Explorative study towards the integration and combination of three technologies into a virtual control system

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Executive Summary

Interacting with holograms is something which is widely speculated about. Combining holographic projections with haptic feedback and gesture control might bring this concept closer to reality. This project aims at exploring the possibilities of combining these three technologies into a combined virtual control system.

Project owner Safran initiated the project concerning the combination of three technologies into a single virtual control system. This system could provide added value to a lavatory environment by enabling the passenger to open a door without having to physically touch the unhygienic surface. An analysis phase was concluded investigating the different individual technologies and their respective maturities. Conclusions were drawn based on the ability of the components to be integrated into a system operating in a single volume of space. Next to the technological aspects, business, user and environmental aspects were analysed in order to create a better understanding of the aerospace market, the potential target group and the operational environment. Trends were used to indicate potential opportunities and the user and environmental analysis formed the basis for further conceptualisation.

Different application environments were explored together with respective scenarios. A lavatory implementation was selected as the preferred context for the creation of a functional prototype. The detailing selected an ultrasound transducer array as carrier for the haptic component. An eye-tracking stereoscopic display was selected as the carrier for the holographic component. Finally a camera based sensor using a skeletal algorithm was selected as the most suitable carrier for the gesture component. An architecture was proposed combining these technologies into a single system. The interface was designed for the selected context in order for the development of a demonstrator.

The prototype was created in collaboration with Dimenco, the developer of the Simulated Reality (SR) development kit, an eye-tracking stereoscopic screen. The SR kit was combined with the already acquired Ultrahaptics transducer board and a Leap Motion sensor to start building the proof of concept. The projections were aligned in order for the user to perceive the designed interface in a single volume of space. Functionality was added and visual polishing concluded the creation of the demonstrator. The demonstrator showed the combination of the three technologies into a single interface which allowed the user to interact with a lavatory door. Test results indicated a good understanding of the 3D system with intuitive reactions without additional instructions. However more research is required to prove the viability of a virtual control system in an aircraft environment. Weight and cost play an important factor in the industry, both have to be optimised in order for the system to become viable. The thesis concluded with suggestions for further development.
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01 Orientation
1.1 Orientation

This chapter provides an introduction to the graduation project executed by Bart Spel, Integrated Product Design student at the faculty of Industrial Design Engineering, Delft University of Technology, for Safran S.A. It depicts the different aspects and problems that were encountered during the project and also give insights towards the background of the assignment, its origin and the structuring of the project.

1.1.1 Problem Definition

A virtual control system combining holographic projections, ultrasound haptics and gesture control could provide added value in an aircraft environment, however the readiness levels of the different technologies and the possibilities of the design to provide added value when combining them needs to be explored. Investigating the possible integration and combination of the three technologies requires a design-based approach since there are too many design-dependent variables that influence the integration of the technologies towards a functioning control system. This leads to the following problems that need to be tackled:

1) An explorative study towards the independent technology readiness levels. Technology is always progressing and improving. To determine the added value of the abovementioned technologies, their readiness levels should be determined to draw valid conclusions regarding the implementation and integration of such a system in the aviation industry.

2) An explorative study towards the possible context implementations of a virtual control system into an aircraft environment. Providing the company with potential development areas and inspiring the use of the combined technologies.

3) An explorative design towards the integration of the three technologies into a functional control system. Exploring the possibilities of the technological integration of the three technologies by creating a demonstrator will give insights towards the functioning of the system and its application. Also a trade-off should be made regarding, on one side, the (expensive) technological functionality and, on the other side, the economic cost.

1.1.2 Opportunity

The combination of the three technologies may create interesting opportunities for Safran to explore. A control system based on a holographic projection which also provides feedback might in time replace heavy, wired, control panels in galleys or aircraft cockpits. Other applications might be found in actions executed by flight attendants or passengers, providing a more pleasant, intuitive or efficient experience.

A virtual control system could for instance provide intuitive controls for flight attendants operating galley equipment or ensure hygiene for passengers in lavatories. This project was initiated to explore the possibilities of combining the three technologies mentioned previously into a virtual control system and find potential implementation opportunities in an aircraft environment.
1.1.3 Scope & Approach

The challenge in developing a virtual control system based on holographic projections, ultrasound haptics and gesture control lies in both the readiness levels of the three separate technologies as well as their ability to be combined into one harmonious system. Concerning the volume of the assignment, limiting the scope is essential in order to acquire significant results, thus restrictions will have to be made. This project primarily focuses on exploring the possibilities of integrating the three technologies into a functioning virtual control system. To achieve these goals, various design disciplines need to be integrated such as, physical engineering, digital engineering, user experience design, prototyping etcetera.

The project aims to create a demonstrator which shows the integration of the three technologies into a harmonious system, proving their technical feasibility and allowing evaluation of the desired user experience. In order to achieve these set goals, the project will follow the following six step approach:

- Exploration
- Analysis
- Conceptualization
- Detailing
- Prototyping
- Evaluation

The First part of the project is based on the Design Inclusive Model. This model works with the objective to provide a sound theoretical foundation and a robust methodological approach for designerly inquiry to meet scientific rigor by creating knowledge and using design as a research means to create artifacts (Horváth, 2007). Firstly the project will focus on the exploration of the technologies. Afterwards a more in depth analysis will be made into the technologies and their requirements in order to function properly in a harmonious system. Next to the technology the analysis will also focus on human and market aspects in order to create a holistic view of the project. The second phase of the project will be structured as a Research in Design Context (RiDC). This framing method focuses on exploring the design context, followed by a constructive phase and is concluded with a confirmatory phase. After the analysis the design requirements will represent the acquired knowledge into a design space, which will provide the concepts for the system. The detailing phase will select a single concept to be developed further and finally prototyped and evaluated. The project will finish by giving a list with recommendations in order to keep developing the product. Figure 1 illustrates the project structure.

1.1.4 Deliverables

- The project will be conducted for Safran S.A., the financial support they are providing also gives them the rights to the intellectual property acquired during this project. The following deliverables can be expected at the end of the project:
  - A study researching the technology readiness levels of the individual technologies.
  - An explorative design towards the integration of the technologies.

- An explorative study towards the implementation possibilities of a virtual control system in an aircraft environment.
- A functional demonstrator in order to showcase the potential of combining the technologies.
- Recommendations on the future project steps and research goals.
- Recommendations on further improvements regarding the creation of the system.
Figure 1 - Project Structure
Analysis
Chapter Summary

Three aspects regarding the development of a virtual control system are considered in the analysis. First technology aspects are discussed. Research is done towards the three different technological components: haptic feedback, holographic imaging and gesture recognition. Different technologies are discussed showing their development and indicating their maturity. The patent the project is based on, indicates that the three technologies should coexist in the same volume of space. Ultrasound haptic feedback and camera based gesture recognition are concluded to be most suitable to be combined with a holographic projection. Holographic projections are the most limiting factor for the combination since real volumetric imaging technologies are not ready for application yet. Stereoscopic displays might provide a suitable alternative since they are also able to create a perceivable image in free space.

Business aspects are briefly discussed, illustrating a picture of the stakeholders in this project. A trend analysis shows the current developments in the aerospace industry, indicating self service galleys, first class seating and heads up displays as potential implementations for a virtual control system. A user and environmental study are done in order to illustrate the potential target group and the aircraft environment. Three implementation horizons are found for a virtual control system. Suggesting that in the first implementation, passengers are the preferred target group. The environmental analysis illustrates the different areas that can be found in and around an aircraft.

Finally, the chapter concludes with a list of design guidelines based on the previous analysis. It also suggests a desired user experience based on the expectations of the target user: ‘Airline passengers often encounter complications during flight regarding stress, boredom and/or irritation. These complications make the experience of the flight less pleasant for the passengers. The virtual control system in its envisioned design will assists the passenger in the numerous complications they might come across during their flight. It will be able to provide comfort in uncomfortable situations and distract the passenger from the boring hours in flight when needed.’
2.1 Technology Aspects

The most important enabler of this project is the technological readiness of the three technologies discussed in the problem definition. In the next chapter the technologies will be discussed in three parts: the haptic technology that provides the tangible feedback, the holographic device that provides the visual stimulation and the gesture recognition. Appendix A - Technology Analyses contains a full overview of the technological analyses.

2.1.1 Haptic technology

There are three main strategies for producing haptic feedback in free space (Hoshi, Abe & Shinoda 2009, 7-11). The first strategy is through direct-contact wearable devices, such as gloves or haptic jackets (Arafsha, Alam & Saddik, 2013). The second is through manipulating the location of the haptic actuators themselves such that they only touch the user when feedback is required. An example of this strategy is an electrotactile display (Sato, Kajimoto, Kawakami & Tachi 2007, 3-8). The third strategy, contactless haptic feedback, is to produce the haptic feedback to the user from a distance without direct skin contact. This means that the user does not have to wear gloves or hold a device. But is instead able to perceive the intended output of the system in mid-air. This project will focus on the last of the three technologies since the feedback has to be combined with a holographic projection which operates in mid-air. It also enables the user to experience the haptic sensations without the need of an additional device. Contactless haptic feedback is produced using two main techniques: air-jet, and ultrasonic radiation pressure (Kim, Kyung & Kwon 2007, 354-360).

The air jet method uses a straightforward implementation and can give acceptable force feedback. It is also able to project haptic sensations over a longer range. A drawback of using the air jet method is that the technology is unable to create localized force due to diffusion (Iwamoto, Tatezono, & Shinoda, n.d.). It also has low spatial and temporal qualities that are necessary for multimedia applications (Hoshi 2011, 569-573). The ultrasonic method uses a 40 kHz modulated frequency that creates focal points in the air. These focal point can be perceived by the user of the system as feedback. It has high spatial and temporal qualities, providing a more accurate sensation than air jet haptics. Studies show that the optimal operating distance of ultrasonic sound projections lies around 250mm. This limits the reach of the technology (Hoshi, Abe & Shinoda 2009, 7-11). Next to the limited travel distance, the transducers in ultrasonic devices create audible sound which might be of concern in some applications (Arafsha, Zhang, Dong, & Saddik, 2015).

2.1.2 Holographic technology

A hologram is a projection of an image which appears to be three dimensional and which can be seen with the naked eye. Holography is the science and practice of making holograms. Typically, a hologram is a photographic recording of a light field instead of a 2 dimensional image formed by a lens (photograph of video). Holography is described as a diffraction-based coherent imaging technique, which can reproduce a complex three-dimensional (transparent) object on a flat two-dimensional screen. Holography might be the most limiting technology in this project since holographic technologies are nowadays barely capable of projecting in vacant air (Zhou 2015, 15-16).

Technology Readiness Levels (TRL) will play an important role in the decision making process for this project. Appendix B - Technology Readiness Levels gives a description of the TRL’s, as they are used by Safran and the aerospace industry. An alternative for holographic displays could
be to use a medium to project on. Fog screen projectors and helio displays are technologies that allow the projection of high quality images in the air. (Agarwal, Garg & Parihar 2018, 1001). By using multiple projectors, fog screens and helio displays could also create 3D projections (Yagi, Imura, Kuroda, & Oshiro, 2011). Next to these air holographic projections, stereoscopic displays are able to create 3D content. The basic technique of stereoscopic displays is to present offset images that are displayed separately to the left and right eye. Both of these 2D offset images are then combined in the brain to give the perception of 3D depth. Volumetric displays create 3D content inside a volume by either rotating a reflective surface (swept) or projecting onto multiple different layers (static). Photophoretic trapping is an experimental technology which creates image points that can be seen from almost all angles because their radiation is not limited by a bounding aperture (Smalley et al., 2018).

Figure 2 shows a summarised comparison of all the different holographic technologies, their advantages and shortcomings. In addition to this, it indicates their respective technology readiness levels. The only real 3D volumetric display technology, photophoretic trapping display, is in its early development phase, and is not able to operate outside of the controlled environment of a laboratory. More research is needed for this technology to mature which will arguably take a long time. Stereoscopic displays are further along in their development and some commercial applications can be found. However, stereoscopic displays are not real volumetric displays. They have limited viewing angles and are susceptible to clipping. Multiview stereoscopic displays are heavy and require a lot of power. Eye-tracking stereoscopic displays are able to create better 3D visuals but are limited in the amount of viewers. Volumetric displays have overall higher resolutions and require less space. However these are also not real 3D volumetric images. The biggest drawback of volumetric displays is their inability to coexist in the same volume of space as the haptic projection. Finally, fog screen displays and helio displays are only able to create 3D images when using phase shifting principles. They are cheap and easy to implement, however they are very sensitive to environmental conditions and rely on a secondary medium (fog or smoke) to project on.

