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AUGMENTING HEADS-UP DISPLAYS WITH INTELLIGENT AGENTS: A HUMAN FACTORS APPROACH

Grant Edward Morfitt
Rowan University

AUGMENTING HEADS-UP DISPLAYS WITH INTELLIGENT AGENTS: A HUMAN FACTORS APPROACH

by

Grant Edward Morfitt

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Thesis Chair: Shreekanth Mandayam, Ph.D., Professor, Department of Electrical & Computer Engineering

Committee Members:
Nidhal Bouaynaya, Ph.D., Professor, Department of Electrical & Computer Engineering
Patrice Tremoulet, Ph.D., Associate Professor, Department of Psychology

Dedications

I would like to dedicate this thesis to my parents, Roger and Janet Morfitt. They have given nothing but unwavering support through my darkest days and longest nights, and for that I am eternally grateful. Every person wants to be able to proudly say they made it on their own, but I know I would not be here if it were not for you. Thank you.

As my father has always told me, “It may be difficult, but this too shall pass”

- And so it has.

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Abstract

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Shreekanth Mandayam, Ph.D.
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Situational awareness, both tactical and strategic, is essential for humans engaged in complex tasks in civilian and military theaters of operation. Previous work has shown that heads-up displays are effective tools for providing critical information to operators performing in military and civilian scenarios. Hitherto, heads-up displays have been designed to relay instrument and sensor information to the operator in a topical, timely, and accurate manner. There is a large body of complementary work in human factors that deals with presenting information to a user without detracting from the primary goal of operation. This thesis investigates, measures, and validates the effectiveness of a framework to provide additional information to an operator in an augmented reality format.

This thesis focuses on applications of heads-up displays for rotorcraft pilots. Virtual reality (VR) environments are augmented to accept externally computed situational awareness information using established frameworks for human systems engineering. These frameworks will ensure that such additional information will not negatively affect the pilot’s cognition in performing flight-critical tasks. The research work described in this thesis will increase the understanding that such augmented heads-up displays can provide civilian and military actors with enhanced tools for operational effectiveness, safety, and survivability especially in critical situations.

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Chapter 1

Introduction

In 2009 book, The Checklist Manifesto, the author Dr. Atul Gawande, a surgeon and public health researcher, showed the remarkable effectiveness of the use of checklists in healthcare environments [1]. In the book, Dr. Gawande recounts the nearly apocryphal tale of the invention of the checklist in the aviation industry – the 1935 crash of Boeing's "Flying Fortress" during its inaugural flight at Wright Air Field in Dayton, Ohio. The Army Air Corps recognized even highly decorated and experienced pilots such as Major Ployer P. Hill, when confronted with complex and advanced technology, find difficulty in successfully completing a set of simple sequential tasks. The pilot's checklist, over the course of the last century has become routine in the practice of aviation worldwide, irrespective of the experience and capability of the flight crew. It could be argued that the implementation of the checklist has been critical to the impressive safety record of the aviation industry and the growth of commercial aviation in general.

Dr. Gawande then goes on to describe the astounding success checklists have in a multitude of industries. In spite of the fact that checklists have revolutionized safety standards in a vast variety of applications, checklists themselves have become more complex, reflecting the complexity of the underlying technology.

This thesis lays the groundwork for the use of augmented reality (AR) to enable rotorcraft pilots in successfully completing a helicopter flight. Previous work has shown the capability of heads-up displays in flight deck environments in ensuring safety, reliability, and accuracy for aircraft operations. The work described here develops a general framework for transcribing the critical components of a checklist to a heads-up display in a helicopter cockpit.

1.1 Motivation

The United States National Airspace System (NAS) is regarded as one of the safest airspace systems in the world. The backbone of this statement is a strong culture rooted in professionalism and safety, which in turn requires commitment to continuous improvement. Checklists are a critical component in contributing to the safety of the NAS and its passengers. In keeping with this philosophy, the integration of Augmented Reality is critical to meet the demands of today's aviation systems. Heads-up displays have been utilized for decades; however it is only recently that the cost and technology barriers have lowered to allow commercially available AR devices to be used within the cockpit. Previous technology was developed for specific airframes, giving rise to copious amounts of paperwork to meet applicable FAA airworthiness standards. Now, it is possible to develop and test visualization techniques agnostic to the hardware being deployed.

As technology continues to grow, so does the complexity of the checklists that pilots must follow. In addition is the variability that occurs between different portions of flight and different categories of aircraft. This variability creates both a need, and a large amount of checklists.

The motivation of the work presented in this thesis is the development of a framework that visualizes the critical information a pilot must be aware of within a HUD environment which will assist pilots in completing flights safely, as a supplement to the complexity of the checklists in the cockpit. Users of the HUD are presented with an intrinsic understanding of this critical data, as the framework has been designed with a human factors approach.

1.2 Objectives

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

1. Identify the critical components of a checklist that is utilized in aviation, which is amenable to adaption for heads-up displays;
2. Develop a framework for designing an augmented reality heads up display for pilots that can integrate information provided by the checklist at the appropriate time in the flight plan;
3. Utilize established principles of interaction design in order to prioritize, organize and present the information to the pilot to be easily understood, without distraction;
4. Test the AR system on simulated flight platforms.

1.3 Scope and Organization of the Thesis

Chapter 1 introduces the importance of checklists in general, within the aviation industry in particular. The introduction of heads-up displays in flight deck environments is discussed. The remainder of this document is organized as follows. Chapter 2 provides a literature survey of the technologies implemented in this thesis including augmented reality heads-up displays, checklists and interaction design principles. Chapter 3 develops the framework of converting checklists to AR heads-up displays. Results implementing the AR environment in a rotorcraft cockpit display are shown in Chapter 4. The thesis presents conclusions and recommendations for future work in Chapter 5.

Chapter 2

Background

2.1 Virtual Reality

As stated by the great Harry Houdini, "What the eyes see and the ears hear, the mind believes” [1]. Houdini may not have been aware of VR, but the illusionist was correct in his statement about the human senses. The term VR was not widely used until the 1960’s with devices such as the Sensorama [2]. This term, however, is still difficult to define today 60 years later, and varies highly based on the scholar defining it [3]. For the purposes of this thesis, VR can be understood as the intersection of immersion and interactivity within a fabricated environment.

