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DEPARTMENT OF COMPUTER GRAPHICS AND MULTIMEDIA
ÚSTAV POČÍTAČOVÉ GRAFIKY A MULTIMÉDIÍ

FUTURISTIC COCKPIT FOR URBAN MOBILITY
FUTURISTICKÝ KOKPIT PRO MĚSTSKOU MOBILITU

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Student: **Bohovic Samuel**
Programme: Information Technology
Title: **Futuristic Cockpit for Urban Mobility**
Category: Modelling and Simulation
Assignment:

1. Research the evolution of urban mobility concepts.
2. Get familiar with the state-of-the-art and future flight data visualization trends for urban mobility.
3. Design a modern flight data visualization concept for an optionaly piloted flying urban vehicle.
4. Implement your design into a simulation environment using VR glasses.
5. Evaluate achieved results and discuss potential further improvements.

Recommended literature:

- According to supervisor's recommendations.

Requirements for the first semester:

- Items 1, 2 and partially item 3.

Detailed formal requirements can be found at http://www.fit.vutbr.cz/info/szz/
Supervisor: **Chudý Peter, doc. Ing., Ph.D. MBA**
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Abstract

Rising interest in urban air transportation is creating room for development of user interfaces for use in urban aerial vehicles. Following thesis is a concept of displaying flight data and user interface for such transportation vehicles. This was done through review of past and modern flight data visualization methods. The resulting concept was implemented in a simulation in virtual reality. Implementation was done using Unity and HTC Vive virtual reality headset. The concept is modular and built with private and commercial use in mind. The result is a demonstration of modern aerial urban mobility vehicle's user interfaces could look.

Abstrakt

Rastúci záujem o mestskú leteckú dopravu vytvára priestor pre vývoj užívateľských rozhraní pre mestskú leteckú dopravu. Nasledújúca práca je koncept zobrazovania letových dát a užívateľského rozhrania pre tieto dopravné prostriedky. Toto bolo dosiahnuté skúmaním minulých a moderných metód zobrazovania letových dát. Výsledný koncept bol implementovaný do simulácie vo virtuálnej realite. Toto bolo dosiahnuté pomocou Unity a okuliarov pre virtuálnu realitu HTC Vive. Koncept je modulárny a bol postavený pre súkromné aj komerčné použitie. Výsledok je demonštrácia toho ako by mohli vyzerať užívateľské rozhrania pre moderné lietadlá pre mestskú mobilitu.

Keywords

urban mobility, Unmanned Aerial Vehicle, Head Up Display, visualization, cockpit, Unity, Blender, Virtual Reality, HTC Vive, flight, data, concept, plane, simulation, drone, helicopter, Augmented Reality, aerospace, automotive

Klíčová slova

mestská mobilita, bezpilotné lietadlo, priehľadový displej, vizualizácia, kokpit, Unity, Blender, Virtuálna Realita, HTC Vive, let, dáta, koncept, lietadlo, simulácia, dron, helikoptéra, Augumentovaná Realita, letectvo

Reference

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Rozšířený abstrakt

Rastúci záujem o mestskú leteckú dopravu vytvára priestor pre vývoj užívateľských rozhraní pre mestskú leteckú dopravu. Nasledújúca práca je koncept zobrazovania letových dát a užívateľského rozhrania pre tieto dopravné prostriedky. Toto bolo dosiahnuté skúmaním minulých a moderných metód zobrazovania letových dát. Výsledný koncept bol implementovaný do simulácie vo virtuálnej realite. Toto bolo dosiahnuté pomocou Unity a okuliarov pre virtuálnu realitu HTC Vive. Koncept je modulárny a bol postavený pre súkromné aj komerčné použitie. Výsledok je demonštrácia toho ako by mohli vyzerať užívateľské rozhrania pre moderné lietadlá pre mestskú mobilitu.

Úvodná časť bakalárskej práce sa venuje prehľadu vývoja mestskej mobility a zobrazovania letových dát. Definujú sa užívateľské a komerčné požiadavky pre navrhovaný koncept a tiež sa skúmajú podobné koncepty. V časti o zobrazovaní letových dát je prehľad historických technológii a aktuálnych štandardov. Toto slúži na identifikáciu letových prístrojov potrebných na zobrazenie informácii o stave lietadla.

Nasledujúca časť sa venuje návrhu samotného konceptu. Ako prvý vznikol návrh testovacieho lietadla. Tento je založený na podobných návrhoch of rôznych spoločností v leteckom priemysle. Kapitola taktiež obsahuje stručný popis technológii potrebných pre stavbu popísaného návrhu. Potom nastáva návrh samotného konceptu zobrazovania letových dát. Zvolili sme možnosť zobrazovania dát okolo pasažierov pomocou rozšírenej reality. Týmto spôsobom sa redukujú náklady na stavbu palubnej dosky a taktiež je možná modularita zobrazenia. Modularita je dôležitá vlastnosť popísaného návrhu. Cieľom bolo vytvoriť koncept, ktorý by bolo možné implementovať do existujúcich lietadiel.

V implementačnej časti je porovnanie a výber simulačnej platformy. Hlavné podmienky pre výber boli dostupnosť, obsah dokumentácie a podpora virtuálnej reality. Podpora virtuálnej reality je dôležitá pretože sme sa rozhodli demonštračný projekt implementovať pomocou okuliarov pre virtuálnu realitu HTC Vive. Virtuálna realita bola zvolená ako cieľová platforma hlavne kvôli schoptnosti presne reprezentovať simuláciu rozšírenej reality. Taktiež vo virtuálnej realite nie je nutné postaviť hmotnú repliku kabíny testovacieho lietadla. Ako simulačnú platformu sme zvolili Unity 3D.

Po výbere simulačnej platformy je nutné zhrnúť fyzikálne vzťahy potrebné pre popis letu lietadla. Táto implementácia využíva simuláciu fyziky obsiahnutú v Unity, ale znalosť fyzikálneho popisu letu bola dôležitá pri implementácii ovládacích prvkov letu. Návrh má možnosti manuálneho a automatického letu. Automatický let je implementovaný ako jednoduchá navigácia medzi bodmi v priestore. Manuálny let používa ovládače HTC Vive pre zber užívateľského vstupu. Podľa aktuálnej hodnoty na dotykovej ploche ovládača sa mení pomer výkonu motorov lietadla, čo má za následok náklon alebo rotáciu.

Zber letových dát prebieha pomocou programových rozhraní Unity. Unity zbiera informácie o polohe a orientácii telies v 3D priestore. Tieto informácie sú pomocou rozhrania spracované a vystavené pre zobrazenie. Dáta sa zobrazujú v priestore okolo užívateľa. V tomto momente je nutné si uvedomiť obmedzenia zobrazenia užívateľských rozhraní v Unity. Zobrazenie je postavené okolo základovej plochy umiestnenej v 3D priestore. Prvky užívateľského rozhrania jú umiestnené okolo tejto základovej plochy. Pri väčšej vzdialenosti od plochy alebo pri väčšom uhle voči ploche dochádza k skresleniu. Takéto skreslenie je nežiaduce pri potrebe zobrazovať presné dáta. Ako riešnie sa ponúka možnosť použiť prvky užívateľského rozhrania Unity iba na zobrazenie statických textových prvkov. Týmto sa obmedzí skreslenie a zachová sa vizuálna presnosť. Vzniká ale nutnosť vytvoriť ostatné zobrazovacie prvky ako 3D objekty a taktiež ich umiestniť do priestoru. Táto možnosť je konštrukčne náročnejšia, ale uľahčuje proces zobrazenia dát. Textové prvky užívateľského

rozhrania Unity majú programové rozhranie pre zmenu textu a 3D prvky majú programové rozhranie pre zmenu polohy a orientácie. Preto je možné zobrazovať dáta priamo z riadiaceho program bez nutnosti použiť animačný systém Unity.

Po vyriešení zobrazenia letových dát je nutné navrhnúť ostatné prvky užívateľského rozhrania ako výber destinácie a riadenia a navigačné pomôcky. Výber destinácie a riadenia je realizovaný pomocou užívateľských rozhraní Unity. Základová plocha je už na mieste kvôli zobrazeniu letových dát, preto zaniká nutnosť novej základovej plochy. Užívateľské rozhrania Unity majú vo svojom programovom rozhraní možnosť riadenia udalosťami. Tieto udalosti sú napojené na riadiaci program, kde ovplyvňujú nastavenia letu. Ponuky výberu destinácie a riadenia letu využívajú animačný systém Unity aby dosiahli príjemný vizuálny zážitok.

Navigačné pomôcky sú bežne realizované pomocou GPS zobrazenia na palubnej doske. Tento návrh neobsahuje palubnú dosku preto bolo nutné navrhnúť iné riešenie. Jedna z možností by bola zobraziť mapu v priestore okolo užívateľa ako plávajúce okno. Táto možnosť je jednoduchá, ale zaberá veľké množstvo zorného poľa. Preto sme zvolili možnosť zobrazenia plávajúceho letového tunela. Tento tunel sa vykresľuje pred lietadlom ako séria prstencov, ktoré opisujú naplánovanú trasu. Zobrazenie plávajúceho letového tunela nezaberá veľkú časť zorného poľa a poskytuje intuitívnu formu navigácie.

Posledná časť implementácie bola venovaná testovacej scéne. Nezvolili sme reprezentáciu existujúcej lokácie, ale postavili sme model prímestskej oblasti. Testovacia scéna obsahuje niekoľko mžných destinácii pre demonštráciu návrhu v manuálnom a automatickom lete.

Testovanie prebiehalo v dvoch častiach. Prvá časť prebiehala počas samotného vývoja a bola zameraná na presnosť zobrazenia letových dát a na manuálne ovládanie letu. Testovanie bolo primárne vykonané autorom práce. Pre druhú časť testovania bola zvolená testovacia skupina osôb. Každá osoba obdržala dotazník v prílohe práce a funkčnú kópiu projektu. Testovanie bolo primárne zamerané na použitie rozhrania pre automatický let, ovládanie manuálneho letu a celkový dojem z návrhu. Testovacia skupina bola zložená z väčšej časti z osôb bez skúseností s pilotovaním lietadla.

Z výsledkov dotazníku a komentárov členov testovacej skupiny môžeme vyhodnotiť závery. Kvôli použitiu virtuálnej reality a odlišného ovládania lietadla vznikla aklimatizačná doba v rozsahu jednej až dvoch hodín. Počas tejto doby užívateľ nadobudol istotu pri ovládaní rozhrania a lietadla. Ďalej návrh dostal vysoké hodnotenia vo všetkých cieľových oblastiach. Je nutné vvýrazniť pomerne nízke hodnotenia automatického letu od členov testovacej skupiny so skúsenosťami s pilotovaním lietadla.

V závere môžeme konštatovať, že tento návrh z pohľadu užívateľov dopadol úspešne. Samozrejme je nutné zohľadniť aktuálny stav leteckej prepravy v mestskej mobilite. Predtým ako nastane komerčné rozšírenie tejto možnosti mestskej dopravy musia potrebné technológie a spoločnosti, ktoré ich vyvíjajú prekonať isté zábrany. Technologické zábrany ako váha a kapacita batérii brzdia stavbu funkčných prototypov lietadiel. Z legálnej stránky nastáva problem certifikácie týchto lietadiel z hľadiska bezpečnosti prevádzky. Z pohľadu infraštruktúry musíme vyriešiť problém integrácie leteckej dopravy do existujúcich systémov hromadnej dopravy.

Futuristic Cockpit for Urban Mobility

Declaration

Hereby I declare that this bachelor's thesis was prepared as an original author's work under the supervision of doc. Chudý. All the relevant information sources, which were used during preparation of this thesis, are properly cited and included in the list of references.