<table>
<thead>
<tr>
<th>Technology</th>
<th>TRL</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fog Screen/ Helio Display</td>
<td>2</td>
<td>• Easy implementation</td>
<td>• 3D requires multiple projectors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relatively cheap</td>
<td>• Sensitive to environmental conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Predictable projection</td>
<td>• Low quality</td>
</tr>
<tr>
<td>Multi View Stereoscopic</td>
<td>2</td>
<td>• Multiple simultaneous viewers</td>
<td>• Large and heavy screens (due to multiple projectors)</td>
</tr>
<tr>
<td>display</td>
<td></td>
<td>• Good quality</td>
<td>• Limited viewing angle (70 Degrees)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Clipping occurs</td>
</tr>
<tr>
<td>Eye-Tracking Stereoscopic</td>
<td>2</td>
<td>• Create realistic depth perception</td>
<td>• Limited amount of viewers</td>
</tr>
<tr>
<td>Display</td>
<td></td>
<td>• Very high quality</td>
<td>• Limited viewing angle (150 degrees)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large pop-out effect</td>
<td>• Large computing power</td>
</tr>
<tr>
<td>Swept Volumetric Display</td>
<td>2</td>
<td>• Good quality</td>
<td>• Large volume due to actuators</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large viewing angle (360 degrees)</td>
<td>• High bandwit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• in-volume 3D effect</td>
</tr>
<tr>
<td>Static Volumetric Display</td>
<td>2</td>
<td>• Very high quality</td>
<td>• Limited viewing angle (50 degrees)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Easily scalable</td>
<td>• High Bandwit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• In-volume 3D effect</td>
</tr>
<tr>
<td>Photophoretic Trapping</td>
<td>1</td>
<td>• True 3D volumetric display</td>
<td>• In early development stages</td>
</tr>
<tr>
<td>Display</td>
<td></td>
<td></td>
<td>• Limited size projections (100 cubic cm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Low frequency (10 Hz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Extremely sensitive to environmental conditions.</td>
</tr>
</tbody>
</table>

Figure 2 - Holographic technologies
2.1.3 Gesture recognition

Different input devices for gesture control can be identified. The working principles of these devices can generally be subdivided in two groups; touch and touchless input devices. Touch-based gesture recognition uses physical devices to register the input. Wired gloves and gesture-based controllers (wii-mote) are examples of touch based input devices. The gesture recognition device in this project will have to coexist in the same volume of space as the holographic and ultrasound projections. This makes the second group of gesture recognition devices more suitable. Touchless user interface (TUI) is the process of commanding the computer via body motion and gestures without touching a keyboard, mouse, or screen (PCmag, z.d.). Touchless gesture recognition can be achieved using multiple technologies. Cameras can be used to register the motion of the user. Single 2D cameras can be used to detect robust gestures but lack the accuracy of stereo and depth cameras. Stereo cameras use multiple views to generate a 3D representation. Infrared light could be used to increase the depth perception. Gestures are directly detected in combination with direct motion measurement, making stereo cameras effective for detecting hand gestures (Lee, Kim, & Hong, 2007). Specialized cameras such as structured light cameras or time-of-flight cameras can create a depth map of what the camera registers at a short range. Their short range capabilities make them also very suitable to detect hand gestures. Next to camera’s, radar or electro-magnetic tracking could be used in order to detect gestures. Both methods however are less suitable for hand tracking since they trade range for accuracy. (Benford et al., in press).

Algorithms used to create the model of the hand and detect the gesture can be divided in two segments, 3D model-based and appearance-based. 3D model-based algorithms use volumetric or skeletal models. Volumetric models are the most accurate but are computationally more expensive, making them less suitable for real-time tracking. Skeletal models keep their 3D representation but overcome the computational drawbacks by using joint angle parameters and segment lengths. Appearance based algorithms use a template database creating a colour, silhouette or contour model of the hand. Due to the limited detail of the model, these template based models are primarily used for tracking, but are able to be used for simple gestures (Pavlovic, Sharma, & Huang, 1997). Camera-based sensors using skeletal models are most suitable in the described system, because they offer the best balance between 3D depth maps and computational requirements.

2.1.4 Technology combination

According to the patent, in order for the virtual control system to operate as intended, the volume of space containing the haptic and holographic projection should at least partially overlap. Figure 3 shows a schematic representation of the combination. The ultrasound haptics are able to create a projection in a volume of space, which can be accessed by the user and thus recognised by the free space gesture recognition device. In order for the holographic projection to work efficiently with the other technologies, the projection should be aligned with the haptic hologram.
Stereoscopic displays have seen some commercial application. Stereoscopy, eye tracking and multi view, create an illusion of an 3D image which does not have a fixed position in a volume of space. This makes it difficult to align the image with the ultrasound haptics and requires large amounts of computing power. Eye tracking could create a walk around effect by keeping track of the users position, creating the illusion of a volumetric projection, thus making them a viable option.

Fog screens and helio displays are not real volumetric displays, but 2D projections on an in air screen. The use of phase shifting creates the illusion of a 3D shape. Phase shifting requires a separate projector image for every viewing angle limiting the compactness of the display.

Volumetric displays are not able to create an image which exists in the same volume of space as the ultrasound projection due to their volume filling nature. However the quality of volumetric displays is the best of the display technologies. Volumetric displays are the closest technology to commercial application, making them interesting to work with if implementation in the near future is desired.

The final technology discussed was the free space volumetric display. Photophoretic trapping creates a real 3D volumetric image which can be perceived from all angels by multiple viewers at the same time. Because the image truly exists in a volume of space it is suitable to be combined with the ultrasound projection. However due to the immaturity of the technology more development en resources are needed for this technology to be commercially viable. Based on the current research and development in this technology, commercial application is most likely not to be expected in the coming 10 years.
2.2 Business Aspects

Next to the technological aspects, business aspects should be taken into consideration when designing for a specific market. This chapter will start with a brief introduction to the company that provides this project. Afterwards some insights will be provided in both stakeholders and market trends. Appendix C - Business Analyses contains more information on the discussed topics.

2.2.1 Safran S.A.

Safran S.A. is a French multinational aircraft engine, rocket engine, aerospace-component and defense company. It was formed in 2005 by the merger of the aircraft and rocket engine manufacturer and aerospace component manufacturer groups SNECMA and the security company SAGEM. Zodiac Aerospace, also a French company, which specialized in supplying systems and equipment for the aerospace industry, was taken over by Safran in 2017.

This project falls under the department of Safran Cabin R&T, based in Alkmaar, the Netherlands. Safran Cabin’s mission is to design, certify, manufacture, and support the world’s most innovative aircraft cabin interiors, providing airlines and OEM customers with distinctive aircraft branding, and their passengers with a safe, comfortable and enjoyable flying experience.

Safran Cabin provides all elements of a seamlessly integrated Commercial, Business Jet and VIP cabin interior. From the overhead bins, lavatories and galleys to crew rests and cargo containers, either as independent world class products or as a fully integrated cabin.

![Safran Logo](Figure 4 - Safran Logo)

2.2.2 Trend analyses

A trend analysis was conducted to provide insights in the movements of the aviation market. The full trend analyses can be found in Appendix C - Business Analyses. Potential opportunities for a virtual control system could be spotted together with threatening findings regarding its implementation.

Based on the conducted trend analysis, a few conclusion can be drawn regarding opportunities and complications that might occur with regards to the development of a virtual control system. The most promising trends that will support the implementation of a virtual control system are:

- Welcoming experience & self service galleys
- First and business class seating experience
- Heads up display for pilots

Fists of all the trends regarding seating layout and floor plan design indicate an ongoing development in the level of comfort and experience provided to the customer. This creates possibilities for a virtual control system to be implemented. Looking at the connected aircraft, AI and Heads Up display trends an increase in electrical assistance can be spotted in the aviation industry also creating opportunities for the implementation of a well functioning control system. The shift from wide body to narrow body aircraft might form some complications since single aisle aircraft are generally more efficiency focussed and leave less room for disruptive innovations.
### 2.2.3 Stakeholders

An analysis was conducted to determine which stakeholders are relevant in relation to the graduation project. Furthermore, the relation and influence they have on one another are indicated. An overview of the different stakeholders and their power and interest can be seen in Appendix C - Business Analyses.

Different stakeholders are involved on different levels in this project. Figure 5 illustrates the determined stakeholders and their relevance to the project. Passengers and flight crew were determined as the primary stakeholders. They will be the user of the virtual control system and therefore their needs and demands should be consulted. A more in depth look into these groups is given in the User chapter. Secondary stakeholders include the interior supplier in this case Safran S.A., and the designer. They determine the design and execution of the project and are able to tailor the virtual control system to the needs of the user. Airframe manufacturers, engineers and airports are considered tertiary stakeholders in this process since they are able to work closely together with secondary stakeholders but have no interest in tailoring it to the needs of the potential customer. Finally, latent stakeholders could be defined as governments, regulatory instances and the media. They have low interest in the project but their laws and regulation will play an important role in the detailing of the final product.

![Stakeholders Map](image-url)
2.3 User Aspects

In order to provide added value with a system as described before, a potential user should be determined. Safran S.A. has not given a preference for a specific target group. In Appendix D - User Analyses an introduction to the possible users of the virtual control system will be given together with a description of their persona.

2.3.1 User

Looking at an aircraft environment, four possible potential users can be identified. First off all pilots can use a virtual control system to assist them with their job of piloting and navigating the airplane. Flight attendants are able to use such a system to assist them with the various tasks they have to perform onboard, during the different stages of the flight. Passengers in their turn might benefit from a virtual control system in the form of in flight entertainment or other service related topics. Finally ground crew members might come in to contact with a virtual control system when performing maintenance work on the airplane.

Looking at the different potential users, their expectations and demands of a virtual control system differ strongly. Based on these expectations, three implementation horizons can be concluded. Figure 6 shows a graphical representation of these implementation horizons together with their respective user. Firstly, horizon one, the passengers can be targeted by creating a control system that increases their comfort and experience during the flight. In the second horizon the system could be implemented in more functional processes where reliability and functionality are more important. In this horizon the system could exist in order to assist cabin and ground crew with their routine based work. Finally in the third horizon, a virtual control system could be implemented in the cockpit to be used by the pilots flying the airplane. In this stage the system is trustworthy and provides accurate control in order to uphold safety regulations. For this project the passenger will be selected as the user due to the readiness of the technology as discussed in the technology analysis.

Figure 6 - Implementation Horizons
2.4 Aircraft Aspects

The virtual control system proposed in this project is situated in an aircraft environment. Insights will be given into different types of aircraft combined with the different zones that can be found within commercial aircraft. This project will limit the focus to commercial aviation and will thus exclude military and other types of aircrafts. A full description can be found in Appendix E - Aircraft Environment.

2.4.1 Aircraft environment

Looking at the environmental analysis, aircraft types can be divided in different categories with different floor plans and purposes. Narrow body, short haul flights, provide low levels of comfort and are revenue oriented. This makes them less suitable for the implementation of new systems since the focus of the aircraft is to be as cheap as possible. This means they mostly incorporate economy class only, with less spatial separation between seats. Long haul and wide body aircraft might be more suitable for the implementation of a control system since, especially at the higher classes (first and business class), comfort and the provided experience have more influence on the layout and systems inside the aircraft. Looking outside passenger classes, galleys and cockpit have higher requirements of the systems use since they rely more on functionality and safety. Finally, lavatories or lounges can be considered as public spaces in the aircraft environment, providing services to passengers and flight crew. Figure 7 shows a brief description of these zones.

Figure 7 - Aircraft Zones
2.5 Design Guidelines

In the following chapter the conclusion and findings from the previously conducted analysis will be combined. This will use the knowledge fields of technological, business and user aspects in order to define the desired user experience. They also define the design boundaries for the envisioned product in the form of a program of requirements. This is done to limit the options that can be explored during the conceptualization phase.

2.5.1 Desired user experience

The goal of the project as stated in the orientation is to explore the possibilities of the combination and implementation of three technologies into a virtual control system. This system should provide added value to users in an aircraft environment in order to be able to be implemented. During the technology phase the limitations that come with the maturity of the technologies are already discussed. Because of these issues it makes it hard to determine the specific user experience that should be acquired with the system. However what can be defined is the desired impact of the system. This impact can be defined in an value proposition:

‘Airline passengers often encounter complications during flight regarding stress, boredom and/or irritation. These complications make the experience of the flight less pleasant for the passengers. The virtual control system in its envisioned design will assists the passenger in the numerous complications they might come across during their flight. It will be able to provide comfort in uncomfortable situations and distract the passenger from the boring hours in flight when needed.’

Next to the passenger, other stakeholders were discussed. The project aims at validating the right of existence of a virtual control system in an aircraft environment. Since there are no current competing systems on the market, the system should also impact the market by creating interest in the technology and its application. This should provide Safran with a competitive advantage on its opponents in this market.

2.5.2 Requirements

The requirements of a virtual control system can be distributed in three different groups. Firstly there are technology based requirements (TR). These requirements focus on the hardware and software problems the system has to solve. User based requirements (UR) focus on the interactions of the intended user with the system. Finally business requirements (BR) focus on the market demands in order to gain a competitive advantage.

Technological Requirements:

TR1: The ultrasonic transducers operate at 40kHz-70kHz with a 100Hz-300Hz carrier frequency.
TR2: The haptic projection should be created in a volume of space within reach of the intended user.
TR3: The array geometry is created to strengthen the focal point creation.
TR4: The ultrasonic sound produced by the haptics device should not interfere with other processes in and around the aircraft environment.
TR5: The holographic projection is visible in an aircraft environment with the corresponding environmental conditions.
TR6: The holographic projection is not perceived...
by the user as blinking (refresh rate under 25Hz). TR7: The holographic device does not require a secondary medium to project on.

TR8: The motion sensing device is able to distinguish hand and finger gestures in a predetermined volume of space.

TR9: The motion sensing device is able to detect motion up to 1m distance from the created volume of space.

TR10: A combination of the three technologies should be able to simulate a hologram which can be haptically perceived due to ultrasound focal points. This combination should take place in the same predetermined volume of space.

TR11: The technologies do not compromise individual functions in the predetermined volume of space.

TR12: The software and coding language in the virtual control system is universal over the individual components.

TR13: The hardware is easy to access and support maintenance processes when required.

TR14: The hardware meets all the safety requirements set by the aviation industry.

User Requirements:
UR1: The combination of the technologies should create an intuitive and understandable control interface.