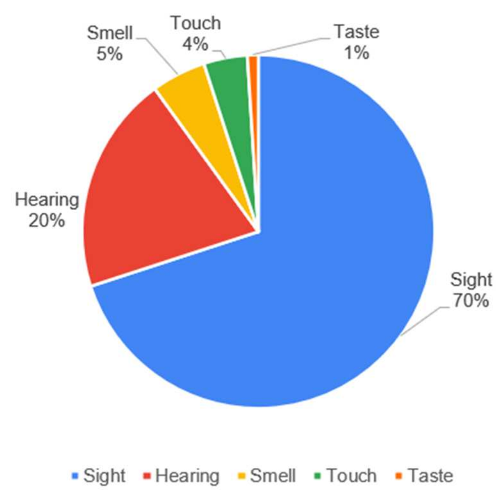
The most straightforward way to understand VR is to investigate the technology being used [2]–[4]. While the most straightforward way, this method leaves something to be desired. Defining VR based strictly on the technology being used imposes some limitations that other definitions do not offer. One of the largest of these limitations being the exponential increase in technology capabilities. Modern day devices offer display resolutions and capabilities that vastly outnumber devices of decades past.

Many people consider Virtual Reality (VR) a relatively new technology, referencing modern consumer devices used for entertainment platforms. VR however, has been around for decades. In 1787, the Irish painter Robert Barker patented what he called the panorama. This was a circular, 360-degree painting that was displayed and illuminated in such a way that the user could consider themselves a part of the environment. This was revolutionary for the time, as all experiences previous to this had been from a birds-eye perspective [5]. The type of painting Barker used had been painted before. What was unique to Barker's device was the ability to control what the user was able to see and interact with. His design included specifications for the lighting, an isolated viewing platform halfway up the canvas, and restrictions preventing the user from getting too close to the image [6]. His device was one of the first to *immerse* the user in the environment. More than 200 years later, virtual reality still relies on the idea of immersion.

The word *immersion* is a term present in nearly all literature discussing virtual reality and is key to understanding VR [2], [4], [7], [8]. Immersion is the process of convincing the user that they are in the environment being presented to them. Generally, VR can be categorized into either immersive or non-immersive [7]. Non-immersive VR is most found in entertainment, in which the user can control some activities within the environment but is not immersed in the experience. The user maintains a level of conscious or subconscious awareness that they are not truly immersed in the environment being presented. Comparatively, immersive VR is more difficult to achieve than non-immersive VR. Many challenges surround the process of convincing the user they are truly in an environment [9]. To fully create a virtual reality, every sense must be simulated to create the environment. There are obvious issues surrounding implementing systems to mimic some senses such as the olfactory sense. It has been found that the inclusion of smell increases a user's sense of immersion in the environment [10]. Almost all VR experiences today, however, lack the inclusion of the auxiliary senses such as smell. It is more than likely that this is due to the amount of bandwidth given to each sense by the brain. Seen below is an estimated breakdown of how the brain prioritizes each of the five senses [11]:

Figure 1

Prioritization of Human Attention for Each of the Five Senses



Human attention gives approximately 70% attention to sight, and 20% attention to hearing, therefore an estimated 90% of the human attention can be captured with only two of the senses. This is one of the main reasons that most immersive VR devices prioritize these two senses and neglect to include the senses of smell, touch, and taste. This is not to suggest that no devices exist that include these senses as there is support for haptic feedback systems that increase user immersion. These are however, outside of the scope of this thesis and will not be discussed in detail.

The other key factor involved in understanding VR is interactivity, and by extension, navigation of the environment. A lack of interactivity within the environment is detrimental to the immersion of the user. Interactivity is what separates a VR experience from a passive experience such as viewing a movie. Barker's original panorama design allowed interactivity to a certain extent, allowing the user to navigate the environment [5]. While rudimentary, it gave the user a sense of control when interacting with the fabricated reality which further increased the feeling of immersion [4].

The crossroads between immersion and interactivity is where the definition of virtual reality exists. Scholars have defined VR in terms of the computer human relationship [4], in terms of its relation to communicating information to a user [12], as well based on the potential use cases it encompasses. The definition of VR is strongly correlated to the area in which it is being utilized, whether that be in computer human relationships or in a broader sense, simply communicating information to the user. Previous scholars have spent months attempting to define the term and yet still may not have completely covered all that the technology encompasses and what it may encompass in the future. As mentioned previously, VR can be understood as the intersection of immersion and interactivity within a fabricated environment.

2.2 Augmented Reality

Unlike Virtual Reality which *replaces* reality with an artificially generated one, Augmented Reality(AR) aims to *supplement* the user's reality with additional information on top of the current environment. The amount of real-world supplementation exists on a spectrum that some authors have referred to as a virtuality continuum [13].

Figure 2

Virtuality Continuum

On this spectrum is one end which exists complete real-world imagery with no enhancement, and on the other end of the spectrum is a completely virtual reality. This makes the extension of virtual reality even more difficult to define, further abstracting an already abstract concept. One way to understand AR is to investigate the various ways in which the information can be relayed to the user as well as the type of information being relayed.

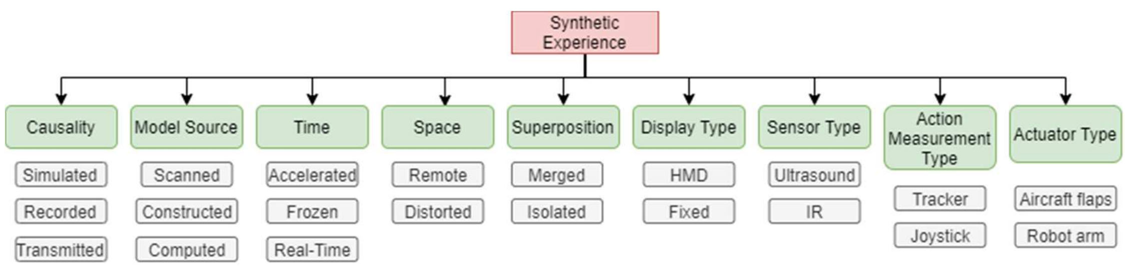
2.2.1 AR Taxonomy

Since its inception, many scholars have proposed definitions for describing Augmented Reality. Something that becomes apparent when researching this definition is that every scholar appears to propose something different. As stated by one of these scholars, discussion is "…somewhat biased by my own experience …" [14], which holds true for most definitions one comes across. The classification of AR can be broken down into multiple categories, ranging from the obvious such as the type of display being utilized, to the less obvious such as the purpose of the augmentation. Warren Robinett is most known for his proposed synthetic experience taxonomy, in which he suggests nine dimensions that can be utilized to categorize synthetic experience. Synthetic experience is what Robinett uses to define all virtual experiences, being anywhere from flight simulation to Head Mounted Displays(HMDs).

Robinett's taxonomy categories can be seen below [14]. He suggests that these should be interpreted as more of an independent matrix, each aspect of the taxonomy being separate from the others.