. . . .
Samuel Bohovic
May 13, 2019

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I would like to thank doc. Chudý for his academic support, guidance, feedback, technological support and advice required for the creation of this thesis. Furthermore I would like to thank his team for useful feedback during demonstrations and my friends at Atlas Defense Industries for their advice and suggestions.

Contents

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List of Symbols

u - velocity in x-axis, $m.s^-1$

v - velocity in y-axis, $m.s^-1$

w - velocity in z-axis, $m.s^-1$

p - body-axis roll rate, $rad.s^-1$

q - body-axis pitch rate, $rad.s^-1$

r - body-axis yaw rate, $rad.s^-1$

θ - pitch angle, rad

ϕ - roll rate, rad

ψ - yaw angle, rad

m - total aircraft mass, kg

F_T - total engine thrust, N

$\overline{X}$ - axial force component, N

$\overline{Y}$ - lateral force component, N

$\overline{Z}$ - normal force component, N

$\overline{L}$ - rolling moment, N.m

$\overline{M}$ - pitching moment, N.m

$\overline{N}$ - yawing moment, N.m

x_E - x position with relation to Earth, m

y_E - y position with relation to Earth, m

z_E - z position with relation to Earth, m

I_x - roll moment of inertia, kg.m^2

I_y - pitch moment of inertia, kg.m^2

I_z - yaw moment of inertia, kg.m^2

I_{xz}, I_{xy}, I_{yz} - products moment of inertia, kg.m^2

Δt - time interval, s

List of Abbreviations

AR - Augmented Reality

VR - Virtual Reality

UAV - Unmanned Aerial Vehicle

UAM - Urban Air Mobility

MFD - Multi Functional Display

PFD - Primary Flight Display

EFD - Electronic Flight Display

HUD - Head Up Display

LCD - Liquid Crystal Display

CRT - Cathode Ray Tube

VTOL - Vertical Take-Off Landing

RAF - Royal Air Force

SA - Situational Awareness

UI - User Interface

Chapter 1

Evolution of urban mobility concepts

The core concept of urban mobility is getting from point A to point B inside a city or an urban area. Urban mobility has been around ever since humanity built it's first larger settlement. It's not only a problem of moving people around but also goods and material.

Historically at first getting around a town was done by walking or on horse back and goods were transported on carts or carriages. This limited the size of most cities to a diameter of about 5 kilometres and forced them into a circular shape. At this point we are dealing with a lack of a mode of transportation that would enable outward growth of cities [33]. As seen in Figure 1.1, a map of Vienna from before it's rail system was build.

Figure 1.1: Map of Vienna, 1809, before the city rail system was built (retrieved from [40])

In the 1890s with the invention of electric engine first tram lines were built around the world which allowed the cities to expand to greater sizes along the built tracks. Soon after that came the rise of ownership of personal motor vehicles. With this rise came the need to change the way we work with the space available and how we design our cities. Parking became a major problem [35].

After the World War II there was a global increase in construction of highway networks. Highways connect central districts to outlying urban areas of cities. In some areas of United States and Europe this rise of highway networks caused the economic destruction of some railway services. In some cities such as London we would see decrease of use of surface tramways in favour of subway systems [35].

In recent years, especially in progressive countries, we see a push towards larger integration and cooperation of transit systems in urban environments. And besides that we see applications of modern technologies and even social media in transportation [35].

1.1 Transport policies

With further advances in automotive industry and construction technologies a more complicated means of urban travel and public transport were created. Around this time we see some of the first transport policies around the world. Of course with the increased car ownership and car travel, these policies were mainly focused on motor vehicles. This means for example removing tram systems to create room for cars. Or using new zoning policies or non-traditional street patterns that are more suitable for cars than sustainable transport modes [25].

However it soon became apparent that focusing infrastructure on car travel is not sustainable. Unrestrained growth of car use in urban areas would soon lead to exhausting the capacity of existing roads which in most cases cannot be expanded. This is not such a big problem in areas with low population density. But big cities with hight population density and geographically limited layouts such as London cannot rely on highways and car traffic. Increased car traffic brings other issues as well. Most notable examples being increased air pollution and frequency of car accidents [25].

This presents a problem of having to handle increasing amount of traffic with the same infrastructure and environmental impact. To solve this problem we have to think about getting from one place to another first and the means of doing so second [25].

In the case of most large cities the solution is to invest in a high quality public transportation system and zone restrictions on car travel. Most city planners choose to use underground or elevated rail systems. Both of these share the same advantage of not consuming valuable surface area in areas with dense construction. This has also been associated with a resurgence of interest in the role of cycling and walking in cities, as offering sustainable and healthy modes of transport, and in enhancing public space and providing pedestrian space again for street activities [25].

1.2 On demand transport services

In recent years smart devices and social media play an important part in transportation. Services such as Uber create a whole new way of satisfying the need for personal transportation. Uber creates dangerous competition for conventional taxi services because of how it handles changing demand. Another important selling point is availability. Most of young people today own a smart phone and having an application to manage their transport needs is preferable to calling a taxi [28].

This on demand system is not good only for transporting people but food as well. On demand delivery services provide logistic infrastructure for restaurants that don't have their own delivery system in place.

1.3 Autonomous vehicles

Autonomous vehicles have been used by major logistics companies to sort packages and retrieve items in their warehouses and logistics centres. Automated vehicles increase transport speeds in this case and eliminate human error. This would translate to road traffic as well. Main promise of autonomous vehicles in road traffic is to decrease congestion. Studies suggest that congestion is caused by a small proportion of vehicles. If those vehicles were automated, then traffic would flow more easily, which could mitigate the need for extra road capacity and free infrastructure funds for other purposes [35].

In recent years we are seeing delivery companies using autonomous vehicles to deliver goods. The best example would be Amazon and it's drone delivery system. In some parts of United States and Europe fast food chains utilize self-driving cars for delivery of their goods. Such as the Amazon vehicle seen in Figure 1.2.

Figure 1.2: Amazon autonomous delivery drone (retrieved from [15])

1.4 Current trends

Besides ever increasing volume of traffic, goods and people moving around the issue of environmental impact of modern transit system. This combined with the everlasting effort to minimize cost of running a transit system creates a difficult problem to solve.

Since a growing share of the global population is urbanized, sustainability has increasingly become focused on urban areas. Major cities are requiring a vast array of supporting infrastructures including energy, water, sewers and transport. A key to urban sustainability issues is linked with the provision and maintenance of a wide range of urban infrastructure. Every city has specific infrastructure and environmental problems [33].

Modern transit systems are shifting their focus from individual car traffic towards mass transit. Large cities are spending large portions of their funding to construct new systems or to modernize the existing ones with faster and more fuel efficient vehicles. Increased attention and effort is given to integrating autonomous vehicles and systems to further minimize expenses, traffic congestion and increase transport safety.

The city of London is known for it's intricate public transport system. More notably, its underground railway system. It is argued to be the best public transport system in the world. Just the subway system services around 1.3 billion passengers every year [4]. And the entire transit system operates on an annual budget of 10 billion pounds. Almost 30% of which goes to renewing and improving the existing transit network [1]. A network of this size has to rely heavily on automated technologies and computer systems for it's daily operation. This serves as a great example of an existing large scale transit system with extensive use of automation.

There is a social aspect to urban mobility as well. Recent advances in car sharing technologies and the potential for self driving vehicles underline a much more sustainable usage of car assets that could remove up to 90% of the vehicles from the streets. This adds up to the ongoing technological improvement in engine and drive technology, which have reduced vehicle emissions [33].

1.5 Aerial Urban Mobility

However until now one aspect of our cities has remained unused. This aspect is the airspace above and around them. Until very recently planes were only used for long range transport. But in recent years several companies have started research into fast and sustainable ways of moving around cities using aerial vehicles.

Due to the nature of city architecture an obvious choice for a city aerial vehicle would be a Vertical Take-Off Landing(VTOL) plane [30] or a multi-rotor helicopter. To reduce pollution it should be powered by electrical engines instead of fossil fuel based ones. The main advantages of travelling by air in an urban environment are the ability to avoid traffic and to travel large distances in short time.

As with aerial delivery of goods, automation of flight controls and navigation would significantly increase safety and travel speeds. Besides that automated flight would enable these vehicles to fly themselves to the location where they are needed.

Of course, personal flying vehicles are facing many technological challenges. Safety is the most critical concern. The fact that air travel is currently the safest mode of transportation does not necessarily translate into aerial urban mobility. In this case we have to consider the safety implications of many small vehicles flying at low altitudes close to buildings and other city structures. This calls for accurate navigation and collision avoidance systems as well as a robust air traffic control systems.

Currently discussed uses for aerial urban mobility are air ambulances, airport shuttles, air taxis or executive transport. As with any new technology there are other non-technological concerns.

Vision of Urban Air Mobility

As mentioned before, the idea of urban air mobility is on the rise. City planners and visionaries are looking for ways to make transportation smoother, cleaner and more profitable.

Aircraft

Correct design of the vehicle is a key part of launching urban air mobility. Companies are actively experimenting with various designs, there are three major groups. Important factors are design complexity, variability of use, certification requirements and profitability.

Multirotor aircraft

Multirotor, as the name implies, is a rotorcraft with two or more motors, often arranged in a ring around or atop the cabin. Flight control is accomplished by varying the speed of the individual rotors. Multirotor systems have the twin advantage of being fairly simple and offering safety through redundancy. This concept is mostly used with commercial drones such as camera drones or delivery drones. The German startup Volocopter is exploring this concept in terms of urban air mobility. This design would be the fastest to earn needed certifications because there are already some regulations in place for commercial drones. But it's not the most effective in terms of speed and weight limits [20].

Lift and cruise aircraft

This design uses separate engines for generating lift and movement, it usually includes fixed wings to generate cruise lift and rotors to take-off and land vertically. Thanks to the fixed wings they also have longer range. The basic technologies of both elements are already available, and the overall complexity of hybrid models is in the middle range, depending on a particular system's design. The Aurora electronic Vertical-Take-Off-Landing (VTOL) aircraft uses this design [20].

Tilt-X aircraft

These designs have rotating components. Either rotors or entire wings rotate to transition between the lift and cruise phase. This concept shares the advantages of lift and cruise systems with separate propulsion systems but at the lower cost of only having to construct and maintain one type of propulsion. The major disadvantage of this system is that rotating components have a higher risk of failure. This technology will need further development before it's ready for certification and commercial deployment. The Lilium jet, which is currently undergoing trials and development, is a prime example of this design.

Cost and profitability

As with any emerging technology, profit is the main driver. Urban air mobility fills a gap in the transportation systems of modern cities. However this comes at a cost. We currently see the usage of drones for last-mile parcel delivery, presumably this is profitable for the companies utilizing this technology.

Further considering the parcel delivery example. Where available this is arguably the fastest option for delivering small packages, however it does come at an increased cost to the customer.

Implications for passenger transport

In comparison with car based taxi services the vehicle and infrastructure acquisition and operational costs are significantly higher. This is magnified even further in the emerging market of urban air transportation. On the other side we can compare it to commercial airline flights, these however have more passengers and with increasing engine efficiency we could speculate that the price per distance is better than the initial cost for air taxis.

General operational costs that reflect on the final price for the customers would be prices of electricity(assuming use of aircraft powered by electricity), furthermore the maintenance costs of the vehicles and the infrastructure such as landing locations and air traffic control systems. These are the factors that drive up the final customer price. There is one decisive factor that makes this transportation option desirable and that is the distance traveled and distance spent traveling. Urban air mobility vehicles are capable of taking a more direct route than car based taxis and they also travel an much higher speeds. The fairly obvious drawback of this is that these vehicles won't get you all the way to your destination. To achieve true door-to-door travel this system would have to be supplemented by cars or mass transit [24].