UR2: The control system can be operated in the limited space of an aircraft environment.

UR3: The control system can be operated by the large and diverse user group that can be found in an aircraft environment, varying in age, sex, religious beliefs and nationality.

UR4: The control system generates an understanding by users with no prior experience with such a system.

UR5: The combination of the technologies can be controlled by users with varying physical dimensions.

UR6: The control system is comfortable to use and does not contribute to stress levels or annoyance.

UR7: The control system is safe to use without physically or mentally hurting the user.

UR8: The control system creates amazement and wonder with the user due to its technologically advanced nature.

Business Requirements:
BR1: The combination of the three technologies is able to be implemented in the aviation industry.

BR2: The combination of the three technologies creates value with respect to all different stakeholders.

BR3: The system is able to provide added value for the aviation industry.

BR4: The system is able to inspire usage in other implementation areas besides the first iteration project.

BR5: The Combination of the technologies into a combined system should inspire further research into the respective areas.

BR6: The virtual control system should follow aviation trends to gain traction and be more likely to be implemented.

These requirements will show the boundaries within which the virtual control system should be operational. In order to further investigate the functioning of the virtual control system and the collaboration of the three subsystems a context needs to be created. This context would be based on an aircraft environment since Safran operates in this market. The next chapter will focus on exploring and creating a context setting for the demonstrator to operate in.
03 Conceptualisation
The focus of the project was to explore the integration of the three technologies into a virtual control system. In order to do this, the conceptualisation focused on creating ideas and context for the virtual control system to be implemented. Based on the previous analyses, it started with the exploration of the potential application environment. A creative session was conducted with Safran Cabin employees to determine all interactions between the different user groups and the environment. The lavatory, first class seating compartment and the self service galley were selected as the most suitable context environments. Scenarios were created for the three application environments in order to identify the interaction in which a virtual control system could be implemented. A further description with the respective function requirements was created for each concept. A lavatory door control system, a first class seating control system and a self service galley control system were compared based on different criteria. Finally, after consultation with Safran, the lavatory control concept was selected as the most suitable concept for further detailing. In addition to it having simple functional requirements, it also provides clear added value. A research study performed by Safran already shows the problem of the lavatory door controls being perceived as unhygienic. A virtual control device could provide added value by enabling the user to open the lavatory door without physically touching it. The other concepts require further validation of their use case in order to prove their added value.

Chapter Summary

The focus of the project was to explore the integration of the three technologies into a virtual control system. In order to do this, the conceptualisation focused on creating ideas and context for the virtual control system to be implemented. Based on the previous analyses, it started with the exploration of the potential application environment. A creative session was conducted with Safran Cabin employees to determine all interactions between the different user groups and the environment. The lavatory, first class seating compartment and the self service galley were selected as the most suitable context environments. Scenarios were created for the three application environments in order to identify the interaction in which a virtual control system could be implemented. A further description with the respective function requirements was created for each concept. A lavatory door control system, a first class seating control system and a self service galley control system were compared based on different criteria. Finally, after consultation with Safran, the lavatory control concept was selected as the most suitable concept for further detailing. In addition to it having simple functional requirements, it also provides clear added value. A research study performed by Safran already shows the problem of the lavatory door controls being perceived as unhygienic. A virtual control device could provide added value by enabling the user to open the lavatory door without physically touching it. The other concepts require further validation of their use case in order to prove their added value.
3.1 Application Environment

In order to come up with viable results and a demonstrative prototype the conceptual phase was structured as a research in design context (RiDC). The cycle is divided in three phases. the first phase is oriented around exploration. Secondly, a constructive phase followed by the final and confirmative phase. In Chapter 2 - Analysis, the requirements for a virtual control system were discussed. In order to further investigate the combination of the three technologies and their functioning, a design context needs to be created.

3.1.1 Application ideation

The first step in the process of creating a suitable design context is to determine a suitable application environment. This is done by exploring the possible interaction from the various potential users with the environment. Both the potential user and different aspects of the environment were already discussed in Chapter 2 - Analysis. A creative session, Appendix F - Application Ideation, was held with the design student and several Safran employees in order to list potential interesting application environments. The various application ideas were grouped in three different groups. Each group represents a zone in the aircraft environment with its corresponding application ideas.

Figure 8 - Application ideation
Cockpit context

Firstly the cockpit area was discussed. This section focuses mainly on high accuracy and flight critical systems in order to operate the plane. Also security is very important since access must be restricted to qualified personnel only.

<table>
<thead>
<tr>
<th>Context idea</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cockpit Door Access</td>
<td>To enter the cockpit, the door has to be opened via a virtual lock. The code to open the doors in knows to flight attendants and pilots and will include a set of motions. The camera used for the gesture recognition could also be used to scan the person entering and use their profile to grant or deny access.</td>
</tr>
<tr>
<td>Pitch Control</td>
<td>When controlling the pitch of the airplane the pilots are able to lay their hand on a projected version of the plane and tilt their hand in order to tilt the plane. The haptics will provide accurate feedback instructing the pilot of the plane's motion.</td>
</tr>
<tr>
<td>Navigational Control</td>
<td>Navigating is an important aspect of the flight controls. A virtual control device would assist the cockpit crew with a more detailed representation of the landscape, combined with radar it could help position the plane with regards to other flying objects. Haptics could provide warnings for storms and other objects to avoid.</td>
</tr>
<tr>
<td>Service Portal</td>
<td>The pilots would have a customized service portal to access different services such as food, drinks and emergency equipment. The virtual control system could give 3D representations of the objects making it easier for the pilot to access different products. Haptics and gesture could even be used for the pilot to use the portal without looking at it.</td>
</tr>
</tbody>
</table>

Figure 9 - Cockpit context ideas

Figure 10 - Cockpit context
Cabin context

The second area that was discussed was the cabin. This area also contains the lavatories and the galleys. The main focus from these areas is service and comfort oriented. Passengers spend most of their time in one of the compartments of the cabin and need to pass the time. Passengers are looking for more gimmicky and distracting features. Cabin crew operate the galleys and provide the passengers with food, drinks and other required services. They are, in contrast to the passengers, driven by clarity and functionality and need organised and clear information.

<table>
<thead>
<tr>
<th>Context idea</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lavatory Controls</td>
<td>Lavatories are perceived as unhygienic, resulting in a lot of discomfort. Passengers using the lavatories are reluctant to touching surfaces inside. A virtual control system could provide an improved sense of comfort by enabling the passenger to control without physical touch.</td>
</tr>
<tr>
<td>Combined Galley Controls</td>
<td>An integrated control panel that could be used by the flight attendant to oversee and control all the separate devices. This enables them to accurately assess the different devices in the galley in one place. The haptics could provide additional feedback warning the flight attendant for potential problems or devices left turned on.</td>
</tr>
<tr>
<td>Self Service Galley</td>
<td>Self service galleys will enable the passengers to get their own drinks and snacks during the flight. These galleys can use a virtual operating system providing detailed and realistic imaging of the different products for sale. The passenger can use the control device to grab miniature versions of what he desires and walk away with the real product.</td>
</tr>
<tr>
<td>Advanced Service Controls</td>
<td>Larger chairs in business and first class cabins are equipped with advanced control systems in the seat rest. These control devices can be used to order food, call flight attendants or adjust settings in your private compartment. It can also be used to intuitively control panels and shutters to increase privacy and comfort.</td>
</tr>
<tr>
<td>IFE Control</td>
<td>The inflight entertainment system gets a 3D upgrade, selecting screens, flight details, commercials and games can now be perceived in 3D increasing the experience and entertainment values.</td>
</tr>
<tr>
<td>Advanced Sleeping Pod</td>
<td>The sleeping pods are equipped with a virtual control system to control several features. These can be controlled without getting up and from a lying position. Similar to the advanced service controls in the higher class seats it enables the passenger to control all systems from one place.</td>
</tr>
</tbody>
</table>

Figure 11 - Cabin context ideas

Figure 12 - Cabin context
Exterior context

The final area that was explored, was the close surrounding environment of the aircraft. Maintenance and ground crew workers are primarily driven by efficiency and want their processes to be fast and clear. Ground crew members assist with the boarding process at the gate and are also driven by functionality to keep turnaround times as short as possible.

<table>
<thead>
<tr>
<th>Context idea</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access Hatch</td>
<td>Access hatches on the outside of a plane can be opened using a virtual control device. Levers and actuators that are otherwise harder to reach can be accessed more easily this way. Also in the winter, gloves do not become an inconvenience when trying to open compartments.</td>
</tr>
<tr>
<td>Automated Turnaround</td>
<td>A separate control unit operates all devices and vehicles needed for the turnaround of an airplane. The virtual control device provides a 3D map of the position of all units with respect to the plane and create a virtual space for one controller to operate multiple machines in one place. This will make the process of refueling, (un)loading, boarding etc more convenient and faster.</td>
</tr>
<tr>
<td>Lounge Access</td>
<td>First class and airline specific lounges can be accessed using a virtual control device at the entrance. Passengers will be using personalized codes in the form of a 3D puzzles to enter. This will increase the experience of the passenger when entering and increase the feeling of special treatment.</td>
</tr>
<tr>
<td>Seating Layout</td>
<td>At the boarding entrance, flight attendants who are guiding the process have a 3D representation of the plane and its seating layout. If passengers switch seats or are not checked in it will give them a clear and structured overview of the procedures. It will also indicate the availability of storage space in the overhead lockers.</td>
</tr>
</tbody>
</table>

Figure 13 - Exterior context ideas

Figure 14 - Exterior context
3.1.2 Application environment selection

In order to select the most suitable application environment the described ideas were graded. This grading was done based on the following criteria:
CR1: Technical feasibility
CR2: System demands
CR3: Added value
CR4: Spatial complications
CR5: System complexity
CR6: Usability

The first two criteria judge the technical feasibility of a virtual control system and indicate the technical demands that are requested from the control system in the respective context. Other criteria that are judged are the added value the system provides for the user in the respective context implementation and spatial complications that might occur when implementing the system. Finally the complexity of the system and the intuitiveness of use are indicated by the final two criteria.

Grading was done using a method based on the severity of foreseen issues. Each context idea was graded based on the different criteria. Since technical feasibility and system demands are considered more determining values, scoring in these categories are weighted double. Scores of one to three will be given meaning; 1, mayor issues can be expected. 2, moderate issues can be expected. 3, minor issues can be expected. Reasoning behind the grading can be found in appendix G - Idea Selection.

The first selected application environment was the lavatory. Next, the IFE system and the advanced service controls were combined since the both apply to the same application environment, a first class seating compartment. Finally the self service galley was selected as the third application environment. The selected application environments will be further into user scenarios.

Figure 15 - Selected application environments
<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>COCKPIT Weight</th>
<th>DIRECTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cockpit Door acces</td>
</tr>
<tr>
<td>Technical feasibility</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>System demands</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Added value</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Spatial complications</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>System complexity</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Usability</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>14</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

Figure 16 - Cockpit selection

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>CABIN Weight</th>
<th>DIRECTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lavatory Controls</td>
</tr>
<tr>
<td>Technical feasibility</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>System demands</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Added value</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Spatial complications</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>System complexity</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Usability</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>19</strong></td>
<td><strong>13</strong></td>
</tr>
</tbody>
</table>

Figure 17 - Cabin selection

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>EXTERIOR Weight</th>
<th>DIRECTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Access Hatch</td>
</tr>
<tr>
<td>Technical feasibility</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>System demands</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Added value</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Spatial complications</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>System complexity</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Usability</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1</strong></td>
<td><strong>11</strong></td>
</tr>
</tbody>
</table>

Figure 18 - Exterior selection
3.2 User Scenarios

User scenarios are created for each chosen application environments. Each user scenario will indicate the interactions the user has with the respective environment. Based on these interaction propositions for the implementation of a virtual control system will be made.

### 3.2.1 Scenario 1: Lavatory

Figure 19 shows a scenario sketch of the use of a virtual control system in a lavatory context: A passenger will approach the lavatory (1) and use the virtual control system to open the unlocked lavatory door (2). The door will automatically open letting the user enter. Sensors recognize the person inside the lavatory and automatically lock the door. After relieving himself (3) the passenger uses the tap controls (4), potential

### 3.2.2 Scenario 2: First class seating

Figure 20 shows a scenario sketch of a virtual control system in an in flight entertainment context: After entering the airplane the passenger will proceed to his chair (1). Enclosed first class compartments could be unlocked with a personalised code, displayed on a virtual control device (2). Inside the compartment the seat is equipped with an integrated screen in the armrest. This screen displays a virtual control panel providing the passenger with various control options surrounding his seat (3). Food can be ordered (4) or the in-flight entertainment system could be used (5). The 3D interface of the screen can be turned on and off (6) in order to suit different features. Virtual control systems will increase the user experience of longer flights for higher class flyers, providing them with integrated controls and a luxurious feeling (7).

### 3.2.3 Scenario 3: Self service galley

Figure 21 shows a scenario sketch of the use of a virtual control system in a self service galley context: After finishing his work, the passenger notices the empty feeling in his stomach (1). Still some time away from the next regular meal he decide to stretch his legs and go for a snack at the self service galley (2). At the control interface of the self service galley the passenger scrolls through the different 3D representations of the available products (3). After selecting the desired products he takes them out of the galley (4) and returns to his seat (5). Satisfied with his little snack he sits down again and enjoys the remainder of the flight (6).
Figure 19 - Lavatory scenario
Figure 20 - First Class Seating scenario
Figure 21 - Self Service Galley scenario
3.3 Concept development

Based on the previously described user scenarios, the three most prominent interactions will be selected as concepts for the implementation of a virtual control system. These concepts will create the necessary context in order for the project to progress further. A description will be given for each concept based on its functioning and specific requirements. Finally one concept will be selected to be further detailed.

