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An In-Flight Extended Reality Tool for General Aviation Situation Awareness

Geomatics Master Thesis 2024

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Abstract

Flights in General Aviation (GA) are commonly operated under Visual Flight Rules (VFR). Under VFR, pilots navigate by comparing features on the earth's surface to a 2D map. This mental process entails a focus split between inside and outside the cockpit. The focus split decreases the mental capacity of the pilot. Other tasks, such as looking out for traffic, are neglected, thus the overall situational awareness of the pilot is reduced. Although paper maps are still encouraged to be used as a main navigation tool, 2D moving maps on mobile devices are getting more popular to support the pilot with digital information. However, displaying information in 2D in an attempt to capture the 3D world in which the flight takes place is still inadequate. Projecting flight-relevant information directly into the real world would be the logical next step. Despite Augmented Reality (AR) technology being already used in commercial aviation, no such tool exists to support GA pilots. This work explored the effect of AR technology on the situational awareness of a pilot in a GA aircraft operation under VFR. While the main focus of the still sparse research for AR technology in the GA sector lies either on highlighting traffic or implementing an approach guidance tool, this work expanded the possibility of more geographically relevant information during different phases of VFR flight. An AR application was developed for Microsoft HoloLens 2, featuring six scenarios set in Switzerland, integrating non-visible aeronautical information, VFR navigation features, and hard-to-see hazards. A user study with 19 pilots in a flight simulator was conducted to evaluate the tool's effect on situational awareness. The results indicated that the AR tool positively influenced situational awareness, particularly in disorientation scenarios during cruise flight in unfamiliar areas. The novel 3D visualization of airspace structures and the tool's ability to identify and display the current and upcoming airspace were found to enhance situational awareness. However, the effect of AR during approach phases was less conclusive, likely due to the early development stage of the application and limitations of the flight simulator. Participants raised concerns about the potential occlusion and distraction from real-world environment due to the AR content, which could negatively impact situational awareness. Moreover, an AR menu was evaluated as an interaction method within the application but found not optimal for a cockpit environment.

Scan the QR Code to get to the GitHub Repository for this project.

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Glossary

Abbreviation	Term	Description
AR	Augmented Reality	AR is an interactive experience that combines the real world with computer generated digital 3D content.
ATC	Air Traffic Control	Coordinates air traffic in controlled airspaces
ATPL	Airline Transport Pilot License	The ATPL is required to command aircraft over 5700 kg or with over nine passenger seats.
ATZ	Aerodrome Traffic Zone	Airspace in vicinity of uncontrolled airfield
AWY	Air Way	Controlled airspace used for cruise flight of IFR traffic.
BAK	Basic Aviation Knowledge	Theoretical material for student pilots divided into nine subjects.
CPL	Commercial Pilot License	Allows to fly aircraft with up to nine passengers for commercial purposes.
CRS	Coordinate Reference System	A CRS consists of a coordinate system and a referencing datum. The datum defines location and of the origin as well as the orientation of the axes.
CTR	Controlled Traffic Region	Airspace in close vicinity of an airport.
DEM	Digital Elevation Model	Generic term for digital representation of the earth's surface.
DME	Distance Measuring Equipment	DME is a radio navigation aid.
EASA	European Air and Space Agency	European agency for flight safety
FI	Flight Instructor	Rating needed to train student pilots.
FIZ	Flight Information Zone	Airspace in which flight information service is provided. Controller can only give information, no commands to flight crews.
FOCA	Federal Office of Civil Aviation	The FOCA is responsible for the supervision of civil aviation activities in Switzerland.
ICAO	International Civil Aviation Organization	International organization with the aim to standardize civil air traffic.
IFR	Instrument Flight Rules	One of two basic flight categories. Under IFR pilots navigate relying on instruments and ATC.
IMU	Inertial Measurement Unit	IMU is an electronic device measuring a body’s specific force and orientation using a combination of accelerometers and gyroscopes.
IOPA	International Aircraft Owner and Pilot Associations	IOPA is a non-profit organization that advocates for general aviation.
LAPL	Light Aircraft Pilot License	Allows to command aircrafts with a maximum take-off weight below 2000kg with max. 3 passengers non-commercially.
LS-D	Lower Europe Switzerland - Danger Area	Indication of hazards for air traffic in this airspace.

LS-R	Lower Europe Switzerland-Restricted Area	Airspace that is prohibited to enter by aircrafts.
MR	Mixed Reality	Middle part of the extended reality spectrum, between VR and AR.
MSFS	Microsoft Flight Simulator	Flight simulator developed by Microsoft
POI	Point of Interest	POI is a location the one may find interesting or useful.
PPL	Private Pilot's License	Allows to command aircrafts with a maximum take-off weight below 5700kg non-commercially.
SEP	Single Engine Piston	Category of airplanes with one piston engine
TMA	Terminal Maneuvering Area	Airspace in broader vicinity of an airport.
VFR	Visual Flight Rules	VFR means that the aircraft is intended to operate in visual meteorological conditions, avoiding adverse weather conditions. Most GA operate under VFR
VOR	Very High Frequency Omni-directional Range	VOR is a radio navigation aid.
VR	Virtual Reality	VR is a fully immersive experience into a digital environment.

1 Introduction

According to the civil aviation statistic published by the Federal Office of Civil Aviation (FOCA) and the Federal Statistical Office (FSO) in Switzerland (FSO, 2023) the number of civil aviation movement in Switzerland in the year 2022 was 1.3 million (take-offs and landings), with general aviation (GA) accounting for 74% of these movements. The International Civil Aviation Organization (ICAO) defines GA as "all civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire" (ICAO, 2009). This encompasses activities like recreational flights, pilot training, business aviation, civil search and rescue and many more. This aggregates a worldwide market with approximately 700’000 pilots involved, according to IOPA Europe, which is the European branch of the International Council of Aircraft Owner and Pilot Associations (IAOPA) (General Aviation (GA) | SKYbrary Aviation Safety, n.d.).

Flight operations can be split into flights following Instrument Flight Rules (IFR) and Visual Flight Rules (VFR). It can be said that scheduled air services (passengers and cargo) usually operate under IFR. VFR, however, is used in a wide range of GA activities. The main difference between the two types of flights is that IFR traffic is guided by air traffic control (ATC) and navigates with the help of cockpit instruments. VFR traffic, on the other hand, uses the earth’s surface as a reference for orientation and navigation, thus being visual. In VFR traffic, the responsibility to keep a safe distance from other traffic, obstacles or terrain and navigate around airspace sections he has no clearance to enter lays solely with the pilot, not as for IFR traffic.

Focusing on Switzerland again, Figure 1 shows a timeline of the split in civil aircraft movements in Switzerland. The only category not counting as GA is the “scheduled flights“ category. Commercial pleasure flights (also part of GA) are not included in the figure. The graph showcases the large proportion of GA traffic in Switzerland.

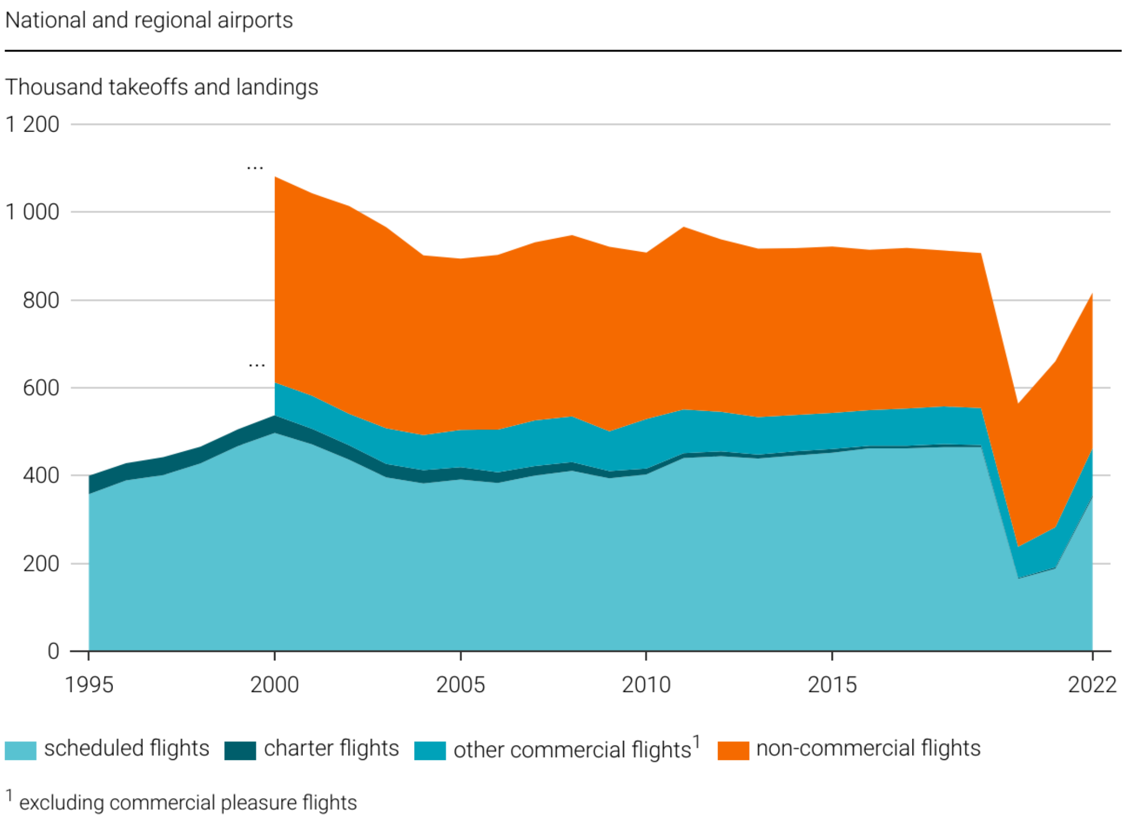


Figure 1: Aircraft movements in civil aircraft (FSO, 2023)

Looking at Figure 2, one can observe the geographical distribution of the GA movements (take-offs and landings). Whereas the big international airports Zurich and Geneva are mainly used for scheduled flights, regional airports are used for GA activities. The rather small territory of Switzerland brings these civil aviation activities close together, increasing the risk of conflicts.

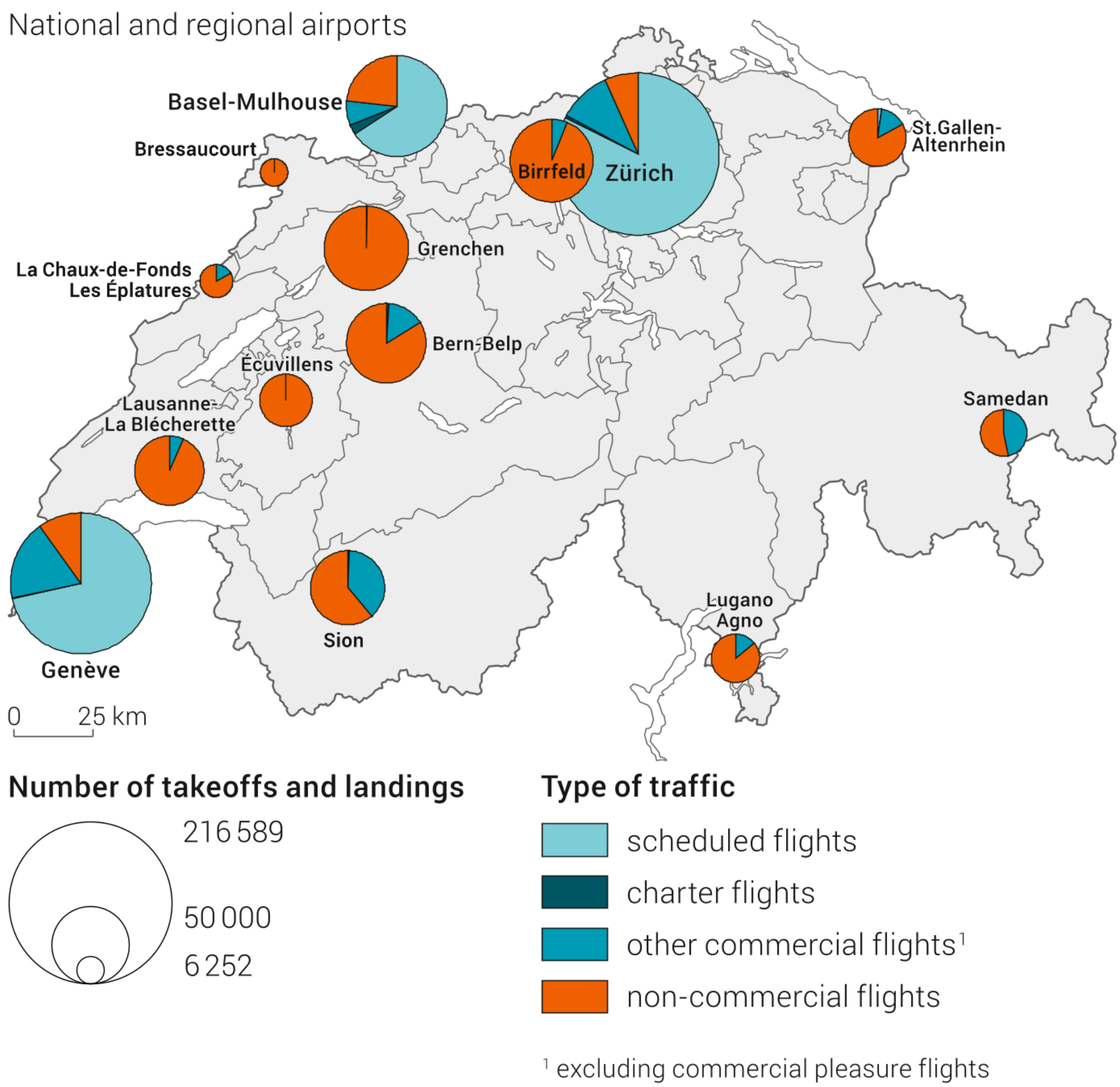


Figure 2: Aircraft movements in civil aviation, 2022 (FSO, 2023)

To minimize the risk of mid-air collisions, there are international standards on how to structure the airspace in a way that all traffic types are able to complete their flight safely. Each airspace section is categorized. The category defines the rules to obey while flying in this airspace section. More on that will be explained in Chapter 4.2.5 about the airspace data used in this project. When looking at Figure 3, one can see how these standards are realized in Switzerland. The polygons with blue outlines indicate the controlled airspace sections, each with a lower and upper limit. The regions around Zurich and Geneva stand out particularly due to their complexity and fragmentation.

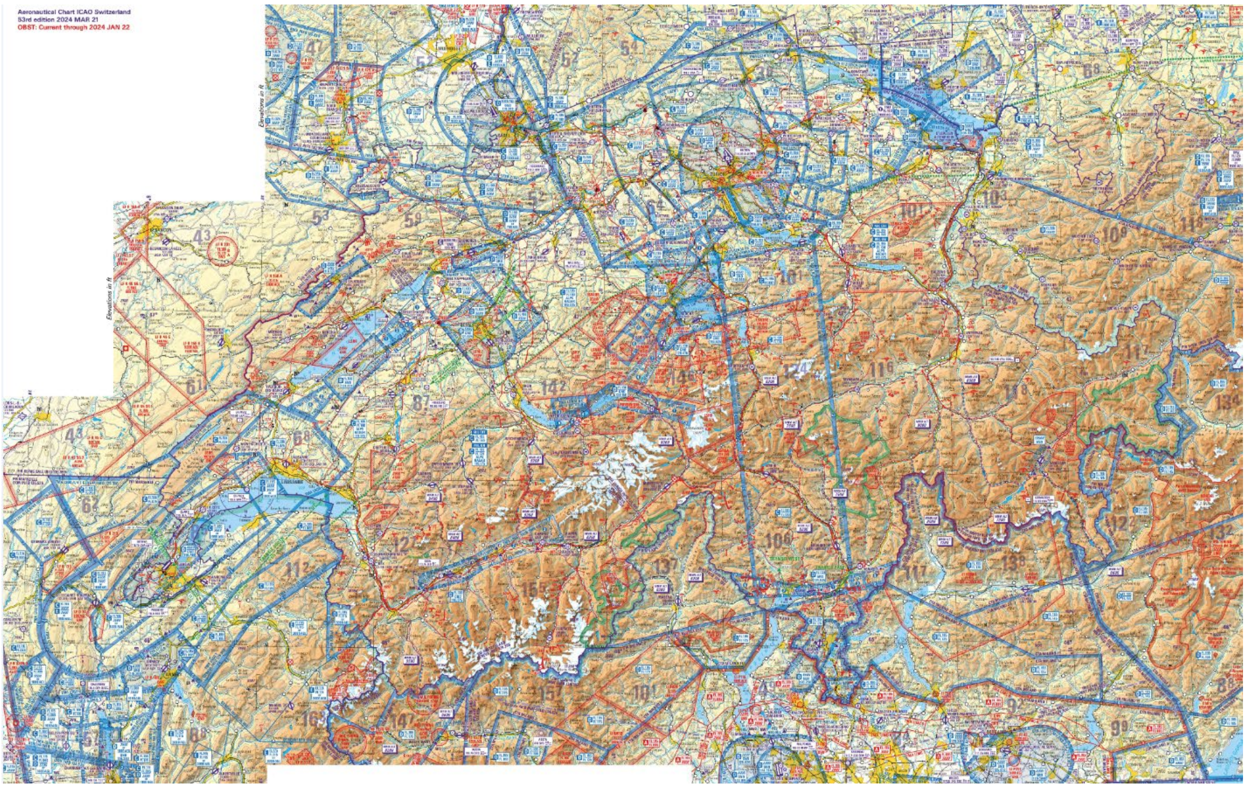


Figure 3: ICAO Chart Switzerland (swisstopo, 2024b)

The chart shown in Figure 3 is nowadays still used as a main navigation aid by many GA pilots. During pilot training in Switzerland, a student is only allowed to use a paper map version of the ICAO chart. After training, it is still encouraged to continue navigating in such a way by flight schools and the FOCA. The biggest disadvantage that this entails is the split of focus between the paper map (looking inside the cock-pit) and referencing the corresponding location in the real world (looking outside the cockpit). A normal map reading process, which is aggravated by multiple factors in the cockpit and can have negative effects on the situational awareness. As mentioned in an earlier paragraph of this introduction, VFR pilots are navigating only by identifying terrestrial reference points to orientate themselves and determine where to go next. Factors like ambient lighting, turbulence, and the small space available in the cockpit, make it harder to complete this map reading process inflight. Digital versions of the ICAO chart (or a similar chart) on a tablet have the advantage of being used as a moving map, showing the position of the aircraft on the map at all times with the help of GPS. Technology to increase situational awareness in GA nowadays is focused on such tablet applications and therefore still requires the pilot to take away focus from the outside world. In military and commercial aviation augmented reality (AR) technology such as heads-up displays (HUD) and head mounted displays (HMD) have proven to be beneficial for situational awareness. This technology allows the pilot to keep their focus on the outside by projecting flight relevant information directly into the field of view of the pilot. However, this technology has not yet reached GA. Only little research has been performed in the GA sector regarding such technology. Relevant papers will be presented in Chapter 3.

This thesis focuses on the effect such an AR tool has on situational awareness. Hereby, the orientation and navigation aspect is at the forefront. The scope of this thesis comprises the development of an AR navigation aid tool and testing its effect on the situational awareness of a pilot with the help of a user study. A thorough evaluation of what information is most relevant for VFR navigation, how it can be visualized and what are suitable hardware options is included. The user study was carefully designed to effectively test the research question, which is stated in the next chapter.

1.1 Thesis Goals

The goal for this thesis is to develop an Augmented Reality (AR) tool to support the situational awareness of general aviation (GA) pilots and test it in a user study. During the development, the focus should be on visualizing non-visible aeronautical information (e.g., airspace structures, advisory points, waypoints, approach procedures, etc.) and hard-to-see hazards (e.g., antenna towers, traffic, wires, cable cars, etc.). Additionally, displaying information aiding pilots with their tactical decisions during flight under VFR could be beneficial for situational awareness in flight (e.g., airports, villages, mountain peaks, etc.). To be able to measure the performance of the application, the following research question and hypotheses were formulated:

RQ: *What are the effects of an augmented reality tool to the situational awareness of the pilot in a general aviation cockpit?*

H1*: AR will allow the pilot to raise the situational awareness by noticing hazards faster.*

H2: *AR will increase situational awareness by increasing awareness of nearby airspace structures.*

H3: *AR can support regaining location awareness in case of disorientation.*

H4: *AR will allow to fly the planned flight more accurately and precisely.*

1.2 Vision

With the goal in mind, a vision of what the application could look like was created by overlaying digital content as sketches on photographs taken inflight. The photographs were taken by the author. Figure 4 shows the vision for two different flight phases. In the left image, a cruise flight scenario is captured, while on the right image, an approach is depicted. The information displayed was already selected to support finding an answer to the research question however, the exact information types to be displayed were evaluated more thoroughly before starting the development of the application.

During cruise flight, the task of orientation is imagined to be supported by highlighting town names, obstacles like power lines, and points of interest such as power plants and monasteries. Another idea in the vision was to display the surrounding airspace structure to raise the awareness of the pilot on where the boundaries of airspace sectors are. Some sort of menu should be included to toggle different information.

Figure 4: Illustration of Vision

During an approach, the circuit layout is envisioned to be projected into the real-world as gates to fly through (green gates in Figure 4). Information about the destination airport should be displayed near the airport to make the pilot aware of radio frequencies, runway directions, runway length and elevation of the airport.

2 Aviation Theory

This chapter aims to give a brief introduction into theoretical aspects of aviation relevant to this thesis. Some basics on VFR navigation is presented before giving an insight on GA safety.

2.1 VFR Navigation

This chapter is based on the Swiss Basic Aviation Knowledge (BAK) subject 061 (Bruno Guggiari, 2020) and the Pilot's Handbook of Aeronautical Knowledge chapter 16 by the American Federal Aviation Administration (FAA) (2023). Whereas the BAK documents are used for pilot training in Switzerland, the airplane flying handbook is the equivalent for the US basic flight training program.

According to the Pilot's Handbook of Aeronautical Knowledge, chapter 16, pilotage is a crucial part of VFR flight. Pilotage is defined as navigation by reference to landmarks or checkpoints on the earth's surface. These checkpoints should be prominent features common to the area of the flight. Such features include roads, rivers, railroad tracks, lakes and powerlines. The book recommends not relying on only one feature per checkpoint, as structures such as antennas might be difficult to see or could lead to false identification. Especially weather conditions and lighting scenarios can make it difficult to identify features. GPS has become a great asset to VFR pilots, increasing navigation capabilities and situational awareness. It is clearly stated in the book, that a pilot should never rely solely on GPS for navigation. Many of the GPS receivers used in GA are not able to display position errors or loss of the required numbers of satellites in view. Another critical point in terms of digital navigation aids is the veracity of the data. Regularly updating the database is mandatory to avoid outdated information. Pilots are encouraged to minimize the head-down time (focus inside the cockpit) and maintain a sharp lookout for traffic, terrain and obstacles.