Deadhead ratio

For any taxi or ridesharing vehicle, a portion of the trip miles traveled are non-revenue miles required to reposition the vehicle to pick up the next paying customer. This factor is called the deadhead ratio, and for air-taxis relates to the flight miles traveled to reposition the air-taxi to another landing location to meet the next passenger. The factor depends greatly on the fleet size versus the geographic area served [24].

Environmental factors

The environmental impact of human progress and development is becoming an increasing concern and a factor with emerging transport technologies. We have to consider that transport and industry are the largest contributors to pollution and greenhouse gas emissions. In this case we are considering electrically powered aircraft, instead of engine emissions we have to consider emissions created during the production of electricity. The cost and environmental impact vary from country to country depending on local regulations and portion of green energy produced.

Noise

With any type of public service, especially aircraft, noise is a very important environmental and societal factor. Noise control technology is now integrated during the design phase, not as an "add-on", with aircraft quieter than road/train traffic around airports. "Active" noise control allows quiet zones to be created for special mitigation of noise. However, there is a growing concern about a new type of pollution; 'visual pollution' resulting from the sheer number of aircraft in operation [22].

Chapter 2

State-of-the-art flight data visualization trends

2.1 Historical overview of flight instruments

Early days of flying

In the pioneering days of aviation, flight was restricted to times of good visibility and good weather. In early flight operations, the pilot maintained visual contact with the ground below him at all times and used it as a reference point for executing all maneuvers. In these early day most of currently used instruments were replaced by pilot's own senses. However this made flying at night or in difficult weather conditions next to impossible.

As aviation technology became more advanced, several types of flight instruments were proposed and tried. First instruments were mechanical utilizing springs, gyros and magnets to display information about the aircraft. The rise of flight instruments started the debate on what should be the standard configuration of instruments in a cockpit.

Wartime flying

As we know and observe over the decades, wartime and military are powerful drivers in technology. Aircraft saw increasing use during The Great War by all sides as scout aircraft, artillery spotters, attact and close air support.

This poses several challenges. The main and first problem was accurate navigation in clouds or fog. The compass would become the basic instrument for navigation combined with maps. However the compasses available at the start of the war were plagued with issues. As the engine power of the aircraft increased so increased the vibrations caused by the engines, which cause issues with the older designs of compasses. Poor weather effects and constant maneuvering to evade enemy anti-aircraft fire only amplified this issue. This lead the Royal Air Force (RAF) to the development of new compass arrangement and anti-vibration mounts [17].

A further issue was how to drop munitions on target accurately. The issues of navigation and ordnance accuracy carried over to the second World War where they became even more important to resolve. In terms of close air support, where the aircraft are providing support fire for ground troops there is usually a person (a forward observer or Joint-Terminal-Attack-Controller) that guides the planes on target from the ground via radio. However this is not possible with long range bombing operations such as the ones seen heavily during World War II.

With the increased use of night time bombing raids by both Allies and Germany it was crucial to maximize the effectiveness. This lead to development of radio navigation devices such as the X-Device and Y-Device based on radio beams and pulses. However at the start of the war on August 24, 1940 these were not available, which lead the German bombers intended to bomb a British military target to fly off course and drop bombs on London. In retaliation the RAF bombed Berlin the next day. This lead to the start of a long and bloody bombing campaign. Towards the end of the war, Allied bombers were achieving high accuracy due to emerging radar and radio navigation technologies.

Post-war flying

The end of the war brought significant advances in technology, the most important being jet engines for aircraft. There was also a rise in transatlantic flights. At this point we see a rise in reliability of electronics and their increased use in aircraft. One of very relevant inventions during the war was the head-up display. It was developed from the reflector gun sight. It projects key flight information in front of the pilot so that there is no need to look down at the instruments.

Standardization

In 1937 the British Royal Air Force selected six flight instruments to use in their cockpits. This panel configuration would remain the standard for the next twenty years [32].

Instruments in RAF standard panel configuration Instruments in RAF standard panel configuration are the following:

- altimeter,
- airspeed indicator,
- turn and bank indicator,
- vertical speed indicator,
- artificial horizon,
- heading indicator.

With advancements in electronics and invention of new display systems the turn and bank indicator became obsolete. It was replaced by improved functions of the artificial horizon. It was still included in the first jet airlines but later it was removed.

In Figure 2.1, the six standard instruments can be clearly identified on the left side of the instrument panel. Another thing that can be seen in Figure 2.1 is the T arrangement of instruments. With the artificial horizon in the top center, airspeed indicator on the left, altimeter on the right and heading indicator bottom center.

Figure 2.1: Avro Lancaster instrument panel (retrieved from [31])

2.2 Technological overview of flight instruments

Mechanical Instruments

The earliest technologies for displaying flight data date back to the first flight of the Wright brothers. The most common instruments were the engine rev counter to indicate engine speed. The anemometer which is a device used to measure wind speed. It could be used to get an approximate reading of current airspeed depending on the weather. And finally a weather vane used to measure the angle of incidence [26].

Electro-mechanical Instruments

The rise of this technology is concurrent with the RAF's standardization of the „basic-6“ instruments and dashboard layout. As mentioned before, this layout was later replaced with the „basic-T“ configuration. The Lockheed Electra was the first plane to have a fully electronic cockpit. However it's layout didn't use the standard configuration as can be seen in Figure 2.2. Along with it's competitor the DC-3 they saw increase in civilian air traffic after World War II [26].

Electro-optical Instruments

Towards 1970s digital electronics reached sufficient level to be used for flight data displays. This meant the use of Cathode Ray Tube (CRT) displays. At the start this technology and instrument panel configuration were mostly only available to the military as the monochrome green displays were not suitable for civilian use. Once colored CRT was available first of these instrument panels were made for civilian use. The first plane using this technology was the Boeing 757 [26].

2.3 State-of-the-art visualization systems

With the increasing size, complexity and variation of commercial aircraft the focus of visualization systems and flight instruments shifted towards computers and Liquid Crystal Display (LCD) displays.

In modern aircraft every necessary flight instrument is displayed on a LCD panel. These are called Electronic Flight Displays (EFDs) or commonly referred to as „glass cockpits“.

Figure 2.2: Lockheed Electra instrument panel (retrieved from [31])

EFDs include flight displays such as Primary Flight Displays (PFD) and Multi Function Fisplays (MFD). This has changed not only what information is available to a pilot, but also how the information is displayed. In addition to the improvement in system reliability, which increases overall safety, EFDs have decreased the overall cost of equipping aircraft with state-of-the-art instrumentation. Primary electronic instrumentation packages are less prone to failure than their analogue counterparts. No longer is it necessary for aircraft designers to create cluttered panel layouts in order to accommodate all necessary flight instruments. Instead, multi-panel digital flight displays combine all flight instruments onto a single screen that is called a primary flight display (PFD). The traditional set of six instruments is now displayed on one LCD screen [23] .

This extensive use of computers and LCD screens in displaying flight data allows to change the way it's displayed or what data is displayed. EFD often include options to change color schemes or brightness of their displays on the fly.

Primary Flight Display

PFDs provide increased Situational Awareness (SA) to the pilot by replacing the traditional six instruments used for instrument flight with an easy-to-scan display that provides the horizon, airspeed, altitude, vertical speed, trend, trim, rate of turn among other key relevant indications [13]. Figure 2.3 shows standard PFD layout for modern aircraft.

Multi-Function Display

In addition to a PFD directly in front of the pilot, an MFD that provides the display of information in addition to primary flight information is used within the flight deck. Again, using LCD displays allows to change the information displayed. This means there don't need to me as many dials and displays. In case of a malfunction information from a primary flight display can be displayed on a multi-function display and vice versa. This provides higher redundancy than previous designs of flight instruments [13].

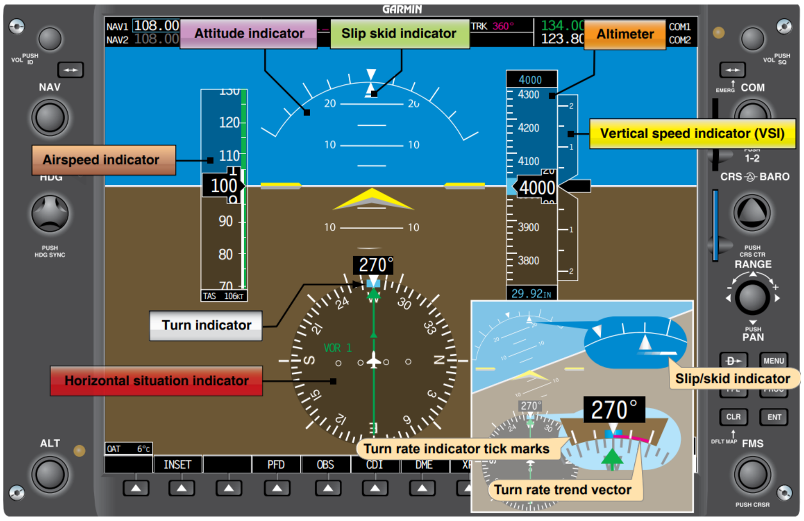

Figure 2.3: Standard PFD layout (retrieved from [13])

2.4 Future concepts in flight data visualization

Much like in the past even now new technology is changing the way we display flight data. It also aims to change the way we fly planes. Flight systems are becoming more automated to reduce the changes of human error and thus increase safety.

In terms of displaying flight data we are trying to find a way of using new technologies to increase modularity and precision of given data. One of the most recent trends aerospace companies are looking into is augmented reality. Augmented reality is the next step from transparent heads-up display. Augmented Reality (AR) allows not only to visualize the data but also the control elements. Which allows huge modularity for cockpits and cost reduction for their construction.

Figure 2.4: Airbus A380 instrument panel (retrieved [14])

Chapter 3

Flight data visualization concept for an optionally piloted flying urban vehicle

From the previous chapters we know that a urban flying vehicle would most likely be a lightweight Vertical Take Off Landing (VTOL) aircraft. The goal would be to create minimalistic and visually pleasing instrument panel and control elements. The aircraft itself needs to have sophisticated navigation and collision avoidance system and may include the ability to fly autonomously.

3.1 Vehicle design

To reduce weight and keep the instrument panel small a decision was made to use Augmented reality (AR) to display flight data. So instead of a full instrument panel there will be only a small central panel, similar to what you would see in your car, containing controls for navigation and media functions. The necessary flight data will be displayed around the pilot using Augmented Reality (AR) glasses.

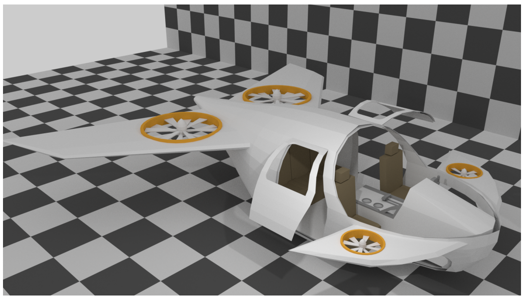

Figure 3.1: Angled view of concept vehicle

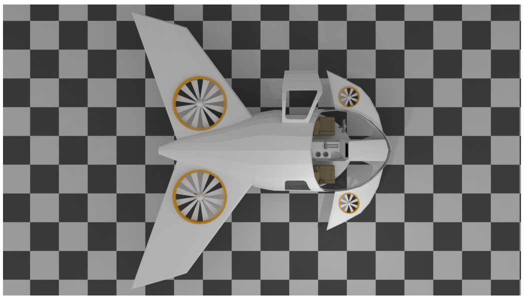

Figure 3.2: Top view of concept vehicle

For the purposes of this thesis the vehicle itself is not that important, seeing as the goal is to create a prototype of a visualization system that would be universal and modular enough to be reused in different urban mobility flying vehicles. For testing we designed a simple four rotor VTOL plane.