Figure 3

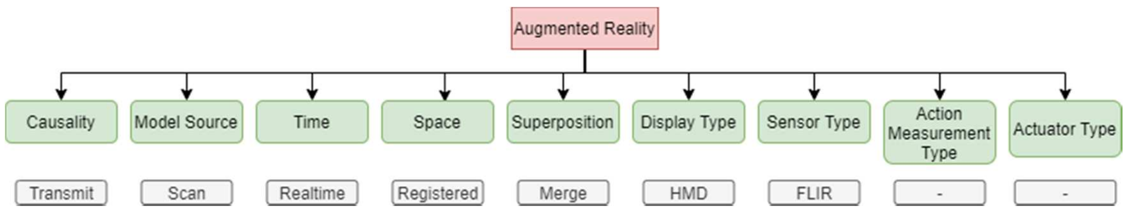
Synthetic Experience Taxonomy



Augmented Reality definitions fit within Robinett's classification of synthetic experiences. Under this classification, he proposes the following for the classification of Augmented Reality

Figure 4

Augmented Reality Classification



Causality refers to the way the way that the user perceives the world. *Transmit* indicating that to be classified as AR, the device needs to present the user with a real time image of the world. The simplest way to do this is to overlay a screen over the environment, however AR devices exist that stream the data to the user via a camera and auxiliary display device

Model Source refers to the definition of the world that the user is perceiving. This category can be split into three different categories. The user can be presented a scan of the world, a construction of the world that is built by a modeler, or a computation of the world that is built by a real time algorithm. In AR experiences, the user is presented a scan of the world. An example of this definition is Night Vision Goggles(NVGs), in which the device scans the environment and presents that augmented scan to the user.

Time is relatively straightforward; it describes the way in which the user perceives time in the environment. AR for most applications is a 1-to-1 real time representation of the world.

Space defines the way in which the environment is displayed to the user. The scan of the environment and the resulting display of that scan may be displaced, different in scale, or be distorted to some extent. In AR applications the space category can be described as registered, where the display to the user mimics the environment being scanned by the model.

Superposition is the amount of real-world imagery merged into the virtual environment. Another way to understand this category is the *virtuality continuum* seen above. For AR, real world imagery is merged with virtual imagery to enhanced the user's reality. Most AR applications exist towards the left side of the continuum seen in figure 2.

Display Type is the way that the data is displayed to the user. For AR applications, the best way to augment the environment is to utilize an HMD which will be discussed in subsequent sections. The term HMD is broad and can define anything from a fully immersive device such as an Oculus Rift to an AR device such as a Hololens 2.

Lastly, is ***Sensor Type*** which the devices use to get a scan of the environment. Robinett mentions in his classification outline that the sensor type is not a necessary hard requirement to define AR. For AR, forward-looking infrared (FLIR) are often used to get a capture of the environment for the model.

2.3 VR/AR Applications

Many individuals harbor a specific mental image that comes to mind if they were asked to describe Virtual Reality or Augmented Reality. The typical stereotype associated with this technology is that its sole use is in entertainment. The image many have is adolescents wearing a Head Mounted Device interacting with their friends, participating in activities such as crafting virtual worlds and navigating their creations. While this is one use case of VR, the capabilities extend much further than this. VR and AR applications span countless industries and disciplines, having been used extensively in research and military applications. This technology has seen success in human factors research, low vision rehabilitation, as well as extensively to support the United States military. The applications described in the following are only a small subset of the possible use cases of this technology, however they closely align with work outlined in this thesis.

2.3.1 Virtual Reality Applications

Virtual reality has extensive applications in the areas of research and training. Immersion and presence, two critical tenets of VR, allows a user to see and interact with a world separate from their own.

The field of medicine offers many different use cases for the technology. VR has seen use in physical rehabilitation, pain management, as well as surgery training [2]. VR has also been used to help those with low vision, or people with partial blindness. This can be done through the process of enhancing a user's vision with a head mounted display or through therapy with VR devices [15].

VR provides unique advantages when it comes to research. The ability to immediately reload a configuration for testing makes testing quicker, easier, and less taxing for the participants. Situation Awareness Global Assessment Technique(SAGAT) testing, discussed in subsequent sections, is a human factors analysis technique that requires the user to have the environment hidden during the questioning period of the study. This can be easily done in a VR environment which further increases the reliability of the results.

Figure 5

FAA S-76 Simulator Cockpit

2.3.2 Augmented Reality Applications

Augmented Reality has an advantage over Virtual Reality in its ability to allow the user to continue to have awareness of their environment. This is unique and has many applications in both aviation and military environments.

AR offers extensive capabilities in training and equipment maintenance. In the United States military, the complex equipment maintenance requires a high level of knowledge. This high level of knowledge can be difficult to pass on to new members. One use case of AR is in the field of equipment maintenance on this expensive and complex machinery. The technology enhances what the user is seeing as well as providing operational steps for the maintenance. While the trainee is working with the equipment, remote operators can see what the user sees through the head mounted display and assist them in completing the task [16].

The National Aeronautics and Space Administration (NASA) launched their first AR device to the International Space Station on December 6, 2015 which they refer to as Project Sidekick [17]. This device is being used for a combination of training and maintenance onboard the ISS. Similarly, to the military applications, Sidekick allows remote operators to see what the astronauts see and overlay information to the individual performing the maintenance. In addition to this mode is a self guided mode in which astronauts are given visual instructions for performing tasks while conducting the maintenance. Diagrams and designs are overlaid on the user's view to assist in the maintenance operation.

AR has had applications on the battlefield as well. A U.S Army project, named “The Land Warrior” was a concept that provided the soldier with overlaid thermal sight, video camera, and digital compass alongside a Global Positioning System(GPS). This was deployed in Iraq in July of 2007 that demonstrated the technology’s contribution to wartime operations [18]. Research is continuing on the battlefield at Rowan University’s Virtual Reality lab in a collaborative effort with the Picatinny arsenal. Similarly, to the Land Warrior project, this effort is focusing on improving a soldier’s situational awareness and survivability.

2.4 Situational Awareness - Introduction

On January 26th, 2020, the infamous Kobe Bryant tragedy occurred. The famous athlete’s pilot made multiple bad judgement calls on the day of the accident. The final, and arguably most influential, was the decision to fly into Instrument Meteorological Conditions (IMC) while operating under Visual Flight Rules (VFR). IMC conditions are flight conditions that require the pilot to fly with precision instruments for navigation, altitude, and attitude reference with limited or no outside visual reference [19]. IFR(Instrument Flight Rules) must be followed when flying in IMC conditions. According to the NTSB(National Transportation Safety Board) report, Bryant’s pilot experienced spatial disorientation and loss of control quickly after [20]. Rotorcraft, such as the Sikorsky S-76 mentioned here, require a larger array of data to be consumed and acted upon by the pilot compared to that of fixed-wing aircraft. Rotorcraft have an additional axis of movement which increases the workload on the pilot. This complexity and by extension, workload, is compounded upon in limited visibility environments such as those experienced by Bryant’s pilot. It is therefore crucial for pilots to maintain situational awareness to prevent spatial disorientation from occurring. To understand how to prevent spatial disorientation, first situational awareness must be understood.