According to the definition of the BAK, VFR navigation relies on navigation by terrain references and can be supported by radionavigation equipment. Such equipment is prone to errors due to technical or atmospheric disturbances. When planning a VFR route, a pilot should consider choosing waypoints visible on the VFR map. In addition to this, it is recommended to lay the route along distinctive features in the terrain to avoid disorientation. In some cases, this even justifies a small detour. Features mentioned in the BAK are highways, rivers, lakes, railroad tracks and valleys. The presence of multiple features at a waypoint help clearly identify the point or built-up area. However, they should not be further away than three kilometers to avoid false identification. It is also recommended to define catchlines to indicate one is still on the planned route. A small subchapter in subject 061 in BAK is about the comparison of the map and observations in the real world. The mental process of comparing the features on the map and placing them in the real world includes verifying those features with the help of a compass or gyro and combining multiple such features. This increases the workload of a pilot and lowers the mental capacity for other flight relevant task such as for example looking out for traffic. Figure 5and Figure 6 showcase two examples of real world observations vs. the map excerpt. The view angle icon indicates the position and orientation the image on the left was taken in. The town of Dagmarsellen (see Figure 5) provides strong features such as the curve of the highway, the small river crossing the highway and a road crossing the highway at an angle of ninety degrees, simplifying identification of the town. In the second example, the small village of Dürrenroth (see Figure 6) in the canton of Bern is harder to pin down. Especially as there are quite a few towns in this region that look alike.

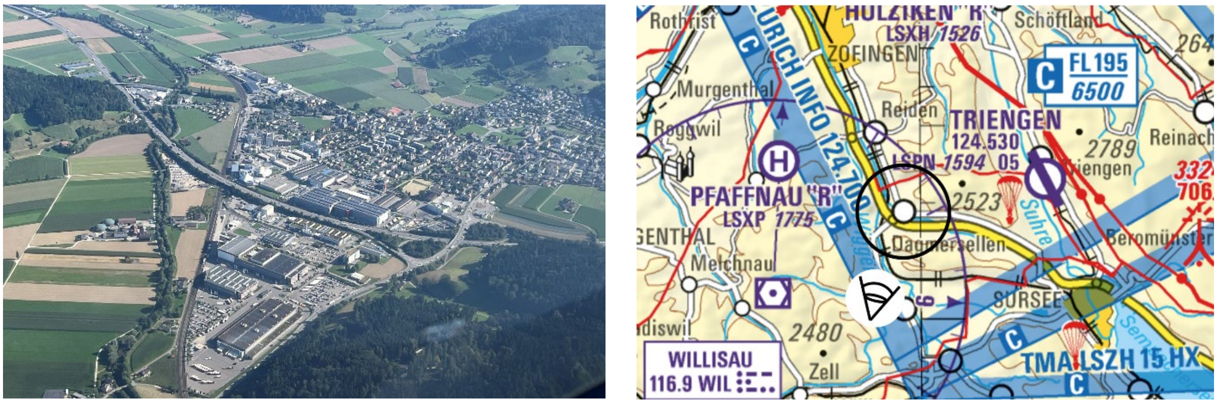


Figure 5: Dagmarsellen observation (own image) vs. map excerpt (swisstopo, 2024b)

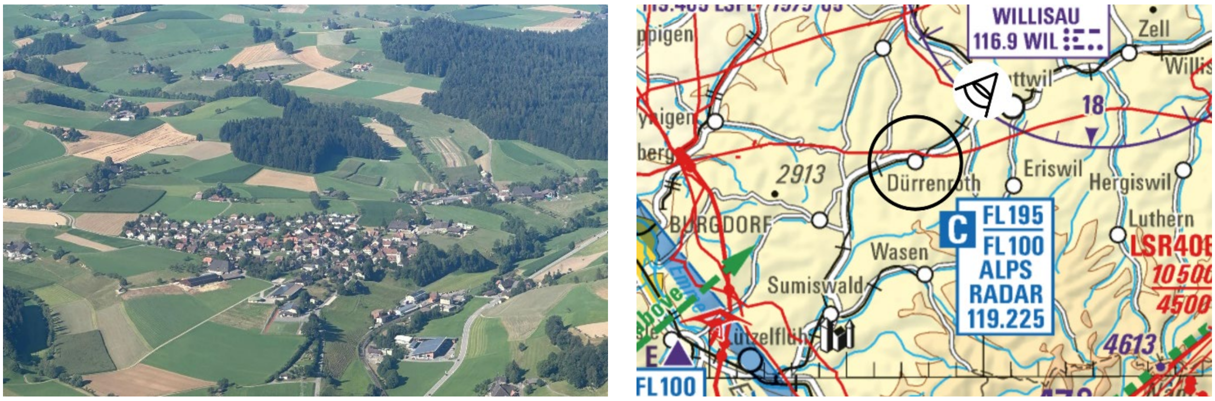


Figure 6: Dürrenroth observation (own image) vs. map excerpt (swisstopo, 2024b)

The paper "Evaluating and Comparing Airspace Structure Visualization and Perception on Digital Aeronautical Charts" by Sarbach et al. (2023) takes up the topic of the mental process during map reading mentioned in the previous paragraph. Sarbach analyzed VFR charts from different countries and emphasizes the challenge of visualizing 3D space (airspace) on a 2D map. Next to analyzing the charts, a conducted user study revealed what medium is used inflight to view charts and what features on the earth's surface are relevant for VFR navigation. Figure 7 shows the result on what medium is used (left figure) and what features are used for VFR navigation (right figure). 27 Swiss private pilots participated in the user study. Paper maps were the main medium used by the participants, followed by digital maps on tablets. Looking at the features on the map relevant for VFR navigation water bodies, mountain passes, roads and railroads, prominent buildings, aviation infrastructure, settlement boundaries, aviation obstacles, as well as settlement labels are listed.

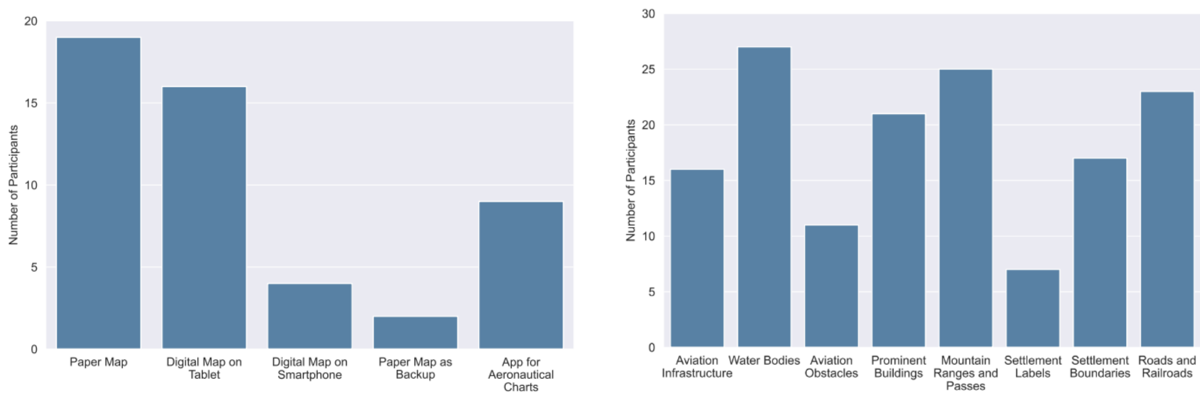


Figure 7: Chart medium and features for VFR Flights (Sarbach et al., 2023)

2.2 Circuit Terminology

A circuit is a standardized procedure in aviation referring to the patterns and altitudes to be flown during a departure or approach. At uncontrolled airports, pilots coordinate and communicate their movements with other traffic within the circuit. The pattern can be divided into five legs. The terminology for each leg is introduced in Figure 8. These terms will be referred to in the results and discussion of this work.

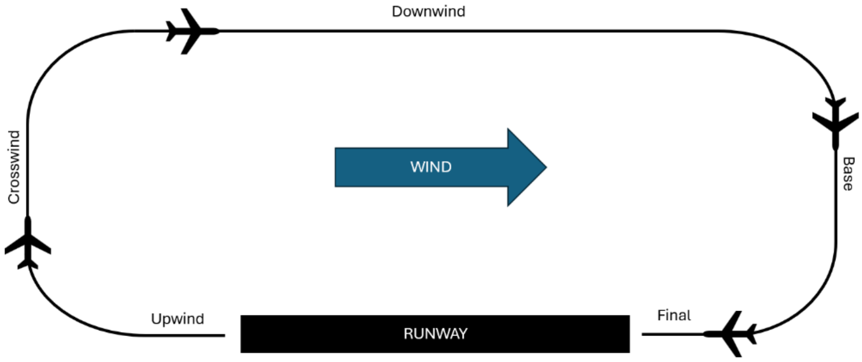


Figure 8: Circuit terminology

2.3 General Aviation Safety Issues

The European Air and Space Agency (EASA) identifies the “Key Risk Areas” for general aviation flight safety as aircraft upset (aircraft attitude and airspeed out of the normally intended limits), runway excursions and ground collisions. Hereby, aircraft upset has a high number of occurrences and is assessed at a high risk in an accident. Figure 9 highlights the safety issues in terms of risk and number of occurrences. Second, after the system reliability, the issue of perception and situational awareness is stated. Directly after that, decision making and planning, as well as flight planning and preparation, are listed. Another issue related to this thesis listed is approach path management. (EASA, 2021)

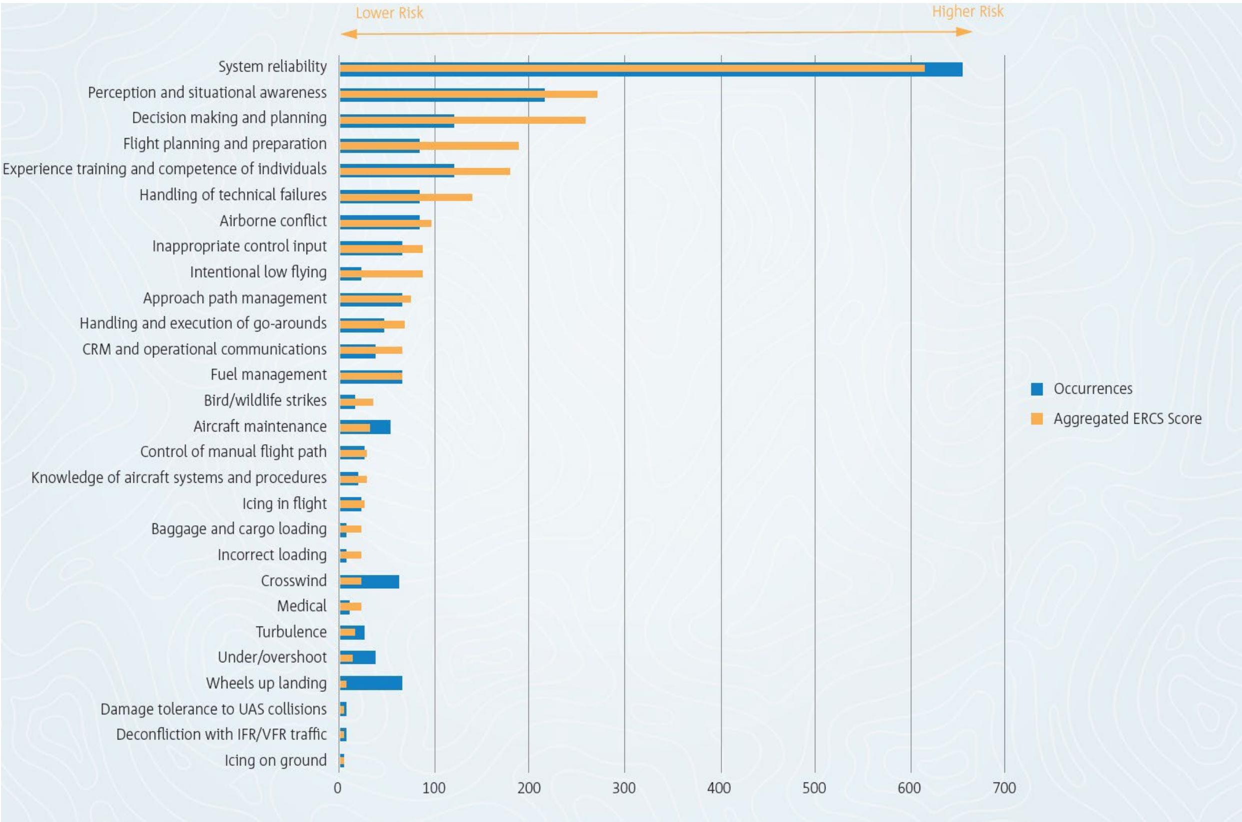
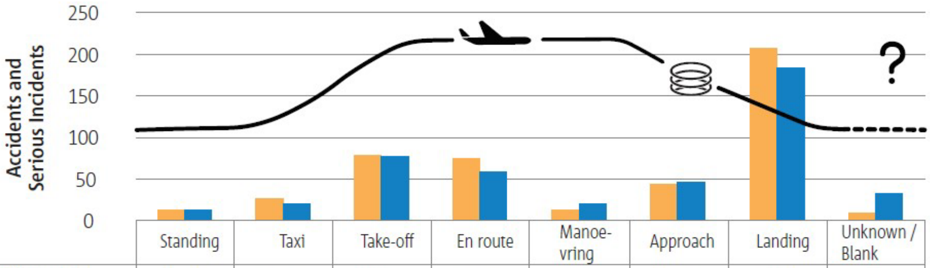


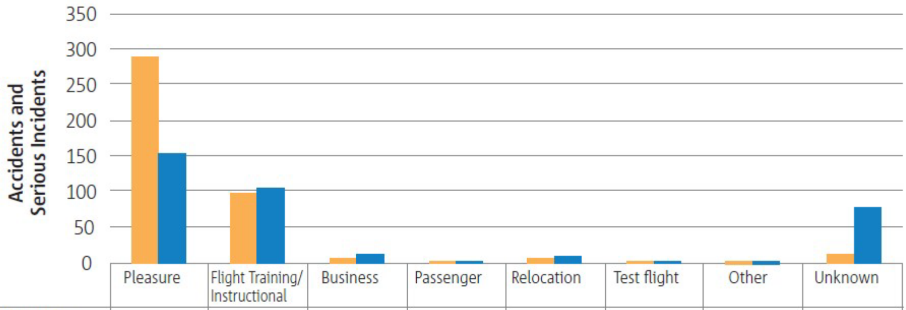
Figure 9: Safety issues and topics (EASA, 2021)

The subsequent step, following the identification of safety issues, is to determine the specific phases of flight and types of operations in which accidents are most frequently observed. **Error! Reference source not found.** is taken out of the EASA Annual Safety Review 2020 (EASA, 2020) and indicates that most accidents occur during the landing phase, followed by take-off and en route. The landing and takeoff phases are especially critical as the aircraft is operated at slow speeds close to the terrain, leaving little to no room for errors and recovery. Looking at Figure 11, most accidents occur either during pleasure flights or flight training. Both operation types mainly operate under VFR conditions. There are exceptions in which these operation types fly under IFR.



	Standing	Taxi	Take-off	En route	Manoe-vring	Approach	Landing	Unknown / Blank
Average 2009-2018	12.4	26.3	78.8	73.7	14.3	44.4	207.4	9.9
2019	13	20	76	60	19	45	183	32

Figure 10: Accidents by flight phase (EASA, 2021)



	Pleasure	Flight Training/ Instructional	Business	Passenger	Relocation	Test flight	Other	Unknown
Average 2009-2018	286.8	97.4	9.3	4.9	7.1	5.9	6	14
2019	156	106	14	3	10	1	1	80

Figure 11: Accidents by operation type (EASA, 2021)

3 Related Work

In this chapter related work is presented. First, work on AR in general aviation is introduced. Lastly, work on situational awareness is presented.

3.1 Augmented Reality in General Aviation

As mentioned in the introduction, the topic of AR in general aviation cockpits is yet only sparsely explored scientifically. However, there exists some very interesting work on this topic. The following paragraphs will give a brief overview of work related to AR in GA cockpits.

A paper published by Katins et al. (2023b) captures pilots opinions regarding Mixed Reality (MR) headsets in GA cockpits. The motivation for the paper was the inadequate visualization of 3D space on a 3D map displayed on tablets. Twelve participants (pilots with SPL, LAPL, MPL or PPL licenses) tested a MR application developed for this paper in a full-size simulator (aircraft type Diamond DA40) and gave verbal feedback in an in-depth interview. The results revealed valuable insights into pilots' concerns, design prerequisites for future systems, and potential use cases. The MR prototype was found useful by most of the participants. However, the lack of experience with MR led to a higher workload perceived by some participant because of the novelty and unfamiliarity with the technology. Participants stated that with the proper familiarization with the prototype, they could see a reduction in workload. This is due to the fact that the prototype supports the scanning (looking for traffic), navigation and general situational awareness. Additionally, it was found that using MR in aviation is highly individual. The device used for the study was a Microsoft HoloLens 2 (a more in-depth introduction to this device will be made in chapter 4.6 of this thesis). The device was found to be acceptable in terms of wearing comfort. Concerns about use in GA cockpits were still raised, mainly due to its weight and the effect of g-forces in flight. Regarding the information display in the prototype, participants wished for more adaptability of the information, either manually or automatically. During the interview ideas on what features to implement in such a MR navigational aid tool were collected. The included illustrations of airspaces, flight paths, airport traffic patterns, or weather information.

In another paper published by Katins et al. (2023a), the researchers investigated the impact of MR in GA flights in terms of user experience and task load. The data used for this evaluation was acquired at the same user study as the paper mentioned in the previous paragraph. The task performed by the participants, was to fly approaches. One with and one without AR support. Hence, it was a within-subject study design with the independent variable being with or without AR. Airports to be approached were altered between cases. The weather was simulated to be overcast (high covering clouds) and the time was set to 10 o'clock, ensuring good visibility. While flying the approach, pilots were asked to announce any traffic occurring in their field of view. To measure the task load, the NASA TLX (Hart & Staveland, 1988) questionnaire was chosen. For evaluation of the user experience, the UEQ questionnaire (Laugwitz et al., 2008) was used. The results showed no significant reduction in task load when performing the task with AR. However, seven participants reported lowered task load during the AR condition. Flight paths were recoded and it was found that in general the traffic patterns were followed more consistently when using the AR prototype. Additionally, more traffic (3.5 aircraft instead of 0.25 without) was detected in the with AR condition. When analyzing the results from the UEQ, the condition with the AR prototype positively stood out in terms of perspicuity, stimulation and novelty. Efficiency, dependability and attractiveness showed no significant deviations in both conditions.

Also worth mentioning, is a paper by Haiduk (2017). As for this thesis, the motivation for this paper was the head-down time current navigation aid entail, reduction of the look-up time inflight. A flight guidance display for smart glasses was developed and evaluated as part of this work. Similar to the user study by Katins, participants were asked to fly approaches in a flight simulator and detect traffic through the task. Twenty pilots participated in the study. Haiduk used an Epson BT-200 smart glass for his work. Guide lines towards a next waypoint were used to augment the path anticipated to be flown. The projected information was head-referenced. Meaning the projection stays the same when the user turns his/her head. The results showed no significant difference in workload between the group with and without the smart glasses. Oral feedback by the users stated that the information display can be distracting from the information in the background (simulator). In addition, participants mentioned that the information should at least be airplane-referenced, if not world-referenced.

A more technical approach was pursued by Walko et al. (Walko & Maibach, 2021). Flight testing and the integration process of the Microsoft HoloLens 2 as a head-mounted display (HMD) on a helicopter are discussed in this paper. To be able to use the HoloLens 2 in a real aircraft, a more advanced tracking system had to be developed. Scenarios with only internal tracking, only external tracking and a combination of both were evaluated. The visual perception of displaying an artificial horizon, airspeed, attitude, flight path tunnel visualizations, as well as generic terrain (from generic lidar data) and generic obstacles were assessed in a flight test. A certification was necessary to use the HoloLens 2 inflight. Tracking was found to be most stable when using a combination of internal tracking by the HoloLens 2 and an external tracking camera. When only relying on the Inertial Measurement Unit (IMU), the drift is unacceptable. Using only external tracking results in strong jitter. Another topic tested was the visibility of the holograms inflight. It was found that using tint foil with 20% light transmission on the HoloLens 2 visors allowed to still clearly see the holograms, even in strong sunlight. The small field of view in the HoloLens 2 was found problematic in some scenarios. The paper concludes that a HMD implemented in low-cost hardware (compared to military hardware) is possible and can turn out to be beneficial in assisting pilots in a large variety of tasks.

3.2 Situational Awareness Research in Aviation

Endsley defines situational awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995). Building up and maintaining good situational awareness is crucial in an cockpit environment, as it affects decisions and actions taken in highly dynamic situations. Nguyen et al. published a paper (2019) that provides an overview of different situational awareness evaluation methods used in aviation research and development. Their main motivation is to help enhance systems in aviation, by helping with the decision on how to test certain systems about their influence on situational awareness. In the paper, it is stated that loss of situational awareness is the main cause for controlled flight into terrain accidents. They describe the scenario of loss of situational awareness as follows. "The pilot continues to absorb information from the environment and restructure his/her mental model until the occurrence of an event that triggers a highly disconcerting awareness that the pilot's mental model of the current environment is actually false. When the pilot realizes that the model is wrong, there is a collapse of this erroneous model followed by a frantic reassessment and rebuilding of the model, if he/she is still alive and there is enough time and enough control bandwidth." In short, the loss of situational awareness begins when the pilot's mental model starts to deviate from reality. Therefore assessing a pilot's situational awareness brings valuable benefits for flight safety. Advantages and disadvantages of six categories of SA assessment methods, including freeze-probe techniques, real-time probe techniques, post-trial self-rating techniques, observer rating techniques, process indices, and performance measures are being discussed in the paper. While freeze-probe and real-time probe techniques have the advantage of being direct and objective, their disadvantage is the high effort needed to set up such assessments. In real-time probe methods, an additional disadvantage comes with the fact, that the task resumes while the participant evaluates the situational awareness. The observer rate technique does not take the participants focus away from the main task; however, assessing situational awareness solely by observation is prone to being subjective. In addition to that, finding clues on a person's awareness as a third person may be challenging. Performance measurements are often used to back-up other methods. Process indices consist of procedures that record and analyze processes the subject goes through to establish situational awareness. Eye-tracking is a tool often used for such assessments. The disadvantage lays in the comprehensive and time-consuming data analysis. Finally, self-rating techniques are quick and easy as well as non-intrusive (performed after the main task). The downside is that "humans are normally poor in recalling details of past events. Self-ratings are sensitive; e.g., subjects often rate poor SA inaccurately as they may not know that they suffer from poor SA from the beginning." The paper concludes that no method should be discarded; however adapting methods to one's study is encouraged. Finally, combining different methods can be beneficial, as one can cross-check results between the techniques.