The initial concept was to create a four seat plane that is flown by a pilot. However this concept was proven as not ideal in this case. Rather than that a fully automated, pilotless design was chosen. Figures 3.1 and 3.2 show renders of the vehicle in greybox stage of design pipeline of the original concept.

The updated concept focuses heavily on executive users. Four seats are replaced by only two with touch screen control panels on both sides. This concept also includes additional displays to allow the passenger to work while in flight.

For safety reasons all glass elements of the vehicle were replaced with solid construction. To keep the passenger aware of the position of the vehicle flight data is displayed on internal screens. One concern about fly-ability of the vehicle was discussed, the lack of a rudder. That's why the updated concept includes a rudder. Figure 3.3 shows the updated concept plane in it's greybox stage of design.

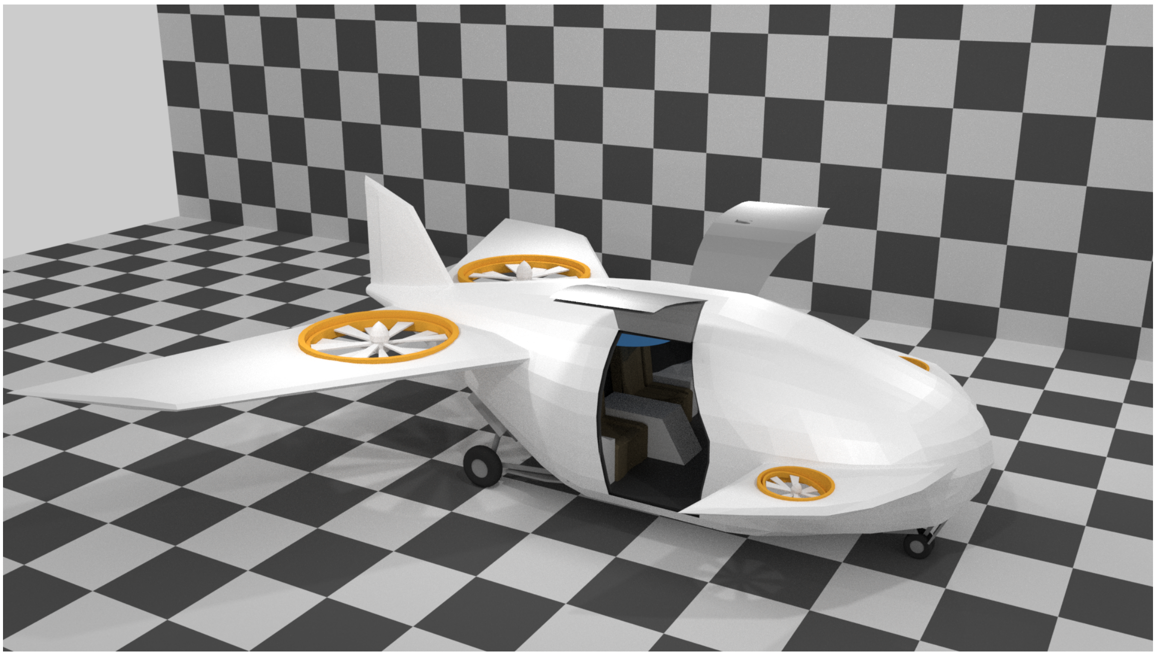

Figure 3.3: Angled view of the updated concept

But even this concept was not quite what we were looking for. It was too bulky for city flight. That is why the final concept looks more like a drone than a plane. The spherical shape of the cockpit allows for sleek look while having enough space and also providing additional safety.

3.2 Futuristic flight deck concept

With the flight being fully automated there is little need for conventional flight control elements and advanced and detailed data visualization for the passengers.

However to avoid claustrophobic feeling of the interior some flight data should be shown. Such as direction, elevation and speed. Navigational data should also be displayed so that the passengers know how far they are from their destination. The idea is to minimize the amount of date show no the user in order to allow them do work. Seeing as the target users are high level executives, the operation of the vehicle should be as easy as possible and the

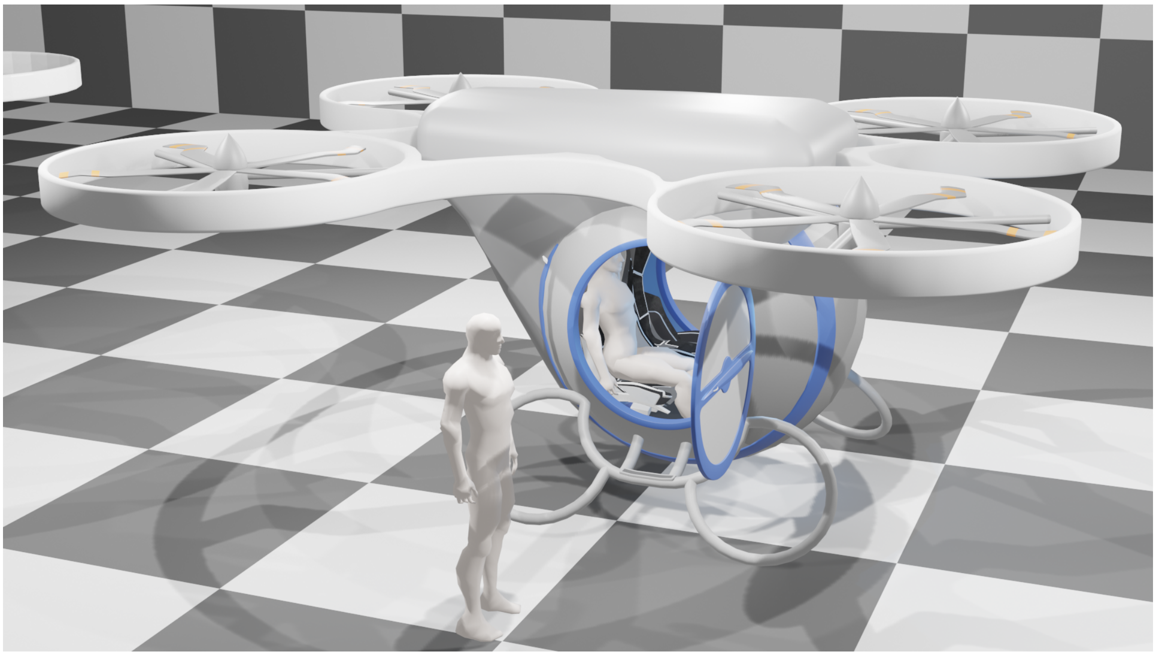

Figure 3.4: Final concept

flight itself can't be distracting. That's why the visualization system should include the ability to display data from one's phone or laptop after boarding.

The visual idea is to use transparent elements and indicators to display data. In addition to that all menus and text elements should be done in a similar way, using a modern design.

During design we have to keep in mind how Unity displays user interfaces. Generally the distinct elements are displayed on a canvas which serves as a base. This however doesn't always have to be the case, sometimes elements can be placed in front or behind the canvas. Elements can also be placed under an angle to the canvas. This does create some distortion the farther and more rotated the element is.

We want some of the navigation indicators to be floating around the user. For this distortion of user interface elements would be a destructive factor. These indicators will also be moving, for user interfaces this is best done through animation but animations are not easy to control in a way that is accurate for displaying data. This is why rather than using canvas elements to display flight data we will use small 3D mesh objects. These can be rotated and moved without distortion.

The mesh elements are designed as sets of rings with the same pivot. Mesh objects like these are easy to control from a script which makes them very suitable to display accurate flight data.

We are still going to be using canvas based elements. We will use these to display text and numbers because they provide the interface to change them from a script. We also know that the text displays won't move around the cockpit. The canvas itself is a plane without curvature. Same applies to the interface elements. We recognize text elements, image elements and combined elements. Text elements would be data readouts for altitude, heading or elevation. Image elements would be bars and sliders used to display throttle status. Combined elements put together images and text. This is used with the buttons used to trigger engines or media displays or flight setup.

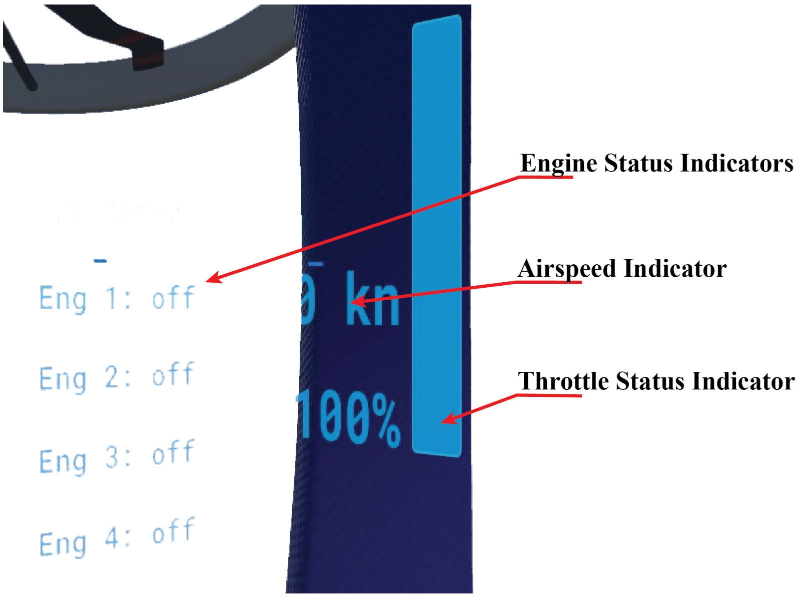

Figure 3.5: Data visualization concept engine section

From a technical standpoint we know that virtual reality has seemingly reduced field of view. For this reason important interface groups are placed around certain points. For example the media menu is placed along the top edge of the forward viewport.

Airspeed, throttle and engine indicators are also placed close together on the left side of the cabin as seen in Figure 3.5. We opted for a very large throttle status indicator and rather simplified engine status indicators.

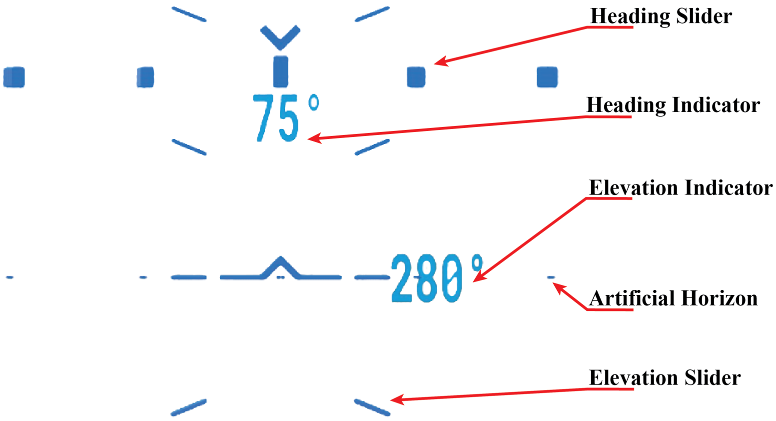

Figure 3.6: Data visualization concept orientation section

The middle part of the screen is reserved for important information about the current orientation and heading of the aircraft as seen in Figure 3.6. It's common practice to have this information near the middle of the display.

