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Enhancing Situational Awareness for Rotorcraft Pilots Using Virtual and Augmented Reality

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ENHANCING SITUATIONAL AWARENESS FOR ROTORCRAFT PILOTS USING VIRTUAL AND AUGMENTED REALITY

by

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A Thesis

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Dedication

This thesis is dedicated to my parents Shkelzen and Anila, who have supported me in all ways possible throughout my life and academic journey.

Acknowledgments

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Abstract

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Rotorcraft pilots often face the challenge of processing a multitude of data, integrating it with prior experience and making informed decisions in complex, rapidly changing multisensory environments. Virtual Reality (VR), and more recently Augmented Reality (AR) technologies have been applied for providing users with immersive, interactive and navigable experiences. The research work described in this thesis demonstrates that VR/AR are particularly effective in providing real-time information without detracting from the pilot's mission in both civilian and military engagements. The immersion of the pilot inside of the VR model provides enhanced realism. Interaction with the VR environment allows pilots to practice appropriately responding to simulated threats. Navigation allows the VR environment to change with varying parameters.

In this thesis, VR/AR environments are applied for the design and development of a head-up display (HUD) for helicopter pilots. The usability of the HUD that is developed as a part of this thesis is assessed using established frameworks for human systems engineering by incorporating best practices for user-centered design. The research work described in this thesis will demonstrate that VR/AR environments can provide flexible, ergonomic, and user-focused interfaces for real-time operations in complex, multisensory environments.

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Chapter 1

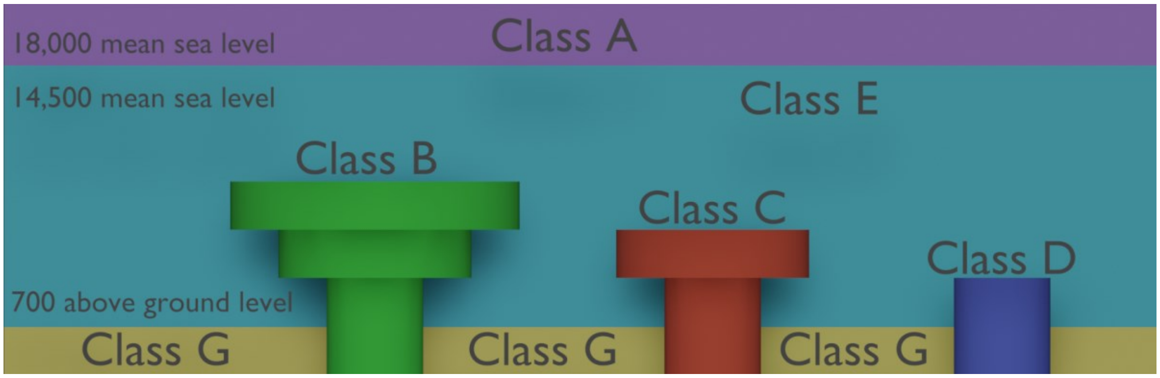
Introduction

Wilbur and Orville Wright demonstrated the first successful flight of heavier-than-air powered aircraft in Kitty Hawk, North Carolina on December 17, 1903. Well over a century since, the national airspace system (NAS) of the United States has evolved to become one of the most complex in the world. The NAS is managed by the Federal Aviation Administration (FAA) and is a network of both controlled and uncontrolled airspace, both domestic and oceanic. It also includes air navigation facilities, equipment and services; airports and landing areas; aeronautical charts, information and services; rules and regulations; procedures and technical information; and manpower and material. Every day, the FAA provides air traffic service to more than 45,000 flights and 2.9 million airline passengers traveling across more than 29 million square miles that include a large portion of the world's oceans. Until 2020, the United States was the location of the world's busiest airport with Atlanta's Hartsfield-Jackson International airport where 44 takeoffs and landings take place every hour; 1,070 every day; and served 110 million passengers in 2019 [1]. It has since been superseded by Guangzhou Baiyun International Airport.

The NAS defines six different classes of airspace, each with their own detailed rules and regulations. The different airspace classes and their areas of effect can be seen in Figure 1.

Figure 1

Airspace Classes

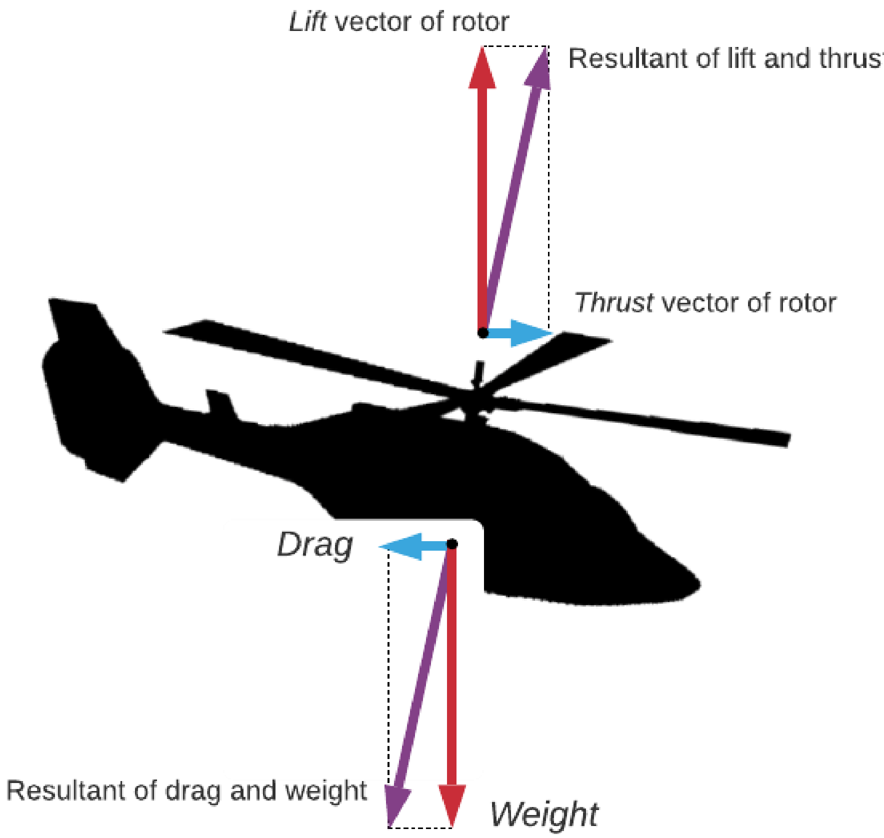


Regardless of the type of aircraft, whether it be a drone, rotorcraft, or fixed wing, all aircraft must adhere to these regulations that prescribe protocol. Class B airspace is reserved for the nation's largest airports. Aircraft in this area must establish two-way radio communication with air traffic control and confirm clearance before being allowed to enter. Certain requirements such as a transponder are also a necessity for aircraft to enter this airspace class. This allows air traffic control to maintain traffic separation standards implemented by the FAA. In all cases, safety and pilot training is of maximum priority [2].

Due to mechanical differences, piloting a helicopter is a completely different experience than piloting a plane. Due to its rotor blades, a helicopter can generate lift without moving forward. This allows the helicopter to hover in one area or take off and land vertically without the use of a runway. As a result, helicopters can be used in congested or isolated areas that fixed-wing aircraft are not able to access [3]. However, helicopter pilots must also be able to carefully manage the different forces presented in Figure 2 to maintain a hover and navigate congested areas.

Figure 2

Four Forces Acting on a Helicopter in Forward Flight



A significant challenge arises when a helicopter pilot is required to grasp a multitude of flight and environmental data, integrate it with prior experience, and make informed decisions during rapidly changing circumstances. Furthermore, it is important that display gauges presenting flight and environmental information do not detract from the pilot's mission, whether it is safely landing at a helipad or engaging enemy forces. It has been shown that Virtual Reality (VR) technologies can be leveraged to provide users with immersive, interactive, and navigable experiences [4]. A more recent evolution of VR is

Augmented Reality (AR), in which the user continues to remain immersed in the "real" world, while AR adds digital information to the world that can be interacted with in the same manner as the physical world [5]. The potential benefits of virtual reality are numerous, and benefits continue to surface as the technology progresses. One such benefit is that virtual HUDs can be rapidly prototyped and updated throughout its entire life cycle while traditional gauges are much harder to update due to the complex installation that is necessary. Virtual HUDs can also present information to the user without necessitating that they look away from the outside environment.

1.1 Motivation

Rotorcraft safety is integral to the safety, security, capacity, and efficiency of the U.S. National Airspace System. The U.S. Federal Aviation System supports active programs in rotorcraft safety research and testing including modeling, simulation, data mining and analysis, and flight test activities. The motivation for research work presented in this thesis is the development of an augmented reality head-up display for helicopter pilots operating in complex and rapidly changing environments. The display presents flight and environmental data to the pilot that aims to be prioritized and organized in a user-friendly interface. Users within the virtual environment will have the added capability of viewing aerial systems and the surrounding visual environment from multiple observer/operator perspectives to create an end-to-end virtual/human-in-the-loop environment. It is anticipated that enhanced simulation environments such as these will become very important to the FAA's overall capability to effectively study and support the development of safety enhancements for rotorcraft.

1.2 Objectives

The specific aims of the research work described in this thesis are to:

1. Design and develop an augmented reality heads up display for helicopter pilots that can integrate flight and terrain information;
2. Prioritize, organize and present the information to the pilot to be easily understood, without distraction;
3. Test the AR system on simulated flight platforms;
4. Implement a framework for the evaluation of the AR display

1.3 Scope and Organization of the Thesis

This thesis is organized as follows. Chapter 1 provides an introduction to the US national airspace system, the complexity of rotorcraft piloting, and the need for supporting helicopter pilots with augmented reality displays containing operational and environmental information. Chapter 2 presents a literature survey of head mounted displays, and the application of virtual/augmented/mixed reality for enhancing operational safety in aircraft and other vehicles. Chapter 3 describes a flow chart for the development of the AR display and a methodology for the evaluation of the effectiveness of its design. Chapter 4 presents results demonstrating the success of the techniques developed in this thesis. Chapter 5 offers conclusions and recommendations for future work in integrating HUDs with artificial intelligence (AI) algorithms.