4 Application Development

In this chapter the data, software architecture and the development state is introduced. Furthermore decisions made during the application development process will be laid out.

4.1 General Workflow

In general, this thesis can be split into two main phases, an application development phase and a user study phase. The development phase started with literature research, data gathering and conceptual decisions. A selection of hardware was evaluated according to the suitability for this project. Required data and functionalities for the application were defined. Should the application be developed to test in a real aircraft or a simulation was another question to answer early on. Testing the application in a simulator turned out to be the best option for this thesis. Development and testing on a real airplane was found to be financially unfeasible, legally questionable, as well as introducing further technical challenges (as seen in (Walko & Maibach, 2021)). The software was developed with the renowned game engine Unity (Unity, n.d.). Scripts were implemented in C#; more details on the application development will be provided in the following subchapters.

The goal of the second phase is to test the hypotheses (stated in Chapter 1.1) and usability of the application. For this, a study design with four tasks to be completed by each participant was built. In addition to the tasks, a pre-study questionnaire captures the demographic information and aviation experience of each participant. More about the study design will be described in Chapter 5.

4.2 Data

Before starting with the development of an application, it was important to decide what information is needed to fulfill the goal stated in Chapter 1.1. During the conceptual phase of the project a list of data and information to be displayed was established (see Appendix A). In a next step, the list was filtered and sorted to find the most important data for this thesis, as due to the time limit of six months for this master's thesis, not all ideas could be processed and integrated into the application. The final list of data used during the development of this project is shown in Table 1. The filtering was not only based on the goals for the thesis, but also opinions from flight instructors at a local flight school in Switzerland were collected and the findings of the paper by A. Sarbach et al. (2023) were considered.

Table 1: Data Overview

Data	Description
Base Terrain	DHM25 data to create occlusions of terrain
Airports	Information about runways, elevation, Available Fuel Type
Obstacles	Cables, Power lines, Stacks, Buildings, Poles, Cranes
POIs	Castles, Power Plants, Monastery, Passes, Tank Farms, Factories
VOR / DME	Radio Navigation Aids
Airspace structures	TMA, CTR, danger zone, restricted zones
Towns / Build-up areas	Town names
Circuits	Circuit according VAC chart
Advisory points	Published points to advice ATC when overflying during approach or departure (W, E, etc.)

Additional data listed in the conceptual phase were traffic information, flight plan path, mountain peaks, water bodies, paradropping activities, noise sensitive areas and more. Due to the limited time of six months for this thesis, these other ideas had to be postponed for future work.

As part of the pre-processing for each data type, filtering and a conversion into a .csv file format were performed. This allowed for easier handling of the data in Unity. To make handling the files easier, the structure was also standardized. The exact datasets used and their pre-processing steps will be stated in the following subchapters.

4.2.1 Base Terrain Data

To model the terrain in the application, the SwissDHM25 (swisstopo, 2024a) and SwissImage 25m (swisstopo, 2024d) were used. Excerpts of approximately 150km² (10x15km) were selected for different parts of Switzerland. What locations were chosen and why will be described in more detail in Chapter 5.2.3. The main purpose of the terrain data was to use it as a reference during development and in the final application to use it to model terrain occlusion. More on the visualization of terrain in Chapter 4.4.1.

For this project, a highly detailed representation of the terrain was not necessary, which is why the DHM25 was preferred over other digital elevation models such as SwissAlti3D (swisstopo, 2024c). The same applies to the orthophoto resolution used to better check the location of thematic layers. A 25-meter resolution was sufficient.

4.2.2 Obstacle Data

Aviation obstacle data in Switzerland is provided by the Federal Office of Civil Aviation (FOCA) in .csv or .kmz file format (2024b). According to the FOCA, obstacles to aviation are structures and installations (including antennas, buildings, cables, cranes, cable cars, high-voltage power lines, and wind turbines) and plants that may impede, endanger or prevent the operation of aircraft or air traffic control systems. The data includes permanent as well as temporary structures that are higher than 25 meters in undeveloped areas and higher than 60 meters in developed areas.

As part of the pre-processing of the data, it was filtered geospatially to only include the obstacle for the specific scene. The goal was to lower the amount of processing power required by instantiating and rendering objects.

4.2.3 Points of Interest, VOR/DME and Advisory Points Data

The next category of data combines various point data. Starting with points of interest (POI) data, this includes power plants, castles, monasteries, tank farms and production sites that are clearly visible from the air. Very High Frequency Omnidirectional Radio Range (VOR) and Distance Measuring Equipment (DME) beacons are stations on the ground, that help pilots navigate with instrumental aids. They are often used as waypoints, also for VFR flying. Advisory points are official points stated by each airport, which have to be overflown during approach and departure into/from an airport. As they have to be reported to Air Traffic Control (ATC) upon reaching, it is crucial for pilots to know their exact location.

Points of Interest, VOR/DME and Advisory Points data for Switzerland is only available in raster format embedded into the Aeronautical Chart ICAO Switzerland (swisstopo, 2024b). Therefore, the points had to be vectorized in GIS software. This was done manually, as the ICAO chart is complex and no algorithm was found that could efficiently vectorize the selected data needed for this project. Attributes such as names of points or additional information such as frequencies (e.g., for VOR/DME) were added manually.

4.2.4 Airport Data

Airport data in Switzerland is provided by the FOCA (2024c) in a shape file format. The data was processed by adding additional attributes to each airport. For this, information like longest runway length, runway directions, frequencies and elevation was looked up in the official approach charts of each airport.

4.2.5 Airspace structures Data

Airspace can generally be divided into seven International Civil Aviation Organization (ICAO) standardized categories, named after the letters A-G. Each category defines different rules to be followed by the pilots. In this thesis no further details about the rules are discussed. If interested, one can look up the rules in the ICAO Convention on International Civil Aviation Annex 11 Chapter 2 (ICAO, 2018). In Switzerland, only four of the seven categories (naming: C, D, E, G) are used.

While E and G sectors are uncontrolled, meaning there is no ATC guiding the traffic (only flight information services are available), in airspaces C and D the contact with the ATC is mandatory, pilots will be guided through the sector, and they have to request permission to enter. Controlled sectors are mainly found around international or national airports as well as in higher altitudes. Control zones around airports are distinguished between Controlled Traffic Region (CTR) and Terminal Maneuvering Area (TMA). Some sectors can be active or inactive depending on various reasons, such as time of day, weather, special events and more. Restricted (LS-R) and danger (LS-D) are dependent on military activities and severe weather events. The active state of these sectors is published in the so called Daily Airspace Bulletin Switzerland, short DABS (FOCA, 2024a).

The airspace data used in this thesis is provided on the aviation.kernberatung.ch website (Hans-Peter Kern, 2024) in a .kml file format. Figure 12 shows an overview of data. Especially around the two main international airports (Zurich and Geneva), the structure is dense and cluttered. Various military training sights are visible in red and orange symbology. The turquoise areas included in the data are not official airspace sectors but mark the areas of uncontrolled airfields. Not visible on the map is the vertical gradation of different airspace sectors. On the official paper chart used for VFR flight, the vertical limits are stated in text form on the map.

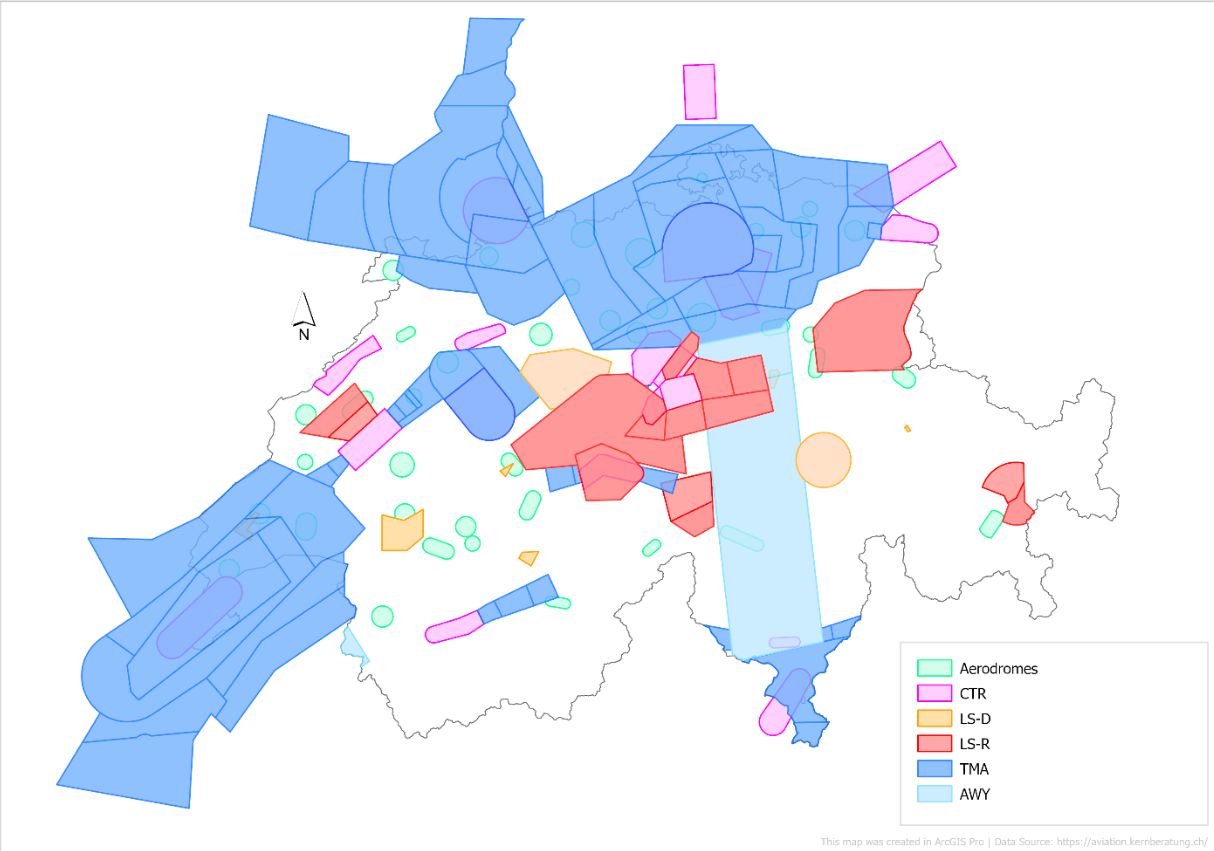


Figure 12: Airspace Structure Data

4.2.6 Town Data

For the town names, the SwissTLM Regio (swisstopo, 2024e) dataset was used. The main reason for this choice was that the names are modeled as a point in the heart of town and not just as a center point of the municipality. This ensured better visualization in the final product, by avoiding the placement of names outside of developed areas or even worse in water bodies. Another advantage of this dataset is the categorization of towns. With categories according to inhabitant numbers, the filtering of bigger (better visible from the air) towns was straight forward.

4.3 Software Architecture

In this chapter, the integration of the data mentioned in the previous chapter into the application and the general software architecture and application development will be introduced.

Figure 13 shows an overview of the software architecture. The two main components are the flight simulator (top left) and the Unity application (bottom right). The dark blue boxes were developed during this thesis. To be able to connect the flight simulator with the Unity application, an API was used to read the desired plane variables from the simulator. Via a database, the plane variables are sent to the Unity application.

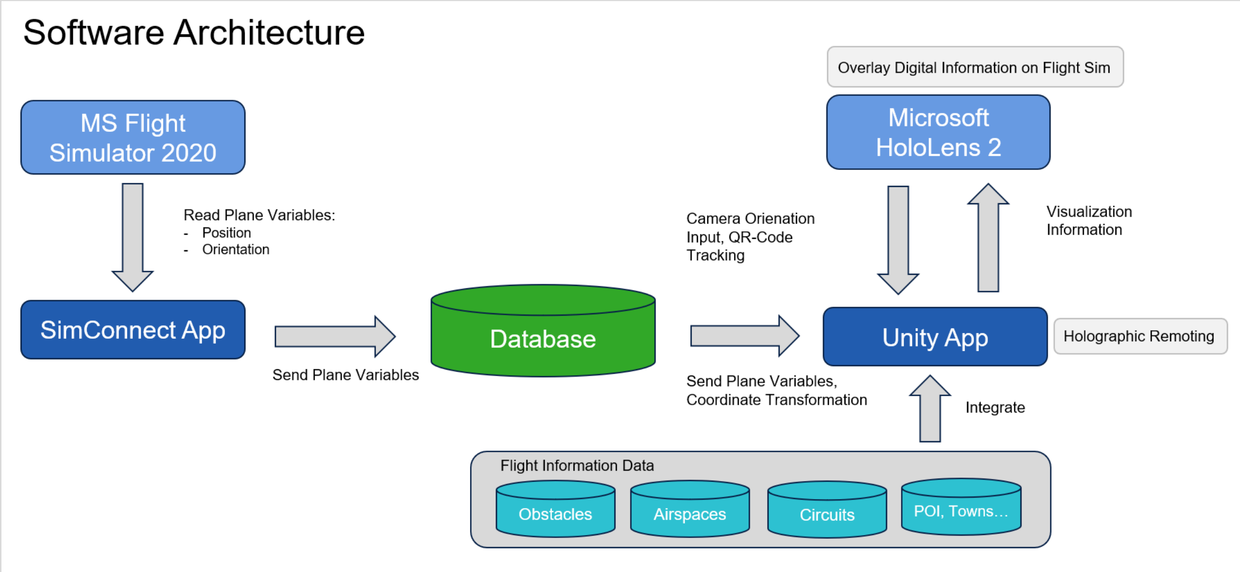


Figure 13: Software Architecture

Flight information data is integrated into the Unity application and visualized through the Microsoft HoloLens 2. The AR device is not only used as a visualization output, the camera orientation of the device is used as an input to the application. This allows the user to look around the scene. Additionally, the sensors of the AR device are used for the alignment of the projected information and the scene in the flight simulator. For optimal performance, the application is running on a laptop, and only the visualization is sent to the Microsoft HoloLens 2 via holographic remoting.

In the following subchapters, the different components in Figure 13 will be described in more detail.

4.3.1 Flight Simulator Choice

There are several high-end flight simulator software on the market. Two important factors to look at when selecting a flight simulator are visualizations of the world map and implementation of flight physics. As the simulator is used for VFR flying in this project, visualization is weighted higher than flight physics. This led to the decision to use Microsoft Flight Simulator (MSFS) 2020 (Microsoft, 2024b). Then, although its main competitor software, X-Plane 12 (X-Plane, 2024), is known to be very accurate on flight physics, MSFS 2020 is ahead on realistic visualization of the world map. In addition to that, MSFS 2020 was available to the author since the beginning of the project.

4.3.2 SimConnect App

MSFS 2020 provides a variety of tools for developers to build add-ons to the simulator. Especially important is the SimConnect API (Microsoft, 2024d) which allows to read simulation variables in intervals shorter than the frame rate. For this project, position (lat, lon, altitude) and orientation (role, pitch, yaw) of the plane are read through the API. During the development, it was also considered to include additional variables. In the end, it was not needed and therefore left aside, but any sim variable could easily be included in future versions of the application. A Python script is used to call the API and write the variables to a database on a server via the following SQL query.

```
SQL Query = INSERT INTO simconnect.simconnect3 (lat, lon, alt, heading, pitch, bank)
            VALUES($1, $2, $3, $4, $5, $6)
```

The code is run in asynchronous tasks to improve performance on database and API calls.

4.3.3 Database

The database used for this project is an open relational source database called PostgreSQL (2024). All variables are stored in one table on the database. As the coordinates are stored as floats and not in any geometry type, any other database system can be used. This particular database system was provided by the chair of geoinformation at ETH Zurich.

4.3.4 Unity Application

As already mentioned in the Chapter 4.1 General Workflow, the main application was developed in the Unity game engine. The “Mixed Reality Tool Kit 3 (MRTK 3)” (Microsoft, 2024c) package by Microsoft enabled the development of AR applications in Unity. The package includes basic functionalities, scripts and prefab game objects allowing to implement interactable digital content for the Microsoft HoloLens 2. The terrain tool (Unity Technologies, 2024) is used to create the base terrain.

The Unity application is structured in different scenes, each representing another geographic location in Switzerland. The scenes correspond to the locations chosen for the user study. Within each scene, the hierarchy of game objects includes, an MRTK rig, aviation content grouped per information type, a server connection game object, an interaction menu, as well as the QR-code tracking. The MRTK rig includes the scenes main camera, which corresponds to the view from the Microsoft HoloLens 2. Also included in the MRTK rig is the handling of hand interaction with other game objects in the scene. More on the interaction is described in Chapter 4.5. The aviation content is initiated on run time only, meaning that a script for each type of content is run upon starting the application to create the content. These scripts are written in C#. The QR-tracking will be elaborated in Chapter 4.3.5.

The server connection is handled by a separate C# script. It connects to the database and reads the latest entry to get position and orientation of the aircraft. These variables are then transformed and used to position and orient the camera within the scene to match the viewing point in the simulator.

Another important script is the coordinate transformation handler. This script includes functions to transform coordinates between Coordinate Reference Systems (CRS) and is used for the positioning of aviation content as well as within the sever connection. To be more precise about its functionalities, it handles the transformation from WGS84 (epsg: 4326) to LV95 (epsg: 2056) and from LV95 to the local unity coordinates. For the transformation between WGS84 and LV95, approximation formulas provided by swisstopo (2016) are used. Although these formulas have a reduced accuracy, they are sufficient for navigational purposes, as stated in the swisstopo documentation. To get from LV95 coordinates to the local unity coordinates, an offset in northing and easting and a scaling have to be taken into account. The offset is dependent on the geographical location, whereas the scaling is kept independent at a factor thousand.

4.3.5 Alignment with the Simulator

In order to align the augmented reality content with the flight simulator, a QR-code was used. The Microsoft HoloLens tracked the QR-codes relative position and orientation to the device. The feedback from the HoloLens was then used to adjust the direction of the aircraft heading in the augmented “play space” to the direction of the QR-code. For this to work, the QR-code was placed on the top edge of the monitor in the middle of the multiscreen set-up. The calibration was renewed with any detected change in the relative positioning of the code. In case the tracking did not recognize the code, the last calibration metric is taken. As the coordinate system in Unity was scaled down for more efficient processing of the program, the alignment is especially sensitive in turns. This had to be taken into account as the QR-code remained fixed in relation to the monitors (different from the simulated world coordinate reference system and augmented reality “play space”). If the QR-code was fixed to a real airplane, this challenge would not have occurred, as the code would have moved with the turn rate or the aircraft. Figure 14 shows this scenario. However, due to using a simulator, the QR-code remained on the position of the code with solid lines in Figure 14 instead of moving. This discrepancy had to be calculated and included in the calibration.

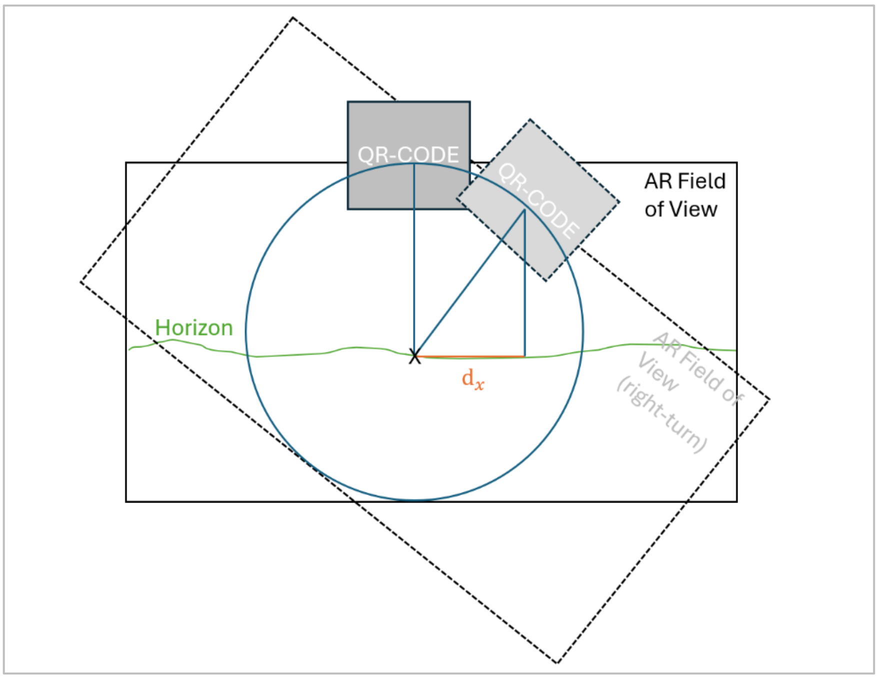


Figure 14: QR-tracking in turns

4.4 Visualization

This chapter elaborates on the visualization used for the aviation content included in the application. It has to be mentioned that all visualizations are world-referenced and rendered from three-dimensional objects. Creating the perception that the objects are placed directly in the environment.

4.4.1 Base Terrain Visualization

As mentioned in Chapter 4.2.1, terrain data was used as a reference during the development process. For this, orthophotos were overlayed over the DHM25 as seen in Figure 15. The imagery allows for better cross-checking of instantiated game objects, such as, for example, airport or town names. Additionally, it was helpful to check the alignment of the projected content in the HoloLens 2 with the flight simulator scene.

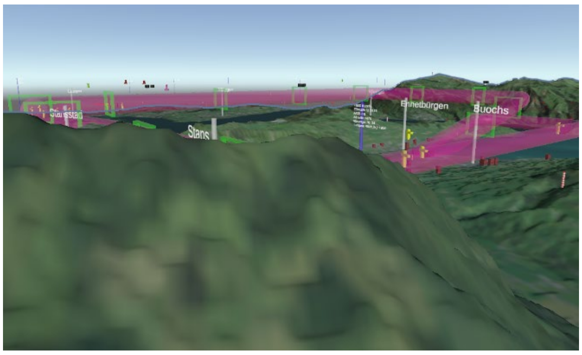


Figure 15: Terrain Visualization during Development

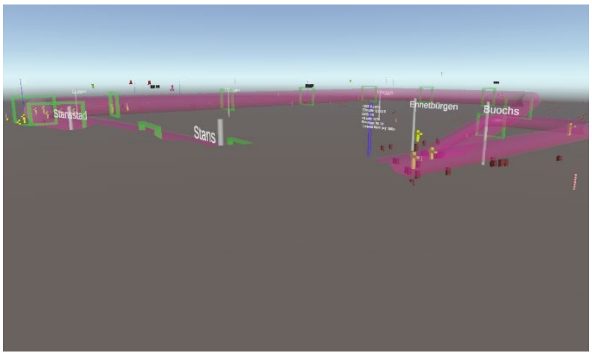


Figure 16: Terrain Occlusion in final Application

In the final application, the visualization was changed. As the terrain is provided by the simulator (or real world), including terrain with highly detailed texture was not needed. The occlusion of digital content by the terrain however, had to be modeled. Figure 16 shows the same camera angle as Figure 15, but with the material of the terrain object set transparent, yet still masking the objects behind. This was achieved by using a specific material shader in Unity.