The construction of the vehicle visually splits the display in three sections. We covered two of them. The final section is dedicated to altitude and vertical speed data. Emphasis is

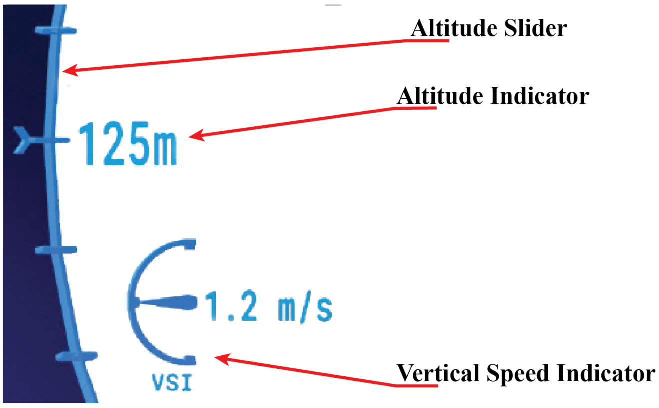

Figure 3.7: Data visualization concept altitude section

placed on an altitude slider that covers whole height of the cabin as can be seen in Figure 3.7.

Navigation tunnel

Current modern planes use GPS navigation based on GPS position. The course and position data is displayed on a map. However for this concept this way of display is not ideal. That's why we developed a new way of showing desired heading and altitude for this concept.

Our concept employs augmented reality. Rings are drawn in space ahead of the plane to show the planned path. The selected path is drawn using pre-defined points. Rings are placed at regular distances. Destination landing site is also highlighted. The flight tunnel is shown in Figure 3.8.

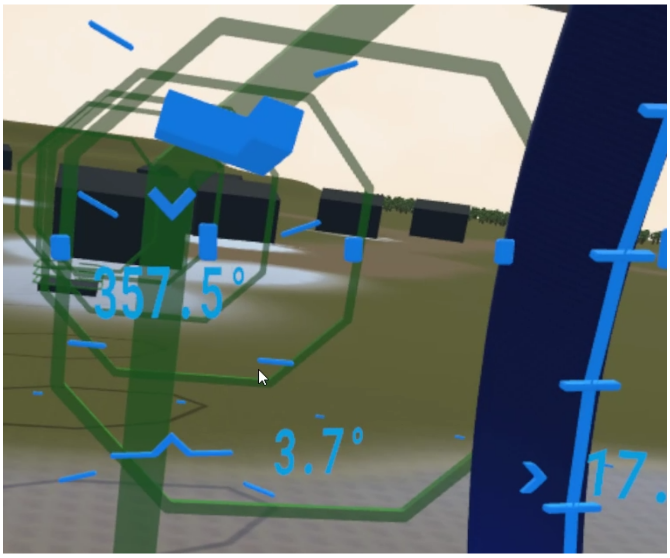

Figure 3.8: View of the navigation tunnel from the cockpit

Basic flight instruments

Considering that this concept has to instrument panel, the standard T configuration can't be used. But inspiration can be taken from glass cockpit's PFD screens. These already change the way of displaying data without altering the instruments too much. This concept steps that idea up by using augmented reality to project the flight instruments around the cockpit with slight modifications. The layout can be seen in Figure 3.9

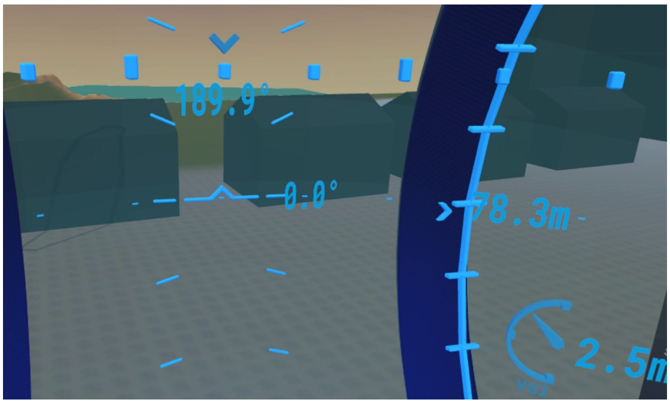

Figure 3.9: View of the basic instruments as seen by the pilot

Multi Functional Displays

MFDs were altered in a similar way to primary instruments, with the exception that they are displayed at the edges of pilot's area of visual focus. These display elements are used to show current engine status for all engines as well as the status of the currently connected smart phone.

3.3 Design specific changes

A major addition to the scheme is the engine throttle indicator. This serves the pilot as a visual guide to how much engine power they are using.

The heading indicator rather than being a semi-circle above the elevation indicator is designed as a full circle in the upper part of the cockpit with a pointer and a numeric reading directly ahead of the pilot.

Vertical speed indicator was adjusted to look more like the ones found in helicopters. Seeing as the vehicle is a quad rotor design this makes sense. The indicator contains a numerical representation as well as a „physical“ indicator.

Onboard entertainment option

An important addition to the design are the media media displays. You could view these as apps mirroring those on the phone connected to the vehicle or rather as visualizations to data provided by the phone.

This thesis doesn't explore the full implementation of these windows. It includes a mock-up of them to illustrate the purpose and basic manipulation.

Batery type	Cell voltage	Charge cycles	Specific energy	Discharge efficiency
Li-ion	3.6V	500-1000	100-265 Wh/kg	80-90%
Li-Po	3.7V	500-1000	100-265 Wh/kg	80%
Li-Ti	2.4V	6000-20000	30-110 Wh/kg	85%

Table 3.1: Lithium battery options

These windows can be moved around the cockpit so that the user has the optimal layout for them. Also the main screen that shows the outside environment dims to a lower transparency to provide a more solid background and reduce overlaying.

3.4 Technologies required

This section covers in detail what devices and technologies would be necessary in construction of this concept. Where possible it will go over advantages and disadvantages of different options. With some components location and weight distribution on the final prototype will be also covered.

Propulsion and power

In this concept we are considering the multi rotor configuration of propulsion. We have four rotor mounts, each of these should be mounted with two separate engines for redundancy. This gives us a total of eight engines. Of course the engines in each pair rotate in opposite directions to counter the torque forces in absence of a tail rotor. With the current technology electric engines are reaching around 60% efficiency [34].

The next thing to consider with propulsion is power. The ideal placement for batteries would be as low as possible under the aircraft's pivot point to create a low center of mass which promotes stability. However this concept might not have enough room near it's bottom for this. The compromise would be to place the batteries in the extruded back section of the passenger cabin. This also offers easier access for charging and maintenance. The next thing to consider is which type of battery would be the most suitable. In this case the key factors are specific energy, which is the ratio of watt-hours per kilogram. We could use energy density as well (a ratio of energy to volume) but weight is the primary concern. Then we also need to know the specific power of a battery which is the number of watts per kilogram. And the final decisive factors are standard continuous discharge current and change/discharge efficiency [18].

In terms of weight Lithium based batteries are the best choice. In the table above you can see other relevant properties of the most widely used Lithium battery variants [18]. Looking at numbers Li-ion technology seems like the obvious choice however Li-ion and Li-Po batteries are at a risk of combustion when damaged(due to the violent reaction of lithium with oxygen and moisture) [19].

Displays

Display technologies are becoming more advanced every year. This leaves us with multiple options to choose from for this concept. The easiest and most readily available would be to have a segmented display mounted on the inside of the passenger cabin. However we have to consider the weight and power requirements of such a large LED display.

Though we are considering a futuristic design so we could omit having a full display in the passenger cabin and make use of retinal displays. These displays draw pixels directly onto the retina. This technology is still in development [29].

Controls

The vehicle is not primarily meant to be controlled manually so for flight controls we might consider retractable or collapsible controls. In recent years, mostly in the automotive industry, gesture control is making a rise [27]. The idea is that the user can use gestures to control the media systems of the car. This seems like a good option for this concept as well. But not only to control the media displays and destination selection but also to fly the aircraft when desired. Most of these technologies are based on infrared proximity sensors [39].

Ideal mounting positions would be around the main frame of the passenger cabin aiming inwards to create a motion detection zone in front of the passenger seats. I we went with the option of having retractable controls, these could be placed under the seats and extend from there when needed.

Telemetry and avionics

Finally we should specify how will the aircraft gather data about it's position and movements.

In a city or suburban environments there are plenty of points that can be used to mount navigation devices. The flight altitudes of the vehicle in question in this thesis would be low enough to use light based technologies to acquire telemetry.

The aircraft should have a small GPS unit mounted at the top the cabin for best satellite reception. This unit's primary function is not navigation but for tracking the aircraft. This would serve as a secondary locator for air-traffic control and for the provider of taxi services using this vehicle to track their fleet.

Another GPS unit, this one more advanced aircraft navigation unit should be mounted on the roof with antennas extended to the rotors for better coverage. This would be the unit providing position data for navigation.

For more precise navigation we suggest using radionavigation and LIDAR technologies. LIDAR is currently used for collision avoidance and obstacle detection with most current autonomous car concepts [37].

A possible placement for LIDAR sensors would be around the intersection of principal axes. This gives us six placements and a fairly good field of detection. We could add two more sensors, having four placed around the belt of the aircraft and one each placed on the top and bottom.

Chapter 4

Design implementation in Virtual Reality environment

4.1 Development tools

As of 2019 there are many available game engines that support virtual reality. All of these platforms support all available virtual reality headsets.

For the purposes of this thesis we have selected the HTC Vive headset and Unity game engine. The reasons for this are simple, HTC Vive has the most advanced and well documented API for Unity [7].

Unity provides a simple but powerful base upon which it's possible to build this project. As mentioned above, HTC Vive and SteamVR are aimed primarily at Unity, but Unity extends support as well. Along with several community based VR packages this makes for a strong set of tools [9].

Rationale behind Virtual Reality

As stated before this concept will be implemented for virtual reality. To some this may seem like an unnecessary complication. Virtual reality technology is still fairly new to the market. Despite this in has made it very far in a very short time. We can see it's variants and applications almost daily. Whether it is 360 degree picture or video or complex applications for surgery and of course gaming.

But why is this important for this thesis? It could be done just as easily without virtual reality or without any virtual implementation. However this is a futuristic concept and we believe that a futuristic technology such as virtual reality is suitable for it's demonstration. The major advantage is that VR offers all-around immersion for the user which allows for easier implementation of more complex and futuristic concepts.

Industry standard simulation frameworks

We already know that this project will be implemented using the Unity game engine. However let's take a short look into other available options to illustrate why Unity was selected and why selecting the correct platform is important.

Unreal Engine

Unreal is possibly the longest running engine on this list. It's base language is C++ but it is capable of including scripts in Python and Lua. It makes use of a moderately advanced physics engine for simulations. It's major upside are so called blueprints, which allow a game designer to put together complex game mechanics using a graphical interface by assembling programmed components using logical and arithmetical operators. It does offer support for virtual reality and augmented reality, however this is in early stages with limited community support and ready-to-go packages are generally not available. Another major downside is the resource intensity of this engine combined with fairly large project size and final product size [12].

CryEngine

Another example of a long running engine. CryEngine also uses C++ as it's main language and has Lua script integration for some types of components. CryEngine has the most advanced physics engine out of all engines on this list. This is mostly characterized by it's voxel capabilities and object and environment destruction only paralleled by the proprietary Frostbite engine. However CryEngine shares downsides with Unreal Engine, large project size and resource intensity. Along with that it's production workflow is longer as it requires all 3d models to be in .fbx format when imported. It's generally not suited for project done by one person. Furthermore CryEngine has very little official support for virtual reality which would cause unnecessary issues with this implementation [3].

Lumberyard

Lumberyard is one of the newest engines on this list. It's a branch of CryEngine so it expands CryEngine's physics engine. It also expands CryEngine's rendering engine creating a truly detailed and customizable system. Of course it shares CryEngine's downsides. It's not focused towards virtual reality so again implementing this concept would be very difficult. Lumberyard is developed for large scale multiplayer projects. So it has a strong client-server setup that allows for expansive virtual environments [5].