2.4.1 Situational Awareness

In the context of flying, Situational Awareness refers to a pilot's understanding of the current state of their aircraft regarding integral flight characteristics and operations. The pilot must conduct the tasks necessary to continue stable flight. These tasks require cognitive activities that include but are not limited to perception of the environment, understanding of these factors, and understanding of the state of the system if the necessary corrective actions are/are not implemented [21]. Mica Endlsey, the creator of the Goal Directed Task Analysis framework, describes these tasks as the three levels of situational awareness [22]. This is discussed in greater detail in later sections. Example tasks for rotorcraft pilots are adding/removing collective input, pitching the nose down, or yawing the aircraft left or right.

In reduced visibility environments, several visual and non-visual hallucinations can occur due to natural processes in the brain. These visual hallucinations lead to what is known as spatial disorientation, which an example of a failure to maintain situational awareness [23]. If not prevented, this often causes pilots to develop a false understanding of how their aircraft is currently oriented relative to the ground, and then implement the corrective measures needed for that orientation. One example of a visual hallucination that pilots are trained to recognize is false horizons, which can be caused by an array of outside factors such as ground lights [23]. This leads the pilot to believe that the horizon is in a different location than its true location. A famous incident occurred to John F. Kennedy in 1999 on a flight he was conducting to Martha's Vineyard outside of

Massachusetts. There were a multitude of intersecting factors that contributed to this fatal crash quite like that of the more recent Kobe Bryant crash. The final however, according to the study conducted by the NTSB, was a loss of situational awareness [24]. There was a light haze the night of the crash in addition to a lack of moonlight which would have assisted in defining the terrain. When the pilot flew over a section of ocean, the report details that he most likely lost reference to the horizon and experienced visual hallucinations that led to him believing the aircraft was in an orientation that it was not truly in. This caused him to pitch the aircraft to an aggressive angle resulting in the fatal crash.

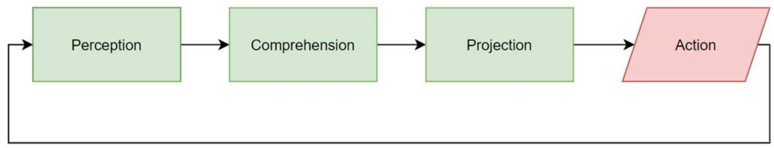
2.4.2 Goal Directed Task Analysis

Goal Directed Task Analysis(GDTA) is a widely used technique to identify situational awareness requirements for an operator [25]. GDTA was designed by Mica Endsley, an engineer and former Chief Scientist of the US Air Force. This analysis is performed by conducting interviews with SMEs in the field of application. From these interviews, a series of goals, subgoals, and decisions is generated. From this list comes the SA requirements needed to make each decision. This process is iterative in nature, and may take weeks to months to generate a concise GDTA. An option such as the one used in this thesis is to take advantage of GDTAs that have already been completed and adopt it for use. Commercial aviation GDTAs have been around for decades and have been used to facilitate the framework described in later chapters.

As mentioned previously, SA can be divided into three sections as shown in figure 6.

Figure 6

Situational Awareness Process



These categories are perception, comprehension, and projection [26]. These are respectively referred to as Level I, II, and III SA requirements within the GDTA process. Level I requirements refer to basic data references. The question "What information may I need?" is answered by Level I. Level II asks the question, "What does this mean?". This is the comprehension level of situational awareness. Level III asks the question, "Now that I know this information, what is going to happen?". Each subsequent level requires a deeper understanding of the information. Level II information can vary highly depending on the operator the information is being presented to. This variation can be drastic depending on the background and prior training of the user in the system. Level III then involves the synthesis of Level I and Level II information, requiring the highest understanding of the system to synthesize and adequately use the information.

Having an understanding and access to all three levels of information builds a platform in which to base situational awareness requirements. Therefore, most of the information displayed within the HUD environment is Level I information.

2.4.3 SAGAT Testing

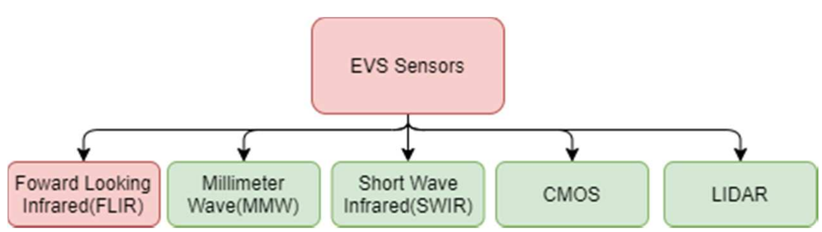
Situation Awareness Global Assessment Technique(SAGAT), is an analysis technique designed by the creator of the GDTA framework, Mica Endsley. SAGAT is a widely used technique for measuring a user's SA [25]. The testing is best done in a simulated environment, as the simulation is paused at random and the subjects are probed with questions relating to the perception of their current situation. This provides an objective, unbiased, measure of SA since the data is collected at random during both high and low workload situations [27].

2.5 Enhanced Vision Systems

Enhanced Vision Systems (EVS) are systems that fall under the category of Advanced Vision Systems in the aviation industry. EVS systems integrate external aircraft-based sensors to provide vision to the pilot in limited visibility environments. These compromise a range of sensors shown below [28]. EVS Systems are traditionally FLIR sensors combined with any number of secondary sensors and navigation devices.

Figure 7

Types of EVS Sensors



EVS sensors then display the information to the pilot on either a Head Mounted Display or more often a Head Down Display integrated into the avionics. The advantages and disadvantages of both displays are discussed in subsequent sections.

These sensors give the pilot a better understanding as to the state of the aircraft relative to the ground and obstacles. This increases their situational awareness which increases rotorcraft operational safety as the increased visibility is provided to the pilot real-time. Guidance suggestions are given by the Federal Aviation Administration in an Advisory Circular(AC) in terms of refresh rate, crew interaction, as well as other display considerations such as prevention of cognitive capture [28].

EVS systems have disadvantages that must be considered during design. One disadvantage present in many Head up Displays is that of cognitive capture, which is discussed in previous work done on this project [3]. Cognitive capture occurs when pilots inappropriately fixate on the display being presented to them. This can be caused by a variety of reasons, some of which being but not limited to display conformality, clutter, and perceptual separation [29]. In addition to cognitive capture is the danger of pilots becoming over-reliant on EVS systems. The Federal Aviation Administration warns of such issues when pilots introduce glass cockpits into their aircraft. One study investigating the effectiveness of head up vs head down displays regarding cuing found that pilots utilizing a cuing system had an extremely high rate of failure after errors were introduced to the system. These errors were introduced after the pilot became comfortable with the technology and it was found that their reaction times to threats more than doubled when the system began to act erroneously [30]. Such disadvantages can be the difference between life and death, and assist in displaying why the airworthiness requirements set by the administration are so stringent.

Airworthiness refers to the FAA document which grants an aircraft authorization to operate in flight. Gaining airworthiness approval for Advanced Vision technology is an extremely difficult and long process. This is due in part to the system needing to add to the pilot's situational awareness without detracting from the primary mission which is operating the aircraft. Numerous studies have shown the benefits of such technology in the cockpit environment. One such study was conducted on crew utilizing an EVS system maneuvering on the ground in low visibility taxi operations. Taxi referring to a phase of flight in aircraft prior to take-off. This study concluded that the inclusion of this system produced fewer route deviations for the aircraft when operating on the taxiway [31]. These systems have been shown to be beneficial in flight as well. Rotorcraft play a vital role in rescue operations. EVS systems can be utilized to show symbology to the pilot to assist them in visualizing the environment through bad weather and other potential hazards such as smoke from wildfires. Japan's Aersospace Exploration Agency(JAXA) conducted a three year study on EVS systems titled Situational Awareness and Visual Enhancer for Rescue Helicopter(SAVERH). The study found that there was a high rate of effectiveness of EVS systems on pilot terrain awareness [32]. This type of awareness is key in preventing accidents such as the Kobe Bryant incident mentioned previously.

Chapter 3

Approach

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

1. Identification of the critical components of checklists utilized in aviation, which are amenable to adaption for heads-up displays;
2. Development of a framework for the design of an augmented reality heads up display for pilots to integrate information provided by the checklist at the appropriate time in the flight plan;
3. Utilization of the established principles of interaction design in order to prioritize, organize and present the information to the pilot to be easily understood, without distraction;
4. Testing of the AR system on simulated flight platforms.

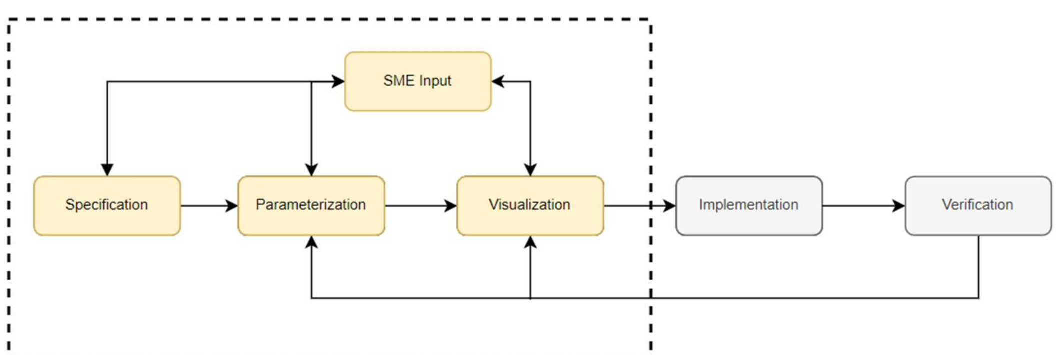
The workflow that is developed in this thesis, which translates a specific checklist item into an appropriate format for visual display is described in Section 3.1. The evaluation framework for determining the effectiveness of the approach is described in Section 3.2. A previously established human-systems engineering framework known as "Interaction, Design and Engineering for Advanced Systems" (IDEAS) [33] is adapted using "Goal Directed Task Analysis"(GDTA) [22] for the specific purposes of the design and development process described in this thesis. The implementation results are presented and discussed in the following chapter.

3.1 Methodology

Previous work utilized a five-stage process for the development of a HUD for in-cockpit displays, as figure 8 demonstrates. The stages for the previous work were respectively: specification, parameterization, visualization, implementation, and verification. The methodology for this thesis follows a similar format, however the stages are adjusted to accomplish a different goal. One of the major differences is the inclusion of Subject Matter Experts (SMEs) in the specification, parameterization, and visualization stages. The SMEs are responsible for determining the content, format, and performance of the subsequent visual displays. Critical differences also exist within the first three stages of the pipeline, as described in the next section. The implementation and verification stages have not been altered and will not be discussed further in this thesis.

Figure 8

Overview of HUD Gauge Development Process



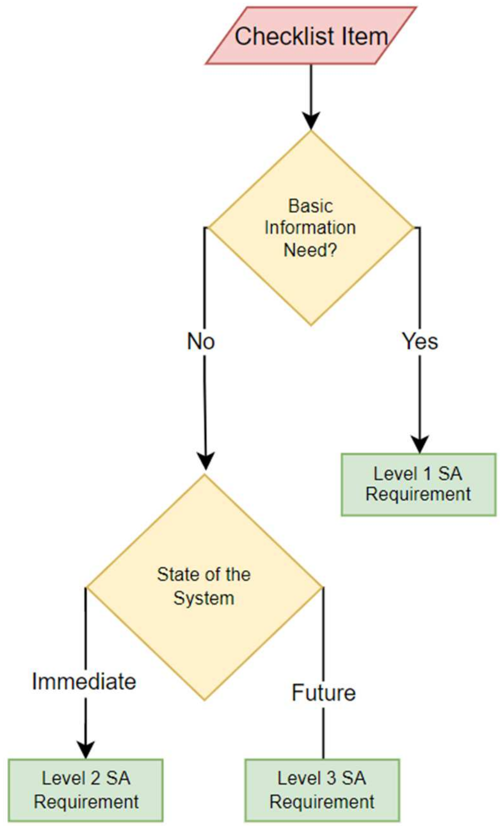
The specification stage begins with the designer deciding what information from the checklist is pertinent to the HUD as well as how it affects the operator's situational awareness (SA). For comparison, previous work utilized the specification stage to define what information to display, how to display it, and the location of the display. This thesis modifies that idea by incorporating an SME and using their input to guide the GDTA design to give insight into SA requirements. This aids the designer in understanding what information they must provide to the end user of the HUD. Previously, parameterization guided the decision of units, ranges, and increments of each display. Similarly, in this thesis, parameterization assists the designer in understanding the best format of the information. The Visualization stage occurs in tandem with the Parameterization stage, in which the designer follows the framework to best display the information to the user. In the implementation stage, the visualization for the checklist item is created in software. Finally, the verification stage includes the end user testing the design and ensuring the operation meets all expected standards.