4.4.2 Points of interest and obstacles

As a first thematic layer in the application, points of interest (POI) and obstacles are highlighted using 3D models and Unity “primitive objects” as prefabs. This is done via a script that reads obstacle .csv files on runtime. An overview of the prefabs are displayed in Figure 17. The prefabs and color choices allow you to easily distinguish between the different point object types. Buildings are colored in red and textured with window facades. Poles are colored in red and white, like many poles near airports are painted in real life. Cranes are simplified with a vertical and horizontal beam colored in yellow. Using different colors for tank farms, power plants, monasteries and castles also enhances faster differentiating of the POI type. Especially, if they are further away and therefore displayed rather small and hardly distinguishable by shape. Line-type obstacles, such as cables, are symbolized as red polylines. To achieve this, a function reads a line obstacle file and connects points belonging to the same line object.

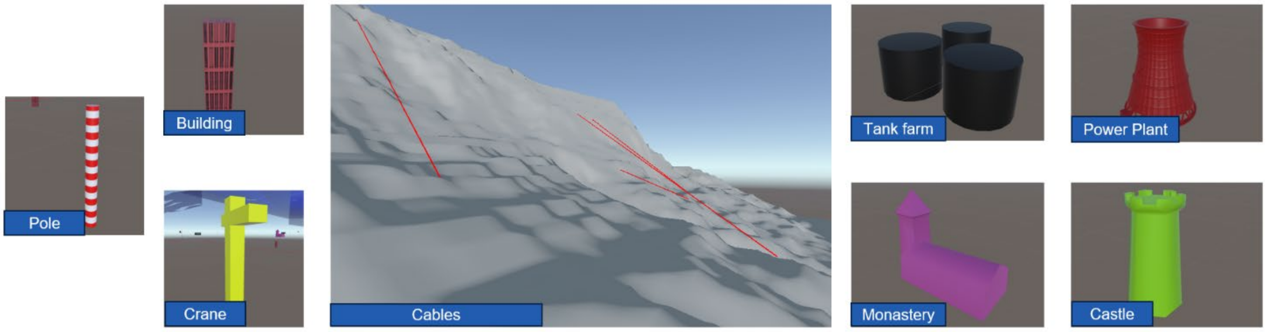


Figure 17: Visualization Obstacles and POIs

4.4.3 Labels

Labels are another type of information included in the application. They are used for town names, advisory points, VORs, passes and airports. Each label is combined with a narrow cylinder protruding from the object. The font size does not adjust depending on the distance to an object. This leads to labels getting smaller the further away from the object the camera is due to perspective projection. The found size was selected by waying out readability vs. obstruction of other content. In order to make the labels readable, independent from the orientation of the camera, a script makes sure the labels are facing the camera at all times. Figure 18 presents the visualization of the labels.

Figure 18: Labels

As the obstacles, the labels are also instantiated on runtime. For this, label objects are created with attributes dependent on the label class. While the town class only includes a name, airport objects include more relevant information for a pilot. These attributes were selected based on what is displayed on the ICAO chart of Switzerland and VAC charts. The attributes support a pilot's decision, whether or not the airport is suitable for landing the plane in case of a deviation or an emergency. This is dependent on the type of aircraft, as for example, the minimum runway length needed for a successful landing is highly dependent on the aircraft type. In addition to emergency situations, information like frequencies helps pilots during normal operation.

For the passes, the elevation is a relevant attribute to be able to estimate the minimum altitude to reach before crossing the pass. As the altitude is indicated in feet by the airplane's instruments, the elevation is also stated in feet.

Advisory points are used for standard approach and departure routes at airports. These points have to be overflown and reported to ATC. In Switzerland, the points are usually marked with a letter of the alphabet, as the example in Figure 18. As multiple airport can have the same letters as advisory points, it is important to also state the name of the airport it belongs to.

4.4.4 Airspace Structures

As Unity is not able to display objects stored in a .kml file as game objects directly, a solution to read and convert the data had to be found. In general, rendering surfaces in Unity is done by triangulation. One approach to triangulating a surface is the ear-clipping algorithm. A simplified version of the algorithm was implemented in C# for this project. Figure 19 illustrates how it works. The number 1 indicates the position of the starting node. From there, the next two nodes of the polygon are added to a first triangle (red). Next, a triangle (green) is defined with the starting node, the last node of the latest triangle, and the n+1 node. This goes on until all nodes in a polygon are members of a triangle. Like so, a polygon I split into multiple triangles with nodes, which can then be rendered by Unity as a game object.

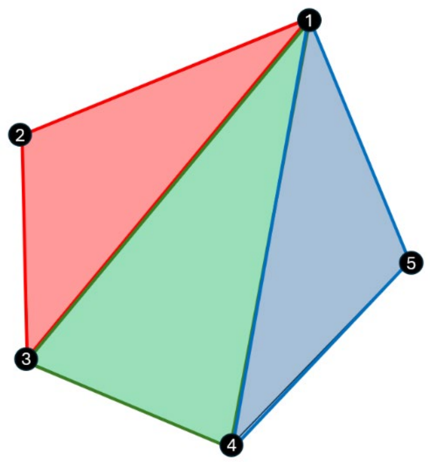


Figure 19: Illustration ear clipping algorithm

With the help of this basic algorithm, the airspace structure polygons can be rendered at the lower limit and upper limit of the airspace. To add the vertical surfaces of the airspace section, the lower and upper limit polygons were combined and their nodes used to triangulate the vertical surfaces. This results in a closed, three-dimensional game object for each airspace sector.

The big limitation of such a simplified triangulation algorithm is that it fails to triangulate concave structures correctly. All triangles of a surface originate at one node, and no check is performed to see if the triangle covers the surface only inside of the polygon. This limitation however, is acceptable for this project, as most airspace sectors in Switzerland are either defined with straight-lined or convex polygons.

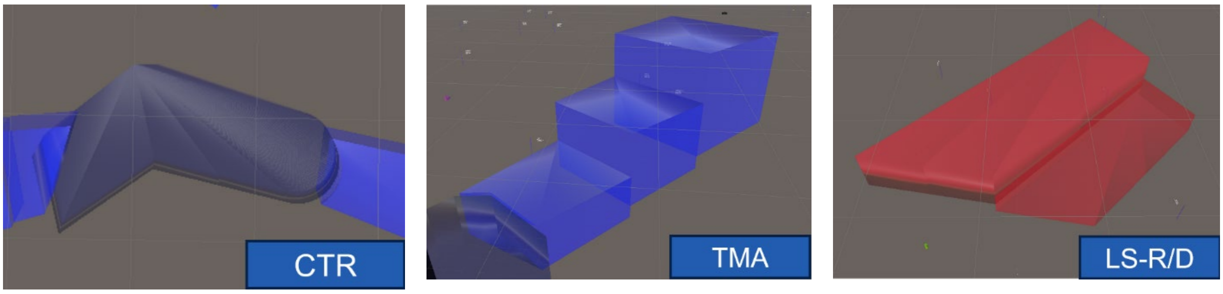


Figure 20: Airspace visualization

In the final renderings, displayed in Figure 20, the triangle structure in each airspace sector is visible. The script is implemented in a way that one can select if all airspace sections over Switzerland should be rendered into the scene or only a specific list of sections. This allows to improve rendering efficiency, if only a part of Switzerland is represented in a scene.

4.4.5 Circuit Modeling

To visualize the approach and departure paths published on the Visual Approach Charts (VAC), the 3D modeling, open source software Blender (2024) was used. Circuits had to be modeled by hand as no three-dimensional data is available. For this, the respective paper VAC chart provided by Skyguide (2024) was scanned. In Blender, the scale of the map was measured using the distance indications on the left side of the chart (see top image in Figure 21). As the paths are only drawn in two dimensions with a height attribute, cylinder objects in the correct height were used as an aid to model the correct height of the path. The cylinder height is defined by subtracting the airport altitude from the circuit altitude (in feet above msl). To scale the cylinder, the scale on the left-hand side was used, and height was transformed from NM to feet. Planes do not fly the marked altitude all the way around the circuit, as they have to climb after takeoff and descend before landing. This depends on the performance of the aircraft and meteorological conditions. Especially during the climb phase, this can make a big difference in where in the path the plane reaches the designated altitude. As for the user study a Cessna C172 is used, the modeling with performance measures of this airplane type. For the descend part, a rate of 400 ft/nm was used. This corresponds to a 4 degree approach, which is a standard angle for a VFR approach.

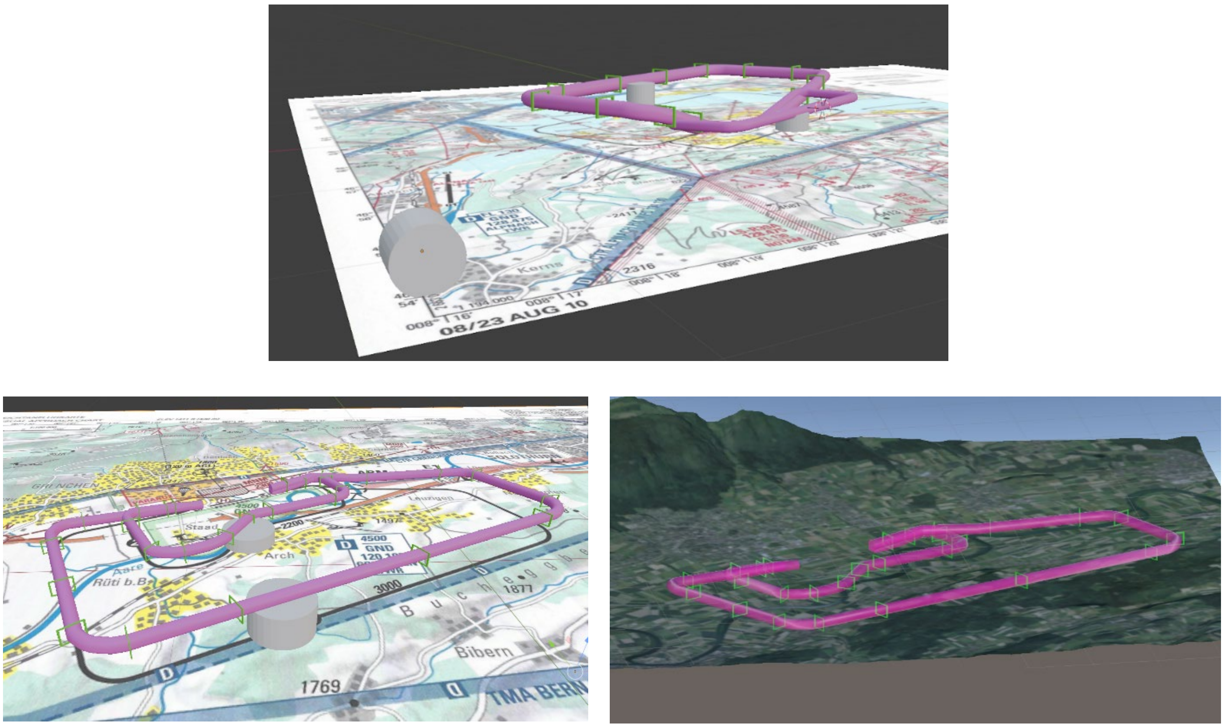


Figure 21: Circuit Modelling

As a result, the circuit was modeled as a tube (purple) as well as in gates (green). Whereas the tube is supposed to give the pilot an indication on where the circuit is located from further away in the approach (a tube is better visible than gates from far away), the gates make sure the pilots can navigate the circuit while being close to it or in it. A tube would obstruct the vision too much when the airplane is within the tube. Gates were chosen as a tool to visualize the flight paths after searching for visualizations of flight path by well-known flight instrument companies such as Garmin . Their G3X Touch instruments (Garmin, 2024) indicate the flight path as shown in Figure 22.

Figure 22: Garmin G3X Touch flight path (Garmin, 2024)

4.5 Interaction

Next to a thought-trough visualization of the digital content, considering how to interact with it is as important during the development of such an application. For this, several design choices, such as menu type, menu size and placement, button type and coloring, were tested. In a highly dynamic and mentally demanding environment like a cockpit, it is important to keep each task as simple as possible. Therefore, implementing a static menu (in reference to the pilot’s seat position) was found more suitable than a menu that follows the left or right hand of the user (hand menu). During development, a hand menu was tested, and the following disadvantages were found: First, to be able to interact with the menu, the left/right hand has to be taken off the controls of the aircraft in order to place the menu in a convenient place to interact with it. Second, the space in front of the pilot is filled with controls and switches, which make it cumbersome to find a suitable position for the menu. Third, making the interaction dependent on the position of both hands, e.g., left hand to place the menu and the right hand to press buttons, adds one more level of difficulty in an environment with already a lot of external factors (turbulence, lighting conditions, etc.). A statically placed menu makes the task of interacting simpler. The position of this menu was found most suitable on the right-hand side of the pilot. The reason being, the pilot in command sits on the left seat of the aircraft and has more free space on his right-hand side. In a more advanced application, the exact position of the menu should be customizable and modifiable to one's preference. The size of the menu is set to interfere with instruments and a potential passenger as little as possible while keeping the interaction points as big as possible. This ensures better user experience when pressing a button or sliding a slider, as the area sensitive to pressing is bigger. For this prototype the menu was kept oversized on purpose.

As the goal is to keep the focus of the pilot outside of the cockpit, finding the correct button in the menu fast is crucial. Icons support efficient identification of a button. Using appropriate icons is key.

The menu keeps the pilot informed on what information is currently displayed. A highlighted background of an icon indicates that the layer is active.

Next to the toggle on and off information, the menu includes a slider to select the projection range. Users select the distance in reference to their own position in which information should still be displayed. This function is important for decluttering information in certain flight phases. During cruise flight, when flying at higher speeds, it is important to be mentally ahead of the airplane, and therefore setting the projection range higher makes sense. During approach however, reducing the range makes sense, as the airplane maneuvers at slower speed in a tighter geospatial area.

Looking at the bottom section of the menu in Figure 23, information about surrounding airspace sections is displayed to the pilot. First, the airspace that the airplane is currently in. Second, the airspace that is five nautical miles ahead of the current position and orientation of the aircraft. The information is updated with the help of so called sphere colliders. The position of the aircraft and five nm ahead are attributed to such a collider to detect when entering or leaving an airspace section. In case the aircraft isn't in a controlled airspace, Class G or E are automatically determined depending on the aircraft's height and terrain height. The limitation in the current implementation is, that the height of the terrain is set to one value per scenario, and not directly read from the DHM.

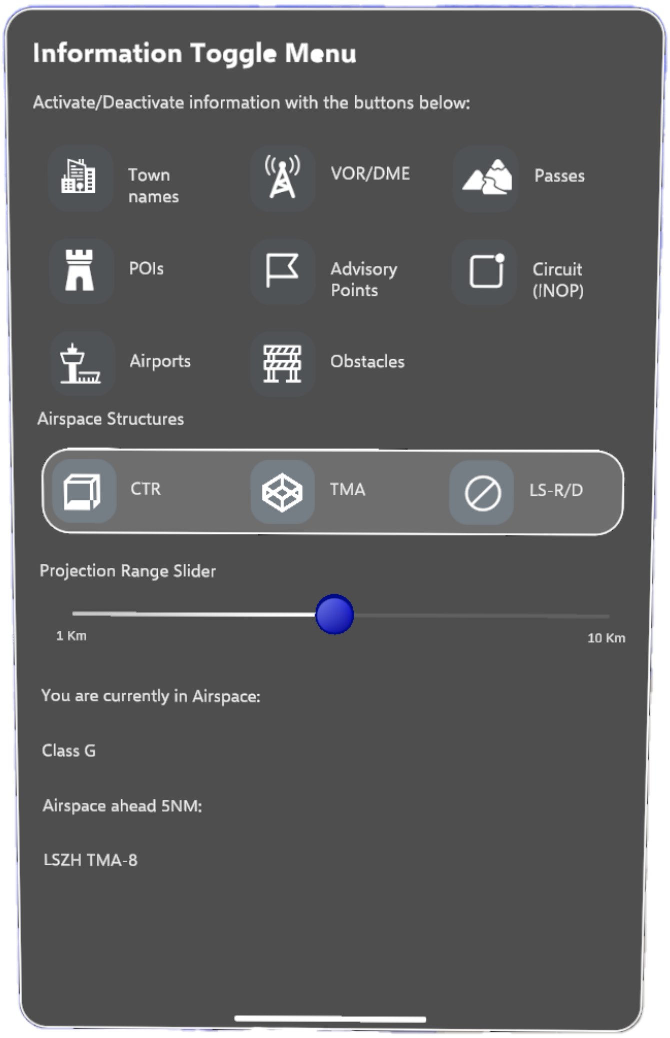


Figure 23: Information Toggle Menu

4.6 Current Development State

Before conducting the user study, it was crucial to reach a development state of the application, which will allow to test the hypotheses through the study. Therefore, the application scenes were tailored to serve the testing purposes. In the current version of the application, all locations in the user study are implemented, but not the whole of Switzerland. The application is running through holographic remoting on a laptop/desktop device; the HoloLens is only used for visualization and some sensor feedback. As the current version relies on position and orientation data from the flight simulator, one cannot use the application in a real world aircraft. A GPS sensor (to determine the position) as well as some sensors to define the orientation of the aircraft and the HoloLens would be needed to achieve this.

Some snapshots in Figure 24 showcase the application as used in the user study. The misalignment between application and flight simulator is noticeable in some of the pictures.

Flying next to TMA sections

View from Echo point in Grenchen

View from Horw approaching Buochs

Flying along the downwind leg in Buochs

Town names in cruise flight

Flying underneath a TMA

Figure 24: Snapshots application state

5 Methodology

5.1 AR Device

At the beginning of the project, a list of possible devices with their advantages and disadvantages was evaluated (see Table 2). The devices included the Microsoft HoloLens 2, Meta Quest Pro, Apple Vision Pro, Apple iPad and Google Pixel Phone. The selection of devices consists of handheld as well as head-mounted AR/VR capable devices, which were available for this project. An exception is the Apple Vision Pro.

As a cockpit is a highly complex environment in a tight space, the head mounted devices have a big advantage over handheld devices. Being able to keep both hands on the controls of the aircraft, reduces the workload that else would arise by holding up a handheld device to project digital content into the real world. Another advantage of head mounted devices is the bigger field of view.

The biggest advantage of handheld devices like tablets and mobile phones is that every pilot already possesses one or the other nowadays. The market for VR/AR devices is growing, but far fewer people own such a device. As this thesis focuses more on research than bringing a product to the market, the above-stated advantage of head-mounted devices overweighs the just-mentioned advantage of handheld devices.

The included GPS antennas in most handheld devices can be seen as another advantage. Here again, testing in a real airplane is not planned, therefore, this argument is weighted less in the context of this thesis.

Table 2: AR Device Overview

Device	Device Type	Advantages	Disadvantages
Microsoft HoloLens 2	AR Glasses	- “Hands-free” use (for displayed information) - Transparent projection glass - Supports remotely running programs (Holographic remoting) wire-less - No to little additional cognitive load as information is projected in real-world directly in field of view - Internal, relative position and orientation tracking	- Limited processing power - No built-in GPS receiver - Field of view for digital content very limited - Risk of motion sickness due to projections inflight
Meta Quest Pro	VR/MR Glasses	- “Hands-free” use (for displayed information) - No to little additional cognitive load as information is projected in real-world directly in field of view - Bigger field of view than Microsoft HoloLens 2 - Internal, relative position and orientation tracking	- VR with see-through (quality of live stream of surroundings) - Risk of motion sickness inflight - Legally challenging option, as pilots looks through screen - No built-in GPS receiver
Apple Vision Pro	VR/MR Glasses	- “Hands-free” use (for displayed information) - No to little additional cognitive load as information is projected in real-world directly in field of view - Bigger field of view than Microsoft HoloLens 2 - Internal, relative position and orientation tracking	- VR with see-through (quality of live stream of surroundings) - Motion sickness in air - Legally challenging option, as pilots looks through screen
Apple iPad	Tablet	- Built-in GPS receiver - Many pilots have a iPad/tablet in their equipment nowadays - IMU sensors for orientation tracking	- Hands needed for displaying information (move tablet around) - More cognitive load (placing the tablet in the correct angle to see desired information)
Google Pixel Phone	Phone	- Built-in GPS receiver - Almost every pilot has a phone in their equipment nowadays - IMU sensors for orientation tracking	- Hands needed for displaying information (move tablet around) - Small screen (tendency to over clutter information) - More cognitive load (placing the phone in the correct angle to see desired information)

Comparing the head mounted devices listed in Table 2, the Apple Vision Pro and Meta Quest Pro are both VR devices with MR capabilities. Therefore, the real-world environment is only visible on a screen via a live feed from cameras mounted on the outside of the device. The Microsoft HoloLens 2 however, projects the digital content on transparent glass. The real world is not blocked out by a screen. This is a big advantage from a legal standpoint. Depending on the screen and camera resolution, details from the real world can be lost, which is another disadvantage of MR.

Considering the argumentation above, the choice for the device used in this thesis fell on the Microsoft HoleLens 2. The AR device introduced by Microsoft in the year 2019 includes the following sensors:

Head Tracking	4 visible light cameras
Eye Tracking	2 IR cameras
Depth	1-MP time-of-flight (ToF) depth sensor
IMU	Accelerometer, gyroscope, magnetometer
Camera	8-MP stills, 1080p30 video

Sensor specifications from Microsoft (2024a)

Figure 25: Microsoft HoloLens 2 (own image)

According to Microsoft the battery life is between two to three hours.

5.2 User Study

Scientifically, user studies are a great tool to evaluate the work and support answering the research question. Additionally, including user tests and feedback in the process of application/software development is key. This elevates the chance of acceptance of the product on the market in later stages. User feedback allows to compare the vision of the developer and the current product with the expectation and experience of a user.

The main goal of the user study was to test the hypotheses stated in Chapter 1.1. A within-subject design was chosen, as it has the advantage of being more efficient than the between-subject design. The biggest limitation of the within-subject design is that it can produce order effects such as fatigue, learning effects or carry-over effects. With an expected number of participants between ten and twenty, the advantage of collecting more data with a lower number of participants was considered more impactful on the result than the stated limitations. In addition, order-effects can be reduced, almost mitigated, with specific design features in the study. Changing sequences is one such feature that was implemented in this user study.

As dependent variables, different orientation and/or navigation performances were defined per task. These help measure the situational awareness of the participant during each scenario. The independent variable consisted of: with or without AR.

Further details about the user study setup, target participants, and result analysis will be provided in the following subchapters. The institutional review board approved this study as proposal EK 2024-N-152.