Design tools

The vehicle and the data display elements were created using Blender open source 3D and animation software. Blender allows us simple creation of needed 3d meshes. It's well documented and has many functions that ease the design process such as mesh mirroring and edge bevelling. It also provides a full texturing and shading suite and also animation tools, neither of these are however used in this case in favor of the following [2].

Some used textures had to be created from photos. For this the Substance texturing suite was used. It provides a powerful physically based rendering suite along with real time texture painting on meshes. The most important tool used in this case is the SubstanceB2M which allows automatic conversion of photos into tiled textures that are suitable for game texturing. It also contains tools for editing the input and output images before export [8].

4.2 Physics simulation

Understanding of Unity's physics simulation is crucial for implementing a believable simulation of flight. Unity builds it's physics simulation on NVIDIA's PhysX API. This API provides core functions necessary for simulating physics. For the purposes of this thesis rigid bodies are the most straightforward option for simulation as they in both PhysX and by extension in Unity have already available options of applying force [6].

Rigid body dynamics

First of all we need some basic understanding of how are rigid bodies defined in regular physics. First we need to define what is a rigid body. In physics a rigid body is an object in which deformation is zero or so small it can be neglected. This means that the distance between any two given points on a rigid body is constant in time regardless of external forces applied to it [16].

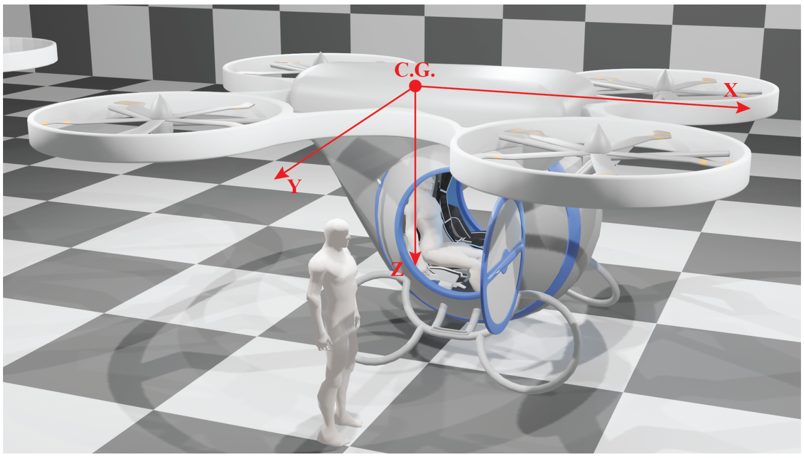

Figure 4.1: Body fixed reference frame axes drawn over the vehicle

Inertial reference frame

Before we get into equations we should define some terms related to rigid bodies and rigid body dynamics. First is the inertial reference frame. Whenever we apply equations of motion, acceleration is measured relative to a inertial reference frame. This term is used to describe a coordinate system that does not rotate and is either fixed in three dimensional space or is moving in a straight line at a constant velocity(i.e, it has no acceleration) [21].

Motion simulation in Unity and PhysX

In Unity object are included into the physics simulation when the user attaches the Rigidbody component to them. This gives them the ability to be acted upon by a force. For this Unity's rigid bodies have two basic important properties, mass and drag. Mass tells us how heavy the object is and drag tells us its air resistance. For example a brick would have a high mass but low drag, but a feather would have a low mass and high drag [9].

For optimal accuracy our vehicle's mass should change with every flight, but for simplification we keep it constant. Same with load distribution. Unity considers the object on which the Rigidbody component is applied as a single rigid body. This means that it considers the selected mass to be even and balanced. In the real world this might not be the case but for us this simplification is sufficient [9].

Unity gives the user methods that enable application of force onto a rigid body. They either offer the option to apply force to rigid body or to apply force to rigid body at a position. The difference is that the former applies the force to the pivot of the object while the latter applies force to a point inside or outside the rigid body(i.e, offset from the pivot point). These are the Rigidbody.AddForce and Rigidbody.AddForceAtPosition [38].

Furthermore Unity differentiates four options of the force applied. These are represented by the ForceMode parameter of the methods mentioned above. These four modes are combinations of continous or instant and mass inclusive and mass exclusive options. In our case we are using the ForceMode.Impulse mode. Which is an instantaneous application of force using the target's mass. This application of force happens every frame, which simulates revolutions of the rotor blades. Also we apply force at the position of the rotors.

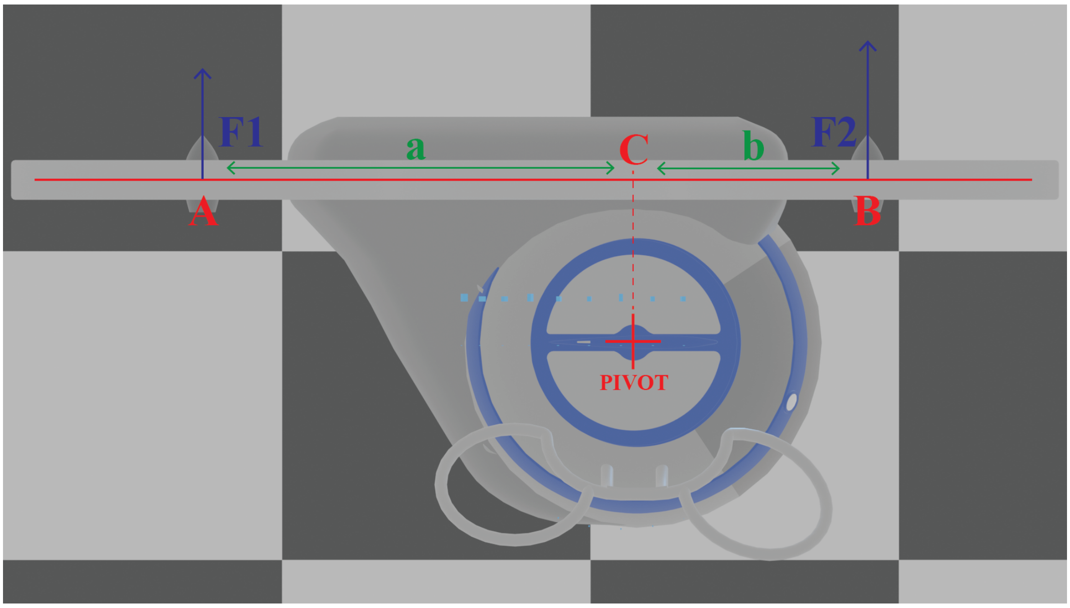

Figure 4.2: Side view of the vehicle showing pivot and forces

To extend the definition of physics behind the simulation, the following sets equations of motion apply. [36].

$$\dot{u} = rv - qw - g\sin\theta + \frac{1}{m}\overline{X} \tag{4.1}$$

$$\dot{v} = pw - ru - g\sin\phi\cos\theta + \frac{1}{m}\overline{Y} \tag{4.2}$$

$$\dot{w} = qu - pv - g\sin\phi\cos\theta + \frac{1}{m}\overline{Z} \tag{4.3}$$

$$\dot{p} = (c_1 r + c_2 p)q + c_3\overline{L} + c_4\overline{N} \tag{4.4}$$

$$\dot{q} = c_5 pr - c_6(p^2 - r^2) + c_7\overline{M} \tag{4.5}$$

$$\dot{r} = (c_8 p - c_2 r)q + c_4\overline{L} + c_9\overline{N} \tag{4.6}$$

$$\dot{\phi} = p + \tan\theta(q\sin\phi + r\cos\phi) \tag{4.7}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{4.8}$$

$$\dot{\psi} = \frac{q\sin\phi + r\cos\phi}{\cos\theta} \tag{4.9}$$

Where the moment of inertia components are defined as following.

$$c_1 = \frac{(I_y - I_z)I_z - I_x z^2}{I_x I_z - I_x z^2} \tag{4.10}$$

$$c_2 = \frac{(I_x - I_y + I_z)I_{xz}}{I_x I_z - I_x z^2} \tag{4.11}$$

$$c_3 = \frac{I_z}{I_x I_z - I_x z^2} \tag{4.12}$$

$$c_4 = \frac{I_{xz}}{I_x I_z - I_x z^2} \tag{4.13}$$

$$c_5 = \frac{I_z - I_x}{I_y} \tag{4.14}$$

$$c_6 = \frac{I_{xz}}{I_y} \tag{4.15}$$

$$c_7 = \frac{1}{I_y} \tag{4.16}$$

$$c_8 = \frac{I_x(I_x - I_y) + I_{xz}^2}{I_x I_z - I_x z^2} \tag{4.17}$$

$$c_9 = \frac{I_x}{I_x I_z - I_x z^2} \tag{4.18}$$

The following set of equations is used to transform properties from the body-fixed frame to aircraft position and orientation in the simulation environment [36].

$$\dot{x_E} = u\cos\psi\cos\phi + v(\cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi) + w(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi) \tag{4.19}$$

$$\dot{y_E} = u\sin\psi\cos\phi + v(\sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi) + w(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi) \tag{4.20}$$

$$\dot{z_E} = -u\sin\theta + v\cos\theta\sin\phi + w\cos\theta\cos\phi \tag{4.21}$$

Singularity and quaternions

The equations of motion above make use of the Euler angle approach for the model. The disadvantage of the Euler angle method is that the differential equations for $\dot{p}$ and $\dot{r}$ become singular when pitch angle θ passes through $\pm\frac{\pi}{2}$. To avoid this, quaternions can be used for the equations of motion [36].

In Unity during editing object's Transform component shows rotations in Euler angles but internally angles are represented as quaternions. Besides avoiding singularities quaternions are more suited for animation. When using Euler based rotation it's possible to cause gimbal lock. Which is a situation in which two of the three rotation axes are aligned [10].

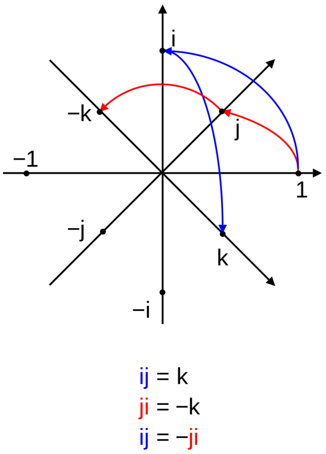

Figure 4.3: Graphical representation of products of quaternion units as 90 degree rotations in the planes of 4D-space [10]

Thrust balance

As you can see on Figure 5.2 the pivot point (denoted as PIVOT) is not exactly in between the rotors (denoted as A and B). This creates an imbalance of applied forces which would cause the aircraft to pitch forward and tip over. We need to adjust the balance of front and rear force by some ratio. We get this ratio using the law of the lever.

Flight simulation

It is difficult to establish how much in common does Unity have with simulation focused tools. However there is at least one aspect that is most likely the same or similar across the two. It's the Δt or the time interval that is being simulated in each cycle of the simulation. In Unity this is based on the frame rate of the game itself. In general, the smaller the change in time between simulation cycles, the more accurate the resulting aircraft position and attitude is. However, we must also concern ourselves with the limited computing power available [42].

User inceptors

Manual flight uses the HTC Vive controllers to control the vehicle. The control scheme is was designed with the aim of being able to use the project in a seated position with possibly having the controllers placed on a desk in front of the user. The image bellow shows which sections of the controller trackpads control which motions of the vehicle.

Input processing

The HTC Vive controller trackpads give a vector of X,Y axis value. The value ranges from -1 to 1 depending on the touch input. This input is taken and used as a modifier for force applied from rotors that keeps the aircraft airborne. This causes changes in pitch and roll. Throttle and rudder are controlled in a similar way but the input surfaces are configured more closely as a slider rather than an joystick input.