3.1.1 Specification

In the Specification stage, GDTA is utilized to gain a better understanding of the information and how it affects the operator's situational awareness. This stage as well as the parameterization stage is done with an SME who assists in the development of the GDTA, if one does not already exist that can be utilized.

Figure 9

Specification



As seen previously, situational awareness can be broken down into three levels, each level requiring a deeper understanding of the situation than the previous stage. Level I refers to a *basic information* need, Level II refers to *comprehension* of the situation, and Level III refers to *future projections* of what will happen next. Categorizing the checklist item into SA levels allows the designer to incorporate a HUD in many different applications.

An example of this is taken from the checklist for an AW-139 rotorcraft.

The checklist item is sampled from the take-off section of the procedures that are given to pilots:

Hover — Establish at 5 feet AGL. If possible avoid relative winds between 135° and 225° (quartering tail winds).

From this the designer can follow the flow chart to understand the SA needs of the pilot when conducting a take-off. According to the GDTA, the designer looks at the checklist item to see what information is required to perform the task. Altitude and winds are required to conduct a hover when performing a take-off. The designer then needs to understand what information level altitude and winds are categorized as. This situation does not require more than basic information values, and so altitude and wind direction would be considered level 1 SA requirements.

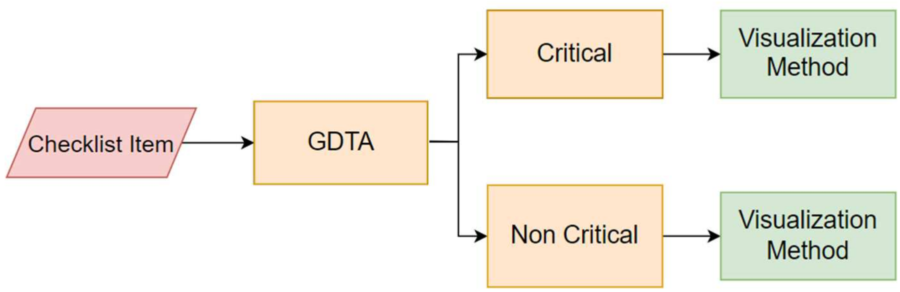
It is important to note that the pilot may need access to information that is not specified in the checklist. Since the designer must be made aware of the complexities of the system/environment, it is important to have SME input at the specification stage. For example, when hovering, a pilot may use line of sight with the horizon to gauge the current orientation of the aircraft. This would be noted by the SME, but not evident within the "hover" checklist item. The SME would relay this to the designer, who can then include this information in the design.

3.1.2 Parameterization

In the parameterization stage, the designer takes the information from the checklist item as well as the SA information gained in the previous stage and utilizes the framework developed in this thesis to help prepare for the visualization stage. Continuing with the hover example from the previous section, the designer would utilize the flowchart in figure 12. Due to the size of the chart, it has been broken into subsections that will be explored. Each decision that must be made is denoted by a yellow diamond. All the decisions that must be made comprise the parameterization stage of the pipeline.

Figure 10

Parameterization High Level Overview



The first part of parameterization involves utilizing the information gained from the specification stage to begin filtering the checklist information. Critical information must be visualized in a different manner compared to normal operating information. In a high workload environment, operators wearing a HUD can become disoriented and experience cognitive capture when prompted to focus on multiple visual sources of information at once [34]. FAA regulatory codes for flight crew alerting also require "…timely attention-getting cues through at least two different senses by a combination of aural, visual, or tactile indications" [35]. This thesis suggests an alternative to just visual displays, in which auditory alerts are utilized in conjunction with the visual displays to alert the pilot to a potential issue. The auditory alert must be used in conjunction with a visual one, as operators have been shown to ignore auditory cues when in a task saturated environment [36]. The visualization of critical information will be discussed further in the visualization stage.

Figure 11

Parameterization Part One: Critical Information

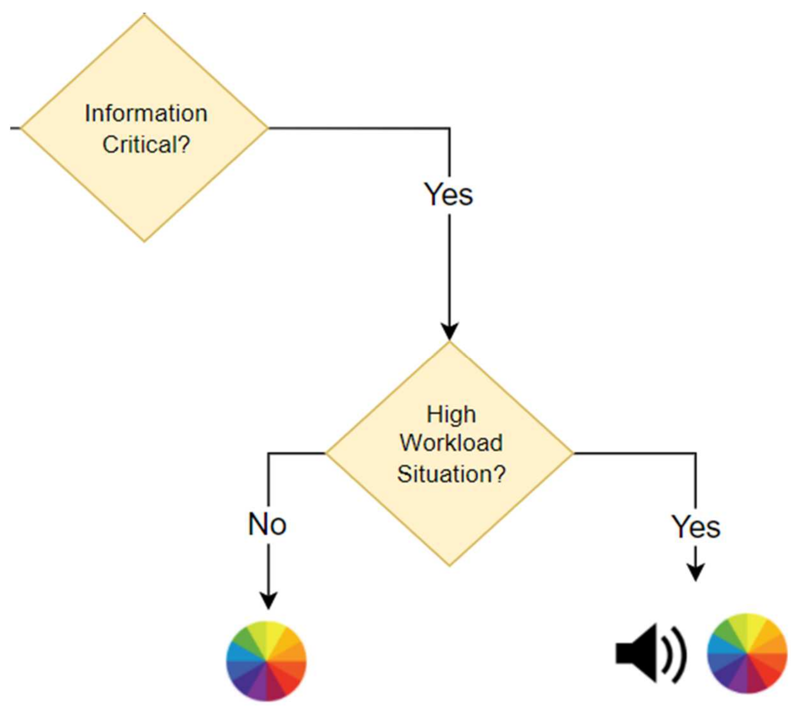
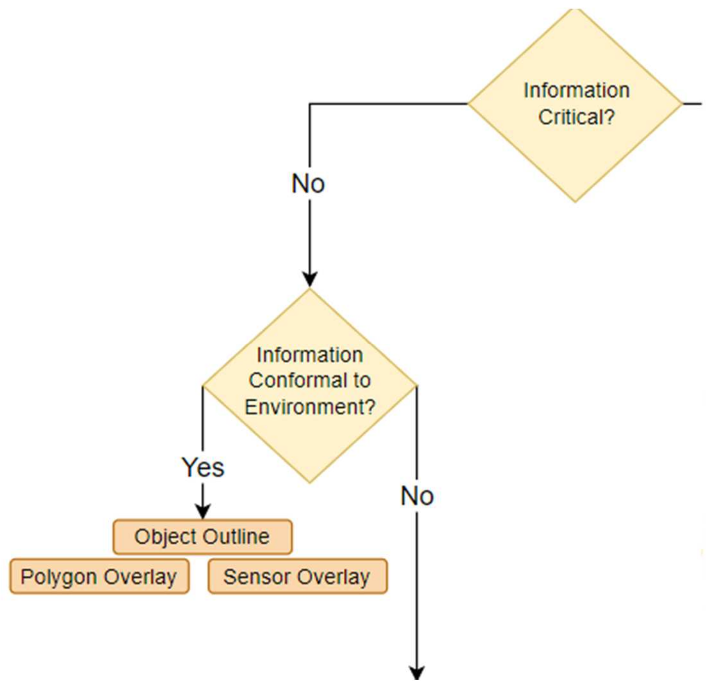