5.2.1 Setup

Several configurations were explored in order to determine which flight simulator setup was best for the user study. The “Zentrum für Aviatik (ZAV) at ZHAW allowed the author to test their ReDSim (Monstein & Pedrioli, 2024) flight simulator. Figure 26 shows an impression of the simulator cockpit. The 180-degree screen and cockpit mockup, together with the realistic control pressures, made the flying experience incredibly immersive. Due to the following implementation limitations, the ReDSim was found not suitable for our research. First, the terrain textures were not as realistic as in MSFS 2020. Second, only the region around Buochs airport in Switzerland is implemented in ReDSim. Another setup tested, was a multi-screen setup with three 65” monitors, as seen in Figure 27. The combination of three big screens allowed a life-size simulation of the cockpit and surroundings. Although the immersiveness was not comparable to the

ReDSim, it was still a lot better than with the smaller 27” screens. Unfortunately, the availability of the 65” could not be guaranteed throughout the user study period, which is why this setup was also not feasible.

Figure 26: ReDSim ZHAW (Monstein & Pedrioli, 2024)

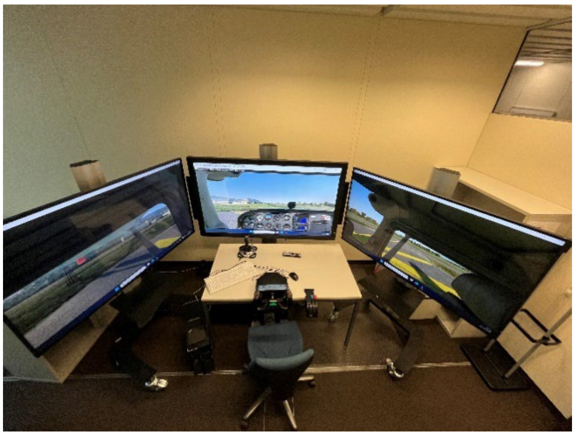


Figure 27: Multi-Screen Setup with 65" Screens

The final setup can be seen in Figure 28 and Figure 29. Three 27” monitors were used for the flight simulator. The field of view in the simulator was kept the same for each participant. The camera zoom level in the simulator was a trade-off between showing all instruments and keeping the field of view as life-size as possible. Due to this, the flaps indicator is not visible on the screen. The participants were instructed to look at the left wing to get an indication about the position of the flaps. A fourth monitor served as an instructor position to manipulate the position of the aircraft, record flight paths and connect the simulator to the AR application. The flight controls included a yoke, rudder pedals, a throttle lever and a flap lever. The blue and red levers are not used in the user study. The reason for this is to keep the controls as generic as possible, as not all participants fly the same type of aircraft. The QR-code for the alignment of the AR content is placed on top of the screen in the middle. Additionally, the participants were provided with an ICAO chart, VAC charts for specific airports and a tablet, which was used for some of the tasks.

Figure 28: User study multi-screen simulator set-up with 27” screens

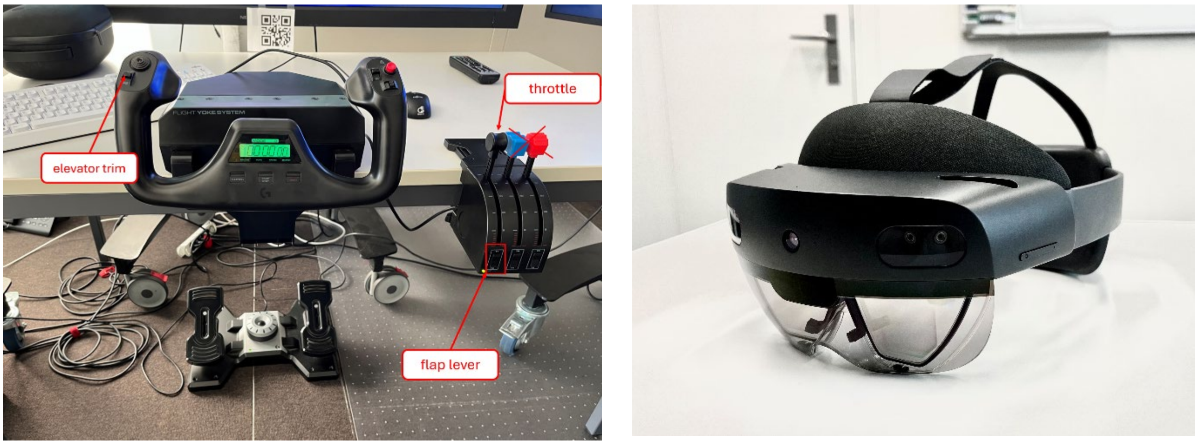


Figure 29: User study controls (left), Microsoft HoloLens 2 (right)

5.2.2 Choice of participants

In order to clearly see the effect of the independent variable on the dependent variable, it was important to narrow down the process variables. They include gender, age, experience with AR and most important for this project, the aviation/flight experience. Therefore, the target group of participants are pilots holding a private pilot's license (PPL) or higher (e.g., CPL or ATPL). Also permitted are people who are currently in pilot training. These regulations ensure a basic knowledge and experience in aviation, which is needed to fulfill the presented tasks. Additionally, getting feedback from pilots is expected to be more precise and meaningful, as they are able to share their experience and challenges occurring inflight.

5.2.3 Task Overview

The user study can be split into three main parts and takes about one and a half hours to complete. Figure 30 illustrates the procedure. The participant is welcomed with a short introduction during which the main idea of the application and study as well as the vision (see Chapter 1.2) is presented. Knowing what to expect from the application, the candidates then first fill out a pre-study questionnaire. The purpose of which is to gather information about different process variables. Afterwards, the main part starts. It is split into four tasks. The first two in a static simulation and the last two in a dynamic simulation. As the study follows a with-case design, each task is performed twice, with and without the AR tool. The tasks increase in difficulty and task two builds on task one. In a final part, the participant is asked to give verbal feedback in a guided interview.

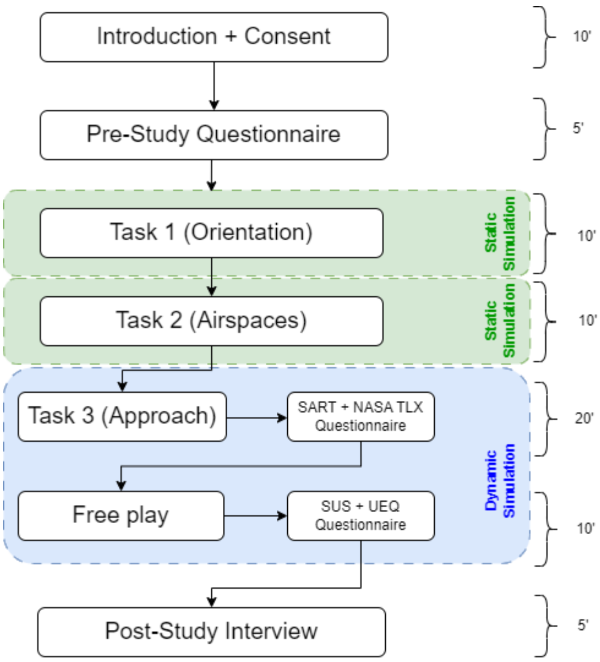


Figure 30: User Study Procedure

The different steps shown in Figure 30 will be described in more detail in the following paragraphs. The task description script used in the study can be found in Appendix C.

Pre-Study Questionnaire

The pre-study questionnaire aims to collect information about the participant; questions like age, gender, augmented reality experience, aviation experience (in flight hours) and type of aircraft the participant usually flies are gathered. The full questionnaire is attached in Appendix B.

Task 1 (Orientation)

The first task focuses on testing hypothesis H3 ("*AR can support regaining location awareness in case of disorientation.*").

Testing hypothesis: H3
Dependent variables: Placement of marker / time
Independent variables: With or without AR

The first task simulates a disorientation scenario. The simulator is loaded into a position in Switzerland and the participant has to determine their location as accurately and quickly as possible. The position is pinned with a marker on a web map on a tablet (see Figure 31) by the participant. The position will be exported for the analysis of the result. The position of the airplane will change between the two times the task is performed. The aircraft does not move while the task is performed. A paper version of the ICAO chart of Switzerland was given to participants as an aid.

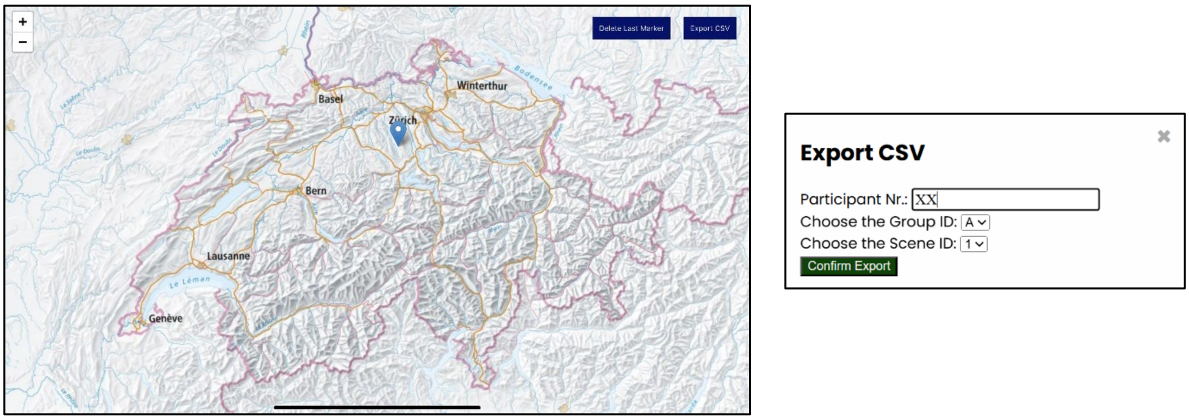


Figure 31: Marker Web Application

The geographical regions for task 1 included Entlebuch (Figure 32) and Zweisimmen (Figure 33). These two regions were selected on the basis of their topological features. Neither region exhibits easily distinctive features like lakes, big rivers, or striking mountain peaks. This should make the orientation task more difficult, and participants are forced to combine small details to determine their position. While the region around Zweisimmen is a mountainous area with higher terrain, the region of Entlebuch consists of smaller hills. This contrast allows to test the application in both major topological types found in Switzerland.

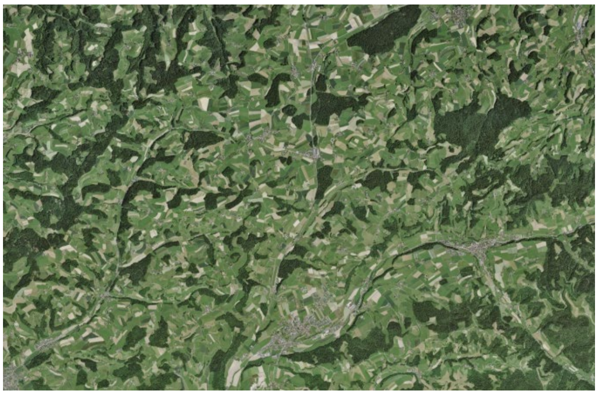


Figure 32: Orthophoto Region Entlebuch

Figure 33: Ortophoto Region Zweisimmen

Task 2 (Airspace)

Task 2 focuses on testing H2 (“*AR will increase situational awareness by increasing awareness of nearby airspace structures.”)* but also includes testing H3 (“*AR can support regaining location awareness in case of disorientation.*”).

Testing hypothesis: H2 and H3
Dependent variables: Statement of airspace section the aircraft is within and section 5nm ahead / time
Independent variables: With or without AR

The second task is about airspace structures. Again, a scene will be loaded in the flight simulator setup. The flight simulator will remain static. The task is to determine where the aircraft is and in what airspace structure the aircraft is currently in (e.g., LSZH TMA-1, LSME CTR, etc.). If not In a controlled airspace (e.g., Class G, Class E…), participants are asked to write down what airspace class they are in. Next, the participant has to find out what airspace is 5 NM straight ahead of their position and write it down on the answer sheet. This task is also performed twice and the position of the aircraft changes between the two times the task is performed. As in task 1, a paper version of the ICAO chart of Switzerland was given to participants as an aid.

The geographical regions for task 2 included Beromünster (Figure 34) and Wil SG (Figure 35). The red markers indicate the position of the aircraft.

Figure 34: Task 2 Beromünster (swisstopo, 2024b)

Figure 35: Task 2 WIL (swisstopo, 2024b)

The similarity in complexity of the airspace structure is the main reason for the choice of these two regions. The topography is comparable. The amount of visual clues for orientation is alike. Although Beromünster has two lakes (Lake Sempach and Baldegger), it was made sure, in the scenario in Wil, the Lake Constance is visible. Wil, on the other hand, has the highway and outlines the city as good visual clues.

Task 3 (Approach)

Task 3 focuses on H4 (“*AR will allow to fly the planned flight more accurately and precisely.”).*

Testing hypothesis: H4 / (H1)
Dependent variables: Flight path / Situational awareness and task load)
Independent variables: With or without AR

For task 3 the participant is flying a VFR approach into an airport in Switzerland. The goal is to fly the published approach path as accurately as possible. The airplane flown is a Cessna C172, a common GA airplane. As the focus lays on navigation, some aspects of flying were left out. Participants were not asked to communicate with ATC or follow an exact checklist. For each approach, the participants were given time to study the visual approach chart (see Figure 36 and Figure 37) to familiarize themselves with the circuit, as they would before a real flight. The simulation starts about 5 nm away from the airport. The time from the start point of the simulation to the beginning of the circuit is ideal to allow the participants to get used to the flight characteristics of the simulator and its controls. After the simulation ends, the participants are asked to self-assess their performance with two standardized questionnaires. The SART (Taylor, 2017) questionnaire is used to assess the situational awareness. The NASA TLX (Hart & Staveland, 1988) questionnaire is used to assess the task load. More on these questionnaires in Chapter 5.2.5.

The airports selected for task three included Buochs (ICAO code: LSZC) and Grenchen (ICAO code: LSZG). They are both controlled airports, meaning ATC is structuring the traffic. Both approaches have their difficulties. While the difficulty in the inner circuit at Grenchen lies in its short and non-standard routing, the righthand downwind for runway 24 in Buochs is demanding due to the little reference points on the ground (flying over a lake).

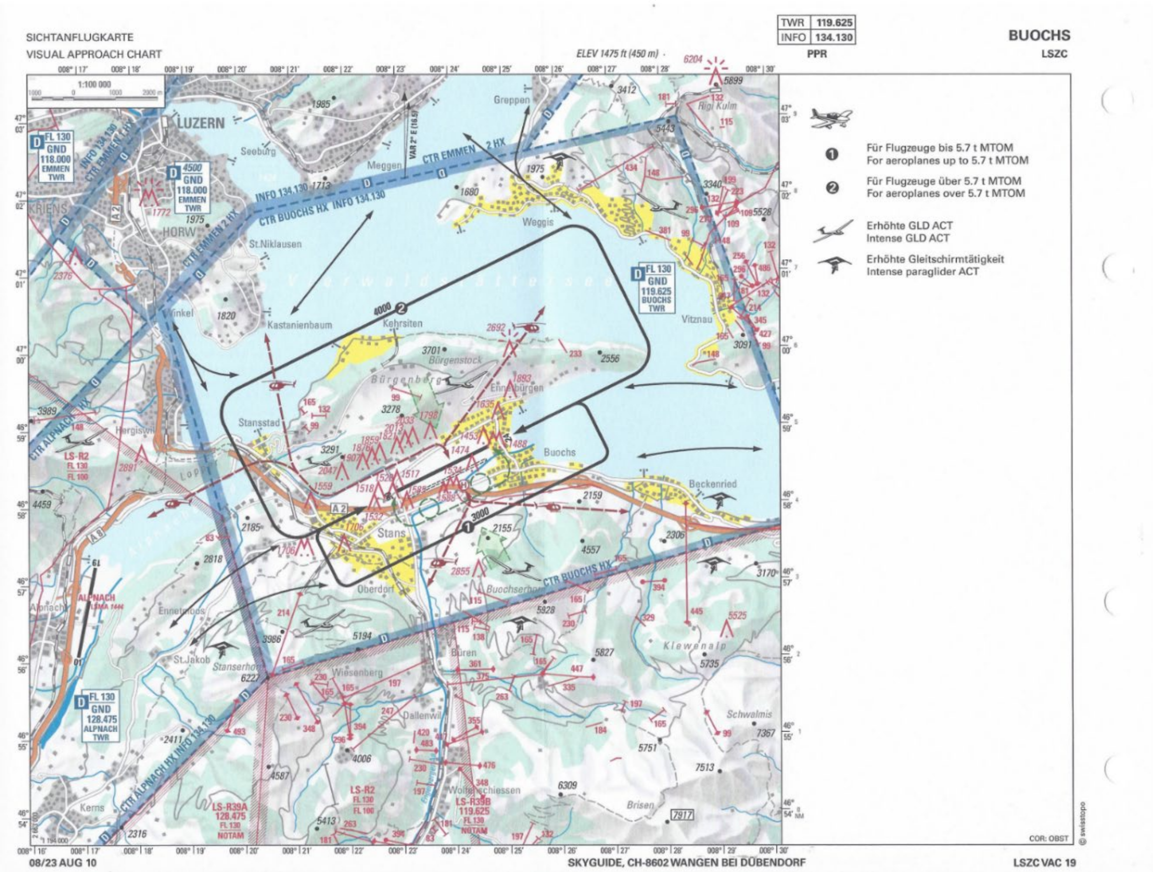


Figure 36: VAC Buochs (Skyguide, 2024)

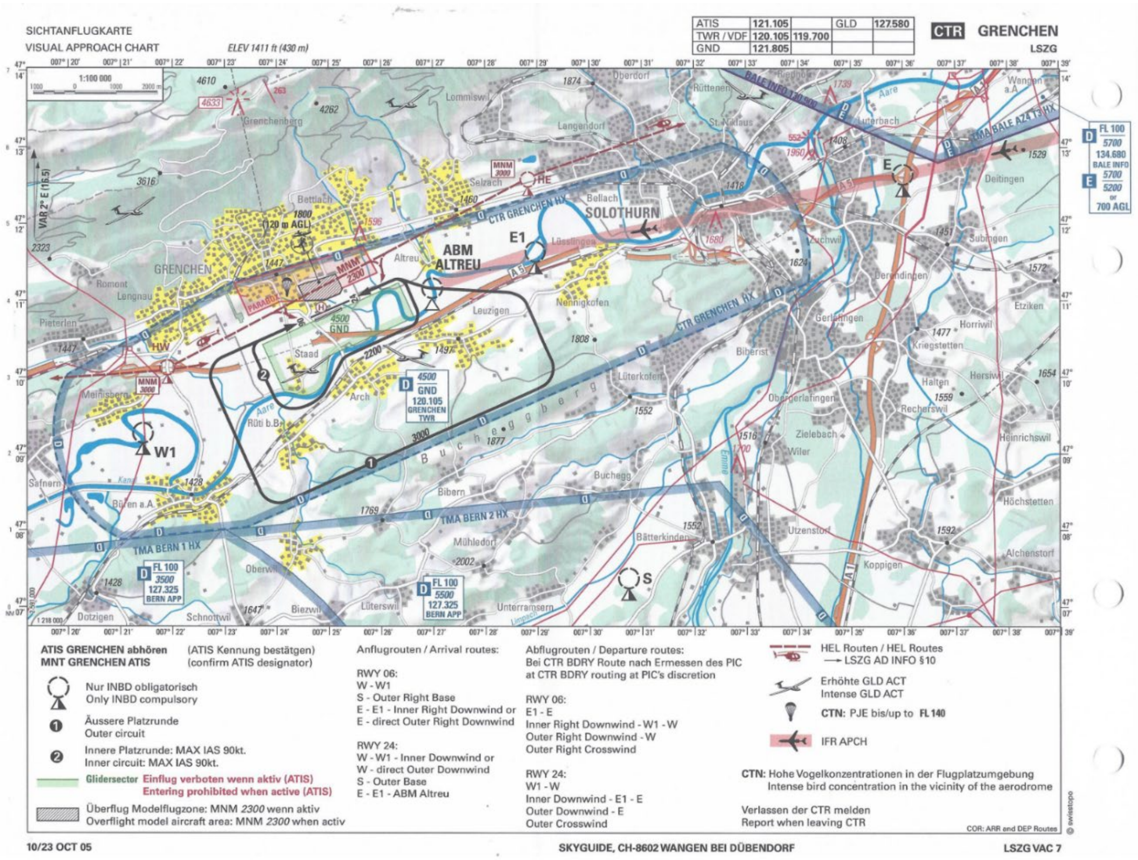


Figure 37: VAC Grenchen (Skyguide, 2024)

Feature exploration

The goal of this unstructured feature exploration is to allow the participants to test the functionalities and interaction with the application, especially with the menu. The participants are encouraged to test the toggles and sliders to see the effect on the information displayed. There is not a specific order in which the participants have to interact with the application. After testing the interaction, participants are asked to assess the usability of the application and their user experience with two standardized questionnaires. The first questionnaires used is the SUS (Brooke, 1996), which assesses the system's usability by asking 10 questions. The other questionnaire is the UEQ (Hinderks et al., 2018), which captures the user experience. Both questionnaires are well known and widely used in application development and usability research.

Post-Study Interview

In addition to capturing feedback in the form of standardized questionnaires, allowing users to express their option on the product in free speech is important. The post-study interview aims to capture verbal feedback on the application and vision for this project. The interview is structured with five prepared questions. Starting by asking about flight phases or scenarios where the application can be most beneficial for the situational awareness and if there are any scenarios where the application clutters the view too much. Next up, the benefits and disadvantages of such an AR application in general are interrogated. Inquire features and information missing in the opinion of the user is an important part of the interview. Finally, open feedback about the user study can be given by the participant. The exact interview questions are attached in Appendix D. The interviews were audio recorded and transcribed into keywords afterwards.

5.2.4 Weather for Scenarios

The weather, daytime and season were kept the same throughout the user study. A clear blue sky during noon on a summer day, was found to keep the environmental influence on the tasks the smallest. Setting the sun at its zenith, the light does not dazzle the participant during the task. A summer day was chosen as build-up areas are best distinguishable from undeveloped areas in summer. An argument for the blue sky is, that the weather simulation cannot be reproduced exactly in the simulator. One can set the amount of clouds and their altitude, but the simulator will render random clouds that approximately fit the settings. In other words, the decision to simulate clear blue skies, eliminated another variable that could have influenced the results.