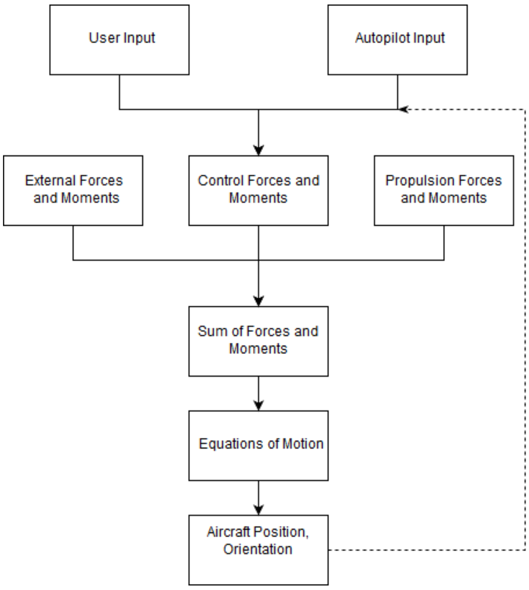

Figure 4.4: Diagram of simulation cycle

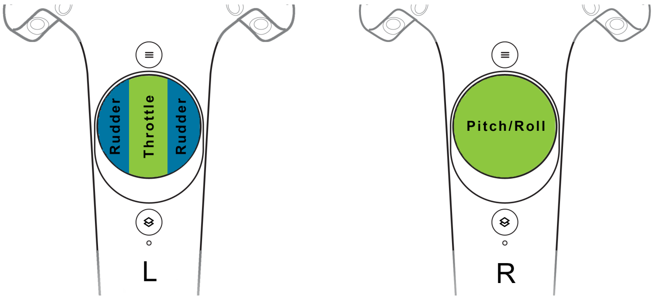

Figure 4.5: Control scheme

4.3 Collecting flight data

To gather flight date we need to track the vehicle's position and rotation and from that we can calculate data to be displayed that is more similar to actual flight data.

Each Unity object has a Transform component or it's variations. This component holds the object's position, rotation and scale. It also holds references to it's parent object and children objects.

- vehicle_parent_object
    - VR_camera_rig
    - hull_object
    - canopy_objecy
    - engines_parent_object
    - flight_data_hud_parent_object
        - menu_hud
        - data_hud

We will gather the position and rotation data in the from the top level object in the vehicle's structure. This object contains all the high level scripts of the vehicle and also it's Rigidbody component which provides physics simulation.

Altitude, heading, pitch and roll can be determined from the properties of the Transform component however some other important flight data can't. Data like vertical speed and airspeed can't be determined from a single data point. That's why the FlightData script. To gather this data the script retains the vehicle's position from the previous frame.

The final pieces of flight data are battery, course and warnings. Battery status is not quite important for the simulation so it's included only for completeness of the design. Most of the warnings are related to being on course and avoiding collisions. Collision detection is done by using Unity's Collider components in their trigger configuration. Navigation warnings are handled in a similar way.

4.4 Aircraft motion

Rotations

In this section we will take a short look on the physics of controlling an aircraft. We define roll, pitch and yaw as rotations around the aircraft from a steady flight state. A steady flight state is a state in flight dynamics where aircraft's linear and angular velocities are constant. The following applies to fixed-wing aircraft [41].

Control surfaces

To execute maneuvers aircraft use control surfaces. Pitching the nose up or down causes a change in lift generated by the wings through change of the angle of attack. A higher angle of attack generates more lift. This is done by using elevators. These are installed horizontally at the tail of the aircraft.

Ailerons are mounted on the trailing edges of wings, they move in opposite directions on each side. Again they cause a change in generated lift. One side's lift is increased while the other side's is decreased this causes the aircraft to roll.

Rudder is fixed to the vertical portion of the aircraft's tail. It's used to control the aircraft's yaw. It generates a bank motion of the aircraft, it can be used to counteract yaw effects of other rotation surfaces [41].

Helicopter controls

Considering that many urban mobility concepts are multirotor concepts or fixed-wing designs with vertical takeoff capabilities we need to delve into helicopter controls as well. Main difference between planes and helicopters is that helicopters use rotors which generate lift necessary for flight [41].

The main control element of helicopters is the cyclic. It controls the main rotor's blades pitch angle independently on each other. This means that each blade will have the same angle of incidence at the same point in the rotation. This controls helicopter's lateral movements [41].

The collective as the name implies controls the pitch angle of all main rotor's blades at the same time(i.e. collectively) regardless of their position in the rotation cycle. This causes a change in lift generated by the main rotor. In level flight this would cause a climb or a descent. If the helicopter is pitched in any direction this will cause acceleration in that direction and some climb [41].

We have to keep in mind that having a rotor generates a substantial amount of torque. There are two mainstream designs to counter act the generated torque. The first is having a smaller tail rotor. It works in a similar way to the main rotor but is mounted at the tail of the helicopter and its vertical. It's controlled by the anti torque pedals. These change the tail rotor's blades pitch resulting in a change of generated lift which causes the helicopter to yaw.

The alternate design uses a combination of two main rotors that rotate in the opposite directions which creates an equilibrium of generated torque. To rotate this balance is changed [41].

4.5 Displaying flight data

The display model is divided into two distinct parts. The mesh objects and User Interface (UI) objects. This is done to improve the design workflow and reduce processing requirements.

The mesh components behave better and have better controls for spatial movement. If the whole design was to be done using Unity's UI objects the movement of these around the pilot would cause undesired deformations. On the other hand creating a mesh based text would be fairly difficult and resource inefficient [38].

UI Objects

As mentioned above, all text displays are done using Unity's UI objects. Unity's UI system is somewhat bulky but very flexible if used correctly. Unity recognizes three major modes of UI:

1. Non-diegetic UI

Non-diegetic UI is the simplest type, rather than having a representation in the 3D environment it's a fixed overlay. This is commonly used to display information to the player such as time or a health bar.

2. Diegetic UI

Diegetic UI is usually attached to some object in the environment. Meaning that it has a physical representation in the game world.

3. Spatial UI

Spatial UI is an alternative to Diegetic UI, but it's represented three dimensionally meaning it can be positioned anywhere in the game world. This is the type of UI used in this simulation [38].

In Unity all UI is dependent on the Canvas object, Canvas serves as a main reference and focus point for the interface. With spatial UI this is less binding but still present.

In this implementation the Canvas is place roughly between edges of the doors of this vehicle. Other UI elements are placed in front of behind it. This doesn't change their visibility or render order. To control their visibility each important group of elements has a

CanvasGroup component in it's top parent. This components allows for controlling opacity of all of its child elements. The top parent also holds the Animator for that group [9].

Only one Animator could be used, attached to the parent object holding mesh objects and UI objects. However this makes is more difficult to transition animation states for opening and closing different menus and mesh objects are not animated which adds more objects for the Animator to keep track of even though they are not used.

An alternative would be for only the UI object's parent object to have this Animator. This would solve the problem of tracking unused objects, but not the state transition.

The implemented solution uses an Animator for each CanvasGroup, this simplifies the animation state machine. The drawback of this implementation is that the script controlling the menus needs to keep references to each of these Animators to control them [11].

Mesh objects

On the other hand mesh objects have a much simpler implementation. They provide a visual guide for flight data in 3D space. For the majority of this implementation this only means counteracting the movement of the vehicle and applying offset based on current flight data. The exception to this is the vertical speed indicator that only shows current data and the nearest waypoint indicator which points at the next waypoint on the currently selected course in case of manual control.

Mesh components of the visualization were created in Blender same as the testing vehicle. The aim was to use very primitive geometry as much as possible. The components are intended to be rendered with some transparency, in this case complicated geometry would only add to the resource requirements. Also with transparent rendering a substantial part of this geometry would simply not be visible. That's why most components are designed from primitive shapes with only minimal amount of edge bevelling [2].

Navigation

In this implementation navigation is done through a set of preset flight paths between landing pads. In a real world implementation navigation to a certain destination would most likely be done using a path finding algorithm.

In terms of displaying navigation data a map display wouldn't be very suitable. Instead we are drawing a physical path in the 3D environment in front of the vehicle, in addition to that the target landing pad is highlighted.

Manual navigation assistance

The flight tunnel along with having visible waypoint loops it has an invisible collider tunnel. This tunnel is activated when a flight path is selected. The vehicle detects collisions with this invisible tunnel, when this happens a warning sound is triggered.

4.6 Test scene construction

This render distance was taken into account when designing the map. This can be seen at the edges, which are empty except for a few locations. All included objects are designed with a low polygon count. The objects that take up the most polygons are the tree models used.

The map includes a simple representation of a city, it's designed using simple road objects and buildings. It takes up a fairly large portion of the area. Buildings are actually only placed at the edges of this area, because the buildings in the back would not be rendered due to distance.

The rest of the environment is taken up by a body of water and a representation of a suburban area with low density of houses. Rather than being visually pleasing this environment is designed to provide a background and reference points for flight.

Technical aspects

The intention of this concept is to be used in urban environments and suburban areas. This was included in the design on the test environment. There are some performance aspects to consider here. It is generally known that VR is resource intensive. To improve performance VR cameras have an implicitly reduced render range, this shows mostly at the edges of the user's vision as cut off edges.

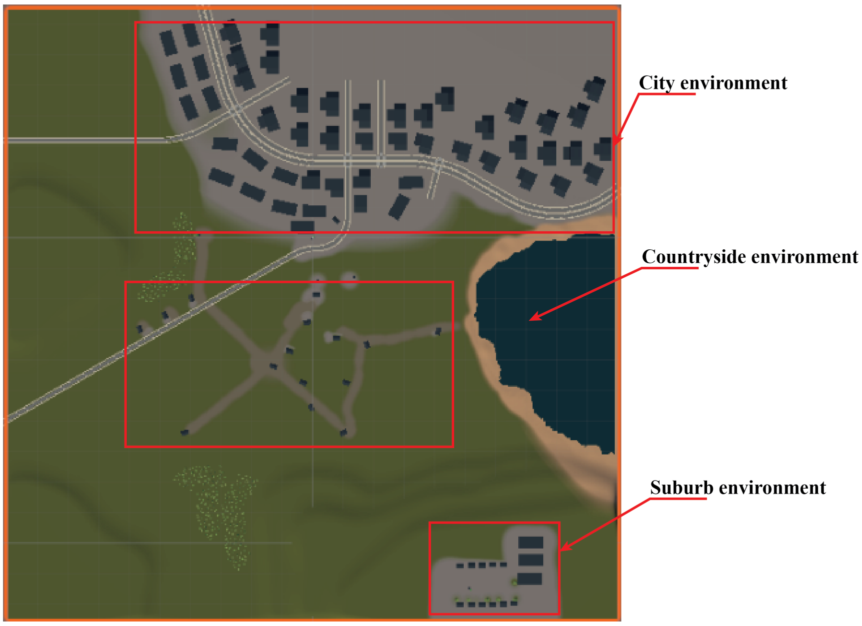

Figure 4.6: Iteration of the test environment

Landing locations and flight paths

The test environment has several flight paths for testing. These are placed in a way that would allow the evaluating user to move around the map using both manual and automatic flight controls. The landing zones feature similar construction to the city area to reduce the number of polygons. They feature a collider, when the vehicle enters this collider after a timer expires the vehicle's HUD is reset to destination selection based on flight paths available.

Chapter 5

Evaluation of achieved results

The progress and results went through a peer review and through a review by various experts in the fields of information technology, aerospace and pilots. The subject of evaluation is they way this concept displays data, the presentation and the accuracy.

5.1 User testing

Seeing as this concept is aimed at the user we have done most of the testing with several subjects with different levels of experience with flying and virtual reality.