3.3.1 Concept 1: Lavatory door controls

The first concept that was selected was that of the virtual control system in the aircraft lavatory. The original idea behind the patent from Safran S.A., found its backing in research towards the attitude of passengers towards the in flight restrooms. The core problem of the idea is to enable passengers of aircraft to open doors and potentially control features inside the lavatory without physically touching them. This provides a sensation of hygiene and might prevent littering in the lavatories. The system provides the user with a projected interface encouraging the user to use it. This interface is graphically represented by a pseudo-holographic device such as a stereoscopic display and combined with the haptics in order to create the experience. Upon using the interface, the gesture recognition device registers the motion of the user’s hand and translates this into the opening of the door. The system could also be of potential use for operating tap controls in the lavatory itself.

The quality of the virtual control system in this context depends on the ability of the system to recognise the gestures and to interpret the intentions of the user. Unlocking the door should not happen without intention. Also, the system should be intuitive in use by passengers without proper training or prior experience with the control device. All components should work together in order generate the content and allow it to be manipulated. The placement of such a system in the thin walls of an aircraft environment might form a problem. Weight and power consumption should be taken into consideration for a successful implementation in an aircraft context.

Looking at the described scenario, several functions could be derived for the development of a virtual control system in a lavatory context:

- The system is able to generate a controllable object by combining a projection with haptic feedback.
- The system should enable the user to open the door using hand gestures.
- The system should detect the presence of the user in being present in the lavatory and automatically lock the door.
- The system should enable the user to unlock and open the door from the inside.
- The system should prevent unintended opening of the door.
- The system should be able to close the door after the passenger leaves the lavatory.

Figure 22 - Lavatory door controls impression
The second proposed concept for a virtual control system is the first class seating controls. In this context, the virtual control system is used as a means to operate the entertainment system and other functions of a first class seating compartment. Serving as a personal 'buddy', the system will provide the user with a luxurious feeling and a single system to tend to all their needs. The system will be implemented in the armrest of the chair and enables the user to select several entertainment options, order food and drinks or call the flight attendant. Another purpose it fulfills is the control of several features of the cabin compartment. For example shutters, panels and seat configuration could be adjusted via the interface. Positioning the interface in the armrest enables the user to operate all the functions from a sitting position.

The quality of the virtual control system in this context depends on the ability of the system to project different function controls. The system should not only provide the user with controls for the in flight entertainment but should also function as a personal device to provide service and comfort. Scrolling through different functions should go intuitively and graphical representations of the functions should be clear and understandable. In first and business class seating compartments there is enough room for the addition of a control device in the armrest, since seat designs are more spacious. A complication that could occur, is eye fatigue when watching at a pseudo-hologram for a longer period of time. Since the system is located close to the user, it should be able to be turned off or go idle when not in use. Weight and power consumption should be taken into consideration for a successful implementation in an aircraft context.

Looking at the described scenario several functions could be derived for the development of a virtual control system in an in flight entertainment context:

- The system is able to generate a controllable object by combining a projection with haptic feedback.
- The system should fit within the armrest of a first class seat.
- The system should enable the user to control various features inside the first class seating compartment.
- The system should enable the user to control the in-flight entertainment system, serving as a remote control.
- The system should be able to be turned off when not in use to prevent eye-fatigue.
- The system should clearly visualize different functions (in flight entertainment and services).

Figure 23 - First class seating controls impression
The third concept that was selected was that of a virtual control system in a self service galley. In this context, the virtual control system will function as the operating system of the self service galley. Self service galleys are emerging concepts in the aviation industry, enabling passengers to acquire their own beverages and food. Similar to a vending machine, it uses an operating point where users can select and pay for products. The virtual control system could provide added value by providing the passenger with 3D representations of the products they want to buy. The system would also provide the passenger with a luxurious feeling and create a wow-effect due to its technologically advanced nature. The interface would display several products with the corresponding options. It would also enable the user to scroll through these products and provide them the option to pay for and acquire them from the galley. The virtual control system should be paired with a monitoring system in the galley, which registers the amount of products still available. The monitoring system should also register the amount of products the passenger takes from the galley to prevent misuse.

The quality of the virtual control system in this context depends on the ability of the control system to display the several products for sale in the self service galley. 3D representations of the products should be detailed and livelike to create the desired effect. The products should be easy to select and the payment method should require little effort. The system should prevent misuse by passengers. The control system should also keep track of the amount of products left in the galley and potentially link this to customer profiles to make predictions for the amount of products to take on the flight. Complications of using a virtual control system in a self service galley can be found in the limited space available in current galley designs. Another problem could be expected with the simultaneous use of multiple passengers at the same time. Also weight and power consumption should be taken into consideration for a successful implementation in an aircraft context.

Looking at the described scenario several functions could be derived for the development of a virtual control system in a self service galley context:

- The system is able to generate a controllable object by combining a projection with haptic feedback.
- The system should provide the user with detailed 3D representations of the products.
- The system should enable the user to scroll through the available products.
- The system should enable the user to select and pay for products.
- The system should prevent misuse of the self service galley
- The system should keep track of the available amount of products and link this to customer profiles.

Figure 24 - Self service galley controls impression
Three concepts for a virtual control system were proposed in this chapter. All three of them have been developed to a level where their general working principles and implications are discussed. A selection has to be made, considering one of these context implementations will be picked to further detail the virtual control system. Detailing is needed to prove the feasibility of the three technologies, described in Chapter 2 - Analysis, into a virtual control system. The context of the chosen concept will also structure the experimental setup for the creation of a demonstrator.

In order to determine the most suitable concept for the design research to continue, the decision making process is based on the following demands:

- Simplicity of the context implementation. In the technology analysis, the immaturity of most of the technologies used to create a virtual control system was already discussed. To acquire the most optimal research results from the demonstrator the implementation context should be kept simple.
- Desired user experience. The preferred context implementation is the one that best represents the desired user proposition described in Chapter 2.5 - Design guidelines. This decision is made in cooperation with Safran due to the subjective nature of the demand.
- Irreplaceability of the context implementation. The context which provides the most valuable scenario for a virtual control system, as described in this report, to be implemented has the preference.

After consultation with Safran, the lavatory control concept was selected as the most suitable concept to be further detailed. In addition to it having simple functional requirements, it provides clear added value. A research study performed by Safran already shows the problem of the lavatory door controls being perceived as unhygienic. A virtual control device could provide added value by enabling the user to open the lavatory door without physically touching it. The other concepts require further validation of their use case in order to prove their added value. The scope of the project is to explore the possible integration of three technologies into a virtual control system. A lavatory implementation provides a solid context for this technological combination to be further developed.
04 Detailing
Chapter Summary

One of the deliverables of the project was the creation of a physical prototype in the form of a demonstrator. In the conceptualisation chapter, a context in the form of a concept was selected in order for this demonstrator to be created. The chapter starts by detailing the hardware components. Technological components required for the creation of the system are identified; an ultrasound transducer arrays for the haptic component, an eye-tracking stereoscopic display for the holographic component and a camera-based sensor using skeletal algorithms for the gesture component. The functions required from the system are described together with a system architecture. When looking at available components for the creation of the demonstrator, the following components were selected: Ultrahaptics development kit, Dimenco SR development kit, Leap Motion sensor, i9-9900k (CPU) and RTX 2080Ti (GPU). The next step was to detail the software components of the system. Unity was selected as the most suitable platform based on its high accessibility and low cost. A flow chart was created showing the system processes. Finally, the detailing chapter proposed an aesthetic design for the cyberware. The design was based on the capabilities of the Leap Motion sensor combined with the limitations of the SR screen and the ultrasound transducer array. Both devices are only able to project perpendicular to their respective surface, limiting the interface possibilities. A palm down orientation of the hand was required due to the orientation of the haptics board. An exploration was done to identify potential shapes that would be easy to understand by the potential user. A final design was proposed using a single activation button which can be dragged in different directions in order to open, lock or unlock the door. Closing the door is done automatically. User cues are provided to the user in the form of changing color indications, arrows and a lock-icon. The understandability of the design will be further tested in the evaluation.
4.1 Hardware

In order for the virtual control system to work, suitable hardware components need to be determined. In the next section, several options for the hardware components will be discussed and a selection will be made. First, the different components will be discussed; namely the haptics device, the (pseudo-)holographic device and the gesture control device. Afterwards, an architecture diagram will be provided, illustrating the hardware setup. Finally, the orientation of the hardware setup will be discussed in order to fit in the chosen context implementation.

4.1.1 Technology Components

Haptic Component

Chapter 2 - Analysis stated that this project will focus on mid-air haptic feedback since the feedback needs to be combined with a holographic projection. The patent states that the technologies used to create need to operate in the same volume of space. Two methods of producing mid-air haptic feedback were discovered: air jet and ultrasound. Comparing air jet haptic devices with ultrasound devices, the major difference can be found in the spatial resolution. Air jet devices are able to produce pressure points with an accuracy of 10cm diameter at 2.5m distance (Sennaar, 2019). Ultrasound devices are more accurate, but at a shorter distance; 8mm diameter at 0.25m (Hoshi, Abe & Shinoda 2009, 7-11). In the proposed context implementation, the spatial resolution need to be as accurate as possible to be combined with a (pseudo-)holographic image. In the lavatory context, the distance from the user to the haptic transducer will not exceed the optimal focal distance of 250mm.

Figure 25 - Visualisation of ultrasound haptic feedback (by Ultrahaptics)
**Holographic component**

It was already concluded in that chapter that true 3D volumetric imaging technologies do not exist at this point. The technology that comes closest to realising this technology, photophoretic trapping, is still in the early stages of development. Thus, photophoretic trapping will need more maturing before being able to be applicable in a real world application. In order for the virtual control system to be created a pseudo-holographic device could be used. Fog screen projectors are least preferred since they require a generated medium to project on. Generating 3D effects with a fog screen also requires multiple projectors, restricting the spatial implementation of such a system. Furthermore, stereoscopic and volumetric displays were discussed. Stereoscopic displays have the preference over volumetric displays, since volumetric displays generate their 3D images inside a volume of body. Stereoscopic displays are able to generate 3D effects by using lenticular lenses or parallax barriers, splitting the image in a right and a left view. Multi-view stereoscopic displays are heavy and require multiple projectors, whereas eye-tracking displays do not. They calculate the position of the viewer and adjust the image accordingly. Since multi-view is not a requirement in the chosen context implementation, the eye-tracking stereoscopic devices are most suitable.

![Figure 26 - Visualisation of a stereoscopic display (by Dimenco)](image)

**Gesture recognition component**

Chapter 2 - Analysis discussed various gesture recognition devices. The working principles of these devices could generally be subdivided in two groups; touch and touchless input devices. It was already concluded that a touchless gesture technology was needed in order to be combined with the holographic and haptic projection. Camera based gesture recognition devices are more readily available and have better spatial capabilities when compared to electromagnetic sensors. Finally, different algorithms can be used to analyse and detect the hand position and the gestures. A trade-off has to be made between volumetric models with high accuracy and colour-, contour- and silhouette-based models which require less computing power. Camera-based sensors using skeletal models are a good compromise between the two ends. They are most suitable in the described system, because they offer a good balance between 3D depth maps and computational requirements.
4.1.4 System Structure

To structure the creation of the demonstrator, a function hierarchy and architecture diagram were made. The function diagram illustrates the intended hierarchy in the functionalities. A differentiation is made between three functions:

- Primary functions are the core functions of the demonstrator in the chosen context.
- Interactive functions are the functions necessary for the user to interact with the system.
- Secondary functions are functions that support the primary and interactive functions in performing their tasks.

The architectural diagram shows how the different components work together. Next to the different function enablers, it shows the required processes and information flows. Three different components can be seen in the architectural diagram. First there are input devices, consisting of the sensors and referential databases. Also, there are the computing components that are responsible for all the calculations. Finally, there are two output components, namely the holographic screen and the haptics array.

![Function Diagram](image-url)

Figure 26 - Function Diagram
Figure 27 - System Architecture
4.1.5 Component Orientation

In order to create the demonstrator as a research means, suitable technologies need to be selected. In this section the preferred technologies are selected and companies working with these technologies are compared in order to find the most suitable components for the demonstrator to be created.

In the previous paragraphs, different technologies for the different components were discussed. A preference was given based on the technological research done in Chapter 2 - Analysis. Figure 28 shows a morphologic table including the discussed technologies and the corresponding companies creating products in these categories. Appendix H - Available Components gives a more detailed overview of these technologies. Figure 28 also highlights the most suitable combination of these components for the demonstrator to be created.

Since the benefits of using ultrasound outweigh the drawbacks, the haptic component will exist of an ultrasound array. For the application in a virtual control system, a high spatial resolution is required. The operating distances fit within a frame of 250mm above the projection surface, removing the disadvantage of the short travel distance. Ultraleap provides a suitable development kit using an ultrasound transducer board. The most suitable holographic component would be a photophoretic trapping display, however, considering this technology has not been developed beyond an experimental prototype, it cannot be integrated in the demonstrator. The Simulated Reality (SR) display from Dimenco also comes in the form of an development kit. An eye-tracking stereoscopic display is preferred over the other elements since it delivers the most ‘pop-out effect’. The display is only able to create a 3D effect for a limited amount of viewers, however, this limitation is of little impact since the chosen context only requires one viewer. Camera-based gesture recognition is most suitable for the gesture component. Detailed 3D models are needed in order to recognise and understand the gestures of the user, limiting the possibilities to stereographic and depth-camera usage. The Leap Motion sensor was selected since it is smaller and cheaper than comparable sensors (Behera, Dogra, & Roy, 2017). In order for the different components to communicate and the visual content to be created, rendered and displayed, suitable processing units need to be selected. In both cases, the more powerful the unit is, the better it is able to process the information. The Central Processing Unit (CPU) is responsible for the communication between different function enablers within a system. Currently, the most powerful CPU available is the Intel Core i9-9900K. The 8 cores in the CPU give it enough processing power to deal with multiple complicated tasks at the same time (Newcome-Beill, 2019). Even more important is the Graphics Processing Unit (GPU), which is responsible for rapidly manipulating and altering memory to accelerate the creation of images in a frame buffer. This buffer is created to optimize the output of (3D) graphical content to a display. The most powerful GPU available, using 4352 cores and with a 11GB GDDR6 memory, is the Nvidia GeForce RTX 2080 Ti (Jimenez, 2019).
<table>
<thead>
<tr>
<th>Component Type</th>
<th>Example Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haptic Component</td>
<td>Ultrahaptics, Aireal (prototype)</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Dimenco, Ultra D (Multi-view), Holovizio (Multi-view)</td>
</tr>
<tr>
<td>Air-jet</td>
<td>Looking Glass (Static), Voxon (Swept)</td>
</tr>
<tr>
<td>Holographic Component</td>
<td>Matd (prototype)</td>
</tr>
<tr>
<td>Stereoscopic Display</td>
<td>Fogsense</td>
</tr>
<tr>
<td>Volumetric Display</td>
<td>Helio Display</td>
</tr>
<tr>
<td>Tracking Display</td>
<td>Looking Glass (Static), Voxon (Swept)</td>
</tr>
</tbody>
</table>

**CPU**
- AMD: Ryzen 9 3900X, Ryzen 7 3700X, Ryzen 5 3600
- Intel: i9-9900K, i7-9700K, i5-9400F
- AMD: Ryzen 9 3900X, Ryzen 7 3700X, Ryzen 5 3600

**GPU**
- Nvidia GeForce: RTX 2080 Ti, RTX 2080 Super, RTX 2070 Super
- AMD Radeon: RX 5700 XT, RX 5700, RX 570 4GB

Selected Component

Figure 28 - Morphologic table
4.1.6 Component Detailing

**Ultrahaptics**

Ultrahaptics, owned by UltraLeap, produces haptic sensations by using ultrasound transducer arrays. The Ultrahaptics device is built up out of a 16x16 array of ultrasonic transducers, capable of producing up to 40kHz sound waves. Ultrahaptics’ technology creates one or more focal points of ultrasonic energy targeted on the user’s palm or finger(s). 40 kHz waves cannot be felt by human receptors, requiring the carrier wave to be modulated. (Ultrahaptics, 2018).

The mechanoreceptors within the skin are responsive to vibrations in the range between 0.4Hz and 500Hz (Gescheider, Bolanowski, Pope, & Verrillo, 2002), but the Ultrahaptics system typically uses a 100-300Hz modulation frequency which corresponds to the peak sensitivity of the tactile receptors. The system is designed for hand-based haptics and works best on the palm and fingers, as these areas are most sensitive to the modulated acoustic field. The modulated ultrasound waves, which are precisely controlled, are transmitted from an array of transducers such that the resulting interference pattern creates focal points in mid-air, which in turn can be felt by the user as pressure on the hand. Since the surface of the skin is not particularly sensitive to a fixed control point, the ultrasound signal must be modulated. This can be done by either changing its position (Spatiotemporal Modulation) or intensity (Amplitude Modulation) to one the skin is sensitive to. The force applied to the skin can reach 16 mN, for a contact area of 20 mm diameter (Takayuki Hoshi, Takahashi, Iwamoto, & Shinoda, 2010).

**Dimenco**

Dimenco, a Dutch company based in Veldhoven, produces a development kit containing what they call a simulated reality screen. The screen is a 32 inch 8k LCD display. It uses a lenticular lens to create a stereoscopic image out of two overlapping 4K images. This enables the viewer to perceive a 3D image without the need for additional devices, such as glasses. To obtain the correct orientation in which to display the images, the screen has integrated depth cameras from Intel’s Realsense to keep track of the eye position and distance of the viewer. The depth cameras create a 3D map of the surroundings and recognize facial contours. Facial recognition software uses several overlays to determine the position of the eyes. Using the tracking software combined with the lenticular lens, the screen is able to create a 3D image with a walk around effect. The position of the viewer is transferred to their specialized Application Processing Interface (API), which calculates the orientation of the two separate views based on the 3D data from their unity plugin. Optimal viewing distance for the screen lies between 20 to 70cm with an optimal viewing angle of 30 degrees (Dimenco B.V., 2019).
Leap Motion
Leap Motion creates a gesture recognition device which is aimed at palm and finger control. From a hardware perspective the device consists of two cameras and three infrared LED’s. The cameras track the infrared light with a wavelength of 850nm. This wavelength is beyond the visible light spectrum and cannot be seen by the human eye. The viewing range is limited to 80cm above the device. Combined with large viewing angles, figure 32, the Leap Motion sensor has an interaction space around 0.22 cubic meters. The device’s USB controller reads the sensor data into its own local memory and performs any necessary resolution adjustments. This data is then streamed via USB to the Leap Motion tracking software. The data takes the form of a grayscale stereo image of the near-infrared light spectrum, separated into the left and right cameras.
The data stream reached the computer where the software takes over. After compensating for background content and ambient lighting, the images are analyzed to reconstruct a 3D representation of what the device sees. Next, tracking algorithms and filtering techniques feed the data into a transport protocol. This protocol in turn communicates with the Leap Motion control panel together with several libraries in order to recognize the gesture (Colgan, n.d.).

Appendix I - Spec Sheets contains the various spec sheets of the components that were selected for the creation of the demonstrator. It can be seen that the Dimenco SR development kit already includes a central and graphics processing unit. The Intel Core i7 8700 available is less powerful than the selected i9 CPU. However, based on the minimal system requirements for both the Ultraleap haptics array and the Leap Motion sensor, the GPU should be powerful enough for demonstrative purposes. No complication are expected based on the GPU since the selected unit matched the available one in the development kit.
4.1.7 Component Ergonomics

An important aspect of the integration of the three technologies into a virtual control system is their respective orientation. Due to the nature of the technologies, the haptic and holographic component proposed in this chapter are only capable of projecting directly above the device’s surface. The visual content can only be perceived by the user if the viewing angle is perpendicular to the screen. The haptic content can best be perceived by the user when the palm of the hand is oriented parallel to the surface of the ultrasound array. Since both devices are not able to work in front of each other, a spatial differentiation between the two will exist. In order to create the best possible sensation for the virtual control interface, the projected area of the haptic and the holographic component should overlap as much as possible. Figure 33 illustrates the mismatch in the cyberware when putting the devices perpendicular to each other.

A potential solution for solving this problem can be found in angling the two devices and positioning them at the appropriate height to stimulate the proper body position. This prevents the user from having to adopt an uncomfortable position in order to experience the projected images. A short ergonomics study was done based on the position of the body when interacting with the virtual control device. A standing position was proposed since this is in accordance with the use case in the chosen context. Figure 35 shows different possibilities concerning the position and orientation of the components in order to be perceived correctly. Position 2 was picked as the most suitable due to its large overlapping area of the two projection areas and little spatial requirements. This position was perceived as comfortable and corresponds with the guidelines of the US department of labor (U.S. Department of Labor, 2004). If the standard measurements of adults worldwide (First in Architecture, 2014) were applied to the model, the optimal height of the interaction area could be estimated. The angle between the two components is also estimated. These estimations could be used in future design steps to implement the system in a lavatory. However they are not representative for the potential user group since they are based on averages.
Figure 35 - Component orientation
4.2 Software

The software is responsible for the communication between the different components of the virtual control device and external devices. It also communicates the internal media streams, and is responsible for the 3D simulation data. To better detail the processes the software handles, a flowchart, figure 37, was created. The flowchart describes the processes handled by the software.

4.2.1 Software Platform

In order for the demonstrator to operate correctly a software platform communicating 3D simulations and models is required. The hardware will need to communicate 3D data in the form of an 'holographic' interface. For this communication, a model of a 3D space is required in order to correctly visualize distances and perspective. For the 3D software, game engines are most suitable since they have a solid combination between 3D models and rendering capabilities. Three software platforms; Unity 3D, Unreal Engine 4 and Cryengine 5, were reviewed and a selection was made based on the 3D capabilities, accessibility and cost. Although very similar, some distinctions could be made.

Unity 3D was decided to be the best and certainly most accessible option of the three platforms for the creation of the demonstrator. The primary reason for choosing Unity 3D is its capability of handling 3D models, where Unreal Engine and Cryengine are more focussed on high quality and photorealism. In addition to this, Unity 3D has the largest range of file formats it supports, giving it a large community of helpful supporters and database of models, audio, animations, editor extensions, materials, scripts and shaders. This makes Unity 3D more accessible when compared to other game engines. Looking at the cost of the different platforms, Unity 3D offers the best plan by offering a free license to their full software platform, provided revenue is lower than 100,000 dollar annually. Is the annual turnover higher, Unity 3D offers plans starting from 35 dollar per month. Unreal Engine asks for 5% in royalties based on all generated revenue based on their software. Cryengine does not offer a free license but only a monthly subscription for €9,90 per month (Thinkwik, 2018).
4.2.2 Flow chart

Figure 37 shows the flowchart that illustrates the software processes in order to enable the functions described in Chapter 4.1.4 System Structure. All source code functions are left out since these processes are already embedded in their respective hardware component. In addition to the decisions, the flowchart shows four states of the system which are determining the actions that can be performed. These states can be identified as locked, unlocked, active and idle. The locked and unlocked states determine which actions can be performed when opening the door and the idle and active state determine the input commands that can be given via the control object. Each state also includes corresponding visual cues which will have to be designed.

![Software flowchart](image-url)

**Figure 37 - Software flowchart**
4.3 Cyberware

The cyberware is the visible part of the virtual control system. In order for the system to work correctly the cyberware should stimulate specific movement sets that correspond with the limitations and optimization of the hardware. As discussed before the haptic projection can best be perceived when the palm of the hand is facing the ultrasound array. The designed cyberware should thus stimulate a hand orientation favourable for the haptics device. The next section will first discuss the requirements for the cyber. Afterwards a design proposal is made for the aesthetics of the cyberware.

4.3.1 Gestures

The proposed virtual control system will use gesture recognition to control the cyberware. This gesture control is provided to the system by a Leap Motion sensor. When designing a gesture control based system, some considerations had to be made regarding the visualisation of the content. Figure 38 shows the preferred hand motions from the Leap Motion device. The hand is the main body tracked by the sensor, and by comparing the captured data with internal models it is able to accurately detect the position, orientation and speed of the hand (Leap Motion, n.d.).

When designing a gesture based interface, some requirements need to be met in order for the system to work properly (Babich, 2019):

- The gestures should be comfortable to use; human body ergonomics should be considered when designing the cyberware to create the best possible experience for the user.
- Gestures that require a lot of physical effort should be avoided; when interacting with the cyberware, heavy physical effort should be avoided to prevent a negative experience for the user.
- The duration of the gesture required for the activation should be minimized; gesture controls are great for short periods but fail under longer timelines.
- The designed gesture should be intuitive; intuitive gestures are able to create a better understanding by (new) users of the interface. It can be reached by mimicking real life gestures and avoiding complex movement patterns.

Another important aspect when designing the cyberware for the proposed context is to take the large variety of users into consideration, as discussed in Chapter 2.3 - User Aspects, an aircraft environment contains many different users. These users have different habits and expectations of the system.

Together with the requirements mentioned above, the system should take the three-part process of habit creation into consideration. This habit formation process is a way of ensuring that new users will be successful when they start using the designed cyberware (Duhigg, 2012). This process is build up out of a cycle containing three stages. The first stage uses a trigger in the form of a user cue in order to motivate the user to act. In the second stage, the user performs an action, which will later become the routine part of the cycle. Finally, the user is provided with feedback which rewards him for correctly performing the action.
Rotating motions

Lateral motions

Finger motions

Swiping motions

Figure 38 - Preferred hand motions (Leap motion)

CUE
Kicks the brain into automatic mode
Tells it which habit to use

REWARD
Prize telling your brain
“this loop is worth remembering in the future”

ROUTINE
Physical, mental,
or emotional response

Figure 39 - Habit creation cycle
4.3.2 Interface Design

In Chapter 3 - Conceptualisation, the functions of the virtual control system in a lavatory implementation were already discussed. Two of those functions need to be actively controlled with the cyberware: opening and locking the door. Based on the technology analyses and the ergonomics study, it was concluded that face down, in-plane movements are preferred for the functioning of the system. In order to create a better understanding of the movements that the cyberware needs to mimic, a mood-board was created, Appendix H - Interface Design.

Based on this mood-board, ideation sketches were made, exploring the possible aesthetic options. The ideation can also be found in Appendix H - Interface Design. Figure 40 illustrates the final aesthetic properties for the cyberware. The shape of the activation button is based on the shape of a computer mouse, a familiar shape for most people. Together with the panel underneath the button and the hand image on the button, the image aims at stimulating a flat hand orientation of the user. The slots in the panel indicate the direction of moving (in correspondence with the software) and the arrows invite the user to slide in a specific direction. Opening the door is indicated by the text and the icon on the right. Locking is similarly indicated by text and an icon on the bottom. Indicator lighting around the activation button will illustrate the state of the system, blue for idle, green for opening and red for locked. Referring back to the habit creation process the large activation button serves as the trigger. The action is illustrated by the arrows while the feedback is provided in colour coding, appearing 'locked' cues and the door physically opening.

The control system contains two different panels: an internal and an external panel. The external panel only contains the option to activate the door. The internal panel will also contain the option to lock the door. When the door is locked from the inside, the external panel will display an in-use pictogram preventing activation from the outside.
Figure 41 illustrates the working principles of the system and the different states. The idle state is shown by blue lighting around the activation button. An opened lock on the bottom indicates that the door is unlocked (1). When the user puts his hand on the activation button, the system will invite the user to swipe the button to the right in order to open the door (2). When the threshold for opening the door is reached, the system will provide a visual cue that the door will open by turning the blue indication light green. The button will automatically move back to its original position while the door is simultaneously opened (3). The control panel on the inside of the lavatory also contains the option for locking. After the door automatically closed when the user entered, the internal panel will invite the user to either lock or open the door with indication arrows (4). When the user puts his hand on the activation button and drags it downwards, the indication light will turn red and the lock icon will show a closed lock (5). The process is then reversed in order to unlock and open the door again so the user can exit the lavatory (6).
05
Prototyping
The creation of the physical prototype started by reaching out to Dimenco. They agreed on providing their Simulated Reality development kit and software coding support. Creating the demonstrator was built up of five phases. The first three phases aimed at creating a proof of concept for combining the three technologies into a single system. The final two stages aimed at improving the system by adding functionality and polishing the experience in order to create a standalone demonstrator.

The first phases linked all components together and implemented the basic projection for both the visual and the haptic component. It was expected that calibration was needed in order to perceive both projections in the correct orientation. However, this is a time consuming process which led to the decision to align the projections by shifting the hardware components in relatively the correct position. Initial testing showed that this alignment created a combined experience which was perceived by the user in the same location. Hand models were imported to allow the user to interact with the created projections. Because two Leap Motion sensors were present in the system, one had to be removed in order to prevent contradictory input values. At this point, the proof of concept was achieved and development of the demonstrator was continued. Functional colliders were added together with user cues and visual styling. Some minor adjustments were made to the design based on limitations of the prototyping components. The suggestive plane was replaced by a suggestive hand, showing the correct location and orientation to interact with the interface. Finally the locking mechanism was placed to the left of the activation button since this allowed better spatial displacement. User validation would indicate if the combined experiences of the components would be experienced in the correct way by the user.
5.1 Demonstrator

In order to prove the feasibility of the three technologies being combined into a virtual control system a physical demonstrator is the next step in the project. In the Chapter 4 - Detailing a proposal was made including the required hardware, software and cyberware. The prototyping starts with a proof of concept aimed at providing insights in the combining of the three technologies and the technical feasibility. After the proof of concept, the demonstrator is further developed along the envisioned design to create a prototype ready for user testing.

5.1.1 Preparation

In order to create the demonstrator, Dimenco, the company producing the SR development kit was approached for a potential collaboration. An agreement was made with the design student and Safran in order to experiment and build the demonstrator. Dimenco would provide the screen and assistance in writing software code. Safran provided the Ultraleap haptics module. The design student was allowed to work in-house at Dimenco in order for the process to run smoothly.

The main goal of the demonstrator is to prove the technical feasibility of the combination of the three technologies into a virtual control system. In Chapter 4.1 - Hardware, the available technological components were already discussed. The interface design and the creation of the 3D model will be created using Unity 3D. Unity uses C++ and C# as its primary coding language. In order to build the demonstrator the prototyping process is divided into five phases.

- **Proof of concept:**
  - Phase 1: will focus on setting up the hardware, acquiring the required software plugins and for the design student to get a basic understanding of Unity 3D. Potential connection and software related issues need to be solved in this phase in order to progress to the next.
  - Phase 2: will focus on the creation of a haptic and holographic projection that exist in the same space and are calibrated to overlap. Potential spatial orientation and delay issues will have to be fixed in this phase in order to progress to the next phase.

- **Demonstrator:**
  - Phase 3: will focus on the controllability of the in phase 1 described projection. For this the Leap Motion sensor will be integrated into the system. Potential delay and overlap issues need to be solved in this phase in order to progress to the next phase.
  - Phase 4: will focus on adding functionality to the created interface. The functions described in Chapter 4.3 - Cyberware will be implemented and the designed user cues will be added to the simulation. Potential functionality issues need to be solved in order to progress to the next stage.
  - Phase 5: will focus on polishing the simulation. Aesthetics and ease of use will be the primary concern of this phase in order to prepare the demonstrator for user testing. Issues concerning formal language and user expectations will have to be solved in order to progress to user testing.
Based on previous research concerning the technologies and the context implementation several issues are expected that need to be solved. Solving these issues can be done by either adjusting the hardware orientation or altering software code in order for the information to be processed correctly. These expected issues and their potential solutions are:

- **Image Shift**: Image shift occurs with stereoscopic displays when the user changes position. This would prevent the haptic and holographic projection to exist in the same volume of space. This issue should be solved by using Dimenco’s eye tracking software to fixate the projected image based on the viewing angle and distance.

- **Content Blocking**: Because a stereoscopic display is not a true volumetric display, the visible content needs a screen to be perceived by the user. Hands blocking the screen or images ‘falling’ off the screen will prevent them from being displayed. This issue should be solved by carefully positioning and scaling the software content in Unity 3D.

- **Spatial Calibration**: As previously discussed, a mismatch could be expected when orienting the haptic and holographic component perpendicular to each other. This prevents the haptic and holographic content to be perceived in the same orientation by the user. This issue could be solved by either changing the hardware orientation or the orientation of the simulation in the software.

- **Hardware and Software Delays**: Delay issues could be expected since the different components use different processes and plugins in order to process the information. Issues concerning delays could be solved by either applying changes in the source code of the different plugins or by implementing delays in the simulation as well.

![Figure 42 - Dimenco SR screen & Ultrahaptic transducer array](image-url)
The next step is to execute the proposed prototyping phases in order to create the demonstrator. The first, three phases will focus on the proof of concept. After these phases the feasibility of the system will indicate the progression of the process. The final two phases are structured around further development of the functionalities of the system and optimizing it for demonstrative purposes. Image 42 shows the setup of the different components. Initial prototyping of the proof of concept was done on a different screen then the proposed development kit, due to its accessibility. Although this screen is smaller and has a lower resolution, it functions identical to the larger version. After optimization of the software code, final calibrations will be done on the development kit in order for the demonstrator to work correctly. Figure 43 shows the different phases of the prototyping process. Appendix L - Prototyping contains a more detailed description of the prototyping process including the corresponding software code.

**Phase 1:**
All hardware is connected to a single CPU. The required unity plugins are downloaded and installed to the newly created unity project. All separate plugins are tested to function correctly and the screen orientation is set up for the desired project.

**Phase 2:**
After setting up all the hardware and making sure the required unity plugins are functioning correctly, prototyping could start. First code is written in order to create a circular haptic sensation and optimizing the distance to the array. This is done in order to maximize the sensation. A game object is added in the form of a ball and given the same orientation as the haptics projection, aligning them correctly moving the haptics component in the correct position. Finally the combined object is given two axes of freedom in order to allow movement along the x-axis and z-axis.

**Phase 3:**
After creating the aligned sensation, the next step is to add a hand model as an input parameter. The data and 3D representation from the Leap Motion sensor is imported and a new game object is created. A collision model is added to the already defined shape and allowed to move when colliding with the hands predetermined collision points. The data from the Leap Motion sensor connected to the SR screen is used. Because the sensor in the SR screen is embedded in the hardware, it is harder to remove. The haptic sensation is projected at a fixed height and will move according to the hand motion. Because of this the hand orientation is of no importance to the projection of the haptic sensation.

**Phase 4:**
After phase 3, the hand models are implemented in the game engine, and are able to interact and manipulate the shape. The next step is to implement collision models and software rules to add functionality to the system. In the detailing the envisioned functions were already described. In order to open and (un)lock the door, two colliders were added. Rules were written to ensure that the appropriate action would be performed when the the controllable object would reach the threshold. A timer was added to ensure closing of the door would happen automatically after the desired duration.

**Phase 5:**
The final phase is to polish the design of the control device. User cues are added in the form of arrows, a lock and color coding. The arrows indicate the direction the control object could be moved in. The lock indicated the state of the door and the color of the control device indicate the state of the system as described in Chapter 4.3 - Cyberware. Together with the user cues, additional graphical changes were made in order to make the content more visually appealing. Finally a door was added in the background to show opening and locking when the correct action was performed, providing the user with feedback.
Phase 2

1. Haptic Projection
2. Add Game Object Ball
3. Allow Movement
4. On Screen view

Phase 3

1. Add Hand Model
2. Allow control by hand
3. On Screen view
4. Leap Motion Data

Phase 4

1. Add opening collider
2. Add locking collider
3. On screen opening
4. On screen locking

Phase 5

1. Add user cues
2. Final Design
3. On screen view

Figure 43 - Prototyping Process
5.1.3 Practical Evaluation

After the prototyping is done, a practical evaluation is made based on the issues that were found when constructing the demonstrator. Also the ability of the created prototype to function as a demonstrator for user testing should be evaluated.

Issues:
Figure 44 shows a representation of the final outcome of the created interface which will be displayed by the prototype. However, due to the nature of how a stereoscopic image is formed, the 3D effect cannot be seen. Multiple issues are found when constructing the prototype. Minor issues are not discussed in this section, they can be found with their respective solution in Appendix L - Prototyping. Other issues that were found and require a more extensive solution are discussed in the next section.

Leap Motion delay
A delay is experienced when using the Leap Motion sensor. This delay is caused by the device going through the processes of recognizing the hand. In Chapter 4.1.4 - System Structure, the process of the gesture component recognizing the hand can be found. The delay prevents the user from immediately using the control component but requires the user to keep its hand in a fixed position inside the motion sensors range. As soon as the hand is detected and the internal model is created there are no further delays to be found. A potential solution could be found in changing the priority of the system. By making the system able to use the full processing power for the detection process this delay could be minimized. The same solution is already used by Dimenco with their facial recognition process.

Calibration of the gesture device and the SR screen
As discussed in Chapter 2.1.4 - Technological Combination, the visual and the haptic component should be able to project in the same volume of space. In order for these two projections to be perceived at the same point they have to be calibrated to overlap. For this calibration the orientation of the devices with respect to each other should be fixed. The calibration is then done by aligning the positions in the software. However, this is a time consuming process. In the creation of the prototype the calibration is done by eyeballing

Figure 44 - Final interface design
the position of the holographic projection and sliding the haptic component in the correct orientation respectively. For experimental purposes the current alignment is deemed sufficient in order for the user to experience both projections correctly.

**Double Leap Motion sensor**
For the creation of the functional prototype two Leap Motion sensors are included. One is already included in the haptics development kit. A next sensor is already included in the Simulated Reality development kit from Dimenco. Both sensors are calibrated to their respective parents orientation. For the prototype the Leap Motion sensor of the haptics board is excluded. Using two gesture input sensors means that the gesture API gets multiple input data streams that conflicted each other. The haptics device can easily be excluded from the system since it is not embedded in the hardware. In a following iteration of the system, a single gesture component will be used preventing the described problem.

**Suggestive plane for hand orientation**
In Chapter 4.3.2 - Interface Design, an angled plane was implemented into the system. The idea behind this plane was that it would in encourage the user to approach the interface with the correct hand orientation. However this plane could not be created using the stereoscopic screen due to it mostly falling outside the screen borders, and thus would not be visible as 3D content. In order to solve this problem the proposed design is altered replacing the suggestive plane by a hand, hovering above the control object. The hand indicates the location the user has to position his hand to interact with the interface. As soon as the control object is activated, the hand disappears. User testing should validate the effectiveness of the trigger.

**Visual polishing**
As was already briefly described with the previous issue, most of the visual cues added to the system to indicate functionality need to be validated during user testing. Visual polishing of the system is an ongoing process. Visual cues could be added or changed in order to make the system more understandable. However the focus of this project is not to create a door opening system. It focuses on testing the combined functioning of the three component technologies into a single system. The visual representation of the current prototype was created in order to validate the understandability of the three components in a virtual control system. Later iterations of the system require more visual polishing and context specific user cues in order to operate correctly.

**Screen and array orientation**
The current prototype started with a perpendicular orientation of both projection devices. This orientation turned out to be sufficient in order to create a combined sensation. However, this orientation is mostly linked to the fixed orientation of the current SR development kit. In later iterations different orientations could be explored in order to optimize the context specific experience as described in Chapter 4.1.7 - Component Ergonomics. The expected mismatch of the two projection components did not turn out to be an issue in the creation of an perceivable experience. No true alignment between the two images is created. Instead the haptics device created its tangible projection at roughly the same location as where the user expects the shape based on the image projection. User validation should indicate if the created sensation is able to create a strong enough experience for the user or that a better alignment of the components is required.

**Screen and array size**
The prototype was built up of two development kits with fixed measures. The dimensions of the different components are not specified to the required interaction and projections. The screen is oversized where the haptics module limits the available gestures. For the demonstration of the technologies working together, the prototype serves its purpose. However a more context focussed demonstrator could take the measures of a lavatory implementation into account. This would include scaling down the screen dimensions. Also the haptics array should be optimized to suit the special requirements of the gestures better.
06 Evaluation
Chapter Summary

The evaluation aimed at creating insights in the functioning of the three technologies in a combined virtual control system. Since the goal of the project was to explore the possible integration of the three technologies, the evaluation focussed on the understandability of the components rather than the functioning of the designed interface. A validation session was planned with Dimenco since the SR development kit would be needed to execute the experiment. A proposal was written, allowing the participant to interact with four different systems in a random order:

- Interface A: 2D instruction screen with gesture control.
- Interface B: 2D instruction screen with haptic feedback and gesture control.
- Interface C: 3D interface with gesture control.
- Interface D: 3D interface with haptic feedback and gesture control.

The participants’ reactions were noted in a code book to evaluate their emotional experience together with their action times for the different actions performed during the experiment.

Results indicated a strong preference from the participants towards the 3D based interfaces. Reaction times confirmed this conclusion by showing more consistent action times for the 3D based interfaces. Looking at the difference between the first action and the consecutive actions, a major difference can be seen when comparing the 2D interfaces with the 3D interfaces. The 2D interfaces show a large difference between the two where the 3D interfaces do not. This suggests that the 3D interfaces are more intuitive to use, where users seemed to struggle with finding the correct interaction space for the other interfaces. Based on the codebook, haptic feedback was preferred by the user, however this was not seen as a significant result in the action times. Results are not considered conclusive since the participant group was too small and did not represent the intended target group of aircraft passengers. The comparison between the 2D and 3D based interfaces should be further developed, creating equally well defined systems. Pure gesture recognition showed the shortest action times after the initial action which might indicate a more intuitive system if executed correctly, more research and testing is required.
6.1 User Validation

This project aimed at the exploration of the possibility to combine three technologies into a virtual control system. The separate technological components were analysed and a context implementation was chosen to structure the design of the system. The design of this system concluded with a functional prototype in order to demonstrate the functionality of the three technologies. This chapter will focus on analysing the user experience when interacting with the system.

6.1.1 Introduction

The user validation will be aimed at creating insights in the functioning of the three technologies into a combined control system. Together with the combined function, the understandability of the technologies and their added value with respect to this understandability will play an important role. The validation will exist of 4 stages, starting with setting up the user test and introducing the participants to the context. After the testing itself, some post-test questions will be asked regarding the experience of the test setup. Conclusions will be drawn based on reaction times and emotional expressions. A more in depth overview of the user validation can be found in Appendix M - User Validation.

6.1.2 Approach

The user test will be built up out of four stages. Stage 1 will focus on the test setup. The second stage will focus on instruction the participant. Stage 3 will be the actual user test. The fourth and final stage will focus on creating insights in the test results and draw conclusions.

Stage 1: Test setup
The created functional prototype will be used for the user validation. The first step is to set up the demonstrator. The SR screen, haptics board and the additional computer are needed for the hardware to function properly. The Test setup can be seen in figure 45. A test run of the experimental setups will be done in order to verify the correct working of all components. The validation is done using students at the faculty of Industrial Design Engineering. Testing will be done by positioning the test subject in front of the screen after a short context introduction.

Stage 2: Pre-test
The second step is to inform the participant of the expected procedures. The participant will be asked to speak his thoughts out loud for reflective purposes. Also, he will be notified that video footage will be made of his actions. If he agrees to this, the participant will have to interact with 4 different user interfaces, and perform the same four action with every iteration.

- Interface A: 2D instruction screen with gesture control.
- Interface B: 2D Instruction screen with haptic feedback and gesture control.
- Interface C: 3D interface with gesture control.
- Interface D: 3D interface with haptic feedback and gesture control.

The lavatory context will be explained to the participant and he will be asked to open (A1), lock (A2), unlock (A3) and open (A4) the lavatory door. When the participant confirms his understanding of the procedure, the next stage will commence.

Stage 3: User test
During the user test, the participant will receive four versions of a control system in order to perform the actions as described in the previous stage. The order of the iterations is written down and after every iteration the three questions concerning the functioning are asked:
1. Did you understand what was expected from you? Why/why not?
2. Did the system operate as you expected it to do? Why/Why not?
3. Would you be able to operate the system again without any additional instructions? After all iterations of the system are used, five more questions concerning the preferences of the user and his opinion are asked:
4. Rank the systems based on understandability (A/B/C/D). Why?
5. Rank the systems based on your personal preference (A/B/C/D). Why?
6. Do you think the haptic feedback provided added value to the system?
7. Do you think the 3D image projection provided added value to the system?
8. What kind of environment would you expect a similar system to operate in?

All results are noted on the form that can be found in Appendix M - User Validation.

Stage 4: Post-test
The post-test stage will focus on acquiring the information that was not written down during the user test. Video footage will be rewatched and time durations will be written down for every participant and the corresponding action. Next to the interaction time, a codebook is created, listing relevant reactions. These codes are able to reveal patterns in order to judge the experience of the participant while using a specific interface.

Figure 45 - User test setup
Lavatory Door Controls

Make Fist To Lock

Open Fist To Unlock

Move Hand In Front

Swipe Left To Open Door

Figure 46 - Interface A, 2D with gesture control

Lavatory Door Controls

Move Left To (Un)Lock

Grab Sensation Here

Move Right To Open

Figure 46 - Interface B, 2D with haptics and gesture

Figure 47 - Interface C & D, 3D with(out) haptics and gesture control
6.1.3 Results

The video and audio footage of every participant has been analysed and transcribed. The transcription is used to link codes to the behaviour and actions of the participants. These codes will be able to provide qualitative feedback on the experience of the participants. It is not possible to use absolute codes since the user experience changes over time and is unpredictable. Appendix M - User Validation contains the full transcripts and codebook, as well as all results. The different codes can be subdivided in three main categories, describing the experience of the user interacting with the system:
- Positive
- Neutral
- Negative

Figure 49 shows the results of the coding with respect to the different systems as well as to the order with which the participant interacted with the systems. Two trends can be clearly seen. First, the amount of positive coding increases with each progressive system. The more often the participant interacted with the various systems, the more familiar he or she became with the technology and thus the more positive their experience. Another result which is notable, is the increase in positive responses when comparing the systems that use the 3D display in comparison with the 2D interfaces.

Next to the codebook, video footage was used to analyse the time each participant took to complete the various actions for the different system interfaces. The summarised results of this experiment can be seen in figure 48. Looking at this figure, it can be seen that the action times of the systems using a 3D interface are on average lower than the ones using the 2D interface. Also the addition of haptics seems to improve the action times for the respective 2D and 3D interfaces. More notably even, is the difference in the action times when first interacting with a system in comparison to later actions. With the 2D interfaces there is a distinct difference in action time between the first action in comparison with the follow-up actions. This difference in action time can not be seen with the interfaces using 3D content.

<table>
<thead>
<tr>
<th>Action</th>
<th>Interface A</th>
<th>Interface B</th>
<th>Interface C</th>
<th>Interface D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action 1</td>
<td>11,8</td>
<td>11,4</td>
<td>3,5</td>
<td>2,3</td>
</tr>
<tr>
<td>Action 2</td>
<td>9,0</td>
<td>3,4</td>
<td>2,8</td>
<td>2,7</td>
</tr>
<tr>
<td>Action 3</td>
<td>2,4</td>
<td>5,4</td>
<td>3,4</td>
<td>2,0</td>
</tr>
<tr>
<td>Action 4</td>
<td>2,8</td>
<td>3,0</td>
<td>2,4</td>
<td>1,5</td>
</tr>
<tr>
<td>Action avg</td>
<td>6,5</td>
<td>5,8</td>
<td>3,0</td>
<td>2,1</td>
</tr>
</tbody>
</table>

Figure 48 - Action times per interface
Figure 49.1 - Coding results based on interface design

Figure 49 - Coding results based on interaction order
6.1.4 Conclusions

Looking at the results from the user validation the following conclusions can be drawn. Firstly the results indicate that the users prefer the interfaces using 3D content. The amount of positive comments and remarks is considerably higher for interface C and D. Looking at specific coding, the participants are more fascinated and impressed by these systems, and feel confident using them.

Interface A and B are considered more confusing by the participants, creating more negative experiences as a result. Also, the first system the the users interact with result in the largest amount of negative coding and learning codes. This number decreases when the uses work with progressive systems, indicating a learning curve. This learning curve results in a larger number of positive comments when interacting with follow-up interfaces, regardless of the interface.

Looking at the action time data, it can be concluded that there is a significant difference in understandability between the various interfaces. Interface A and B have longer action times for the first actions then the follow-up actions. The interfaces using a 3D screen do not have this difference but show consistent action times over all performed actions starting from the first one. From this it can be interpreted that the 3D content clearly indicates to the participant where to interact and what movement to perform.

This conclusion is also confirmed by the transcripts. Practically all participants showed difficulty determining the initial gesture position with interface A and B. However with the 3D interfaces the showed an immediate desire to reach out to the 3D object and grab it, making the action seem very intuitive.

Comparing these conclusions with the intended goal of the user validation, investigating the understandability of the three technologies combined the following statements can be made;

• A control interface with only gestures is initially harder to understand for the user, due to the interpretation of the activation area and how the gestures are interpreted differently per user. However, if the initial interaction area was determined, controlling the interface resulted in comparable action times when compared with more complicated systems.
• A control interface using gestures and haptics, is better understandable since it provides some feedback. However the issue concerning the initial interaction zone still exists, making it more complicated for users to interact with the device when you compare it to the interfaces using 3D content as information carrier.
• A control interface using 3D projections has significant benefits over 2D interfaces in understandability. Users are able to immediately detect the area where they should interact with the interface in order to control the system.
• A control interface using 3D projections and haptic feedback is preferred by the user since it provides additional feedback when the user is interacting with the interface. The 3D effect carries all the information of the system, whilst the haptic feedback assures the user that he or she is operating the system in the correct spot.
• A fast learning curve can be seen when interacting with the system. Due to the simplicity of the actions users are able to easily recreate their actions, even with the interfaces that were harder to understand initially.

Matching these conclusions indicates that a control system consisting out of a holographic projection, haptic feedback and gesture recognition, is able to create a clear understanding with the user. Technically the different projections are not fully overlapping and do not exist at the same point in space, with the same orientation. Nevertheless, initial test results show that the separate technologies are able to create a clear understanding with the user about the functioning of the system.
6.1.4 Discussion

Due to the limited time the demonstrator was available for user testing, the validation group only consisted out of 8 participants. Only 5 of these participants were recorded on video, enabling the timing of the actions. Because of this, more testing will be required to validate the results. The results and conclusions discussed previously should be interpreted as indications but can not be labeled as conclusive. Further testing is required in order to validate the above mentioned findings.

Next to a limited amount of participants, the participants that took place in the validation are not completely representative for the intended user in an aircraft environment. In order for the results to be viable for Safran, further testing is required. This testing should be done with a participant group which provides a better representation of the diverse passenger group that could be found in an aircraft environment.

In the previously described validation, a study is proposed where the different technologies are stacked on top of each other creating progressive system interfaces. A test using simple gesture input was used as a reference. This gesture-based test however, had no design phase behind it and felt very primitive compared to the 3D interface. In order to truly create a distinction between a 3D projection and a purely gesture based system, a better design is required for the gesture system. The learning curve indicates that a purely gesture based system, if worked out correctly, could be comparable in creating an understanding with the user. This would give it significant cost, weight and spatial advantages over the 3D system. Further testing is recommended.

![Participant interacting with the interface](Image)

Figure 50 - Participant interacting with the interface
6.1.5 Quotebook

Looking at the qualitative data some interesting quotes can be found regarding the different system. For the understandability of the report the quotes are translated into english. For every interface two quotes are picked linked to the understandability of the respective interface.

When looking at interface A (2D interface using gestures) the following statements were selected:
• ‘Yes it opened when I moved my hand to the right. But without visual cues it is tricky to determine the state of the door.’
• ‘If you know where to be and what gestures to make it is easily reproducible!’

These statements clearly indicate the shortcomings of the interface. A better designed version should take visual cues into consideration together with an natural and intuitive location to make the gesture.

Looking at interface B (2D interface using gestures and haptic feedback) the following statements were selected:
• ‘Yes! now I can feel it clearly, I think my hand was not in the correct spot before. A bit to low.’
• ‘It was logical where I had to position my hand, you can feel it, you can feel it quite clearly’

These quotes indicate the concluded problem with only using the haptic feedback. Finding the initial position to interact with the system is unclear. However when the spot is found, the haptic sensation does provide feedback to the user.

Looking at interface C (3D interface using gestures) the following statements were selected:
• ‘You can clearly see where to put your hand, it is clearly indicated.’
• ‘That went pretty easy! Yes that is clear. There weren’t really things I was still wondering about.’

These quotes indicate the clarity the 3D content provides. Participants were able to quickly and without hesitation, or making any mistakes, able to identify the position with which to interact with the interface.

Looking at the final interface, D (3D interface using gestures and haptic feedback) the following statements were selected:
• ‘As a result, you also have the idea that there is really something here. This seems like there is something here. It also doesn’t matter how far you get from it, but intuitively you know where to find it.’
• ‘Yes, yes ... I thought it wouldn’t do much more, the feedback from that air, however it’s a bit clearer than I thought it would be.’

These final quotes clearly indicate that, although small, the addition of the haptic feedback clearly contributes to the understandability of the interface. The combination of a 3D visual with a haptic sensation creates a better understandability of the interface the user interacts with.
07 Recommendations
Chapter Summary

The final chapter aimed at creating insights in the performed work. It also listed the future development that is needed to further structure the creation of a virtual control system. The chapter started with reflecting on the taken steps in the project, their conclusions and the respective points of improvement. Afterwards recommendations were given based on the findings in this report.

In the analysis phase, additional research is required towards unexplored topics. Holographic technologies are discussed to great extend. However, alternative technologies for the haptic component and the gesture component might be explored in more depth. Ways of improving the haptic sensation could improve the systems feedback and electromagnetic gesture sensing might be a more accurate and faster alternative for camera based gesture devices. An exploration towards different implementation environments should be conducted to identify potential use cases. This study should also consider implementations outside an aircraft environment. The creation of a second and improved demonstrator could be used to further develop the system and its functioning inside an aircraft environment. The user evaluation could be improved by creating an equally well designed gesture based system and compare this with the current 3D system in order to create valuable insights in the added value of 3D content in a lavatory implementation.

Finally the chapter concluded with providing recommendations for future development of the system. As long as true volumetric displays are not available, there will always be limitation to the use of pseudo holographic devices. Weight and cost play an important factor in the aircraft industry, both have to be optimised in order for the system to become viable. The calibration of the different components is not reached on a single point, but rather uses the perception of the human brain to perceive to separate projections in the same place. If the calibration could be improved the system might improve, however user testing seems to indicate that the current method of bringen the technologies together creates a understandable experience. More research is required to further validate this. Finally a careful consideration with regard to a sole gesture recognition system is recommended in a lavatory implementation since it might provide better value versus cost.
7.1 Project Conclusions

The next chapter will focus on the final conclusions of the project based on the separate chapters. It will list the findings and conclusions of every chapter and show which decisions were made. It will also highlight which assumptions were made in order for the project to progress. Next to the made decisions in the design, the chapter will also highlight shortcoming of the process and suggest potential improvements for further research.

7.1.1 Analyses

The analyses of the project largely revolved around creating an understanding of the three proposed technologies in this project. Available technologies and separate technology readiness levels were needed in order to explore a potential combination. An ultrasound haptics component was already available at the start of the project, the analysis confirmed that this was the most suitable component to use. Photophoretic trapping was concluded to be the most preferable technology since it is the only technology capable of creating true volumetric image. However, due to its technological immaturity, stereoscopic displays were argued to be potential substitutes since they are able to coexist in the same space as the other components. Camera based gesture recognition devices were proposed since they are more readily available and multiple companies providing them could be found. However, radar gesture sensing could provide a more suitable alternative, but more research is required.

7.1.2 Conceptualisation

The conceptualisation chapter started by exploring possible application environments inside an aircraft environment. This section was based on the preceding user and environmental analyses. Creative sessions were held with Safran employees in order to identify potential interesting application environments for a virtual control system. Three environments were chosen; the lavatory, the first class cabin and the self service galley. User scenarios were created for each environment to determine potential implementations inside that scenario for a virtual control system. One promising implementation for each environment was chosen and expanded into a concept for the virtual control system. Since the project focuses on the integration of the three technologies into a virtual control system, the concept choice depended heavily on the simplicity of the implementation combined with the added value of the concept to the described environment and user. After consultation with the project owner, Safran, door controls for the lavatory context were chosen to be a suitable fit. This context would be used in order to further structure the development of the system. This conceptualisation part of the project was heavily marked by fixation. Since there was already a project completed on the lavatory concept, this concept had a clear added value. Future research should include more elaborate studies towards the implementation of a virtual control system inside, or even outside, an aircraft environment.
7.1.3 Detailing

The detailing chapter was used to further detail the chosen concept so it could be prototyped. First the most suitable components were picked based on the technology analyses and the availability of corresponding hardware. Ultrasound haptic feedback, eye-tracking stereoscopy and camera-based gesture recognition were chosen to be the most suitable components. A function diagram and system architecture were created to describe the functioning of the three components together with the corresponding computing components. A morphologic table was created, showing the different technologies and selecting the most suitable components for the creation of the prototype. A brief description was given of the chosen components. A proposal for a software platform and the respective software flowchart were given. Finally the interface was designed for the chosen concept. Based on the possibilities the three technologies provided, a design was created to fulfill the required functionalities.

7.1.4 Prototyping

For the prototyping section, a collaboration was initiated with Dimenco, the company that creates the Simulated Reality development kit (stereoscopic display). Dimenco offered the design student assistance in the form of a software engineer to help with the coding and the availability of a development kit to prototype with. The prototyping was limited by the orientation and structure of the pre-made components. This limited the possibility to place the different components into various orientations. The first part of the prototyping focused on the creation of a proof of concept. Showcasing that the technologies could coexist in the same volume of space to create a virtual control interface. The haptic and holographic components were aligned in software and hardware to create a tangible 3D image. No true integration was required since both projections were created separately and overlapped manually to create a perceivable interface. In addition to the projections, the gesture recognition device was not used to detect gestures but only to generate input in the form of the hand position and orientation for the software. After the creation of this proof of concept, functionality was added and the design was polished in order to create a stand-alone demonstrator.

7.1.5 Evaluation

The user validation started with the set-up of the experiment. Different versions of the control interface were created in order to create an understanding in the functionality of the individual components. More importantly, the validation aimed at investigating the added value of the different components with regards to the understandability of the system. All results were transcribed and coded. Together with the action times the user needed to perform the requested tasks, they formed the results of the validation. The results showed an increased amount of positive reactions towards the 3D based interfaces. Also the action times were more consistent showed a faster understanding of these interfaces. These results however are not conclusive due to the limited amount of participants used in the validation. To further validate the results, a large scale test is recommended, using a better representation of the intended target group. Also equal functioning systems should be created in order to create a valuable comparison. This project focused on the design of a 3D-based interface, where the 2D and gesture interfaces created for the comparison lacked proper research backing the design.
7.2 Future Development

The final result of this project was a demonstrator showcasing the technologies combined in a single system. Due to time limitations, multiple assumptions were made. In order for the envisioned concept of a virtual control system to be further developed more research is needed. The next chapter will recommend future developments in order to create a better understanding of the envisioned virtual control system and is feasibility.

7.2.1 Technology Aspects

Holographic component
The proposed concept uses a stereoscopic display as the holographic component. Due to the way the 3D image is created stereoscopic displays have some drawbacks. Firstly, a screen always has to be present behind the projection in order for the user to see the projected image. Secondly, combining a stereoscopic image with a gesture, results in the hand blocking a part of the screen. Because of this, the 3D effect will temporarily be lost, limiting the functionality of the interface. Currently, eye tracking combined with the screen resolution allows for one viewer at the time. Future improvements based on pixel density and processing power suggest that the viewer count might increase. However the previously mentioned drawbacks will remain the same.

Photophoretic trapping is an experimental technology which does create a true volumetric image which would be a more beneficial technology for the proposed system. Due to its immaturity however, photophoretic trapping is a long way from being implementable. Technological progression should be followed in order to judge if the technology will provide a viable opportunity.

Gesture component
The gesture component in the proposed control system uses an infrared camera sensor to detect the hand position and orientation. The gesture recognition device was chosen because of its already present availability and calibration with the other components. However, during the prototyping of the concept it became apparent that the delay of the device detecting the hand, limited the usability of the control interface. It is expected that this issue can be solved by changing the priorities in the Leap Motion source code. Radar based gesture detection might also be a suitable alternative since it has better accuracy and reaction times than camera based sensors. Experimentation with radar based gesture recognition devices is needed to validate this recommendation.

Embodiment
The embodiment of the proposed concepts was limited to the creation of a demonstrator. The dimensions of the individual components were not adjusted to each other and the context. In order to further develop the demonstrator, the size of the screen and haptic component should be adjusted to better fit the required interaction with the user. This would require for the screen to be scaled down and for the haptics array to be made shallower and wider. The exact dimensions need to be further determined.

Next to the individual dimensions, a shell
needs to be created containing all hardware components. This shell should be integrated into the airplane environment. A more detailed study towards this implementation is needed if a viable control panel is to be created. Complications that can be expected using the current components in an aircraft environment are weight and size. The devices have considerable weight numbers to them due to the large amount of electrical and other components. In an aircraft environment this weight needs to be drastically reduced in order for the system to be implementable. Next to the weight, size might cause several implementational issues in an aircraft environment. A space efficient solution has to be designed for the system to be implementable.

Cost
Another factor limiting the commercialisation of the current design for a virtual control system, is the cost. The current price for the haptic component (including all required hardware and the leap motion device) is €5000,-. The Dimenco SR kit (including CPU, GPU and leap motion sensor) retails at €19.990,-. Over time, and using smaller components, prices of individual components will most likely decrease. However, research and development cost, production cost, transport cost and profit margins still need to be included in the final price. At this point it is difficult to estimate the final price per system with the current technologies, but it will most likely range from €15.000,- to €35.000,-.

7.2.2 Integration Aspects

Calibration
The created prototype does not realise a true overlapping calibration of the proposed technologies. This means that at a single point in the interaction space, there is no coexistence of a holographic and a haptic projection. The current prototype projects two separate images in the same space. These images are given the same orientation and position so they can be perceived by the user as being in the same space. The human brain creates the experience that the two projections belong together. To discover to what extent the two projections are perceived as one, more research is needed. Whether true alignment is even possible using the proposed technologies is hard to say. For true alignment, the orientation issue as proposed in Chapter 4.1.7 - Component Ergonomics comes into play. In order to exist in the same point, the haptic and the holographic device need to have the same direction. This means that since both projection devices are not able to coexist in the same place, one of the projections needs to be redirected. Considering the lenticular lens is needed to perceive the 3D image, the only possibility is to redirect the ultrasound projection. A possibility is to bounce the ultrasound waves, some initial testing showed that glass could be used to bounce ultrasound. However, more research is required.

Orientation
If the current technological components are selected for further development of the system, a closer look has to be taken at the orientation of the two components with respect to each other. Currently, they are positioned perpendicular to each other due to the stock orientation of the selected components. In later iterations of the lavatory implementation, a proper orientation should be designed. Both respective orientation and orientation of the full control panel need to be defined further in order to be used by the passengers. The orientation estimations proposed in Chapter 4.1.7 - Component Ergonomics could be used as a starting point for this ergonomics research.

Sound
Another development that could further improve the understandability of the proposed control system, is the addition of sound. Audio cues might provide an additional level of feedback to the user operating the system. Currently the functional feedback is only provided to the user using visual cues. A limiting factor to the implementation of audio cues might be the ambient sound that is already present in an aircraft environment. A separate study towards the integration of sound should be conducted to validate this proposal.
### Human Aspects

#### Added value
A careful consideration is needed based on the added value of the three technologies into a virtual control system. As was already mentioned previously, the current proposed system has limitations and the costs are high. This project focused primarily on the combination of the three technologies into a combined control device. Added value of implementing a virtual control system can clearly be seen in a lavatory implementation. However, a careful assessment needs to be made, judging if the added value is worth the effort and cost. Based on the findings of this project the results seem to indicate a negative outcome of this assessment. Potential implementation environments might be found outside an aircraft environment. In addition to this, a more suitable solution for a touch-free opening mechanism could be found for the lavatory. Both topics need further investigation.

#### Gesture usage
The current proposed virtual control system does not use gesture recognition in its processes. Gesture recognition would imply that the system would use a database to recognize and interpret a gesture made by the user. Instead, the used gesture control device created a 3D representation of the hand using its position and orientation. This position and orientation are then used to create collision models in Unity 3D in order to interact with the visual content. Using gesture recognition on its own might create an interesting opportunity however. Gesture recognition could be used to create a more intuitive and less limited system (compared to the current proposal) to open lavatory doors. Using solely gestures would require less advanced, expensive and immature technologies, making an implementation more likely. If Safran wants to create a lavatory door opening system, gesture recognition as a standalone technology might create a viable solution.
7.3 Final Conclusion

The project was a mayor challenge due to its technological advanced nature and the explorative nature of the process. The technology research indicated several expected complication when combining the three technologies into a virtual control system. Not all complications were overcome during the development of the demonstrator. Initial testing showed a good understanding of the system by the participants indicating that the use of a virtual control system might add value. Next to this usability, a large interest and amazement towards the technology could be seen, indicating its fascinating nature. However, more research and testing is required in order for the system to be viable in an aircraft environment. Due to its high cost, large spatial properties and weight, entrance barriers into commercial application are high. Implementations outside of an aircraft environment might provide more valuable results. An in context demonstrator could provide additional data on the functioning of a virtual control system in a lavatory implementation and further validate the concept. Figure 51 shows a potential design for an in context demonstrator. For commercial implementation however, it is advised to keep following the technological progression of the proposed components. In a more mature stage of their development, the project could be revisited.

Figure 51 - Look and feel
Sources
IEEE International Workshop on Robot and Human Communication. https://doi.org/10.1109/ROMAN.1993.367718


• Leap Motion. (n.d.). Hands — Leap Motion C# SDK v2.3 documentation. Retrieved November 17, 2019, from https://developer-archive.leapmotion.com/documentation/v2/csharp/devguide/Leap_Hand.html#getting-the-hand-characteristics


• M. Takahashi and H. Shinoda, “Large aperture airborne ultrasound tactile display using distributed array units,” Proceedings of


• Morgan, J., 2008, Manufacturing Readiness Levels (MRLs) and Manufacturing Readiness Assessments (MRAs), Performed by AFRL/RXMT, Wright Patterson AFB, OH.

• Morgan, J., 2008, Manufacturing Readiness Levels (MRLs) and Manufacturing Readiness Assessments (MRAs), Performed by AFRL/RXMT, Wright Patterson AFB, OH.