5.2.5 Evaluation Metrics

As mentioned before, the main purpose of the user study was to evaluate the effect of the AR tool on the situation awareness of a pilot. This was achieved by collecting different data throughout the study. Next to stopping the time it took to complete a task, positions and flight paths were recorded. Additionally, different standardized questionnaires were included to evaluate the situational awareness and task load during the approach task. Usability and user experience were also tested with standardized questionnaires. The big advantage of such standardized metrics is that they allow for an easier comparison of the result with other related research. The following standardized questionnaires were used:

Situation Awareness Rating Technique (SART)

As already mentioned in Chapter 3, the SART (Taylor, 2017) questionnaire is a quick and easy method to assess the situational awareness of a subject. It does so by letting the subject fill out a self-rating with the help of ten questions after the main task. The questionnaire is sectioned into three subtopics: demand, supply and understanding. The SART method was chosen over other methods because it is non-intrusive to the main task, which is especially important in high-dynamic scenarios like flying an approach. The fact that no additional recording equipment is needed has contributed to the decision.

NASA Task Load Index (NASA TLX)

The NASA Task Load Index, or short NASA TLX (Hart & Staveland, 1988), is a widely used assessment tool that subjectively rates perceived workload during a task. As for the SART method, this questionnaire is also based on self-rating after the main task. It contains the following subspaces: mental demand, physical demand, temporal demand, performance, effort and frustration. For this user study, the raw version of NASA TLX (RTLX) was used, meaning the participant did not weight the different subspaces.

System Usability Scale (SUS)

The System Usability Scale, short SUS (Brooke, 1996) , is a simple ten-item scale that allows to assess the subjective usability of a system. The different aspects evaluated are effectiveness, efficiency and satisfaction. Each item is scored from one (strongly disagree) to five (strongly agree).

User Experience Questionnaire (UEQ)

The User Experience Questionnaire, short UEQ (Hinderks et al., 2018) evaluates both classical usability aspects such as effectiveness, efficiency and dependability, as well as user experience aspects such as originality and stimulation. It consists of twenty six attributes to rate between one and seven.

5.2.6 Result Analysis

The user study results were both qualitatively and quantitatively analyzed. The qualitative methods included visualizing positions, flight paths, selected airspaces and writing down key words from the post-study interview. The quantitative methods included calculating statistical values such as mean, median and standard deviation. For testing the statistical relevance, the t-test was performed on some of the results. It has to be kept in mind, that the sample size is rather small to get profound statistical implications.

6 Results

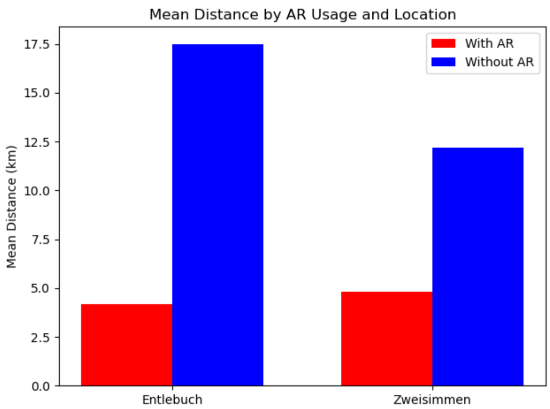
The user study was advertised through a mailing list and flyers distributed at Swiss airports as well as on social media. In total, 26 people showed interest in the study by registering with their contact information. 19 pilots (17 male, 2 female) actually took their time to participate in the user study. A small pilot-study was conducted with one non-pilot and one pilot to check the procedures and tasks of the study beforehand. These two participants are not included in the final group of 19 participants.

6.1 Demographics

The participants were aged between 23 and 68 years ($\tilde{x} = 38$, $\bar{x} = 40$, s= 14). The flight experiences range from 55 to 14'000 hours ($\tilde{x} = 500$, $\bar{x} = 3273$, s= 4897). 11 participants hold a PPL license and 8 participants claimed to hold a CPL or higher. No pilots in training, LAPL or SPL pilots participated. The participants were asked if they ever used an AR, VR or MR device. 16 answered yes, while 3 had no experience with such devices. 5 participants claimed to have used AR, MR or VR devices in aviation (e.g., during your pilot training, in a simulator, or in flight). When asked about the type of aircraft they regularly fly, 14 stated a GA aircraft (Cessna 152/172, Diamond DV20, Acquila A210, etc.), one participant expressed he flies an Eurocopter EC635 helicopter, 6 participants stated transport aircraft (Airbus A320, Boeing 777, Bombardier CL60). Some named both a transport and a GA aircraft. As a main navigation aid during VFR flight, 11 participants use a digital map on a mobile device, 4 use a digital map on the instrument panel and 4 use a paper map. As a secondary navigation aid, 7 participants use a digital map on a mobile device, 3 use a digital map on the instrument panel, 6 use a paper map and 3 stated to use no secondary navigation aid.

6.2 Task 1 (Orientation)

Task 1 was about gaining orientation in a scenario of disorientation. Participants were asked to mark the plane's position on a map, with the help of the AR tool and without. Figure 38 shows the mean distance between the actual position of the aircraft and the guesses on the left. The boxplot on the right indicates the distribution of the answers per location and condition. The great circle distances were calculated from the coordinates with the help of the haversine formula. It is clearly visible that the distance is smaller in the condition with the AR tool. The boxplots indicate that the guesses in the condition without AR are wider spread than in the condition with AR. Additionally, the condition without AR shows more substantial outliers. Interesting to mention is, that the median deviation of the Zweisimmen scenario with AR is higher (orange line in the left plot of Figure 38).



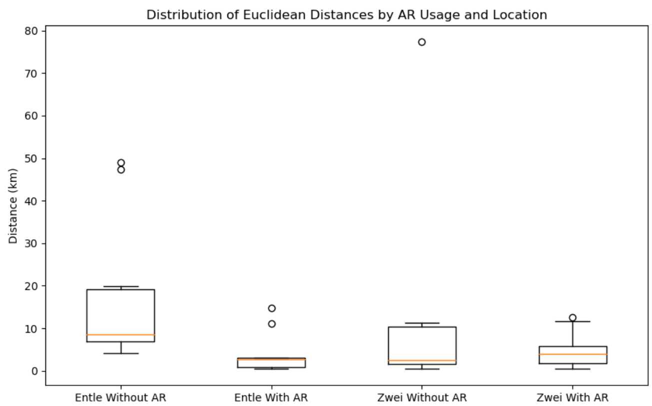


Figure 38: Results Task 1 Mean Distance and Distribution

The discoveries made in Figure 38 coincide with the plots in Figure 39. In this figure again, red represents the condition with AR and blue the one without AR. The dots show the marked positions in latitude and longitude. The blue arrows indicate that there are guesses outside of the area in the plot. By qualitatively analyzing the plots, the pattern indicates a higher accuracy and precision in the condition with AR in Entlebuch. However, the contrast between the conditions is less clear in the scenario Zweisimmen (bottom row). More data would increase the significance of the result and help better recognizing pattern.

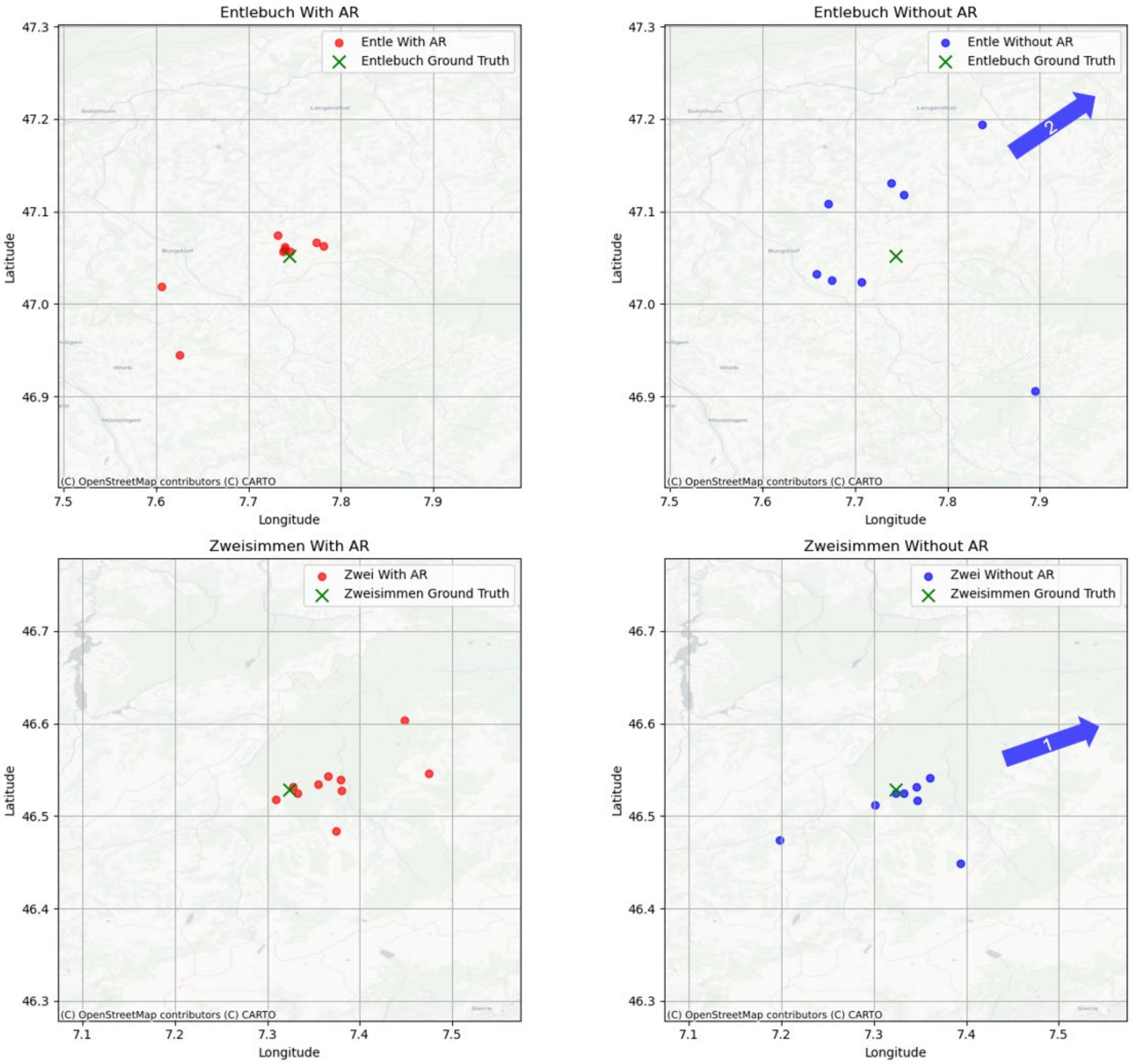


Figure 39: Results Task 1 stated Positions

In addition to collecting the position guesses, the task was timed. Table 3 shows the mean time and standard deviation per condition and location.

Table 3: Stopped Times Task 1

Condition	Mean Time (mm:ss)	Std (mm:ss)
Entlebuch		
With AR	03:36	01:53
Without AR	03:34	02:18
Zweisimmen		
With AR	02:30	01:10
Without AR	03:46	01:39

The mean times lay almost within a minute of each other between locations and conditions. The discrepancy between conditions is higher in the Zweisimmen scenario. It took participants one minute and fifteen seconds longer to identify their location in the without AR condition on average. In the scenario Entlebuch, the participants had two seconds longer to orient themselves in the with AR condition. Looking at the standard deviations, in both locations, the with AR condition exhibits a smaller standard deviation by around thirty seconds. The results of both locations were statistically tested (Zweisimmen: t(17) = 1.827, p-value = 0.085, Entlebuch: t(17) = 0.028, p-value = 0.978) and were found not statistically significant.

The conductor used a stopwatch to measure the time, which could have resulted in timing errors of a few seconds. The timer was started as soon as the scenario was loaded and it was stopped again as soon as the participant pressed the export button.

6.3 Task 2 (Airspace)

The second task was about finding the position and then stating in what airspace section the airplane is in, plus what airspace section comes five nautical miles ahead of the current position and orientation of the aircraft. Table 4 presents the results. The correct airspace section is included in the table. It stands out that only a few mistakes were made regarding the airspace section the aircraft is independent of the condition or location. While in the with AR condition all participants were able to state the correct airspace the aircraft is in, in the without AR condition, three participants made a mistake summed on both locations. The only mistake with the AR tool at hand was for the determination of the airspace ahead in the Wil SG scenario. The without AR condition led to half of the answers being false.

Table 4: Results Task 2

Condition	Airspace Plane is in correct	Airspace Plane is in false	Airspace 5nm ahead correct	Airspace 5 nm ahead false	Total subjects
Beromünster	LSZH TMA-15		LSZH TMA-8		
With AR	9	0	9	0	9
Without AR	9	1	5	5	10
Wil SG	LSZH TMA-11		LSZH TMA-4B		
With AR	10	0	9	1	10
Without AR	7	2	5	4	9

Table 5 reveals the times stopped by the conductor split into orientation and airspace determination. As in task 1, the timer was operated manually, which could lead to time errors in the order or a few seconds. As for task 1, the orientation part was executed faster in the with AR condition in both locations. The mean time as well as the standard deviation are in favor of this condition. Upon inspecting the times for the airspace determination, the task was solved faster in the with AR condition. The standard deviation in the Wil SG scenario is insignificantly smaller. A t-test was performed on the stopped times. It was found that the results are not statistically significant. More data is needed for a profound statement.

Table 5: Stopped Times Task 2

Condition	Mean Time (mm:ss)	Std (mm:ss)
Beromünster		
Orientation with AR	00:52	00:30
Orientation without AR	01:34	01:04
Airspace with AR	00:38	00:32
Airspace without AR	01:27	00:46
Wil SG		
Orientation with AR	02:18	01:32
Orientation without AR	02:35	01:38
Airspace with AR	00:36	00:24
Airspace without AR	01:02	00:26

It was observed by the conductor that not all participants remembered the menu (which would have included the airspace information) shown in the introduction. The majority of participants who looked at the information in the menu double checked their solution with the paper map.

6.4 Task 3 (Approach)

Task 3 was the only dynamic situation in this user study. The participants were asked to fly an approach according to the published route on the VAC chart of the respective airport (see Figure 36 and Figure 37 in Chapter 5.2.3). Here again, the participants had the chance to use the AR tool for one of the approaches. Meaning they either approached the airport of Buochs or Grenchen with AR guidance. Participants were allowed to study the VAC chart in both conditions. Figure 40 shows plots of the altitude profiles in all conditions and locations. The x-axis indicates the distance from the touch-down point in nautical miles, while the altitude (in feet about mean sea level) is represented on the y-axis. The black dotted line represents the manually modeled circuits according to the VAC chart with a descent of around 4 degrees. The horizontal part of the circuit represents the downwind altitude. The exact distinction between downwind, base and final leg is not directly visible in the plots. The dark gray area is a buffer of about 100 feet, which is a widely accepted deviation from the target altitude. The vertical (red) dotted line indicates the approximate intended point of interception between the altitude profile and circuit altitude. As the circuit includes the take-off phase as well, only the part right of the red line is to be compared to the circuit. The circuits were modeled manually; hence, they include some buckling in the vertical profile.

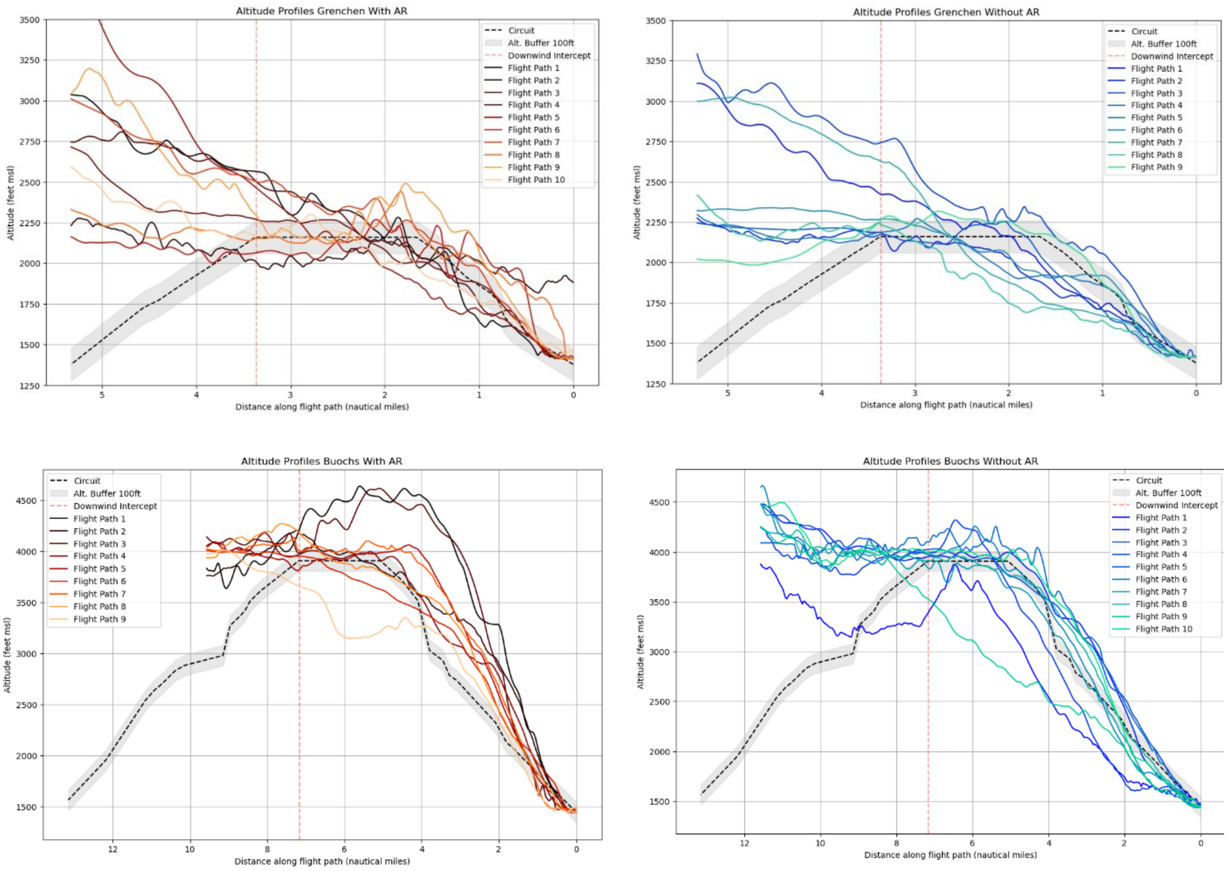


Figure 40: Altitude Profiles of Flight Paths

Concentrating on the flight paths for the scenario in Grenchen (top row), the altitude profile with AR seems to match the circuit slightly better. The flight paths without AR tend to be a bit too low on downwind and only march onto the glide path on the final approach leg. Another observation to be made is the fluctuation of altitude in the with AR condition seems to be slightly higher than in the without AR condition, indicating a more unstable approach. One participant did not manage to land the airplane in Grenchen (flight path 2 in the top left plot) in the with AR condition. In general, the final approach leg seems to be flown more stable in the without AR condition. Looking at the interception, it seems that spread in the different flight paths is smaller in the with AR condition.

Comparing the profiles in the Buochs scenario (bottom row), the flight profiles in the with AR condition are above the circuit altitude until the short final, hence a steeper approach was flown. In contrast to that, the profiles without the AR tool appear to be on or even below the intended glide path. In this second location, the fluctuation in altitude isn't notably different. The vertical profile of the final approach leg is steadier in the with AR condition at Buochs. Interesting to see is that two participants gained altitude upon interception with the circuit and flew the downwind leg with almost 500 feet above the published circuit altitude (in the with AR condition). This led to an even steeper final descent.

Next to inspecting the flight path laterally, it is also interesting to look at them from a top-down view. Figure 41 (see next page) helps to compare the routes geographically. Here again, the black line represents the circuit as published on the VAC chart. Red lines correspond to paths flown with AR and blue lines to paths flown without AR. Each of the two columns represents one location.

Examining the Buochs scenario (left column) first, the interception at the beginning of the downwind leg (as published) was flown more precisely in the condition with AR. Although one participant overshot the path into the infield area and another did only intercept the downwind at the end. One participant started intercepting a left-hand downwind for the opposite runway then given in the assignment for this task, which was communicated by the conductor, hence the 180 degree turn in one of the blue lines. In general, the downwind leg during the without AR condition was flown north of the defined route and not exactly in the opposite direction of the runway. This led to a slow intercept with the downwind leg. A few participants managed to fly the downwind in a correct heading, just turned into the direction too early with no AR guidance. The base leg was rounded off into a downwind to final turn more often in the condition without AR condition. Hence, the specified base leg is better visible in the with AR condition. The airport in Buochs only becomes apparent in the base to final turn, thus in both conditions the participants overshot the final turn. As soon as the runway was insight, the alignment with the runway center line was achieved even a bit faster without the AR tool.

Moving on to the Grenchen scenario (right column), the circuit is tighter and lower above the ground than in Buochs. In this scenario, the participants managed to better follow the circuit without the AR tool as an aid compared to the approach in Buochs. Thus, the difference between with AR and without is not as clear. However, there are a few things worth mentioning. Starting with the interception point of the downwind. The AR tool seemed to have helped, as the flight paths are closer together at this point. Two of the participants flew far south of the defined downwind leg in the without AR condition. One participant landed on the opposite runway, contradicting the assigned task. The left turn before turning base is less pronounced when flown without AR tool. Although this turn is better recognizable in the with AR scenario, it seemed to be difficult to follow the gates in this turn for some of the participants. This resulted in shortened base and final legs and for one participant even had the consequence of not being able to land at the airport (red line with 180-degree turn furthest south in the middle plot). The unstable final approach in the with AR condition, as already seen in the vertical profiles, is also confirmed in the top-down view.