Chapter 2

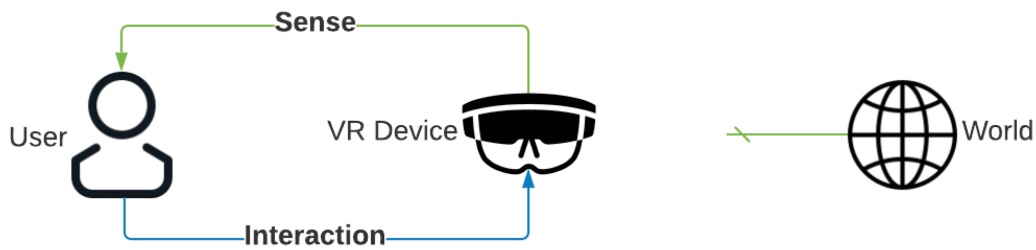
Background

2.1 Virtual Reality

VR and by extension, AR, are emerging technologies whose benefits are still being researched. Virtual Reality involves the use of advanced technologies and multimedia peripherals to produce a simulated or virtual environment that users perceive to be comparable to real world events [6]. All applications of virtual reality strive for immersion, although most fall short. This is due to the difficulty and cost of implementing immersive configurations, with some setups costing upwards of hundreds of thousands of dollars [7]. Total immersion means implementing stimuli for vision, hearing, touch, smell, taste, haptic feedback, and lesser discussed senses such as proprioception. Fortunately, it has been estimated that sight and hearing together capture 90% of a human's attention [8], so relatively high immersion is not very prohibitively expensive to achieve with just these senses. As a result, many developers resort to only simulating the visual and aural senses to save time and money. Figure 3 represents a simple representation of the total real-world replacement that immersive VR accomplishes.

Figure 3

Overview of Sensory Flow in Virtual Reality



2.1.1 Virtual Reality Hardware

Recent advancements in VR technologies have given rise to several new modes of VR. One of these is the Cave Automatic Virtual Environment (CAVE) system, which involves projecting virtual images onto three or more (up to six) walls of a room sized cube [9]. One of its main benefits is potentially increasing the field of view of the user to a full 4π steradians, vastly superior to the 100-140 degree viewing angle available for head mounted displays and the 45 degree viewing angle of a monitor. In Figure 4, the CAVE system at Rowan University can be seen, which implements four sides of the maximum six.

Figure 4

Rowan University's 4-sided CAVE Environment at the South Jersey Technology Park

Head mounted displays (HMDs) are a convenient and portable way to implement Virtual Reality. Despite having a restricted field of view, HMDs are often able to present a higher level of visual acuity due to the small distance between the user and the screen, as opposed to a CAVE. The newest VR HMDs, such as the Vive Pro 2, present a resolution of 2448x2448 pixels per eye, and a 120-degree horizontal viewing angle [10], covering a little over half of the total 210-degree forward facing field of view available for a human [11]. This can be compared to the VFX1 HMD released in 1995, which had a resolution of 263x230 per eye, and a 35.5-degree horizontal viewing angle [12]. Other VR systems focus on complementing areas that HMDs cannot fulfill, such as simulating movement in VR without the use of a controller. These machines usually can cost anywhere from thousands to tens of thousands of dollars and are extremely bulky and unwieldy. Many of these setups include a platform for walking or running, as well as a torso harness to keep the user upright as they are immersed in VR.

2.1.2 Virtual Reality Applications

VR has been often associated with the entertainment industry but possesses incredible potential to improve lives and for training applications. VR has seen widespread use in the field of rehabilitation [13]. Several attributes unique to VR also make it suitable for rehabilitation. While a patient is in a VR simulation, the therapist can monitor patient behavior and vital signs while maintaining strict control over stimulus delivery [14]. VR applications tailored to rehabilitation may not aim for high immersion, but their interactive and navigable aspects provide tremendous benefits to both therapist and patient. For example, a therapist can administer repeated trials, and can adjust difficulty as needed while decreasing therapist support and feedback. The ability to rapidly change the VR environment is also helpful when assessing and optimizing patient behavior and recovery. Indeed, VR has already proven to be helpful in areas such as venipuncture [15], treatment of phobias [16], and reduction of pain during burn care [17].

VR has also been used extensively for training, especially in cases where failure in the real-world applications has dire consequences such as aviation. Simulators allow pilots to practice dealing with dangerous or difficult situations without exposure to the risk that would normally accompany such a task [18]. Simulators allow pilots to familiarize themselves with a variety of aviation skills, such as flying approaches into unfamiliar airports, or learning how the onboard avionics function for a new aircraft. Figure 5 features a flight simulator located in the Cockpit Simulation Facility (CSF) at the William J. Hughes Technical Center that prospective pilots use to practice.

Figure 5

View From Inside an S-76 Helicopter Flight Simulator

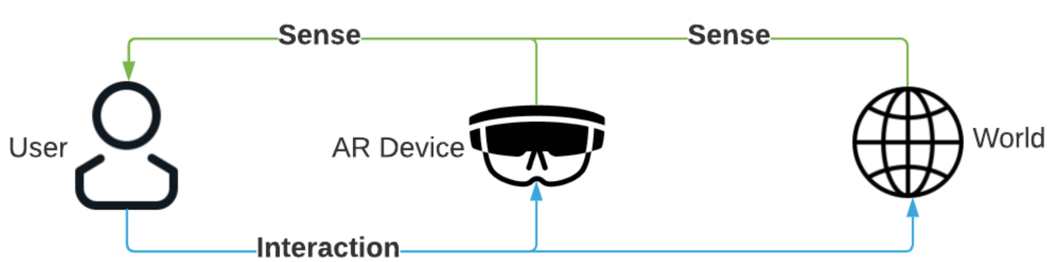
In fact, virtual reality has become so realistic that pilots trained on a simulator with Civil Aviation Authority (CAA) Phase 3 approval can immediately co-pilot an aircraft after their simulation training [19]. Another situation that takes advantage of VR's ability to allows users to experience environments where failure is normally very expensive or unacceptable is an astronaut training program dubbed RAVEN. The RAVEN system allows a trainee to be immersed in an interactive virtual world to practice replacing the Wide Field Planetary Camera onboard the Hubble Space Telescope [20]. Training in the medical field is also burgeoning as VR is being used to train prospective surgeons in operations of the leg [21], eye [22], and using endo-surgery [23].

2.2 Augmented Reality

Augmented Reality (AR) is defined as a system in which virtual objects are added to the real-world in real-time during the user's experience [24]. In other words, AR is a technology that enriches, rather than replaces the real world [25]. Figure 6 presents a simple counterpoint to Figure 3 of sensory flow from the real world and AR devices to the user.

Figure 6

Overview of Sensory Flow in Augmented Reality



AR acts as a blend between the user's environment and virtual objects. As this technology has continued to improve it has led to the rise of new applications and solutions. HUDs are an example of a hardware implementation of AR, but is not the only possible implementation of AR. Fixed panel mounted displays are a common hardware implementation of AR that is less intrusive and avoids the head-weight of an HMD. AR displays found in cars can be considered an implementation of a panel mounted display. AR in cars has been researched as a tool to aid in navigation and obstacle avoidance [26], although it hasn't yet seen widespread adoption in commercial vehicles.

Most AR applications employ the use of an HMD, like VR. These HMDs are similar with one crucial difference. AR HMDs typically have a clear visor similar to a pair of glasses upon which an image is projected. VR HMDs entirely replace the user's view with an image to immerse them inside of virtual reality. While most HMDs fit neatly into one category or another, some HMDs such as the Vive can do both by replacing the user's vision with VR or providing AR by projecting the user's surroundings inside the headset using cameras located in front of the headset.

2.2.1 Augmented Reality Applications

Like VR, AR has important applications in the medical field. Instead of these applications being used only for training, AR applications can aid trained surgeons in performing surgery. For example, AR allows for the overlay of a dataset obtained through an MRI scan to be overlaid onto the surgeon's vision. This would allow the surgeon to "see" inside the patient without the need to perform any incisions [27]. AR can also be used for training. A surgeon in training can employ an AR device that would identify important organs and structures or remind the surgeon of important surgical steps as they perform the surgery [28].

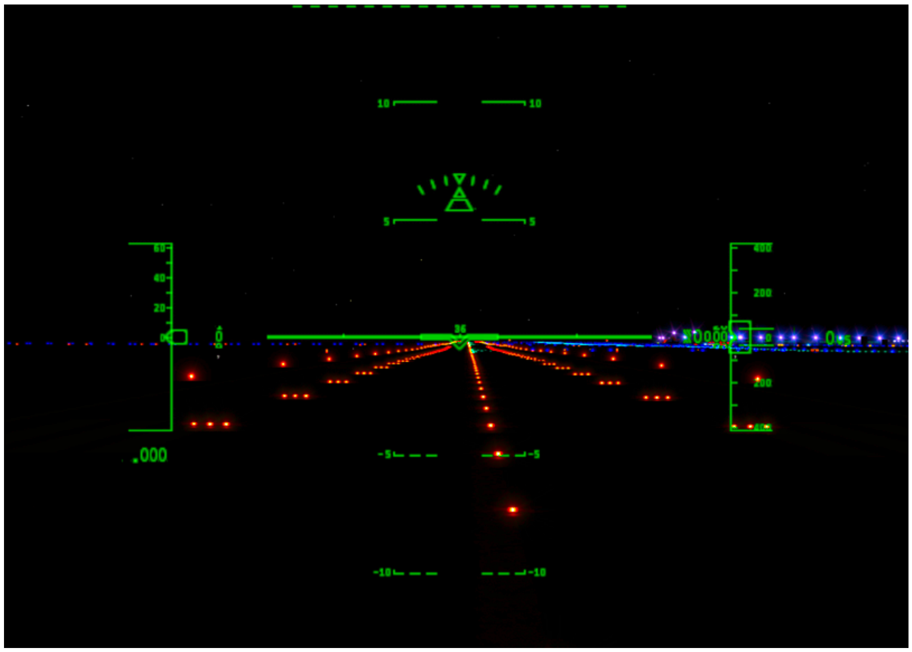
Repairs of complex machinery can also be made much easier using AR. If diagrams were available not only as clunky 2D images on a page but 3D drawings superimposed onto the machinery, repairs could be made more easily and effectively. Boeing is leveraging these capabilities to assist technicians install electrical wiring [29].

2.3 Head-Up Displays

As a form of AR, one might assume Head-Up-Displays (HUDs) are a new technology, but this is far from the truth. In fact, HUDs have been in use for decades in the aerospace industry [30]. A HUD projects basic flight and navigation information into the user's field of view as virtual images that may be similar to standard head-down displays (HDDs). An example of such a virtual image set can be seen in Figure 7.

Figure 7

HUD Symbology Enabled in X-Plane 11



HUD images are projected at a focal distance such that visual accommodation time, or the time needed to switch focus from flight instruments to the outside environment, between HUD information and the outside environment is minimized [31].

The projection of HUD images contribute to the primary purpose of a HUD, to reduce the time needed for the user to obtain information from the display, while at the same time maintaining their attention on the outside world. It has been proven that HUDs confer significant time-saving advantages over HDDs [32]. A typical example of an HDD can be seen in Figure 8. Notice how the pilot must glance away from the outside scene to collect information from flight indicators.

Figure 8

Head Down Displays Inside of a S-76 Helicopter Cockpit Simulator

Most of this time-saving advantage of HUDs can be attributed to the fact the virtual images projected onto the HUD do not require that the pilot look away from the environment. In effect, this means that less visual accommodation is required with HUDs than HDDs [31]. However, HUD accommodation is also a contentious point of HUD efficacy. One major goal of the HUD is to pull the user's focus to optical infinity to minimize accommodation time when switching focus to the outside environment. This contrasts with HDD displays where the user has no choice but to make a greater focus leap when switching their focus from the nearby HDD to the outside environment which requires a focal depth that is much further away. However, when the visual field lacks detail or texture, or if the visual symbology on the HUD lacks sufficient clarity, the user's focal depth can be brought much closer than infinity. This has been attributed to the collimation effort itself [33] but other experts suggest that other factors unrelated to collimation are the major contributors to this misaccommodation. These factors include small image size, poor quality, the projector of HUD symbology, vertical and head gaze angle, or pupil size [30].

Aviation applications of HUDs have shown that HUDs have their own distinct disadvantages over HDDs as well. Between 1980 and 1985, the U.S. Air Force lost 73 airplanes equipped with HUDs owing to pilots that became disoriented [34]. In one study, 2 of 4 pilots were unable to perceive a runway obstacle during a simulation run while using a HUD [35]. A recurring reason in the literature for degraded performance for users using HUDs is “cognitive capture”. This occurs when information displayed in the user’s field of view draws attention away from the outside environment, such that obstacles may go entirely unseen [36]. Another consideration is that the proximity of virtual and real information might disrupt the process by which a user switches their focus to and from these sources. When using an HDD, there are strong cues to switch attention such as the act of looking up, changing convergence, and changing accommodation, but these cues are absent when using a HUD.

When factoring in user workload in aviation safety studies, reaction times were faster using HUDs only in situations with low workloads. When workload was increased, HUDs had longer reaction times than HDDs [37]. For first time users, a “novelty affect” might explain some of this as the user might spend time scanning visual elements of the HUD under low-workload conditions [38]. This might also be due to the simple reason that most pilots are trained with HDD imagery rather than HUDs and are unfamiliar with HUD elements which may lead to an increase in workload.

Some recent studies have suggested that the implementation of an enhanced visions system may help solve the issue of cognitive capture. One study included the using of conventional HUD symbology along with superimposed scene-relevant altitude cues such as buildings. This led to increased maintenance of altitude without the usual cost of flight path performance associated with HUDs [39]. Another concern with HUDs arises from too much information being presented on the display. This is known as "clutter" and can obscure the outside environment or overwhelm the user's information channels. In one study, 11 of 17 pilots turned off the HUD at critical phases of a mission because they claimed it interfered with their performance [40].

More recent studies have taken another look at the cognitive capture effect of HUDs. Pilots often are taught the process of "scanning", attending briefly to each information source sequentially in a set order. It has been suggested that this scanning technique can minimize the chance of distraction and attention capture during critical phases such as take-off and landing [41]. A meta-analysis gave evidence that HUDs are overall beneficial in for both tracking and detection. However, when looking at individual flight phases, the general HUD benefit for detection is reversed during landing [42]. It is clear that while HUDs present certain benefits, much work remains to be done to fully realize these benefits and mitigate their drawbacks.

Chapter 3

Approach

The specific aims of the research work described in this thesis are revisited below:

1. Design and development of an augmented reality head-up display for helicopter pilots that can integrate flight and terrain information;
2. Prioritization, organization and presentation of the information to the pilot to be easily understood, without distraction;
3. Testing of the HUD system on simulated flight platforms;
4. Implementation of an evaluation framework for human systems engineering by incorporating best practices for user-centered design.

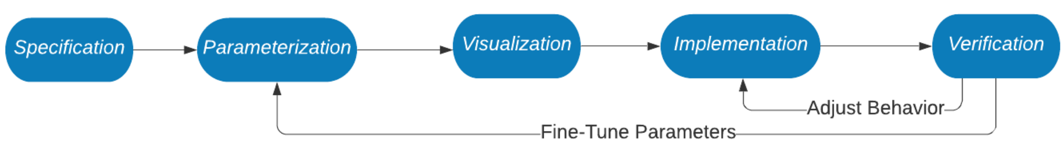
The workflow that is developed in this thesis to address objectives 1 – 3 is described in section 3.1. The contribution of this thesis is primarily in the development of a methodology for a design and development cycle leading to HUD implementation for rotorcraft pilots. The evaluation framework for determining the effectiveness of the approach is described in Section 3.2. A previously established human systems engineering framework known as "Interaction, Design and Engineering for Advanced Systems" (IDEAS) [43] is adapted for the specific purposes of the design and development process described in this thesis.

3.1 Methodology

The overall workflow for the development of the HUD can be divided into five stages, as shown in Figure 9. These stages are respectively: specification, parameterization, visualization, implementation, and verification. In the specification stage, the designer decides which data is to be displayed (what), the manner of display (how) and the location of the display (where). Parameterization allows the designer to decide units, ranges, and increments of each display indicator. The visualization stage identifies the specific, parameterized element that is observable by the user. In the implementation stage, the behavior of each indicator is realized in software and hardware platforms. Verification is a two-step process that involves both the designer and the end user, to ensure that the data visualized in the HMD is topical, timely, accurate and standardized.

Figure 9

High Level Overview of HUD Development Process



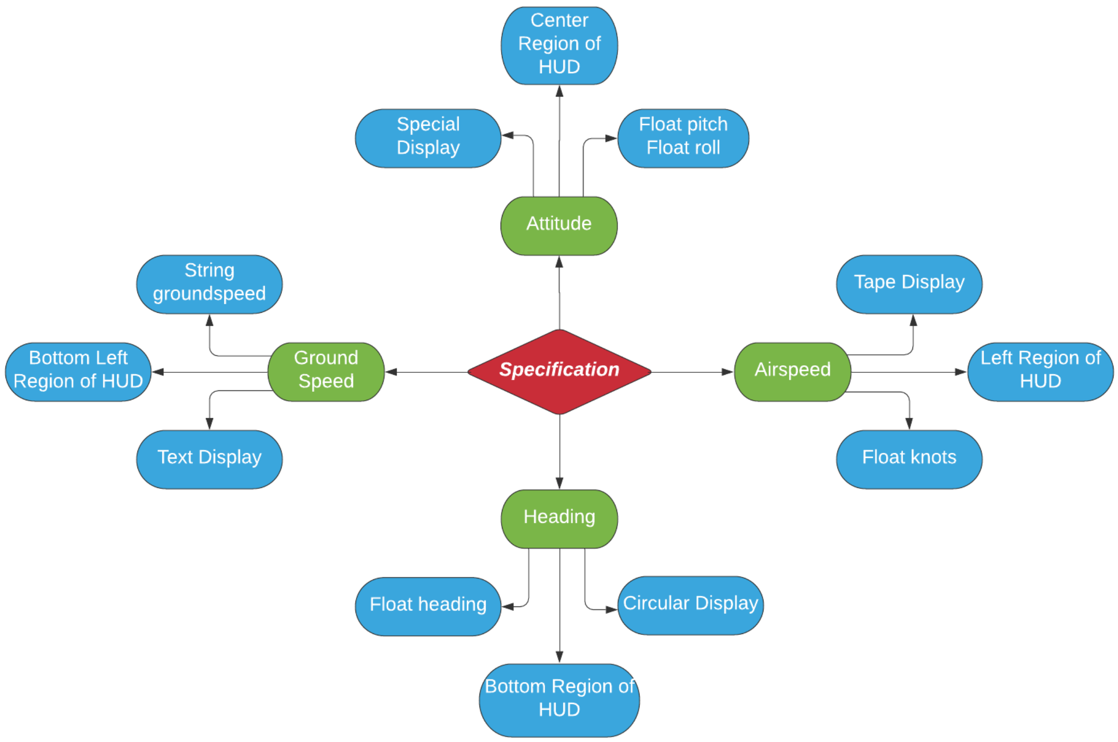
The HUD consists of individual components that operate as an immersive, interactive and navigable system. Many of these individual components work in similar ways, and a generic workflow can be applied to standardize their functionality to assist rapid development. There are two kinds of feedback between the stages for effective HUD development. Major feedback occurs between the parameterization and verification stages, when the overall behavior of an indicator must be changed, such as to achieve greater fidelity in data display or extend/disable some functionality altogether. Minor feedback occurs between the implementation and verification stages when behavior is incorrect or must be slightly adjusted to better accommodate the user. This kind of adjustment is usually faster to implement and more frequent.

3.1.1 Specification

The specification step of the HUD workflow is expanded in Figure 10. In this stage, high-level decisions are made about the appearance, location, and behavior of each indicator. Details of the display are decided in later stages. These decisions are made with the help of media from other modern HUDs, the client's specifications, as well as considerations made with respect to the capabilities of the implementation hardware. For example, airspeed is typically shown on the left side of a HUD as a tape display. This approach was mimicked for the airspeed indicator, but the details of its implementation are left to the individual developers, such as how the demarcations for the tape are displayed.

Figure 10

Specifications Step of Workflow with Examples



In the example specification shown in Figure 10, four elements are identified: attitude, airspeed, heading and groundspeed.

Several of the airspeed specifications are shown. The first is the visual style of display. In the case of airspeed, this style of display is a tape style display. This involves showing the airspeed on a tape that moves vertically on the HUD to convey an impression of slow or rapid change to the user. As a result, the airspeed tape will move vertically up or down according to incoming airspeed data. Another specification is the location where the airspeed is displayed. In this case the airspeed is displayed on the left region of the HUD due to convention and to ease the transition of pilots familiar with HUDs that follow this convention. Finally, the type of data that populates the airspeed is a float type, which is continuous and suitable for behavior that is smooth and able to frequently update the display.