Figure 12

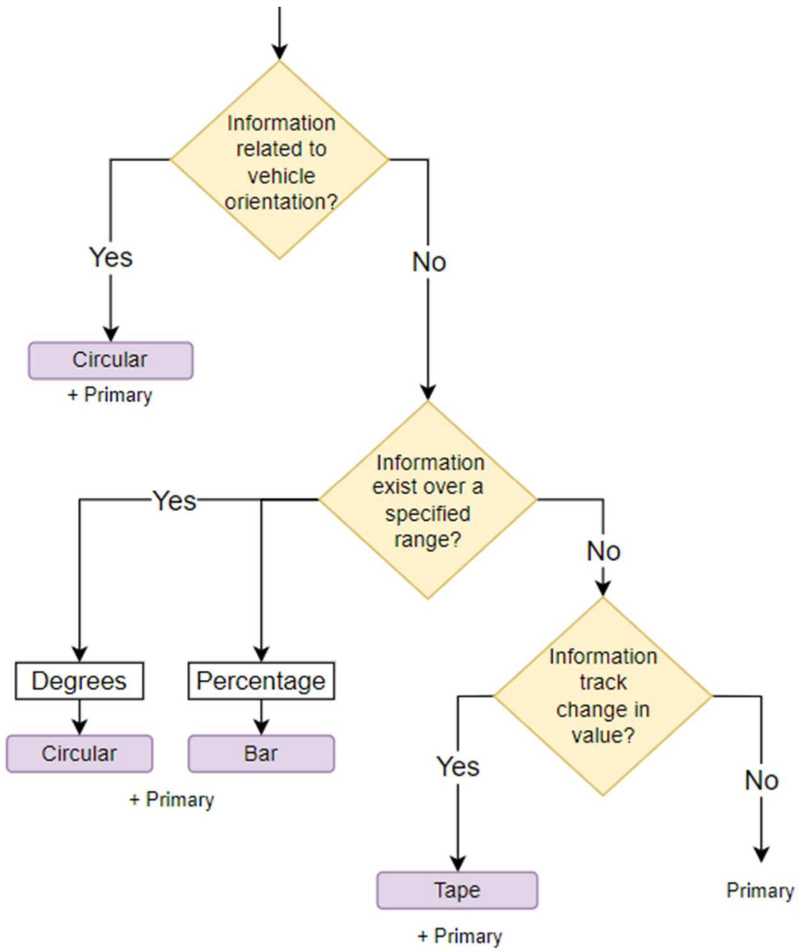
Parameterization Part Two: Non-Critical Information



It must be decided whether non-critical information needs to be conformal with the outside environment. This decision may need to be discussed with the SME. The previous "hover" checklist item seen in the specification stage shows that information may not appear to need to be conformal with the environment upon initial inspection. The hover item could benefit from inclusion of horizon information, which is a projection visualization technique that will be discussed in subsequent sections.

Figure 13

Parameterization Part Two: Non-Critical Information Continued



Two more decisions that must be made are presented in figure 13 above. If the information does not relate to the orientation of the vehicle, then it most likely will fall into one of two types of Level 1 information. If it exists over a specified range and can be measured in degrees or as a percentage, this step will provide the necessary visualization methods. If it is an unbounded value, and tracks a change, it is to be visualized with a tape display. Assuming the information does not fit into any of these categories then it is to be displayed numerically/with text in a simple primary display.

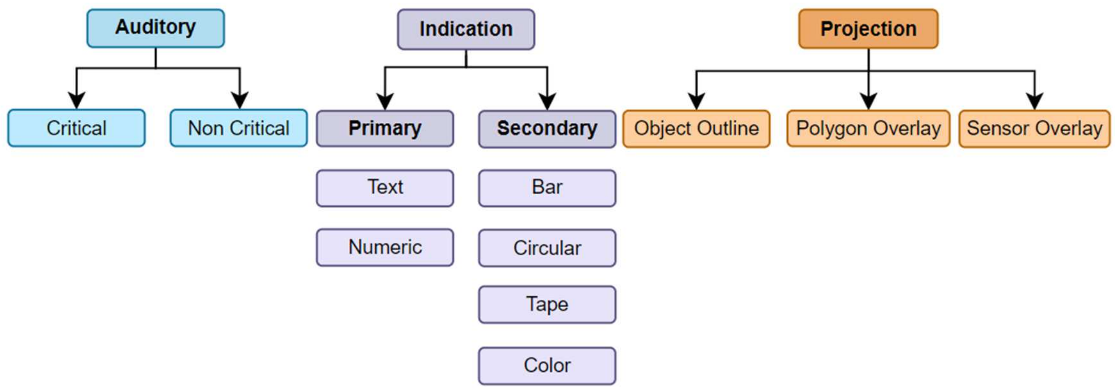
3.1.3 Visualization

The visualization stage takes the result from the parameterization stage and supplies it with the proper display technique. This thesis references visualization as a separate stage, however the flowcharts depicted in the previous section include the visualization information for clarity. This stage builds on previous work and further categorizes the different types of displays that can be provided to an AR HUD.

Previous work introduced several displays which were then recategorized and expanded upon in this thesis. These indicators were previously recognized as Tape, Bar, Circular, and Special displays. These categories failed to include certain key points which have been addressed in this thesis. One of the most prevalent is the lack of environment conformality in addition to auditory cues. Environmental conformality refers to imagery within the HUD environment aligning with a user's external environment. This is a versatile usage of AR that further increases a user's situational awareness. This thesis describes the three main categories of notification in an AR display being Auditory, Indication, and Projection methods.

Figure 14

Notification Methods

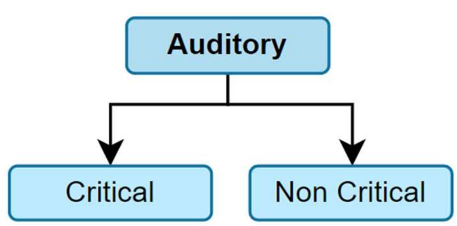


These categories were derived from a body of research focused on displaying information to users in AR formats.