Buochs (LSZS) **Grenchen** (LSZG)

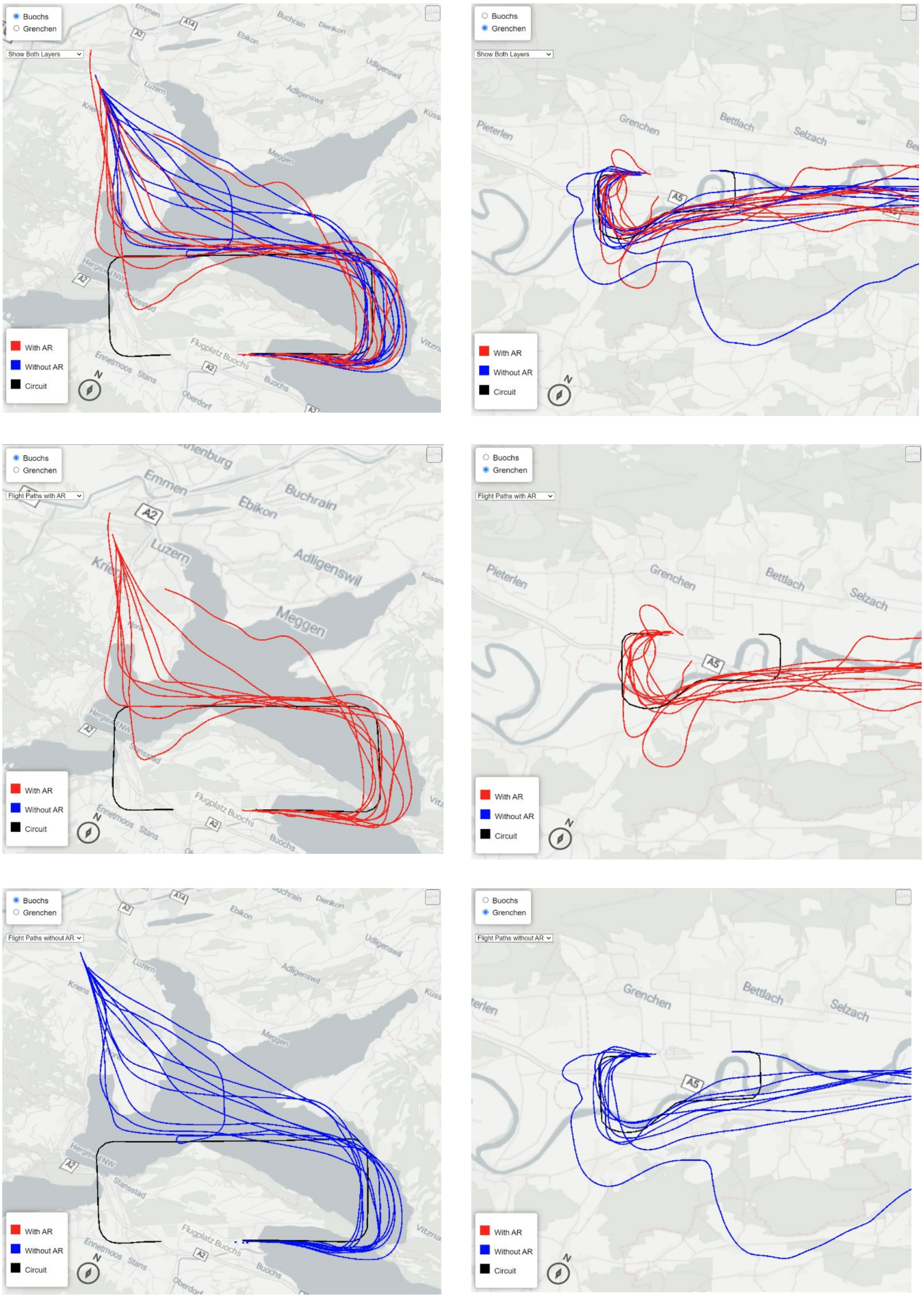


Figure 41: Flight Paths Task 3

Besides recording the flight paths, two self-rating scales were conducted assessing the situational awareness and task load during the approach. As already introduced in the methodology, the SART questionnaire was used to rate the situational awareness and the NASA TLX questionnaire helped estimate the task load. Both can be broken down to one final score per participant. The following paragraphs present the results of these questionnaires.

SART RESULTS

The SART score for the condition with AR ($\tilde{x} = 20.0$, $\bar{x} = 20.7$, s= 6.4) and without AR ($\tilde{x} = 25.0$, $\bar{x} = 25.9$, s= 11.6) shows that the situational awareness was rated significantly higher ((t(36) = -2.63, p= 0.0123) in the without AR condition.

NASA TLX RESULTS

The NASA TLX score in the with AR condition ($\tilde{x} = 46.7$, $\bar{x} = 46$, s= 15.1) and without AR ($\tilde{x} = 50.0$, $\bar{x} = 46.8$, s= 14.4) indicate no significant difference ((t(36) = -0.0059, p= 0.9953) in task load.

6.5 User Experience and Usability

After completing all three tasks, the participants were given the opportunity to test the interaction with the menu, toggling information layers and operating the projection range slider. Afterwards, the usability and user experience were evaluated with the help of the UEQ and SUS questionnaires. In this subchapter first the results regarding the user experience and later the results regarding the usability will be laid out.

UEQ Results

The results from the UEQ questionnaire were analyzed with the help of the official Excel tool provided with the questionnaire. It does not make sense to present one user experience score due to the nature of the questionnaire. The scores are evaluated in six main categories. Each item in the questionnaire is associated with one of the categories. The categories can be grouped into pragmatic quality (Perspicuity, Efficiency, Dependability) and hedonic quality (Stimulation, Originality). Pragmatic quality describes task-related quality aspects; hedonic quality describes non task-related quality aspects. Figure 42 shows the results in a tabular form (left) and graphically (right). Both mean values and variance are presented.

UEQ Scales (Mean and Variance)		
Attractiveness	0.939	0.95
Perspicuity	1.368	1.25
Efficiency	0.658	0.90
Dependability	0.408	1.32
Stimulation	1.605	0.52
Novelty	1.763	0.93

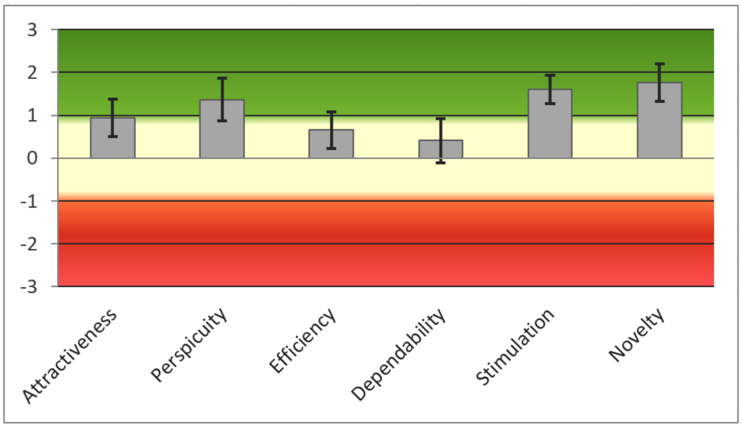


Figure 42: UEQ Results

According to the analysis tool, values between -0.8 and 0.8 represent a more or less neutral evaluation of the corresponding scale, values > 0,8 represent a positive evaluation and values < -0,8 represent a negative evaluation. Best rated was the novelty, followed by the stimulation and perspicuity. The dependability was rated the worst. However, the variance is also the biggest for this quality. The efficiency received a disenchanting score. To summarize, the hedonic quality was rated better, but no quality was rated negative.

The big advantage of using a standardized method of evaluation lies in the fact that one can compare it easily with other work. The analysis tool for the UEQ includes a benchmark comparison with an existing data set. This data set contains data from 21175 persons from 468 studies concerning different products (business software, web pages, web shops, social networks). It has to be noted that this data is neither tailored or filtered to aviation-related nor to AR-related software. Nonetheless it is interesting to see the relative performance of the AR tool. The plot in Figure 43 compares the same qualities as seen before with the benchmark data set.

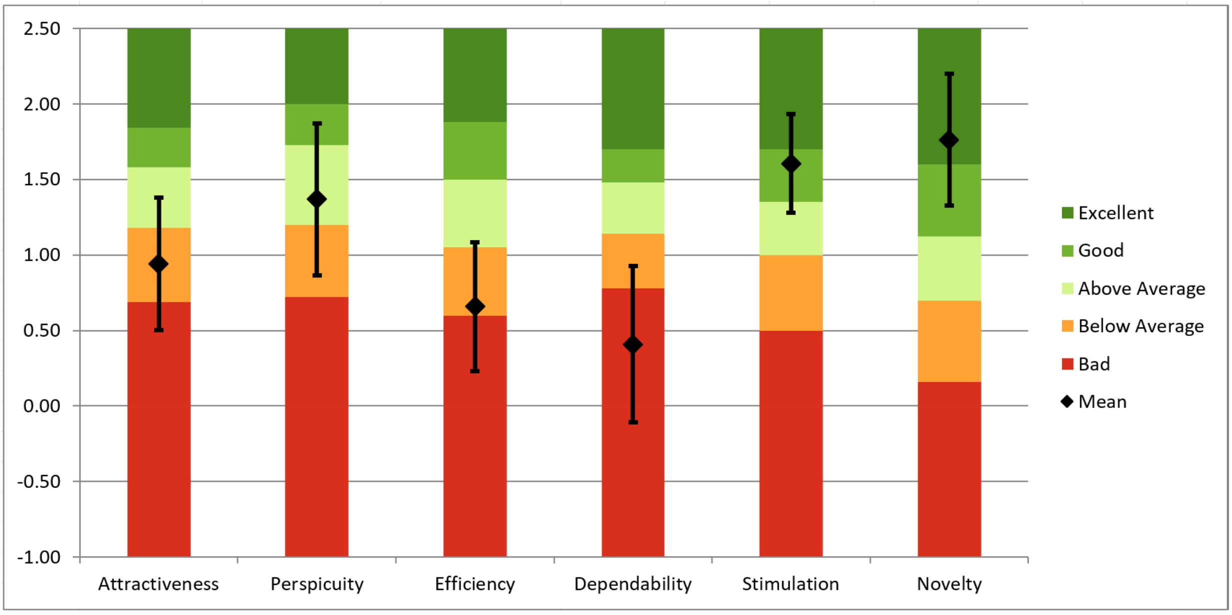


Figure 43: UEQ Benchmark Comparison

In the plot above, the comparison is categorized from excellent to bad. Here again, the hedonic qualities reach above average, up to excellent. The dependability scores the worst and the efficiency and attractiveness also remain below average.

SUS Results

The SUS score yields one number representing the overall usability of a system. Each item in the questionnaire contributes to this score. According to J. Brooke the final score is calculated as follows: “For items 1,3,5,7, and 9 the score contribution is the scale position minus 1. For items 2,4,6,8, and 10, the contribution is 5 minus the scale position. Multiply the sum of the scores by 2.5 to obtain the overall value of SUS. SUS scores have a range of 0 to 100. ” (Brooke, 1996). Looking at the SUS score from each participant, the results for this user study ($\tilde{x} = 72.5$, $\bar{x} = 66.2$, s= 17.1) appear to have a wide spread. Although there are a lot of participants who scored the SUS quite high, thus the median is higher than the mean, the mean at 66.2 stands out to be rather low.

6.6 Post-Study Interview

As a final part of the user study, a ten minute interview aimed at gathering the opinions of the users in more detail led to the following results: Table 6 summarizes the key words transcribed from the audio recordings of the conversations. The column “Count” indicates the number of participants who mentioned the statement in the interview. It has to be mentioned that during the interview a further developed state of the application (close to the vision) should be discussed. This helps collect thoughts on the idea rather than the development state of the application.

Beginning with the positive and negative use cases of such an AR tool in different flight phases, the majority of the subjects agreed that it is helpful during an approach into an unfamiliar airport. In contradiction to that, 6 participants raised concerns about the cluttering of information in the approach phase and therefore said they would not use the application in this flight phase. During cruise flight, 13 participant stated that augmented reality information such as labeling settlements, lakes and POIs can be helpful or orientation. Here again, some participants mentioned that for orientation in a familiar region it is not necessary. Next, the raised awareness of surrounding airspace structures during cruise flight were mentioned by five participants. Three participants mentioned that in a state of emergency the projected information would be too much and rather a disadvantage. Four participants on the other hand, mentioned that, especially for highlighting obstacles in an emergency situation, AR would have big potential. Regarding obstacles, three pilots mentioned that in mountainous terrain, the highlighting of cables could be beneficial for situational awareness (one of them is flying helicopters regularly). Finally, it was mentioned twice that projected information can be helpful in bad weather conditions.

The main concern raised by eight participants is the tendency of cluttering the field of view if the projected information is not adapting to the phase of flight. The fear of not seeing what is behind the projections, missing out traffic or obstacles was mentioned a few times. Brought up in the discussion by seven participants was the unease of the focus split between inside and outside the cockpit, now shifting between real world and projected information. Even before the interviews, during task 3, the observer noticed some participants speaking aloud about where to set their attention during different parts of the approach. Another worry that emerged from the conversations was that pilots might unlearn/forget to navigate without such a digital aid. This was not only related to AR but also to digital maps on mobile devices. Is a pilot still able to navigate even if the digital aid fails?

Table 6: Post-study interview results

Positive Use Cases of AR	**Count**	**Negative Use Cases of AR**	**Count**
Approach into an unfamiliar airport	13	Can get too cluttered during approach	6
Orientation during cruise flight	13	During cruise flight in familiar region not necessary	6
Making aware of surrounding airspace structures	5	In emergency situations too much unneeded information	3
Highlighting obstacles during an emergency	4		
Highlighting cables in mountainous terrain	3		
Low visibility situations	2		

Main concerns:	**Count**
If information does not adapt to the flight phase, there is a tendency for cluttering	8
Focus split between projected information and real world environment (When to focus on what?)	7
Obstruction of the real world due to projection of digital information	4

Pilots unlearn/forget to navigate without digital aid	4
Functionalities/Information that are missing in the current version:	**Count**
Traffic information (e.g. highlighting traffic with a rhombus)	19
Flight parameters (airspeed, altitude, artificial horizon,…)	11
Visualize planned route / direction to next waypoint	6
Glide range laid over terrain	4
Alerting about system failures (e.g. oil pressure, oil temperature,…)	3
Checklists	2
Displaying on route frequencies	1
Ground operation (taxi route, ground obstacles,…)	1

Interesting statements:

- Next step from digital map
- I see a lot of potential in such an AR tool for VFR pilots
- Customizing projected information is key (e.g. with menu as is)
- Highlight digital information more relevant in a scenario
- System has to adapt displayed information per flight phase automatically
- Interaction on touchpad instead of directly in AR
- Add more auditive clues (especially for warnings)
- Are the projections still visible in bright sunlight?
- The AR glasses need to improve in weight and size before potential use

Continuing with functionalities or information that were missed by the participants in the current version, the first immediate answer from all was: traffic. Highlighting traffic with, for example, a rhombus would be a big step forward for all existing traffic alert systems. Including flight parameters such as airspeed, altitude and artificial horizon was mentioned by eleven pilots. They compared it to HUD or HMD in commercial or military aviation. As a further navigational aid, the participants suggested a visualization of the flight plan. Either in the form of a line in the sky or indications as to where the next waypoint is located. Another interesting idea that was mentioned was to display on route frequencies, to better know what ATC controller or uncontrolled airfield should be contacted next. Ideas for emergency situations included alerting about failure of systems or projecting the glide range (terrain dependent) on the surrounding terrain. Integrating checklists or support for ground operations was remarked as well.

Finally, the table includes a collection of interesting statements, which will be further discussed in the next chapter.

7 Discussion

In this chapter, first the development state of the application will be discussed before elaborating on the results of the user study and the limitations of this work.

7.1 Application

The AR application in this work was developed with the purpose of using it to test the hypotheses in a user study. Six different geographical regions around Switzerland are featured. Similar to current work in research around GA technologies, the application is meant to be tested in a simulated environment. The hurdle to overcome for such a tool to be tested in real-world aircraft was pointed out in the work of Walko (2021). While the main focus of the research for AR technology in the GA sector lies either on highlighting traffic or implementing an approach guidance tool, this work expanded the possibility of more geographically relevant information for orientation and navigation during VFR flight. The digital information visualized in this work is world-referenced, instead of head-referenced as in Haiduk's work (2017). The big advantage that results from this is that it is directly linked to real-world features, reducing the mental process explained in the section about VFR navigation in Chapter 2.1. Comparing the application state with the vision (see Chapter 1.2), it becomes clear that further development is needed to match the vision. Especially, the alignment between projected content and the simulated world has upside potential. Although measures were taken to minimize the alignment error, it is still clearly noticeable. Particularly, when turning the head away from the moving direction of the aircraft or during turns. There are two possible reasons for this. Regarding the misalignment due to the head movement, it is likely that the difference in the field of view from the HoloLens (which is not adjustable in the HoloLens) and the flight simulator is causing this issue. When testing the flight simulator setup with bigger screens, the cockpit in the simulator was closer to life-size, which led to better alignment of the digital content in the HoloLens. Unfortunately, the smaller screens forced the author to rescale the cockpit in order to get a similar field of view as with the bigger monitors. A reason for the misalignment in the turns could be the lag induced by the connection between the flight simulator and the AR application. It has to be said that these misalignments influenced the results of the user study, as the confidence in the quality of the information presented to the participants by the AR tool was lowered due to this fact.

Taking a closer look at the visualization choices made, it can be said that a lot of user testing is still needed to find an optimal solution in terms of how to visualize certain information. Throughout the project, it has become clear that preferences are highly individualized.

In the current state of the application, the colors were either chosen to match the color of the feature on the ICAO chart or to make the object stand out from its background and distinguish it from other projected information. For example, cables are visualized in red (as on the ICAO chart) and cranes are symbolically a bright yellow. Poles are inspired by pole objects within an airport (white and red). The colors used to visualize the circuit were inspired by visualizations in state-of-the art navigational technology. Another interesting topic is the color choice of the labels. As the scenarios used in the user study were all simulated blue skies, the white labeling stood out very well from terrain (mostly dark tones) and the blue sky. Imagine the sky being cloudy; the contrast would be eliminated, making it hard if not impossible to read the labeling. Maybe it would make sense to adapt the color according to the current weather manually or even automatically.

For the guidance around the circuit, rectangles were selected. This is also inspired by existing solutions on how to display flight paths (see Figure 22). Thanks to user testing, the chosen symbolization turned out to be less ideal. In general, the gates were too bulky, obscuring too much of what is behind. Some pilots mentioned that gates entice them to only concentrate on flying directly through the middle of it, having the consequence of neglecting other tasks. However, opinions did not speak for one optimal solution. Some pilots stated that the rectangles are good, if just thinner. Others wished to only see a thin line around the circuit. The purple tube, visible from further away, was appreciated by the majority of users.

Not much automatic adaptation of information during the flight is implemented in the current application. However, the labels are implemented in a way that they always turn towards the spectator, and the purple tube indicating the position of the circuit from further away disappears upon getting closer. This choice was made to not obstruct the view too much while flying in the circuit, yet still get a good impression of the path of the circuit from further away. Further adaptation of the information was desired by the participants when asked during the post-study interview. More on that in the discussion of the post-study interview later in this chapter.

When talking about the options for interacting with the application, the menu shown in Figure 23 is the main topic of discussion. It was implemented to be oversized on purpose. This gives users with no XR experience the opportunity to get to know the way of interacting with no haptic feedback easier. For a final product, this would of course have to be further developed and made adjustable to different cockpit environments. As expected, it could be observed that users with less AR experience had a harder time pressing buttons and sliding sliders. In general, the layout of the menu was found to be organized and well thought through by the users. If such an AR menu would be the optimal solution for a highly dynamic environment such as a cockpit was questioned by the users as well as the author. This thought will be brought back up later this chapter.

7.2 User Study

Moving on to interpreting the results of the user study conducted with 19 pilots, the participants represented various age groups and thus brought a wide spread of experience in flying with them. A little under two-third of the participants use digital tools as their main navigation aid, implying their interest in technological advancements in the GA sector. Unexpectedly high was the experience the participants had with XR devices.

Looking at the results from Task 1 (Orientation), the positive effect of AR in a disorientation scenario is clearly visible, confirming the third hypothesis (H3). Adding to that, it seems that the effect on the accuracy of positioning oneself is especially impactful in terrain with less distinctive features (region of Entlebuch). Interesting to see is the average time spent to determine the position is not significantly different in the Entlebuch scenario. This indicates that although the AR tool helps with the orientation, it still is harder to determine a exact location in terrain with less prominent characteristics. In the Zweisimmen scenario, the structure of the valleys and mountain peaks might support relative positioning on a map. By relative positioning, the positioning with a few known points in the scene (e.g., towns) is meant. Of course, identifying a valley on the basis of a few relative points can be a difficult and misleading task. Evidence that supports this thought is the spread of the position guesses that is wide along the valley and narrower across the valley. Regarding the test scenario itself, it has to be commented that adding a last known point to the task description would have made the scenario more realistic.

Similar to Task 1, the result of Task 2 favors the AR condition. All participants were able to correctly identify the airspace sector they were in while using the AR tool as an aid. Although by far not all participants took advantage of the information section in the menu. Without the AR tool to help, the participants were more prone to making errors. Also the time needed to identify the airspace sections was on average double or more in the without AR condition. The locations selected were intentionally areas with a high density of different airspace sections, as this scenario was thought to be the one where such additional information is especially useful. When flying around the Zurich area, avoiding TMAs can certainly be realistic and it is of the highest importance to precisely know one’s position and to identify the correct airspace. In this user study, the aircraft was deliberately placed within a controlled airspace (for which a clearance by ATC would be needed) to more accurately test the situational awareness.

Analyzing the results from task 3 (approach), it is interesting to see that the with AR condition helped flying the published route more accurately in some parts of the circuit however, there are areas where the AR tool seemed to be more distractive than helpful. Starting with the intersection of the downwind, it can be said that the AR tool allowed the pilots to better intercept circuit both vertically and horizontally. The difference is especially remarkable in the Buochs scenario, where the terrestrial features are less prominent. Continuing with the downwind section, the AR tool helped navigate along the specified path. In the Grenchen scenario, the vertical deviation from the published path in the with AR condition is less severe than in the condition without AR. On the other hand, it has to be mentioned that some participants climbed above the downwind altitude, although their interception was at the correct altitude in the approach into Buochs airport. The reason for that might have been that the participants were looking for the gates and lost track of their vertical speed. Whenever the gates were visible to participants, they decreased the deviation from the published route in the downwind leg. Particularly during the approach in Buochs, the downwind leg was estimated to be more north-westerly by participants who did not have the AR tool as guidance. Although the contrast between conditions is less drastic in the approach in Grenchen, the downwind leg still seemed to be flown more accurately with the AR tool. With the downwind leg being placed along the river (better terrestrial features to follow), it makes it easier to mentally place the published path in the real world. Turning into the base leg, the results are very dependent on the location. Whereas the AR tool prevented a continuous downwind to final turn (as flown in the without AR condition by many participants) in Buochs, in Grenchen the guidance seems to confuse a lot of the participants. Pilots usually reference the base leg with the runway. In Buochs, the runway only becomes in the second part of the base leg, tempting the participants to continue the turn from the downwind leg, which ends up in a continuous turn to final. The gates within the AR tool counteracted this effect. However, in Grenchen participants had a harder time using the gates as a reference. It is assumed that this is because of the smaller turn radius and distance of the base leg. Once the pilot left the optimal route, it was hard for them to find the correct gate to use as a reference, leaving them searching and neglecting the look outside to reference the path with real world objects. Another reason for this comes from the misalignment between projected content and the simulator, which is more severe in the smaller circuit in Grenchen. Some participants even commented during or directly after the task that they were searching for gates and admitted to only having focused on the gates. On final, the tool did not improve the alignment with the runway centerline. The opposite was the case, as the flight path shows a rater late establishment of the centerline in the with AR condition. A pilot learns to estimate the picture of the runway he is supposed to see during a four degree final approach (normal for VFR single engine aircraft). Generally, pilots get quite good at this estimation, which could be a reason why the tool did not approve this part of the circuit. However, this picture of the runway in a pilot's head is strongly dependent on the runway length, width and slope. If a pilot is used to landing on a narrow runway, he is tempted to approach a wider runway too high. Here again, the author still believes that AR could provide a helpful guidance to the runway. Of course the alignment of the digital content would have to be spot on. An important point to mention, is that the majority of the participants mentioned they struggled with the unrealistic flight physics of the flight simulator, even after testing the controls. Especially the pitch controls were way more sensitive than to be expected from a Cessna C172 (the plane flown in the task). This would explain the unusual fluctuations in the altitude profile across all conditions.

Summarizing the results of task 3, the AR tool helped the participants, especially in a region with fewer terrestrial features. However, once the participants deviated from the optimal route, it was hard for them to find back and the gates started to become more of a distraction than help. This could be improved with better alignment of the digital content. Another idea would be to implement a function that guides the pilot back to the published route once he loses it. An arrow pointing in the direction of the next gate would be one way to accomplish this. Therefore, hypothesis H4 could not be fully confirmed. Further research is needed to do so.

The divided discussion on the effect of AR on the recorded flight paths in task 3, reflects in the results of the situational awareness self-rating questionnaire (SART) which indicate that the participant on average felt to have a higher situational awareness in the condition without AR. This contradicts the findings in the other results. The main reason for this is believed to be in the development state of the application. As mentioned several times before, the misalignment was misleading the participants, lowering their trust in the tool. As SART was only evaluated on the dynamic task (where the misalignment was most notable) and considering the feedback of the users in the post-study interview about the general idea of an AR tool for GA, this reason is justified.

Comparing the results from the NASA-RTLX, there is no significant difference in task load between the conditions. Unfortunately, the effect of the improbable feelings of the flight controls on the self-rating cannot be separated from the task load induced by the task itself.

The user experience scale (UEQ) shows that the application has been rated neutral to positive. Whereas the hedonic qualities were rated higher, meaning the participants appreciated the novelty of this idea, the rating of the pragmatic qualities confirms that the application needs to be developed further. The poorest rating was given regarding the dependability. Items like predictability, supportiveness and security counted towards the dependability. More user testing throughout the development is crucial to include valuable findings, as already found in this work. Adding to the results of the questionnaire, some users commented that the interaction in AR takes time to get used to and raised the concern that this type of interaction might not be ideal for a cockpit environment. This and the misalignment were the two main reasons for the neutral score in the UEQ. More on possible alternatives to improve the interaction will be discussed in an upcoming paragraph. When comparing the UEQ scores with benchmark data, it is no surprise that the dependability and efficiency perform particularly poorly.

The average system usability scale of 66.2 (of a possible 100) suggests that the usability of the prototype needs to improve for it to become market ready. As for the user experience, the interaction as well as the calibration of the projections are the main pressure points. Furthermore, different visualization choices need to be scrutinized and improved in further development.

After being presented with the vision of this work and testing the AR application throughout the study, the last part, a short interview, aimed to discuss the general idea of such an AR navigation aid for VFR Flight. In general, all participants were very excited about the technology and the majority stated they see big potential for such a tool. The biggest benefit of such an application was found to be in unfamiliar areas. Especially, for approaches into airports one has not yet visited. Additionally, for on route orientation in unknown areas it has turned out to be advantageous. Fortunately, Switzerland provides countless terrestrial features that help the orientation during VFR flight. Which is where some participants stated additional information projected into the real world is not needed, as they are familiar with the area. Participants who regularly fly abroad, referenced situations in foreign countries (e.g., Germany or France) where it is harder to navigate using only topographical clues and a paper map. Reason for that being the homogenous landscape types. Here is where the AR tool extends the situational awareness.

The opinions on visualizing the obstacles were divided. Participants that were against the integration of obstacles argued that in cruise flight they would be well above them anyway and in an approach, they identify them when looking outside. This is a valid point, however, the author still represents the opinion that visualizing obstacles can be helpful, especially in mountainous areas. There, GA aircraft often fly below the mountain peak and are in danger of overseeing cable (e.g., from cable cars) and poles. This thought was shared by at least three of the participants. Some participants even went further and mentioned that highlighting obstacles in case of an emergency, such as an engine failure, could be a big gain in terms of safety. During an engine failure, one of the first tasks to manage by the pilot is to find a suitable emergency landing spot (e.g., a field). This choice can very well be supported by highlighting obstacles, as they are often hard to see from the air, especially cables and small poles. As an example, one can take a look at Figure 6 and search for the power line that crosses the village of Dürrenroth.

Another interesting scenario, which was found to benefit from augmented information, are bad weather conditions. Cloudy skies can obscure features on the ground. In this case, AR would provide the pilot with “X-ray” capabilities to see through the clouds.

Next to the flight phases where AR brings advantages for the situational awareness, two points were mentioned as negative or neutral influence on the situational awareness. The first one, already mentioned before, is that projecting information in areas where the pilot is familiar seems unnecessary. The second one is the fear of information overload in emergency situations. The second point brings up a topic that was discussed with many participants during the interview. How should the information displayed be adapting to different flight phases? This question is included in one of the main concerns stated by the participants. The occlusion of real-world objects by digital information as well as information overload that could occur during flight due to the digital information projected into the pilots field of view. Regarding the risk of occluding relevant information (such as e.g., traffic or obstacles), this for sure would have to be looked into in further development. Ideas like an easy way to switch off all projections or increase their transparency could counteract that concern. Discussing the topic of information overload, this can be prevented by manually or better automatically adapting the content projected per flight phase. As the limit of when an information overload occurs is highly individual, a combination of autonomous and manual adaptation would make sense. A few examples for variants of information could be: hiding obstacles as long as they are no factor in a certain flight phase, for example, during cruise flight well above and ground obstacles. Another example, displaying airspace structures only if the pilot is close to entering them. With that said, increasing the opacity of information that is not relevant at the moment and highlighting objects more relevant would be another method of minimizing occlusions. Here, eye tracking technology would help to identify the objects that are looked at in certain scenarios. Manual adaptations on the other hand, could be performed to set, the amount of town names, lakes, rivers, etc. to be displayed. If the projection range adjusts automatically in different flight phases, during cruise a higher range is set and on approach the range decreases, users could appreciate manually refining the range during a flight phase to their liking.

A second concern raised by some pilots was that the focus split moves from inside and outside the cockpit to focusing on the projected information and outside the cockpit. This effect could also be counteracted by automatic adaptability of the information and various transparency settings. Researching further on how well humans can acclimate to this new focus split and filter the important information at any given time is necessary to better understand the effect AR has on the situational awareness of a pilot.

Another concern worth mentioning is that pilots will unlearn how to navigate without such a digital aid. In the author’s opinion, this does not only regard AR but also already widely used moving maps on tablets. Here, every pilot has to show self-discipline to keep their navigational skills proficient. An electronic device failing in-flight has to be accounted for in any flight. Having an analog backup is therefore crucial. Not only that, but knowing how to use it as well.

Continuing with the functionalities and information felt to be missing in the application, all participants stated that visualizing traffic would be a huge benefit for the situational awareness. In fact, this was originally planned to be included in this work, unfortunately had to be left for future work due to time constraints. There are traffic warning systems available in the GA sector. Either they only show it approximate direction and distance of the traffic or the more advanced systems include the traffic in the artificial horizon in the primary flight display. Both, still require pilots to look out and search for the traffic according to the warning they are given. In case the traffic would be highlighted in AR, with e.g., a rhombus directly overlayed to the object, this mental process would be eliminated and the workload would be reduced. Important here again are the visualization choices. The occlusion and distraction from real world objects have to be taken into account during the development of such a system.

The other points mentioned in this section of the interview are all interesting to look into in future work. Some are more relevant for situational awareness than others. Overall, they are all valuable ideas for research as well as the development of a product in the GA sector.

While transcribing the interviews, the author filtered out some interesting statements (see Table 6) that were either mentioned throughout the interview or as general feedback after the study. In general, the participants gave highly positive feedback, stating such an AR tool has huge potential to become the future navigation tool for VFR flights. Nonetheless, participants alluded to the hardware (HoloLens) still having to evolve to become suitable for the market. The size and weight of the HoloLens were criticized. The author agrees with these statements. For such a tool to be used, the hardware has to get smaller (closer to corrective/sun glasses) and the overall acceptance of such devices has to rise.

One final takeaway from the post-study interview is that shifting the interface from AR to a touchpad could improve the user experience. The author sees this idea as the most suitable way of interacting with the application in a cockpit environment, considering the results of the user study. The interaction is more precise and reactive than in current AR interactions. Besides, using something tangible reduces the step in the evolution between navigation with a moving map and a projected “map” into the real world. This can improve the acceptance of users in the beginning.

Summarizing the discussion by looking at the hypotheses, this work was able to verify H2 and H3. To confirm H1 and H4, further research is needed. The results regarding H1 are only qualitative, as no task directly tested this hypothesis, but it was discussed only in the post-study interview. Quantitative measures as in Katins et al. (2023a).The finding on H4 are controversial and we can neither confirm nor reject the hypothesis.

Finishing off the discussion, a few points to be improved for future studies have emerged throughout the user study. It would make sense to extend the familiarization with the AR tool and the flight simulator before starting with the main tasks. Although the graphical representation of the earth is phenomenal in Microsoft Flight Simulator 2020, the flight physics are far from real. This introduced an unwanted variable in the user study. Maybe this effect could be minimized by more carefully selecting the flight control settings in the simulator or using a more advanced simulator setup.

7.3 Limitations

The primary limitation to this study is the controlled environment in which it was conducted. First of all, the participants could neglect many tasks they would face during a real flight. As a few examples, no radio communication was required, no checklist had to be followed, and no traffic or significant weather was programmed in the simulator. Moreover, the simulator entails reduced situational awareness due to the limited field of view, only limited auditive feedback and other sensory inputs (e.g., no g-forces, no vibrations, etc.) completely missing. Furthermore, the effects of the unrealistic flight physics confirmed by multiple participants were a big disadvantage of the study setup and likely affected the outcome of task 3. Testing the application during a flight in a real aircraft is expected to yield new results.

Another limitation is the number of participants. With a relatively small group of 19 pilots getting profound statistical results is not given, as seen in the statistical tests performed on the results. Therefore, the general statements that followed the results must be interpreted with caution. A bigger group of participants would allow us to draw more generalizable conclusions in future work. Still, it has to be mentioned that the number of participants is comparable with studies conducted in related work. Even though the group of participants was selected based on them having a pilot’s license, the selection of participants can be limited even further for any future user study. This would minimize the effect of process variables induced by varying levels of experience in GA flying within the groups of participants, thus helping to clearly connect the independent and dependent variables. Including the constraint that the pilot must be primarily flying VFR or at least fly a minimum amount of flight hours under VFR a year is one possibility to filter the group even more. It has to be kept in mind that with this, the challenge of finding participants will rise.

8 Conclusion and Future Work

This work explored the effect of AR on the situational awareness of a pilot in a General Aviation (GA) aircraft operation under Visual Flight Rules (VFR). While the main focus of the still sparse research for AR technology in the GA sector lays either on highlighting traffic or implementing an approach guidance tool, this work expanded the possibility of more geographically relevant information during different phases of VFR flight. As the related work, this thesis was able to prove a positive effect of AR tools on situational awareness. However, this effect turned out to be highly dependent on the scenario, visualization and individual preference of the subject. An application for the Microsoft HoloLens 2 was developed, to evaluate the hypotheses. It included six scenes linked to different regions in Switzerland. The information integrated consisted of non-visible aeronautical information (airspace structures, advisory points, waypoints, approach procedures etc.), features used in VFR navigation (town names, POIs, etc.) and hard-to-see hazards (e.g., antenna towers, wires, power lines, etc.). The application was used in a user study conducted with 19 pilots in a flight simulator setup. The study was built to be a with-subject design and was tailored to the hypotheses. Three main tasks allowed to get detailed results on the difference between solving navigational challenges with and without an AR tool as an aid. Qualitative and quantitative measures were taken and analyzed. A short post-study interview aimed to gather opinions on the idea of using AR technology in GA cockpits.

The mental process of conventional map reading involves the search for features on the map and cross-referencing them in the real world. Especially in regions with less dominant terrestrial characteristics, the identification of a position is challenging and can be misleading. The study has shown that the AR tool was able to benefit this process of regaining location awareness in case of disorientation inflight. Projecting information about terrestrial features (e.g., the names of towns), reduces the workload for cross-referencing (if even needed) on a map and therefore improves the situational awareness of the pilot. It was found that such a tool is especially helpful during cruise flight in unfamiliar areas.

Another novelty of this thesis is the 3D visualization of airspace structures in AR. Additionally, the application is aware of what airspace structure the airplane is currently in and what airspace is 5 nm mile ahead. This information is presented to the user in text form within the application, allowing them to effortlessly identify what airspace structure they are in, hence increasing situational awareness. This was proven throughout the user study by letting the participants state the airspace section in the simulation and comparing the results of both conditions (with and without AR).

A third task of the study assessed the advantages of AR in an approach scenario, similar to Katins (2023a). Although the results were not favoring the with AR condition as clearly as in the study by Katins, the analysis showed indications on positive effects of augmented information during an approach. The dampened effect is believed to be due to the development state of the application, but also the physics of the flight simulator setup used in this study. The stated factors led to a decrease in trust in the quality of the information presented. When comparing the recoded flight paths, it can be said that the AR tool especially helps flying approaches more accurately in areas with less terrestrial features. During the post-study interview, this tool was found to be most useful for approaches into unfamiliar airports. Looking at the results of a self-rated situational awareness scale, the scores favor the without AR condition. The task load was rated with no significant difference between the conditions. Here, the application has to be developed further and tested with more participants to make a profound general statement about the effect of AR on situational awareness in an approach scenario. Additionally, more thoughts have to be put into the visualization of the circuits.

To summarize, this work picks up on the current state of research for AR technology in the GA sector by studying the effect of AR on the situational awareness of pilots. It does so by presenting novel, world-referenced visualizations of flight-relevant information for different flight phases. The results were comparable to those from the related work. Although the AR aid was proven to have a positive effect on situational awareness, there are some indications that new challenges arise by using this new technology as a navigation aid. For example, a concern raised by the participants is the potential of distraction from real-world information by the projected information. This can cause negative effects on the situational awareness.

The majority of the participants were excited to test this new to them technology and stated that such a tool has huge potential as a next step in the evolution from moving maps. Nevertheless, it was mentioned that pilots could be tempted to rely on this tool so much that they unlearn to navigate without digital aids. This could lead to potentially dangerous situations in case of malfunctions of the electronic device.

Finally, it has to be said that the results have to be interpreted with caution, as statistical significance for the majority of the results was not reached with a group of 19 pilots. Adding to that, in the authors opinion, the hardware (smart glasses/AR devices) has to evolve in order to raise the usability of such a tool to a level where it is widely accepted by the public.

As suggested by Katins (2023b), this work included research on interaction with AR applications for the GA sector. However, following the results and feedback of the users, the research has to be extended in future work. As suggested in the previous chapter, evaluating the requirements of a touch-pad interaction for an AR tool in the GA cockpit turns out to be an interesting topic to study further. Maybe, compare it with other modes of interaction, such as mouse interaction or gaze interaction.

Furthermore, expanding the research on the distraction and occlusion caused by AR content in a GA cockpit is necessary to better understand its effects on the situational awareness. Hereby, a study on optimal adaptability of the projected information in different phases of the flight could stand in focus. Putting more thoughts into the optimal visualization of flight relevant information in a cockpit environment is another topic to look into in future work. As the digital content is projected on transparent glasses, the effects of various environmental factors such as sunlight, vibrations, or g-forces have to be tested in a real world aircraft. This is the only way to make sure the projections are usable in a real cockpit environment.

Throughout the user study of this work, no significant weather was programmed into the scenarios. Future studies could involve assessing the use of AR in adverse weather conditions. The author believes that further adaptation of the projected content to the surrounding weather is needed to support the situational awareness of a pilot most effectively.

Last but not least, implementing the functionalities and integrating the information suggested by participants during the post-study interview in an AR application will help the still young field of research.

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Appendix A: Data Sources

Information	Description	Data Publisher
Traffic	ADS-B Live Data	tbd
Airports	Information about runways, elevation…, Available Fuel (with prize)	FOCA
Obstacles	Cables, Power lines, Towers, Buildings	FOCA
POIs	Castles, AKWs (with altitude) passes	FOCA
VOR / DME		FOCA
Airspace structures	TMA, CTR, danger zone, restricted zones	aviation.kernberatung.ch
Mountain Peaks	(with altitude)	tbd
Towns / Build-up areas		swisstopo
Railroads		tbd
Roads	highways	tbd
Waterbodies	rivers, lakes	tbd
Flight Plan	Arrow to next waypoint	tbd
Obstacle close to airport		FOCA
Landschaftsruhezonen		tbd
Recommended VFR Routes	GAFOR routes, pass routes	tbd
Paradropping activities	Is currently paradropping is possible at an airport?	tbd
Aerobatic / Glider activities		tbd
Entry Sectors / Routes		tbd
Circuits	Circuit according VAC chart	FOCA
DABS information		tbd
Advisory Points in airport proximity	W, E, …	FOCA

Appendix B: Pre-Study Questionnaire

Basic Demographic information

1. **Age:** __________ years

2. **Gender:**

   ☐ Female ☐ Male ☒ Non-binary

3. **Do you feel fit to participate in this study?**

   ☐ Yes ☐ No

4. **Where did you hear about this study?**

   ☐ Flyer ☐ ETH Contact ☐ Other__________________________

5. **Have you ever used any type of Augmented Reality (AR), Mixed Reality (MR), or Virtual Reality (VR) devices?**
   ☐ Yes ☐ No

6. **If you answered “Yes” in question 4, have you ever used any type of AR, MR or VR devices in aviation, e.g. during your pilot training, in a simulator, or in flight?**
   ☐ Yes ☐ No

Aviation experience

7. **Approximate number of flight hours you have logged:** _______________

8. **Flight certificate(s) you hold:**

   ☐ PPL ☐ CPL or higher ☐ Pilot in training ☐ Other___________

9. **Type of the aircraft that you regularly fly:** ______________________

10. **During VFR flight, what main navigational aid do you primarily use?**
    ☐ Paper map ☐ Digital map on mobil device ☐ Digital map on instrument panel ☐ Other___________

11. **If you use a secondary navigational aid for VFR flight, which one?**
    ☐ Paper map ☐ Digital map on mobil device ☐ Digital map on instrument panel ☐ Other __________ ☐ No secondary navigation aid

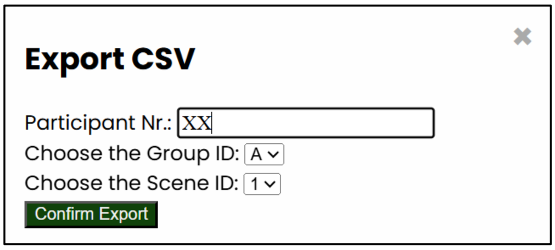
Appendix C: User Study Task Description

Task Description Sheet

MSc Thesis: An In-Flight Extended Reality Tool for General Aviation Situation Awareness
Author: Thierry Weber

TASK 1 (Orientation)

For the first task a scene will be loaded in the flight simulator set up. The flight simulator will remain static. Your task is to orient yourself and **set a marker on the web map (on tablet)** where you suspect your position in the flight simulator is. It is possible to relocate the marker, if needed. For this, either just tap at the new location to set the marker and accept the relocation in the pop-up or delete the old marker and set a new one. As soon as you are satisfied with your choice, press “Export csv”. Enter your participant ID, Group ID and Scene Number (first Scene = 1, second scene = 2).



You will do this with the AR tool as an aid and without. Scenes will be switched in between. The study conductor will let you know, if you start with or without the AR tool.

TASK 2 (Airspaces)

The second task is about airspace structures. Again, a scene will be loaded in the flight simulator set up. The flight simulator will remain static. Your task is to determine where you are and in what airspace structure your plane is currently in (e.g., LSZH TMA-1, LSME CTR, etc.). If not In a controlled airspace (e.g. Class G, Class E…), write down what airspace class you are in. Next, find out what airspace is 5NM straight ahead of your position. Write it down on the answer sheet.

You will do this with the AR tool as an aid and without. Scenes will be switched in between. The study conductor will let you know, if you start with or without the AR tool.

TASK 3 (Approach)

For the third task you will be asked to fly two approaches in a Cessna C172. Again, one approach will be flown with the AR tool as an aid and one without.

You can disregard the following aspects of flying for this task:

- Radio telephony
- Following exact checklist

However, please study the VAC of each airport before flying the approach. The VAC charts will be available on a separate sheets. Try to fly the approach as precise as possible according to the traffic pattern. More information on the approach route and plane will be handed to you on a separate sheet for each approach (see end of task description). The simulation ends once you have stopped on the runway. Fill out the SART[1] and the NASA-TLX[2] questionnaire after each approach.

Figure 2 shows the flight controls available in the simulator.

Ask the study conductor if you still have any questions on how to manipulate the flight simulator on the route to be flown.

Free Gameplay

Finally you will now have the opportunity to try out the AR application in a free gameplay scenario. The aircraft will be loaded into the Buochs scene. Feel free to try out the functionalities of the application on ground and/or while flying. After the gameplay you will be asked a few questions about the user experience in a short questionnaire (UEQ and SUS questionnaire on answer sheet) and in a short interview.

[1] Source SART : TAYLOR, R.M. (1995) Experiential Measures: Performance-Based Self Ratings of Situational Awareness Experimental Analysis and Measurement of Situation Awareness, Edited by D.J. Garland and M.R. Endsley. Embry-Riddle Aeronautical University Press, Daytona Beach, Florida, USA

[2] Source NASA-TLX : https://humansystems.arc.nasa.gov/groups/TLX/

TASK 3 (APPROACH) GRENCHEN

Aircraft Type: C172

Final Approach Speed: 65 KIAS

Flaps Operation Speed: 0 - 10°: 110 KIAS 10 - 30°: 85 KIAS

Flaps when within white arc

Route: E -> E1 -> Inner RH Downwind RWY06

Flaps extension: Flaps 1-> on Downwind

Flaps 2-> on Base

Flaps 3-> on Final

TASK 3 (APPROACH) BUOCHS

Aircraft Type: C172

Final Approach Speed: 65 KIAS

Flaps Operation Speed: 0 - 10°: 110 KIAS 10 - 30°: 85 KIAS

Route: Horw -> RH Downwind RWY 24

Flaps extension: Flaps 1-> on Downwind

Flaps 2-> on Base

Flaps 3-> on Final

Appendix D: Post-Study Interview Questions

1. In what in-flight situation do you think additional information projected into the real world is most beneficial regarding situational awareness? Are there situations when it clutters the field of view too much?

2. What benefits do you see in such an augmented reality application?

3. What disadvantages do you see in such an augmented reality application?

4. Is there anything specific you wished the app had in terms of features or functionalities?

5. Do you have any additional comments you'd like to share about your experience using the augmented reality situational awareness aid application?

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

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I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

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