In contrast, the heading indicator uses a circular display. A circular display is manipulated by its rotation rather than its position as a tape display would be. Its behavior is also dictated by this specification, as incoming heading data will rotate the heading indicator to reflect the aircraft's new heading. The location is usually decided by convention and placed at the bottom, although a magnetic, tape-type, heading indicator is often additionally placed at the top. Again, float type data is appropriate here for smooth operation and frequent updates.

The attitude indicator is unique in that its operation is controlled both by rotation and position. This allows it to convey both pitch and roll information to the user. The artificial horizon is almost always placed at the center of HUD, as it displays pitch and roll simultaneously, which are both critical to the pilot on a real-time basis. Float type data is used to control the artificial horizon, which again is suitable for displays that must be animated smoothly and updated frequently.

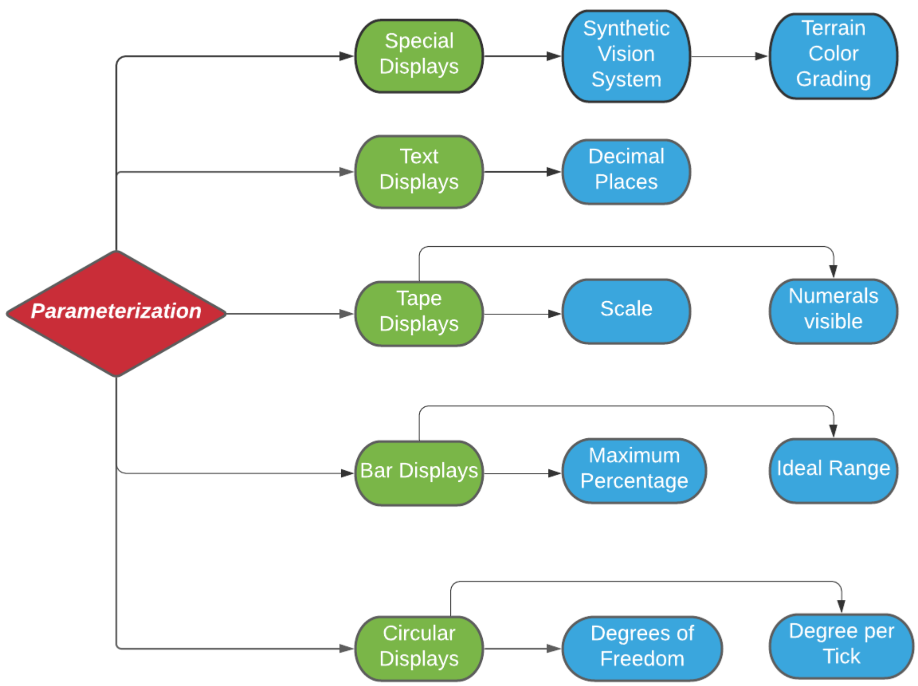
The ground speed indicator is simple to implement but important. It is specified to be a text display such that data can be directly used to populate this indicator. The ground speed indicator is located the bottom left of the HUD, but its placement can vary depending on preference and importance to the end-user. String type data that resolves to text is used to populate this indicator.

3.1.2 Parameterization

In the parameterization example shown in Figure 11, various types of displays are shown, and the specific parameters associated with each are identified. For example, important parameters for tape displays are scale and the number of numerals visible at once. For the synthetic vision system, the color coding of low altitude areas, medium altitude areas, and high altitude areas as well as their classification thresholds are important perimeters.

Figure 11

Parameterization Step of Workflow with Examples



Parameterization choices were guided by technical documents, convention, as well as recommendations by users based on rotorcraft cockpits. As a result, regular testing of the

HUD was imperative in insuring that these parameterization choices were optimal for most users and maximized ease of use.

As mentioned, important parameters for tape displays are scale, and the numbers of numerals visible. The scale for altitude should be coarser than the scale for airspeed, since generally the altitude of an aircraft will vary much more than its airspeed. This is one example of a parameterization choice that was decided by convention. A decision guided by user feedback was to exclude negative values for the altitude, as the end-user felt it to be unnecessary. Another user-guided decision was to decrease the amount of numerals visible on the airspeed tape from nine to seven to decrease visual clutter on the HUD.

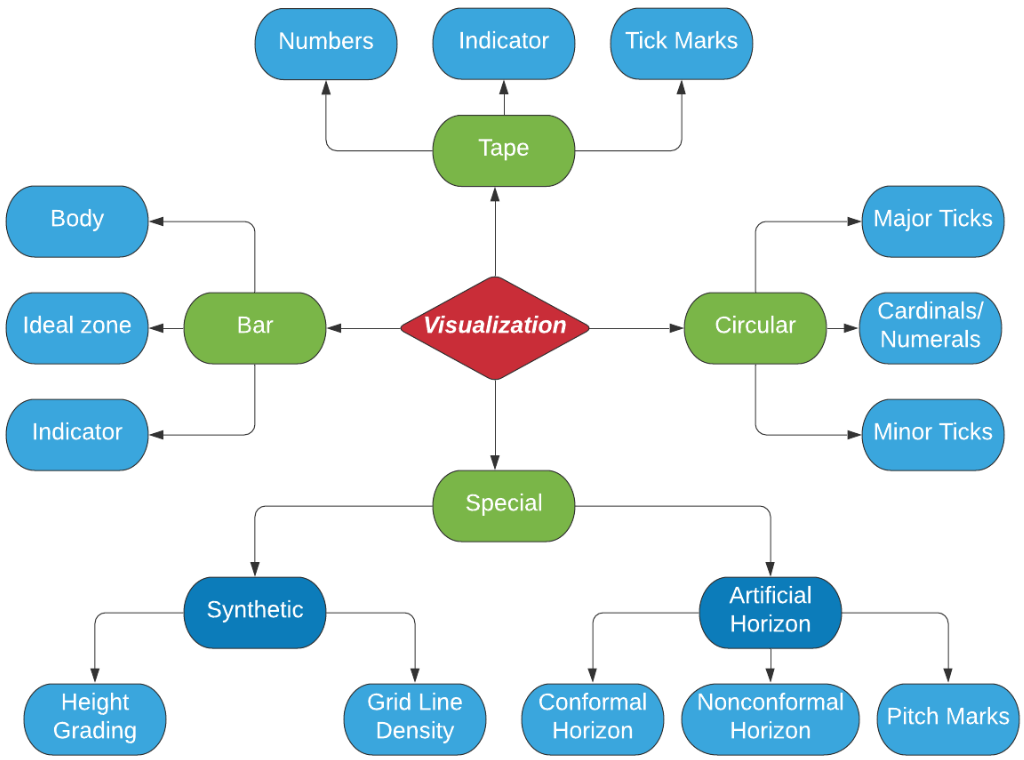
Parameterization choices made for the Synthetic Vision System (SVS) were considerably different than most other indicators. Because the SVS is designed to give the pilot local terrain information, parameterization choices such as the color coding used to color terrain as well as classification thresholds for high, medium, and low terrain must be made. Due to the relative novelty of SVS in HUDs, these parameterization decisions are mostly reliant on user feedback rather than convention.

3.1.3 Visualization

The visualization step is closely linked to the specification step in that it relies upon the specifications set earlier to determine how each indicator is displayed. In addition to this, an overall stylistic theme should be constant in all elements of the HUD. Many of the indicators in our HUD were designed to resemble existing HUD/HDD designs. This was done to make the transition from HDD displays to HUD as easy as possible for pilots.

Figure 12

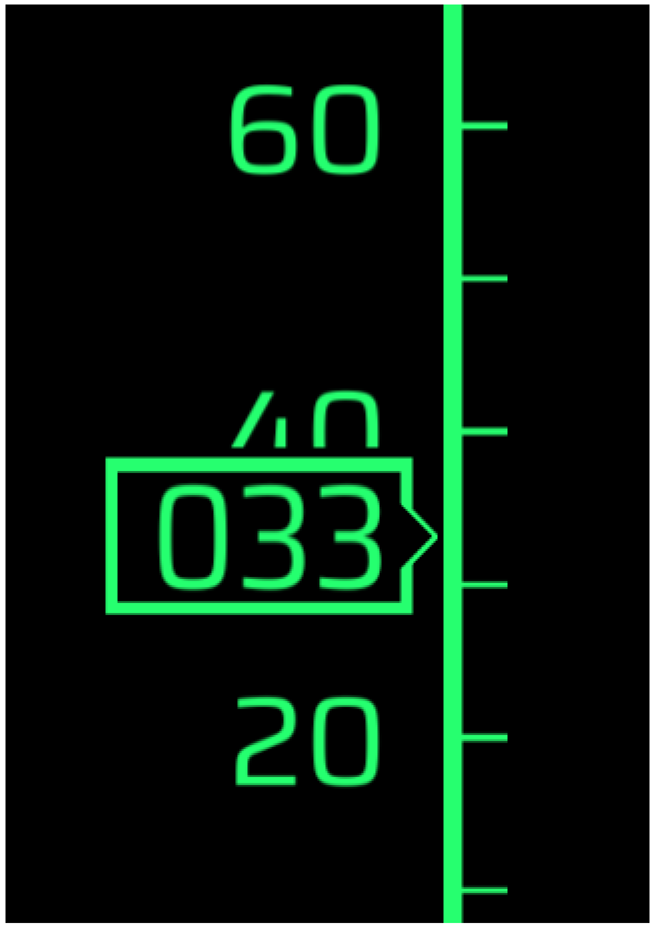
Visualization Step of Workflow with Examples



Various aspects of the visualization stage are shown in Figure 12. Tape displays consist of successive gradations (tick marks) with accompanying numbers. Gradations serve to provide visual markers for the user to estimate their progress between each numeral on the tape. Visual elements move vertically in the airspeed and altitude displays or horizontally in the magnetic heading display. Another display element of a tape indicator is a text box that remains stationary and displays the incoming data as a whole number. The airspeed indicator incorporates all these elements and can be seen in Figure 13.