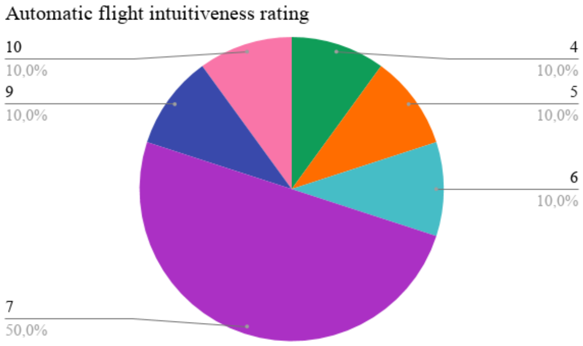

Figure 5.1: Graph of rating distribution (rated 0-10) for intuitiveness of automatic flight interface

We assembled a short questionnaire that we gave to ten volunteers after leaving them to test the concept for several days. They weren't given any special task besides trying to navigate the map using manual or automatic flight. The primary focus was to gather information about intuitiveness of the automatic flight display and entertainment options associated with it. As seen in Figure 5.1 this area has received moderate ratings from the users, we believe the reason for this is different perception of what the optimal interface should be.

Another area of focus was the information value of the manual flight display for controlling the aircraft manually. Figure 5.2 shows slightly better ratings. However it is important to note that all users took between 1-2 hours of flying manually to get used to the control scheme. Surprisingly, the two subjects with previous flight training on real life aircraft had the most trouble adjusting to the control scheme.

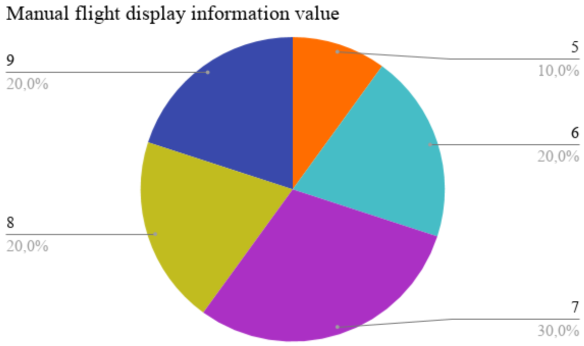

Figure 5.2: Graph of rating distribution (rated 0-10) for information value of manual flight interface

Finally we gathered the subject's overall impressions and notes on the concepts. As you can see in Figure 5.3, overall impressions were very positive. Some users have left notes on canopy opacity during automatic flight, this resulted in making the canopy less transparent while in automatic flight.

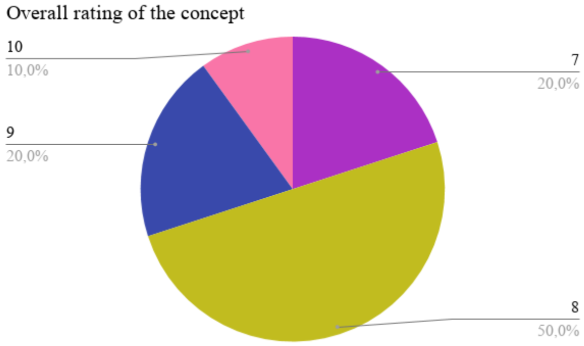

Figure 5.3: Graph overall rating distribution (rated 0-10)

5.2 Design

The thing to keep in mind is that this visualization design was intended for augmented reality displays or a large scale LED displays mounted in the cabin of the aircraft. For ease of implementation this thesis was implemented using a full virtual reality environment.

In an ideal case the demonstration cabin would be actually built as a simulation cockpit in 1:1 size. This concept is also designed to be versatile across multiple vehicles so the ideal testing case would be to actually test it with multiple VR vehicles.

The environment itself is set up in a mostly utilitarian and demonstrative way. This is sufficient for evaluating the design itself, for commercial demonstrations setting up a replica of a real location. Preferably a location that would benefit from using air taxis or other urban air transport service.

5.3 Potential improvements and future development

The scope of a bachelor's thesis is quite small, that's why it's understandable that there is room for improvement and development. This creates and opportunity for the same student or someone else to build upon this foundation and reach further goals and inventions.

Improvements

The physics model used in this simulation is just the Unity default, which provides a solid base but is not that advanced or true to reality in it's basic form. A major improvement would be to use a more advanced game engine such as Unreal Engine, CryEngine or Lumberyard. However these don't have a very developed support for virtual reality which could prove to be quite challenging.

Further flaw with Unity is with the default transparent shaders. It would take some experience with shaders in Unity to find a solution for transparent display elements and environment objects. This would help the overall immersion and if done correctly also have only limited negative impact on performance

A major performance and scale limit is the current virtual reality technology. Improvements could be made as the technology becomes more advanced or perhaps it could be replaced with some other way of displaying the simulation.

For this demonstration the test environment is randomly assembled more for navigation and diversity rather than accuracy. The best possible improvement would be to identify best locations that would be interested in implementing aerial urban mobility and reconstruct these areas for the simulator. Another improvement in this area would be to implement the path finding navigation for the simulated vehicle. The current simulation uses preset paths to demonstrate automatic flight.

The same applies to the concept itself. The vehicle it's displayed in was built for demonstration. A significant improvement or extension would be to adapt this visualization concept for an existing vehicle concept.

Future development

There are many potential developments possible on the basis of this thesis.

First step to any real world implementation would be an in depth study of the potential markets for this concept and urban air mobility in general. This would provide a base for further design and study in terms of requirements for actual implementation as well as testing environment, legal, societal and financial goals. Studies by major transportation companies and agencies show potential for growth and income in this area however many of these studies assume a completed and functional vehicle [24]. Which at the time is not true. This estimate should include the development investment for the vehicle as well as infrastructure and vehicle acquisition cost.

The next step would be to identify technologies that are required to make this concept reality such as air traffic control systems, flight and navigation computers and ground based guidance. We created a short overview in the previous chapters but for a fully functional prototype extensive research, out of scope of this thesis, would need to be done. At the time of writing we can summarize that currently available battery technologies might not be sufficient. Both in terms of performance but also in terms of price and environmental impact of their production.

In terms of university thesis or research the best possible next steps would be to either build a simulation environment based on a real location like described above. Alternatively a simulation cockpit could be built to mimic the design of an actual urban mobility aircraft. This could also be the logical step between a concept and a real world implementation.

Chapter 6

Conclusion

You have to consider that urban air mobility is in it's very early days at the moment. However many companies are exploring this topic. There are many obstacles and concerns to overcome before urban air mobility becomes a mainstream method of transportation [20].

Currently unmanned vehicles are used to fast delivery of goods in urban areas. This ranges from Amazon deliveries to Japanese gangs using drones to transport drugs. This raises the concern of UAM systems and infrastructure being exploited for illegal use.

Though the currently most prominent usage of drones and remotely controlled aerial vehicles is surveillance and photography. Police and military units frequently use unmanned drones to observe areas from a safe distance or to increase their coverage.

The commercial and mainstream spread of urban aerial mobility vehicles for personal transport is inhibited by several technological, societal and legal barriers [24].

Some studies indicate that inhabitants of cities have concerns about autonomous or piloted urban mobility aircraft. We believe that this is more due to the fear of new technology rather than actually having something to do with urban mobility aircraft. The initial gap of public distrust would have to be bridged over time. This effort could be supplemented with advertisement campaigns targeted at the areas where urban air mobility would be implemented. However regardless of the supporting efforts made it still might take substantial amount of time for the public to trust this new technology. Not to mention the time required to make this technology reliable and viable in a commercial setting.

Safety

For a few years now, since the rise of commercially available drones, there has been an ongoing debate about the dangers of civilian drones. There have been incidents of drones interfering with air traffic or road vehicles.

For widespread public adoption of VTOLs as a ridesharing option, riding in a VTOL must be safer than riding in an automobile. In order that VTOLs are accepted by the market, claiming that the vehicles are merely as safe as driving, particularly given the active public discourse regarding potential safety improvements from autonomous vehicles, will almost certainly be insufficient.

The concept presented in this paper is meant to be an optionally piloted vehicle. This alone increases the safety and diminishes or even removes the possibility of a pilot error. Inclusion of collision avoidance systems would reduce the risk of manually piloted flights.

The next highest accident cause is associated with engine failure, which accounts for 18% of general aviation accidents when combined with fuel management errors. This is mitigated with the use of multiple (typically six or greater) electric motors, controllers, and a redundant battery bus architecture avoids the problems of catastrophic engine failure by having full propulsion system redundancy. An engine failure might result in diminished speed or climb capability, but full control over the aircraft can be maintained [24].

Societal barriers

In addition to other issues, introducing a new mainstream traffic option has to take the opinion of the general society into account.

One of the main concerns for the society is the noise created by these aircraft. Considering that this and most urban mobility aircraft use electric motors, which have fairly low noise levels. Furthermore, proximity regulations and air traffic control would control the actual distance of the aircraft from buildings and streets [22].

Another concern for the public is general safety of these aircraft and the benefits provided to the general population. The overarching goal here is to weigh the personal benefits against mass suitability and decide how to best reconcile the increased comfort of travel and transport with the larger cultural change wrought by passenger drones. The public's perceptions and opinions about vertical mobility vary from continent to continent, from country to country, and from city to city, covering everything from fear and scepticism to outright enthusiasm [20].

Legal barriers

For a complete picture of concerns and barriers we have to look at the legal side of things. We expect commercial passenger transport to remain a highly regulated market that will remain under the guidance of the two global regulatory agencies, the FAA in the United States and EASA in Europe. Looking at the regulatory and legal requirements, one can differentiate between certification of the aircraft development organization, the aircraft itself, the aircraft production, the operations, the service, and the pilot license [20].

As mentioned before, commercial and civilian aircraft are heavily regulated by various laws and agencies. In recent years with the increased civilian ownership of drones has prompted law makers around the world to start creating laws and regulations that dictate the use and ownership of these drones. In terms of urban aerial vehicles we need to take these regulations into account as well. Noise and air traffic control will also be subject to legal debate.

Infrastructure

It goes without saying that enabling urban air mobility in modern cities will take some changes in the infrastructure. Currently the city ecosystems don't have room or don't expect the inclusion of urban air mobility. To make urban air mobility a viable part of city and personal transportation systems it has to be well integrated into the existing systems, this would likely involve large investments.

Just going from the basics, it would be necessary to create landing areas for the aircraft, these should include the ability for the aircraft to recharge or refuel. But also should have an area for the passengers to wait for boarding. While this concept is focused more on private users who most likely have landing facilities available it is important to outline the steps needed for commercial or widespread applications [22].

Furthermore air traffic control and air traffic navigation systems would need to be installed within the target areas. These would offer far more efficient flying with virtual corridors maintaining close but safe separation of flights. The air traffic control would be ideally a decentralized automated system that would utilize data from the aircraft's flight computer, weather data and data from navigation beacons around the flight zones [22].

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List of Appendices

Appendix A

User testing questionnaire

About You

1. Gender

☐ Male ☐ Female

2. What is your age?

☐ 20-30 ☐ 30-40 ☐ 40-50 ☐ More than 50

3. Do you have any pilot training?

☐ Yes ☐ No

Concept

1. How intuitive did you find selecting automatic flight?

Rate from 0(not at all) to 10(perfectly intuitive)

2. How sufficient did you find the navigation tunnel for maintaining course in manual flight?

Rate from 0(not at all) to 10(perfectly sufficient)

3. Did the manual flight display provide enough information for flight?

Rate from 0(not enough) to 10(perfectly enough)

4. How was your overall impression of the concept?

Rate from 0(terrible) to 10(excellent)

5. Use this space to write down any notes or remarks you have about the concept: