0.0980])
%          ylabel ('Fy Force in N')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,11)
%          plot(Theta_1,Gx,'Color', [0,0.7,0.9])
%          ylabel ('Gx Force in N')
%          xlabel ('Theta_1 in º')
%          hold on
%      subplot(4,5,12)
%          plot(Theta_1,Gy,'Color', [0.8500 0.3250 0.0980])
%          ylabel ('Gy Force in N')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,13)
%          plot(Theta_1,V_ABC,'Color', [0.4940 0.1840 0.5560])
%          ylabel ('V_3_2_4 in N')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,14)
%          plot(Theta_1,M_ABC,'Color', [0.4940 0.1840 0.5560])
%          ylabel ('M_3_2_4 in N·m')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,15)
%          plot(Theta_1,I_min,'Color', [0.4940 0.1840 0.5560])
%          ylabel ('I_m_i_n in cm^4. Moment')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,16)
%          plot(Theta_1,A_min,'Color', [0.4940 0.1840 0.5560])
%          ylabel ('A_m_i_n in cm^2. Shear Stress')
%          xlabel ('Theta_1 in º')
%      subplot(4,5,17)
%          plot(Theta_1,Hx,'Color', [0.4940 0.1840 0.5560])
%          ylabel ('Hx in N')
%          xlabel ('Theta_1 in º')
%          hold on
%      subplot(4,5,18)
```

```
%         plot(Theta_1,V_EADG,'Color', [0.4940 0.1840 0.5560])
%         ylabel ('V_5_3_1_7 in N')
%         xlabel ('Theta_1 in º')
%     subplot(4,5,19)
%         plot(Theta_1,M_EADG,'Color', [0.4940 0.1840 0.5560])
%         ylabel ('M_5_3_1_7 in N·m')
%         xlabel ('Theta_1 in º')
%         hold on
%     subplot(4,5,20)
%         plot(Theta_1,I_min2,'Color', [0.4940 0.1840 0.5560])
%         ylabel ('I_m_i_n_2 in cm^4. Moment')
%         xlabel ('Theta_1 in º')
% sgtitle('Stuctural Analysis','Color','blue');
% %unknow Ax,Ay,Bx,By,Dx,Dy,Ex,Ey,ME

figure(2)
subplot(3,3,1)
        plot(Alpha_1,h2,'Color', [0.8500 0.3250 0.0980])
        ylabel ('h2 in m')
        xlabel ('Alpha_1 in º')
        hold on
subplot(3,3,2)
        plot(Alpha_1,Az,'Color', [0,0.7,0.9])
        ylabel ('Az in N')
        xlabel ('Alpha_1 in º')
        hold on
subplot(3,3,3)
        plot(Alpha_1,Bz,'Color', [0,0.7,0.9])
        ylabel ('Bz in N')
        xlabel ('Alpha_1 in º')
        hold on
subplot(3,3,4)
        plot(Alpha_1,Cz,'Color', [0,0.7,0.9])
        ylabel ('Cz in N')
        xlabel ('Alpha_1 in º')
        hold on
subplot(3,3,5)
        plot(Alpha_1,Hz,'Color', [0,0.7,0.9])
        ylabel ('Hz in N')
        xlabel ('Alpha_1 in º')
        hold on
subplot(3,3,6)
        plot(Alpha_1,Gz,'Color', [0,0.7,0.9])
        ylabel ('Gz in N')
        xlabel ('Alpha_1 in º')
        hold on
subplot(3,3,7)
        plot(Alpha_1,Mhz,'Color', [0,0.7,0.9])
        ylabel ('Mhz in N')
        xlabel ('Alpha_1 in º')
        hold on
sgtitle('Horizontal Hang structural analysis','Color','red');
%         %unknown h2 Az Bz Cz Hz Gz Mhz
```

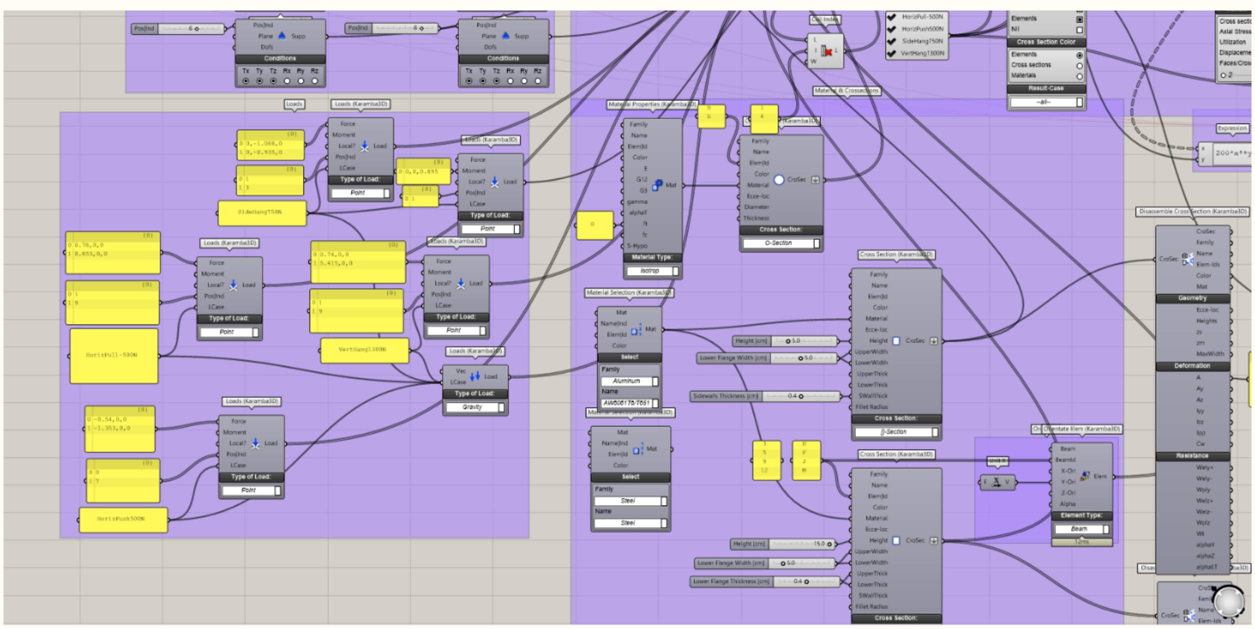
Grasshopper code & process Images







Division
Material length
Concatenate
27.257 m
of material
Metres of material
Quick Graph
Data Recorder
Rec
Nodal Displacements (Karamba3D)
Vector Length
List Item
Vector Display
0 Node displacement in m
1 Node displacement in m
Displacement Analysis (in cm)
Main
Beam View (Karamba3D)
Analyze (Karamba3D)
Model View (Karamba3D)
Display Scales
Render Settings
Tags
Node tags
Element tags
Element Ids
CroSec names
Material names
Eccentricities
Load values
Elements
Nil
Cross Section Color
Cross sections
Materials
Result-Case
Section Forces
Filled
Numbers
Scale [kN] to [m]
Scale [kNm] to [m]
Cross section
Axial Stress
Utilization
Displacement
Faces/Cross section
Value List
HorizPull-500N
HorizPush500N
SideHang750N
VertHang1300N
Optimisation
Expression
200*x³+y
Genome
Fitness



Loads (Karamba3D)
Conditions
Type of Load:
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Gravity
Material Properties (Karamba3D)
Material Selection (Karamba3D)
Material Type:
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Steel
Cross Section (Karamba3D)
Cross Section:
I-Section
O-Section
Height [cm]
Lower Flange Width [cm]
Sidewalls Thickness [cm]
Lower Flange Thickness [cm]
Disassemble Cross Section (Karamba3D)
Geometry
Deformation
Resistance
Orientate Elem (Karamba3D)
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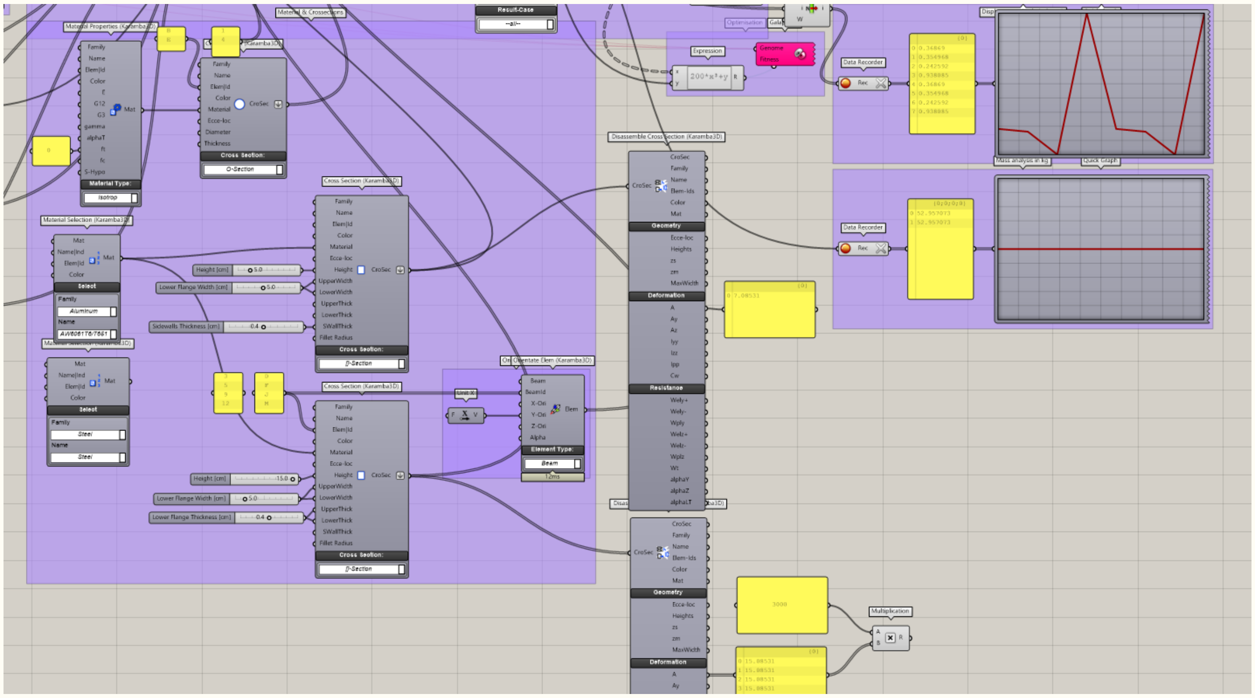
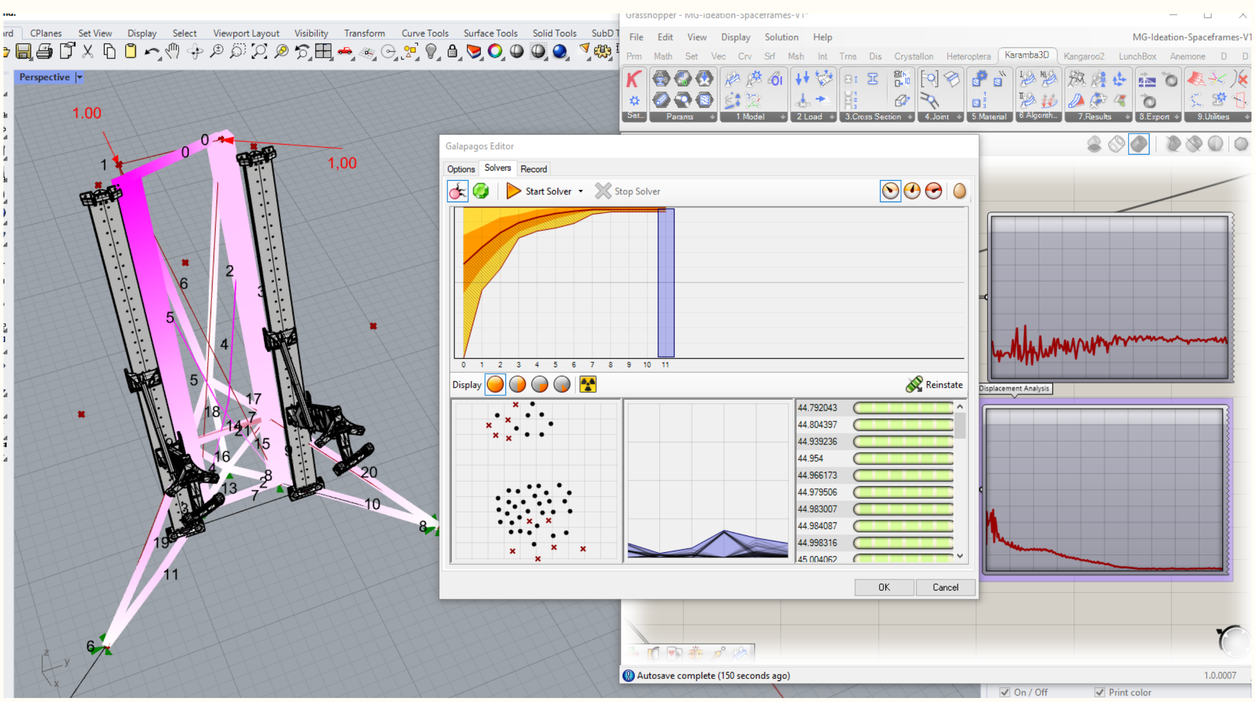
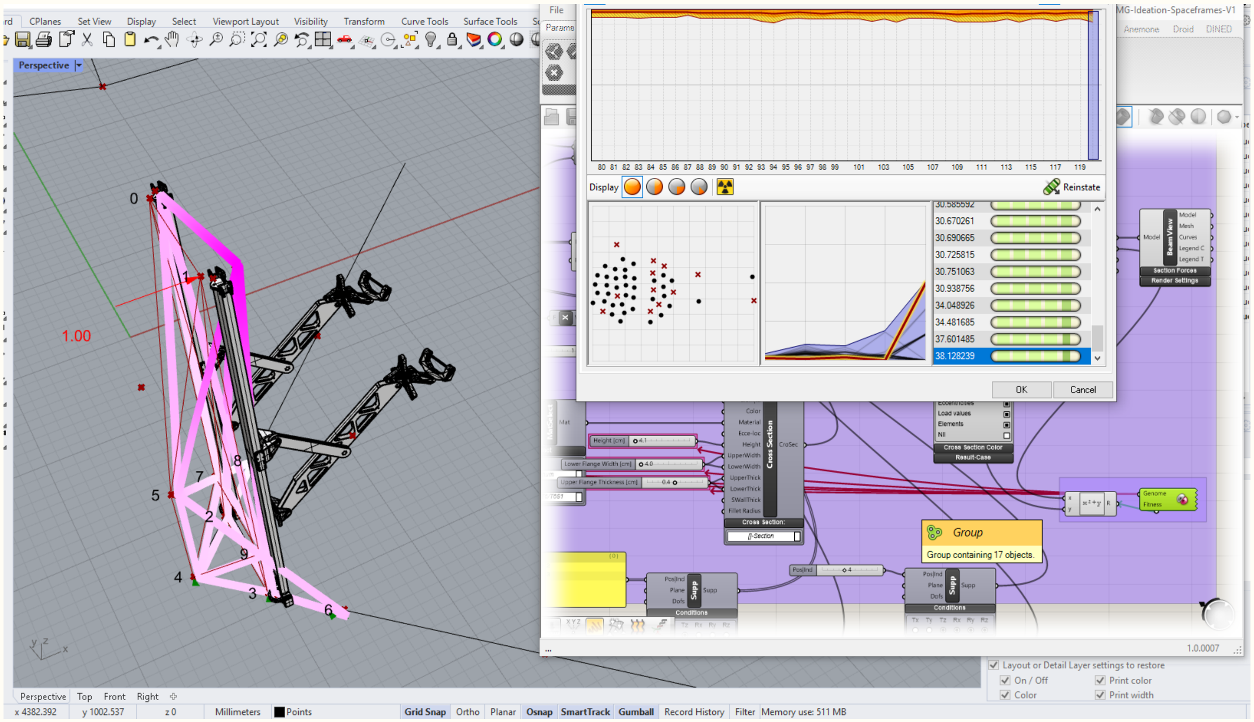
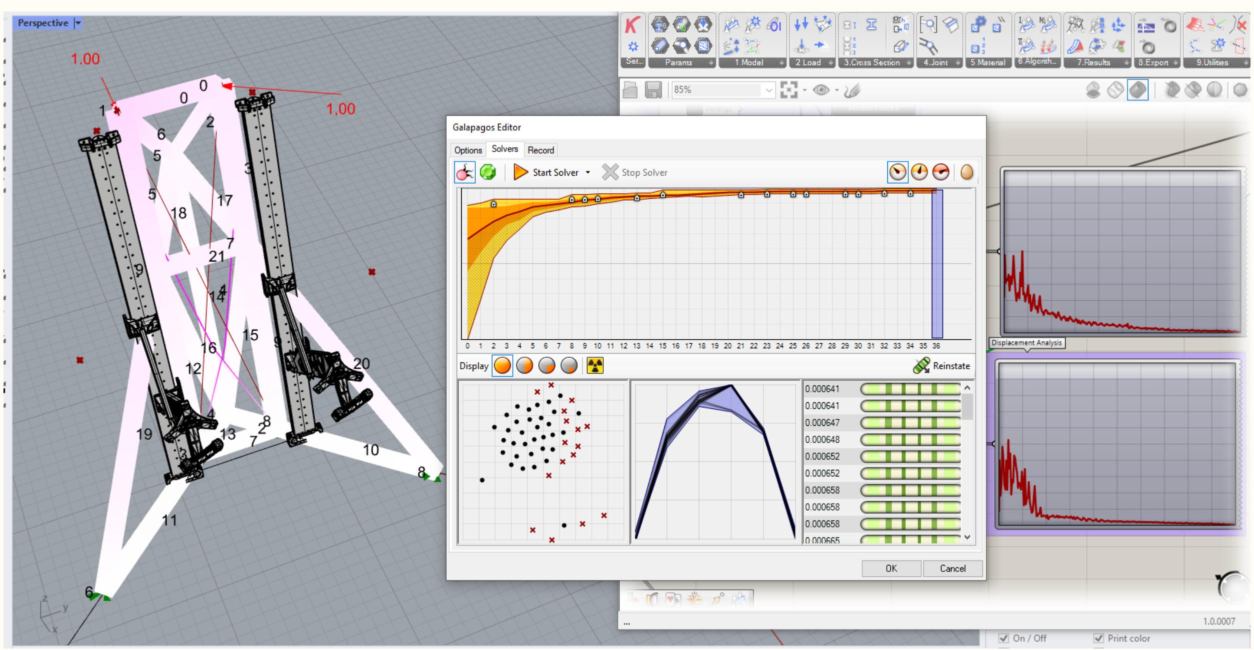
HorizPush500N
SideHang750N
VertHang1300N
VertHang1300N
Expression




Perspective
Galapagos Editor
Options
Solvers
Record
Start Solver
Stop Solver
Display
Reinstate
OK
Cancel
Autosave complete (150 seconds ago)
Displacement Analysis
MG-Ideation-Spaceframes-V1


CPlanes
Set View
Display
Select
Viewport Layout
Visibility
Transform
Curve Tools
Surface Tools
Perspective
1.00
Reinstate
OK
Cancel
Group
Group containing 17 objects
Cross Section
Section Forces
Render Settings
Conditions
Layout or Detail Layer settings to restore
On / Off
Print color
Color
Print width
Perspective Top Front Right
Millimeters
Points
Grid Snap
Ortho
Planar
Osnap
SmartTrack
Gumball
Record History
Filter
Memory use: 511 MB
1.0.0007


Perspective
1.00
1,00
Galapagos Editor
Options
Solvers
Record
Start Solver
Stop Solver
Display
Reinstate
OK
Cancel
Displacement Analysis
Params
1.Model
2.Load
3.Cross Section
4.Joint
5.Material
7.Results
8.Export
9.Utilities
On / Off
Print color
1.0.0007