Figure 13

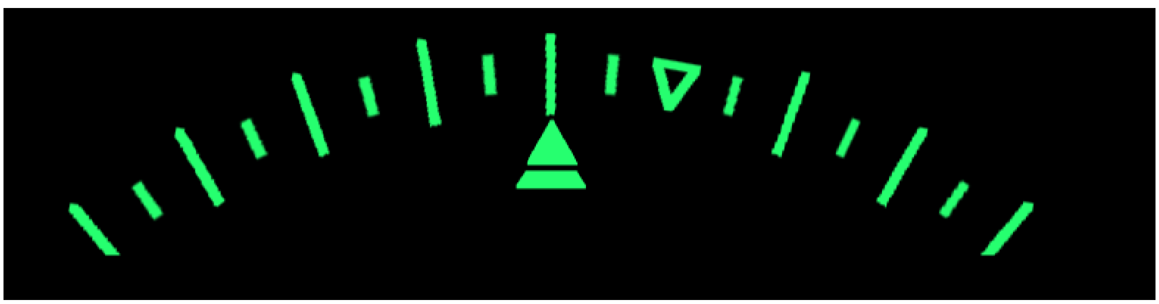
Airspeed Indicator Featuring Visual Elements of a Tape Display



Circular displays incorporate many of the same visual elements as tape displays. The visual elements include successive gradations and accompanying numerals but can vary more drastically than tape displays. An arrow is used to indicate the relevant information to the user. An example of this can be see below in Figure 14, which shows a roll indicator. The roll indicator is showing a ten-degree left bank on the aircraft, as marked by its angular displacement from the center mark. An important note here is that an alternate mode of operation often leaves the hollow marker stationary, while rotating the solid arrow. Both modes of operation can be seen in industry, and the final mode of operation is left to end-user preference or designer choice. Because most aircraft will not deviate more than about 30-degrees when making a turn, it is not necessary to display the full 360-degree of range for the bank indicator, so a mask is used to hide the lower three-fourths. This saves space on the HUD so that more space is left for other indicators.

Figure 14

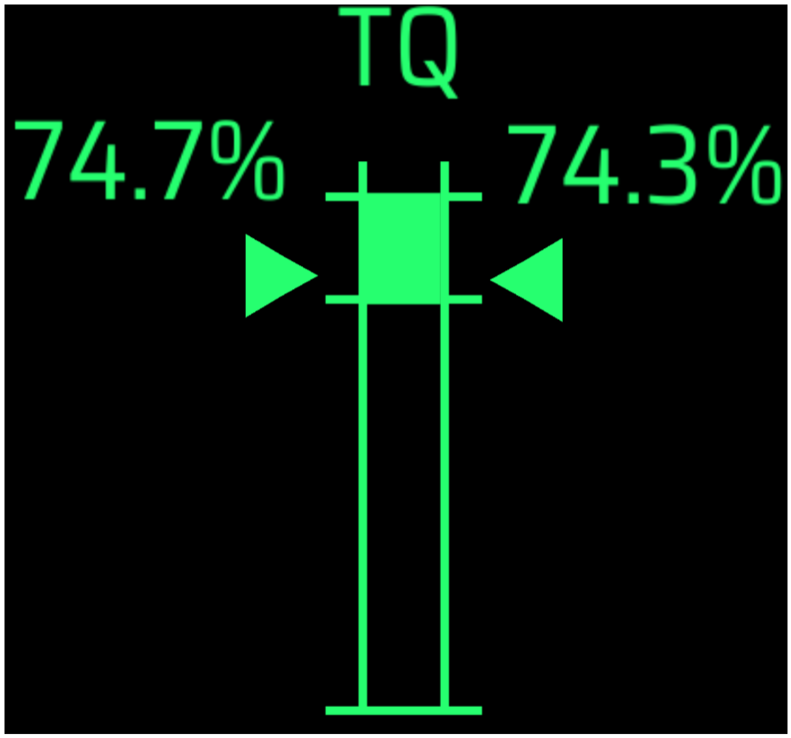
Roll Indicator Featuring Visual Elements of a Circular Display



Bar type indicators are some of the simplest and most self-contained. They incorporate a bar container, an arrow to indicate fill percentage, an ideal zone of operation, and a text display for the exact data figure. An example of this can be seen in Figure 15. The maximum percentage for these types of indicators can go above 100% for many avionics systems such as torque and rotations per minute (RPM). As such, special care must be taken such that data that sets the percentage above 100% does not move the arrow outside of the bar container.

Figure 15

Torque Indicator Featuring Visual Elements of a Bar Display



An example of a special type of display is the artificial horizon, which bears little similarity to any other component. The artificial horizon, displayed in Figure 16, shows pitch marks and a horizon line. The end tips of positive pitch marks are pointed down to indicate positive pitch while ends of negative pitch marks tips are pointed up. A central rotorcraft symbol remains stationary in the middle of the user's FOV while the pitch marks rotate and translate about the central point. This will ensure that the artificial horizon remains in the user's FOV and provides context about the orientation of the aircraft.

Figure 16

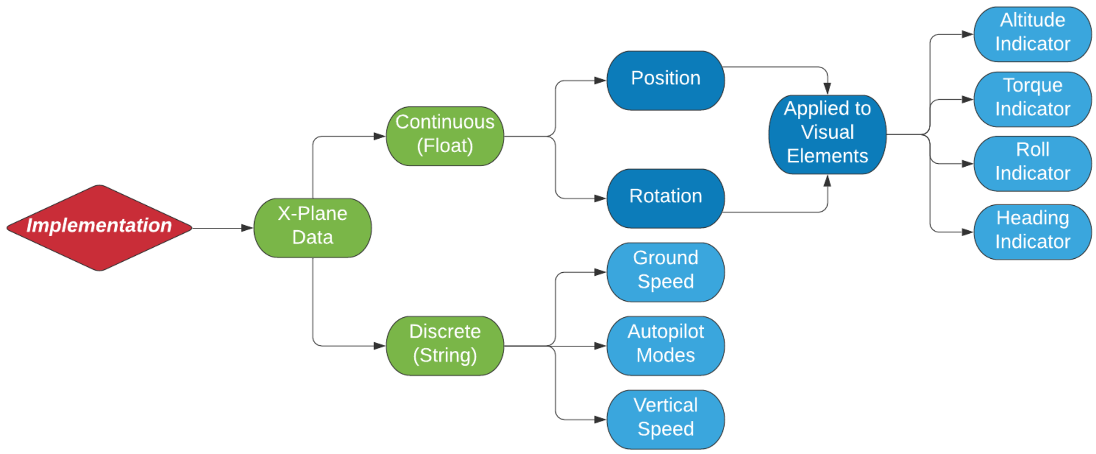
Artificial Horizon Indicating a 10-Degree Pitch and 5-Degree Roll

3.1.4 Implementation

The implementation step is the bridge between the hardware and software platforms that comprise the HUD. In this thesis, the X-Plane flight simulation platform is used to generate flight parameter data for the HUD. In Figure 17, two main indicator behaviors are described: discrete behavior and continuous behavior. Discrete behavior is simple and uses Boolean or String types to populate an indicator of the HUD.

Figure 17

Implementation Step of Workflow with Examples



An example of discrete behavior is the autopilot mode display of the HUD. Depending on the signal from X-Plane, a different string will occupy the field for the collective, roll, or pitch fields as can be seen in Figure 18. These values are discrete and typically limited, so that the number of possible values displayed is fixed.

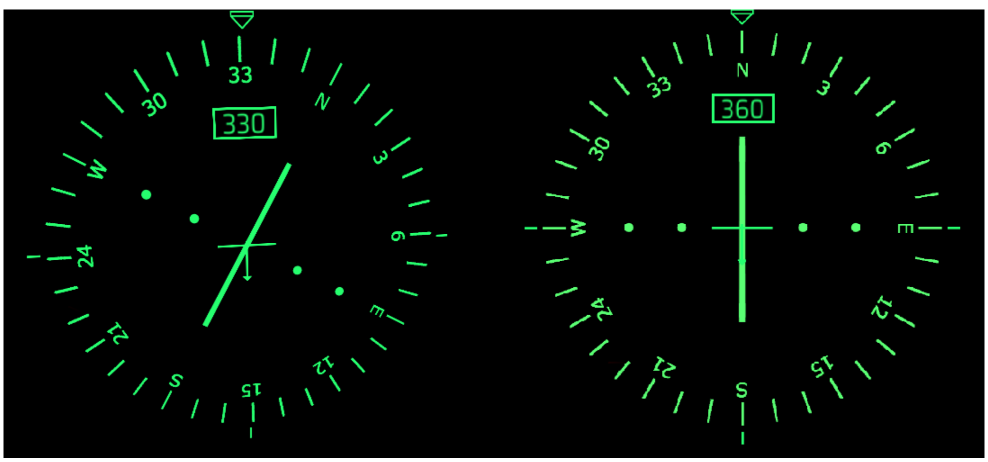
Figure 18

Collective, Roll, and Pitch Autopilot Fields with Example Values

In contrast, continuous values are usually represented by float types. These values are continuous and typically populate indicators such as airspeed, vertical speed, and heading. Because these values are continuous, they are often used to control the position, rotation, or scale of a visual element of the HUD. These values can also be used to populate text boxes, like discrete values. An example of continuous behavior is the heading indicator in Figure 19.

Figure 19

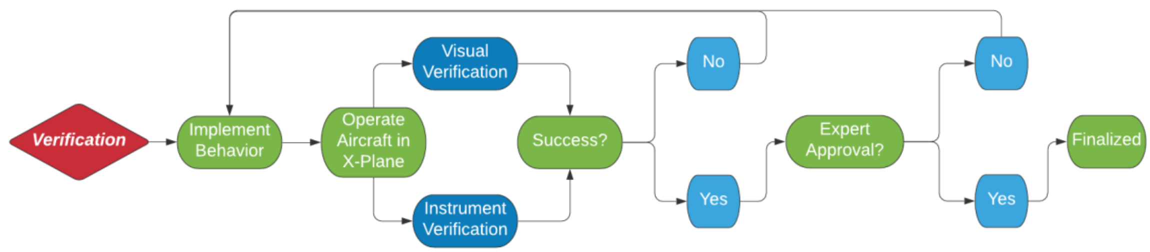
Heading Indicator With a 30-Degree Offset (left) Next to a 0-Degree Offset (right)



3.1.5 Verification

Figure 20

Verification Step of Workflow



As shown in Figure 20, the verification process takes place in two stages. In the first stage, an implemented indicator is tested for accuracy, timeliness, and reliability. In the second stage, the end user verifies that the data visualized in the HMD is necessary, sufficient, and standardized. In the first verification stage, a visual verification of the HUD is done by the designer as well as a dashboard verification which involves comparing the indicator to its dashboard counterpart in the flight simulator if one is available. This is because the indicator in the flight simulator can be expected to behave correctly with few exceptions. If verification fails after either sub-stage, the component is redesigned and reimplemented before it is once again verified.

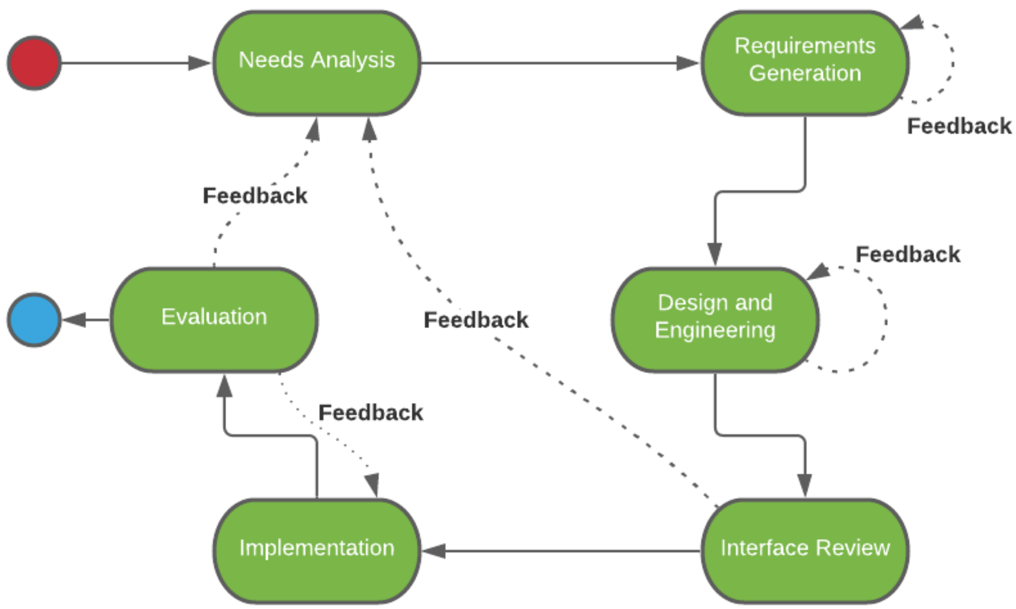
3.2 Interaction, Design and Engineering for Advanced Systems

The Interaction, Design and Engineering for Advanced Systems (IDEAS) methodology is a human systems engineering framework that was developed to incorporate user-centered design best practices into military advanced technology research and development [43]. It introduces a model for including human systems engineering in new technology development that has much in common with living lab framework. In this thesis, the IDEAS framework was employed to validate the design and development process of the HUD.

It has been argued that in system development, there is "a long and successful record concerning the use of training to compensate for poor design" [43]. One development goal for this thesis was to design a HUD that would be easy to use, intuitive, and require little training. To accomplish this, a framework was needed that would take the end-user and integrate them into the development process so that feedback could be elicited in regular intervals and incorporated into the development process. The IDEAS framework [44] proved to be suitable in accomplishing this goal, and the core tenets of this framework can be seen in Figure 21.

Figure 21

The Six Steps of IDEAS



In the needs analysis step, information about the users and the environments in which they operate is gathered. This process seeks to identify users, goals, tasks, and cognitive processes. The requirements generation step is a collaboration between designers and technical experts in the system domain. Requirements can be divided into functional and nonfunction requirements. Functional requirements are explicit capabilities of the software or hardware platforms such as the ability to view airspeed and altitude, while nonfunctional requirements are implicit capabilities such as being easy to use and intuitive. In the design and engineering step, the previous steps constrain development as designers iteratively began to develop a system. This stage involves creating drafts, wireframes, and mock-ups as the project begins to take shape. The interface review step consists of domain experts reviewing the proposed design created in the design and engineering step and may involve several iterations before the implementation step can begin. The next step is the implementation step, where development can begin in earnest after the design has gone through several iterations of interface review. In practical terms, this is when the lines of code are written. Finally, the verification step can begin. A core part of the verification step is usability testing, where a prototype is given to the end-user and the way they work with the system is carefully observed to learn about its strengths and shortcomings. As can be seen in Figure 21, this step can iterate back to implementation, or even needs analysis if necessary.

Chapter 4

Results

4.1 X-Plane Flight Simulation Environment

X-Plane 11 was chosen as the flight simulator of choice. This was due to X-Plane 11's existing compatibility with the FAA's cockpit simulation facility (CSF). Additionally, A plugin to export data references from X-Plane was already available. X-Plane also provides a high degree of realism and provides data references which are well suited for testing HUD functionality. The X-Plane software includes a vast selection of airport selections across the globe with especially good coverage of airports in the United States, as well as the option to choose between piloting fixed-wing aircraft, rotorcraft, and custom imported aircraft. High fidelity textures with accurate placement of runways, buildings, roads, and natural features such as rivers and trees help make X-Plane 11 one of the most popular choices in the aviation industry. Furthermore, X-Plane 11 allows the user to import custom models and textures for buildings or airport structures to correct out of date scenery.

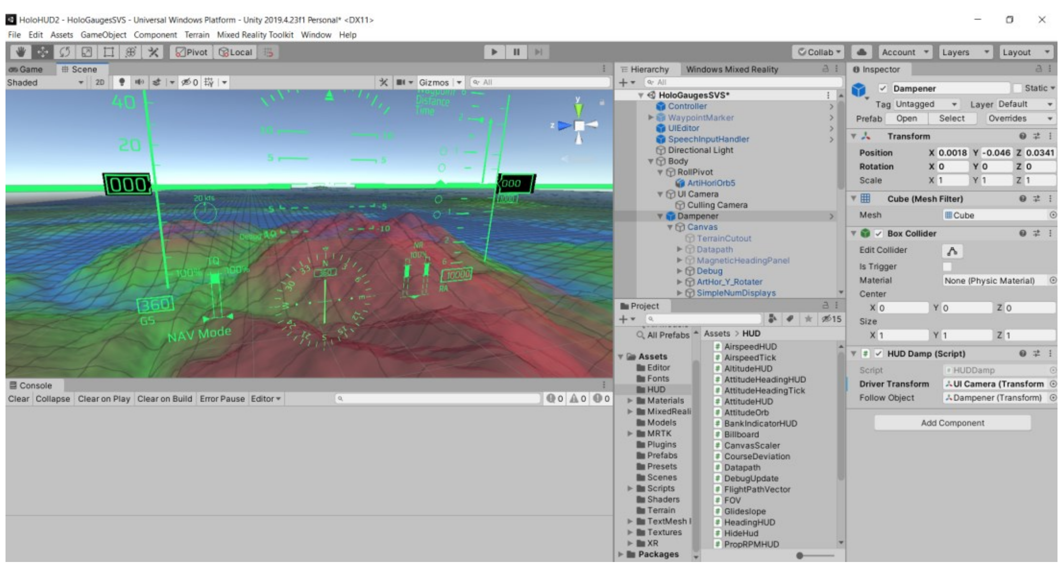
4.2 Unity Environment

Unity was chosen to implement the HUD due to its outstanding support for mixed reality devices that include the HoloLens 1 and 2. While Unity is not the only the only real-time engine that modern mixed reality devices provide developer support for, Unity is unique in that it benefits from widespread support from almost all mixed reality hardware developers. Unity also makes it easy to manage assets by providing a built-in file explorer to easily organize images and scripts that are used to implement the HUD.

Furthermore, Unity provides a 3D space that is perfect for interfacing with the altitude, longitude, and altitude data as well as aircraft orientation data references that X-Plane provides. Unity's shader pipeline allowed us to implement custom shaders for the Synthetic Vision System to color each pixel depending on its height in the terrain. Finally, Unity provides a Holographic remoting functionality that allows for rapid prototyping by deploying the project on the HoloLens 2 without creating a build. A screenshot of Unity featuring the scene, hierarchy, inspector, console, and project windows can be seen in Figure 22.

Figure 22

Unity Screenshot Showing Unity Windows and HUD

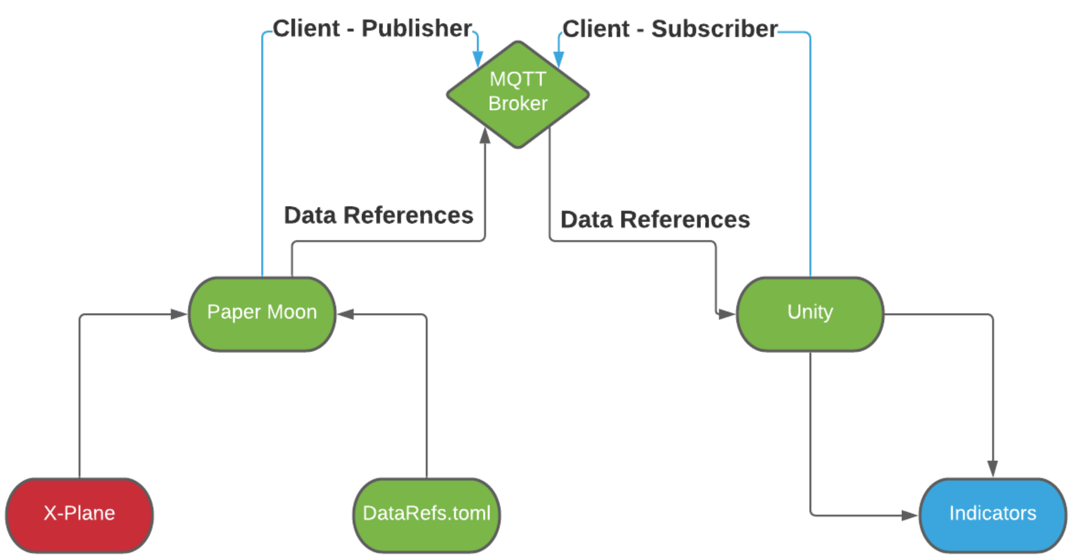


4.3 Dataflow

Data was pulled from X-Plane 11 to model indicator behavior. A MQTT broker was used to transfer data via an X-Plane plugin provided by the FAA. This plugin publishes data references designated in a file named DataRefs.toml such as airspeed, altitude, and vertical speed to the MQTT broker. The Unity application establishes a connection to the broker by subscribing and then requests the same data references designated in the DataRefs.toml file and passes the data references to individual instruments in the HUD. An overview of this process can be seen in Figure 23.

Figure 23

Dataflow From X-Plane to Unity



4.4 Indicators

As discussed in the approach, indicators could roughly be divided into circular, tape, text, and bar indicators, although a few indicators do not fit neatly into these categories. These indicators work together to provide critical information that a helicopter pilot needs while flying. In Figure 24, a labelled snapshot of the HUD can be seen.

Figure 24

Labelled Snapshot of HUD

4.4.1 Tape Indicators

Three types of tape indicators were added to the HUD, the airspeed indicator, vertical speed indicator, and altitude indicator. All of these indicators provide critical information for a helicopter pilot and must be constantly referenced and are prominent in the display. In Figure 24 above, the airspeed indicator is located below label 1, the vertical speed indicator is located below label 2, and the altitude indicator is located below label 3. Both the airspeed indicator and altitude indicator use their respective data references to move the tape up and down, while the numerical indicator shows the value of the data reference itself. The displacement of the tape gives the pilot an idea of the velocity of the data reference. In effect, the tape display will move faster if the data reference is increasing or decreasing at a rapid rate. The vertical speed tape instead has the appearance of a tape indicator but behaves by changing the scale of its arrow. This allows the entire range of the vertical speed change to be in view at once (-6000 feet per minute to 6000 feet per minute). In addition to this, a non-uniform scaling is applied to the vertical speed tape such that the lower ranges (-2000 feet per minute to 2000 feet per minute) are given proportionally more HUD space than the lesser used upper ranges (2000 fpm to 6000 fpm and -2000 fpm to -6000 fpm). At the bottom of the airspeed indicator is a text display of ground speed, while the altitude indicator displays radio altitude below its tape. The text display below vertical speed is simply the vertical speed data reference.

4.4.2 Circular Indicators

The HUD features two circular indicators. The first indicator is the horizontal situation indicator (HSI), also known as the heading indicator, and can be seen to the left of label 4. The second indicator is the combined roll and skid/slip indicator to the left of label 5. The HSI rotates in proportion to the heading data reference, such that the top arrow will point to the correct numeral or cardinal letter. The HSI includes a course deviation bar that can inform the pilot if they must fly left or right to stay on their selected approach. By including multiple components, the HSI can conserve space for other necessary elements of the HUD. The combined roll and skid/slip indicator rotates about the center of the HUD while the solid green arrow remains stationary to indicate the roll of the aircraft. The aircrafts roll is given by how many degrees off the center arrow the indicator rotates. The solid rectangular bar below the solid arrow will also move left or right if the pilot is making an uncoordinated turn, indicating skid or slip.

4.4.3 Bar Indicators

The torque indicator to the left of label 6 and the rotations per minute (RPM) indicator above label 7 are both bar-type indicators. These indicators simply use their data references to translate their the arrow visual element vertically. If a twin-engine helicopter is used to send data references, each of the pointers in the torque indicator are capable of independent movement such that if an engine fails, one of the pointers will move to zero. Both indicators include an ideal range highlighted in green, but because each aircraft has different ideal operating conditions the ideal range is a suggestion instead of a rule. The torque and RPM indicators do not need to be referenced as often as other critical indicators such as airspeed or attitude, so they are placed in the corners of the HUD outside of the forward field of view.

4.4.4 Attitude Indicator

To the right of label 8 is the attitude indicator. It is comprised of a conformal horizon line as well as a non-conformal attitude indicator. The conformal horizon line is the thicker green line that wraps around the HUD to stay conformal to both the synthetic terrain horizon and the outside flight simulator visual horizon. It is implemented on a rotating gimble such that its movement is controlled directly by the pitch and roll data references. In contrast, the non-conformal pitch indicator is moved translationally by the pitch data references and because it always remains centered in the HUD, it provides the pilot a contextual understanding of their orientation. Even if the conformal horizon line falls away from the pilot's view, the non-conformal attitude indicator will remain centered and give the pilot a sense of their current orientation.

4.4.5 Glideslope Indicator

The glideslope indicator to the right of label 9 assists the pilot during the landing phase of flight. If the solid green diamond is in the upper half of its range, the pilot must pitch up for a smooth landing and if the solid green diamond in in the lower half of its range, the pilot must pitch down.

4.4.6 Flight Mode Annunciator

To the right of label 10, the flight mode annunciator (FMA) informs the pilot about what system is controlling the aircraft and what mode is operational. The three flight systems that can be controlled are the collective (throttle), roll, and pitch. Each system has their own unique set of modes that can be set by the avionics system. In Figure 25, the pitch system has been set to maintain vertical speed.

Figure 25

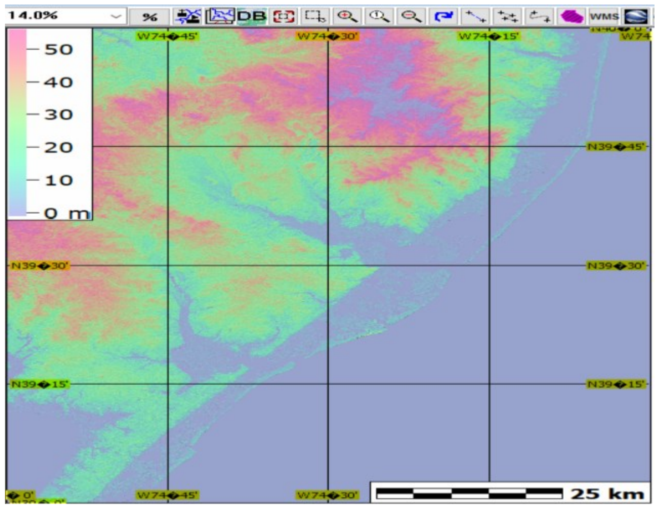
Autopilot Mode Controlling Pitch to Maintain Vertical Speed

4.5 MicroDEM

MicroDEM is a computer mapping program used to analyze and modify .GeoTiff files that contain digital terrain elevation data (DTED). Each .GeoTiff file has DTED for approximately 3,600 square miles of land, which is equivalent to a one degree latitude by one degree longitude area. These .GeoTiff files were downloaded from https://earthexplorer.usgs.gov. MicroDEM is capable of various modes of analysis and can be used to eliminate areas of data that are irrelevant to the HUD, such as areas that lie below sea level. The software was also used to identify areas where elevation was most extreme using the built-in plotting software, and to verify that the DTED was correctly being imported into Unity. For example, terrain was checked to make sure it had the correct altitudes, orientation, and scale. In Figure 26, the GeoTiff for the chunk containing Atlantic City International Airport and the surrounding area is featured.

Figure 26

MicroDEM Display Terrain Chunk Including Atlantic City International Airport



4.6 Geospatial Data Abstraction Library

The Geospatial Data Abstraction Library (GDAL) was primarily used for conversion of .GeoTiff files to .raw files which can be digested by the Unity Engine to create terrain objects. These terrain objects will mirror the DTED in the .GeoTiff files, resulting in a close analog to real world terrain.

4.7 Synthetic Vision System

The synthetic vision system is a reconstruction of the earth's surface generated using satellite data. The data set used was collected from the Shuttle Radar Topography Missions and downloaded from https://earthexplorer.usgs.gov/. The data is available in a .GeoTiff format, each of which covers a one-degree by one-degree chunk, with each chunk encompassing an area of about 3,600 square miles. The data resolution of data located in the United States is about 1 arc-second, or about 30 meters. As mentioned before, MicroDEM was used to cull negative altitudes (below sea level) from data received from the SRTM dataset that was irrelevant to our area of concern. From there, Geospatial Data Abstraction Library (GDAL) was used to convert the .GeoTIFF files to .raw files which could be imported into Unity as a height map with a resolution of 2049x2049. A custom shader that colored each pixel of the terrain according to its altitude was used to add height context to the terrain. An example of this terrain can be seen in Figure 27, which displays a section of a terrain chunk that includes the Seattle area. Figure 28 displays the same area on Google Maps with the red box around the area displayed in Figure 27.

Figure 27

Terrain of Chunk in Unity Featuring the Seattle Area

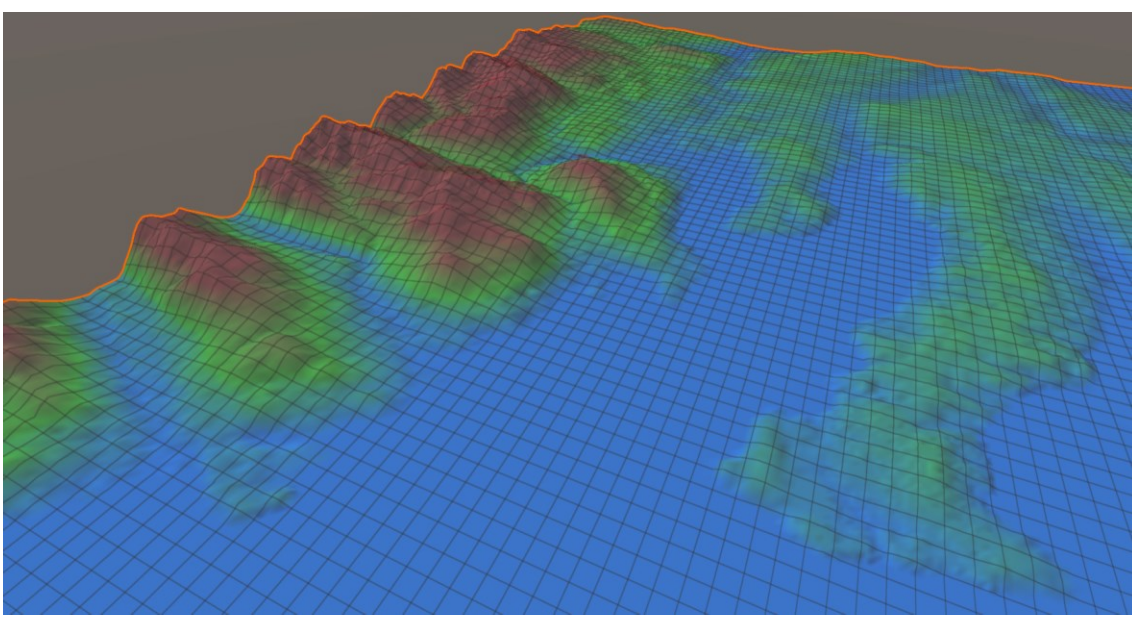


Figure 28

Image with Featured Terrain in Figure 27 Boxed in Red

4.8 Implementation of IDEAS

The IDEAS framework was used throughout development to quicken the development cycle and to take advantage of feedback so that the HUD was more user friendly and ergonomic as well as more effective.

Needs analysis was accomplished through meetings with subject matter experts including rotorcraft pilots from the FAA that identified major goals for the HUD. This included using symbology that was established and popular to reduce initial training and learning barrier for users. The goals of the HUD were to provide a testbed for AR technology in rotorcraft and evaluate the effectiveness of AR in increasing rotorcraft pilot safety.

Requirements generation was also accomplished early in the project, but also continuously over its lifetime. When basic functionality was achieved, the application was delivered to the FAA on a biweekly basis for testing, and this led to new non-functional requirement generation as testing brought up usability concerns such as jitter when the user adjusted their view or difficulty using the voice commands of the HUD. During meetings, feedback guided the next build as well as simulator trial notes that were received after testing.

Design and engineering were accomplished using the Unity engine and GIMP to create textures for the HUD. Design documents guided the overall structure of the HUD, but individual details were designed to maximize ease of use and clarity of data on the HUD. Important metrics were conformality with the outside environment, which was especially important for components such as the artificial horizon and the synthetic vision system which heavily rely on the outside environment to be useful.

Interface review was done continuously over the second half of the project after basic functionality was implemented and reviewed. Several elements such as airspeed changed position after review from the FAA and subject matter experts. The torque and RPM indicators went through several iterations, including a circular gauge format before finally settling at a bar indicator. Video references of the primary flight display from the FAA simulator were used as well as references of HUDs that have been developed across the industry.

Implementation was done by developing the project in Unity and deploying it on the HoloLens 2. As the project developed, focus was shifted from initial implementation of core components to maximizing usability and the accuracy and precision of the components. The Unity engine allows for rapid testing, as new components and additions can be tested immediately after implementation without the need for creating a new build of the project.

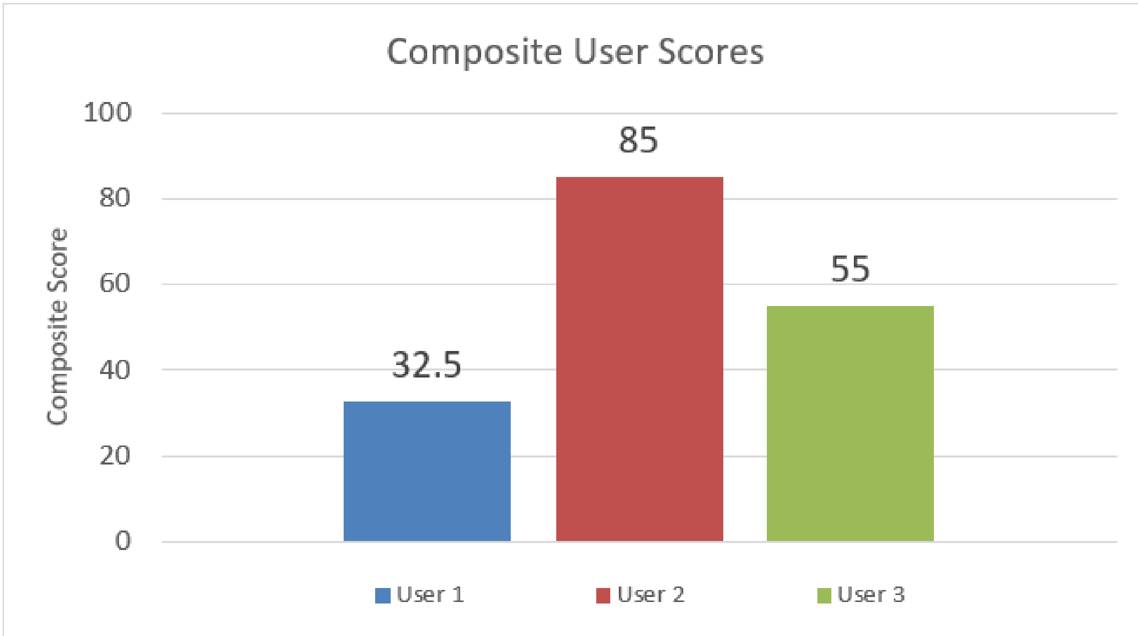
Evaluation has been accomplished by the FAA by testing the HoloLens 2 in simulator trials, but this phase is still ongoing as the project enters its final phases. The primary testers are now experienced with the software and may no longer reflect the experience of a new user that is not experienced with the HoloLens2 or application. This reflects a need for feedback from pilots who have little experience with the HoloLens 2 or virtual HUDs.

4.9 System Usability Scale

The system usability scale (SUS) shown in Figure 29 shows the composite scores taken from user feedback of n =3. The system usability scale was used to gauge the overall ease of use of the HUD, as well as how intuitive the software was for users. A higher composite scores indicates a more favorable impression of the HUD, while a lower score indicates that the user thought the HUD was unintuitive or hard to use. The high variance in scores indicates that the background of the user has a strong influence on their overall impression of the HUD. Overall this means that the HUD must be adjusted such that it is more accessible to all users rather than just those that may already be comfortable with HUDs. The SUS survey can also be readministered for future versions of the HUD to gauge how effective new additions or changes are.

Figure 29

System Usability Scale Composite Scores



4.10 Voice Commands

A helicopter pilot spend most of their time piloting their aircraft with both hands occupied by the cyclic and collective. This leaves little time for hand gestures which are ordinarily the main way of interacting with the HoloLens 2. As a result, all the interaction performed with the HUD application is done with voice commands. In table 1, a summary of these voice commands and their functions is listed.

Table 1

Reference Table of Voice Commands and Functions

Voice Command	Function
Terrain	Toggle SVS visibility
Declutter	Cycle through declutter mode
Increase	Increase field-of-view box
Reduce	Decrease field-of-view box
Debug	Toggle debug window
Lock	Lock HUD elements in place
Field	Disable field-of-view box.
Brightness Down	Decrease alpha transparency
Brightness Up	Increase alpha transparency
Hide	Toggle HUD elements
Clear	Clear set waypoints.
Load	Reload scene

In the future, we hope to bind the functionality of important voice commands to buttons or switches on the cockpit. This will reduce frustration associated with misrecognition of voice commands by the speech recognition software as well as avoid situations where ambient noise (such as the spinning of rotor blades) drowns out the voice of the pilot.

Chapter 5

Conclusions

In 1946 Lt Col Paul Fitts reported that “it has been proposed …to throw the image of certain instruments onto the windscreen so that they might be viewed while looking out of the plane.” [30] The advent of virtual and augmented reality technologies from scientific research labs into the commercial marketplace has heralded their potential application to benefit society. Whereas VR transitioned mainly into gaming and entertainment environments, AR has always shown promise in addressing complex technological problems. Recent developments in this field predict that the greatest benefit of synthetic visualization is in the emerging field of “mixed” reality (MR) [45], where the virtual and the real world exist interchangeably. MR shows the way to address the overarching quest to engage with difficult problems and enable humans to intuitively comprehend multisensory information.

This thesis has attempted to capitalize on these rapidly advancing and converging technologies to provide solutions to a critical issue in rotorcraft flight control. It is well known that piloting rotary wing aircraft (helicopters) is considerably more challenging than their fixed wing counterparts (airplanes). In addition, operating helicopters in varying multisensory environments fraught with potential threats and unknown circumstances, presents a significant increase in difficulty. Furthermore, piloting under such conditions requires one to grasp a multitude of data, integrate it with prior experience and make informed decisions. Most importantly, any additional information that is presented should not detract from the pilot's mission in both civilian and military operations.

The objectives of the research work presented in this thesis were to:

1. Design and develop a head-up display for helicopter pilots that can integrate flight and terrain information;
2. Prioritize, organize and present the information to the pilot to be easily understood, without distraction;
3. Test the HUD system on simulated flight platforms;
4. Implement a framework for the evaluation of the HUD.

To effectively address these objectives, the research work in this thesis adopted a three-fold approach:

1. Exploration of commercial-off-the-shelf head-mounted display technology to design and develop potential methods for providing a HUD to helicopter pilots;
2. Interfacing the HMD with inflight data streams provided by a commercially available flight simulator environment;
3. Adaptation of a previously established human systems engineering framework for evaluating the effectiveness of the design and implementation of the HUD.

The specific contributions of this research work are:

1. The development of a systematic, hierarchical methodology for the design of the HUD that included the following stages: specification, parameterization, visualization, implementation, and verification. The Microsoft HoloLens 2 was used as the platform for implementing these design stages.
2. The X-Plane flight simulation platform was used to provide realistic in-flight data streams for interfacing to the Microsoft HoloLens 2.
3. The IDEAS framework was adapted to enable a user-centered design paradigm for developing the HUD.

Using the methodology developed in the approach, an ergonomic HUD designed with the end-user in mind was developed and tested. The initial results are promising, but much work remains to be done as the HUD is further refined and optimized. The indicators developed for the HUD are the following;

1. Attitude Indicator – Provides the pilot with a sense of their orientation, in particular their heading, pitch, roll.
2. Horizontal Situation Indicator – Provides the pilot with their current heading as well as instruments to keep the pilot on their designated approach.
3. Airspeed Indicator – Provides the pilot with a contextual understanding of their airspeed as well as their ground speed.
4. Vertical Speed Indicator – Provides the pilot with their vertical speed in a manner that is easy to digest.

5. Altitude Indicator – Provides the pilot with a contextual understanding of their altitude as well as radio altitude.
6. Combined Roll and Skid/Slip Indicator – Provides the pilot with their roll as well as a tool to coordinate turns.
7. Torque Indicator – Provides the pilot with their current torque for each engine as a percentage as well as an ideal range for torque.
8. RPM Indicator – Provides the pilot with their current RPM as a percentage as well as an ideal range for RPM.
9. Flight Mode Annunciator – Provides the pilot information about the avionics systems and the current engaged autopilot mode.
10. Synthetic Vision System – Provides the pilot with terrain generated from local elevation data for use in low visibility environments.

The augmented reality instrumentation described in this thesis displays prioritized flight and environmental data to the pilot in a user-friendly interface. Users within the virtual environment will have the added capability of viewing aerial systems and the surrounding visual environment from multiple observer/operator perspectives to create an end-to-end virtual/human-in-the-loop environment. We anticipate that enhanced simulation environments such as these will become very important to the FAA's overall capability to effectively study and support the development of safety enhancements for rotorcraft.

As part of immediate future work, we hope to implement field testing with the HoloLens 2 and gather usage data, survey data, and objective data that tests the efficacy of the HUD. This can be implemented by testing for object detection as well as the quality of landing, taxi, and takeoff. A complementary research project currently underway is investigation of machine learning and artificial intelligence techniques that fuse data from multiple sources and provide it to the rotorcraft pilot as additional information. It is anticipated that this fused data can be added in augmented reality to the head-up display for the pilot.

Three-quarters of a century from Lt Col Fitts' dream of an instrument "thrown on a windscreen," the augmented reality HUD developed in this thesis has the potential to make that dream a reality. As AR technology advances towards mixed reality, the rotorcraft pilot of the future will be fortunate to operate in the "real" environment of the helicopter cockpit while effortlessly switching sensory input to accept new or enhanced information.

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