3.1.3.1 Auditory. Auditory information can be broken into two subcategories, non-critical and critical alerts.

Figure 15

Auditory Display Type

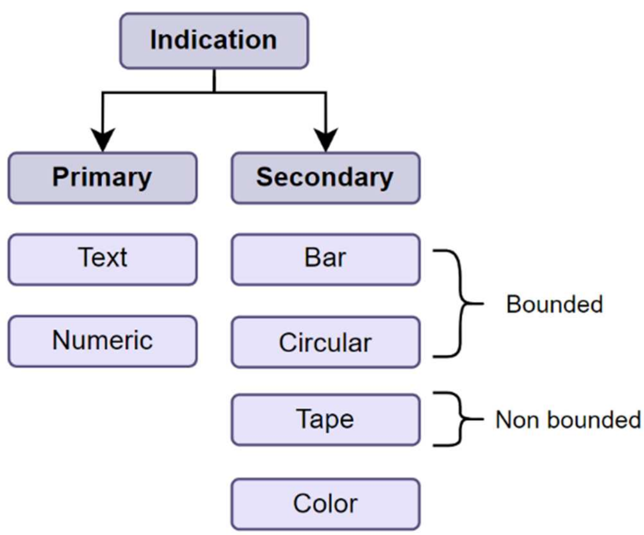


Critical alerts are only utilized when the operator must be notified of a hazard. A prevalent issue with auditory information is that the user is likely to ignore the alert when in a high workload situation [36]. Due to this shortcoming, critical alerts are to be combined with an indication that is not overwhelming for the user. If it is a critical alert, only one piece of information can be visualized at a time or the designer risks causing cognitive capture [34].

3.1.3.2 Indication. Indication alerts can be broken down into primary and secondary indication. Primary provides the main information to the user, the secondary provides auxiliary information which is conveyed to the user by the behavior of the display.

Figure 16

Indication Display Type

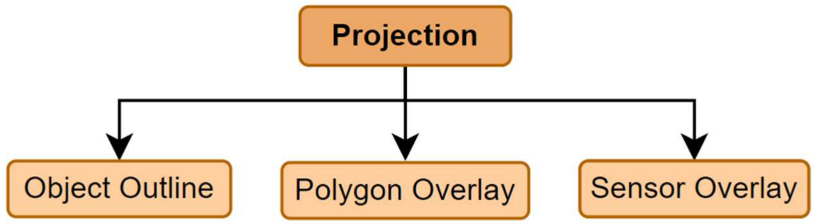


The term “primary” indicates that the display can exist without additional information being necessary. For example, the numerical value of altitude can be presented to the pilot and provide all the information necessary for operations. Secondary displays are from the previous work mentioned, encompassing Tape, Bar, and Circular displays. Secondary displays provide additional information that is useful to the operator, however, are not inherently required for situational awareness. Continuing with the altitude example, a secondary tape display provides information on the change in altitude. A secondary display cannot exist without a primary display; but a primary display can exist without a secondary. Primary displays are then broken into either bounded or non-bounded displays. Bounded refers to information such as helicopter rotor torque which exists over a predefined interval. Unbounded refers to information that does not have a technical limit, such as altitude. Every aircraft has unique capabilities, and thus, the designer can not assume a specific region of altitude when designing a HUD. SME input can be utilized however, and this value could then be treated as a bounded piece of information.

3.1.3.3 Projection. Projection displays refer to information that is conformal with the user’s environment. This is the most difficult visualization method to implement, for a number of reasons that are discussed in the conformality section of this chapter and the results chapter.

Figure 17

Projection Display Type



Projection is broken into three different types. Polygon overlays refer to the projection of a shape overtop of an object in the environment. An example of this would be in maritime applications with reduced visibility. An overlay of a ship, or of the ships navigation lights, can be projected to enable the user to track the ship location even when unable to visually see the ship through hazardous conditions [37]. Object outlines refer to a similar technique, however only the outside of the shape is highlighted for the user. This draws attention to the real-world object without replacing the real-world object with synthetic shapes. This is a popular method of projection, utilized heavily in target cuing for AR military applications [30],[18]. Outlines are displayed to the user surrounding the object of interest, whether it be an object for a task or an enemy posing a threat. The third method of projection is sensor overlay which refers to a special use case of projection. This method involves presenting the user with video or other sensor data which either mimics or fully represents some form of the user's environment. An example to illustrate this is the concept of Night Vision Goggles (NVG). NVGs present the user with a video feed from a set of sensors that enable some degree of night vision. This thesis investigates a method for the implementation of sensor overlay that is discussed in subsequent chapters.

3.2 The IDEAS Framework

Interaction, Design, and Engineering for Advanced Systems (IDEAS) was designed originally during an effort with an interdisciplinary group, with the aim of ensuring that user needs, capacities, and limitations were taken into account during research of new technologies in the defense sector [33]. The application of IDEAS is an iterative process, with some stages taking multiple revisions before a capable product is ready for testing. In fact, the authors suggest that the I in IDEAS could even stand for *Iterative* due to the cyclical nature of the process.

Discussed in the following subsections is each of the stages of the IDEAS process. The integration of IDEAS in this project is further addressed in the results section of this thesis.

3.2.1 Needs Analysis

Needs analysis involves the gathering, or generation, of information about the user and contexts in which they operate. This first step can be accomplished in a number of different ways depending on the size of the project, budget, and time constraints. This thesis integrates the analysis technique of Goal Directed Task Analysis(GDTA) to identify the information that is relevant for the user. A GDTA may also be created in this stage

During this stage, SMEs are also identified that are used throughout the duration of this process. SMEs need to conduct of series of interviews and must participate in the creation cycle of the GDTA if one does not already exist that can be used.

3.2.2 Requirement Generation

Requirement generation is done by taking the needs specified in the previous stage and mapping requirements for the system based on these needs. SME input is critical in this stage, as the designer is not necessarily familiar with the environment, or may be unaware of external information not present within a checklist item. These requirements are mainly grouped in functional and nonfunctional requirements. Functional requirements are related to the functional aspect of the software, such as the necessity of environment conformality with the horizon line. Non-functional requirements refer to aspects such as storage and performance, such as the latency requirement for the EVS system.

3.2.3 Design/Engineering

Typically, an interdisciplinary team is developed in this stage with expertise in a variety of fields spanning from software engineering to human factors. A preliminary product is developed in this stage through an iterative prototyping process before moving on to the interface review.

The artifacts that are created in this stage can be static or dynamic versions of a wireframe or a mock-up of the product. A wireframe is a low fidelity representation, which demonstrates how systems interact and where items such as UI elements will be located. The mock-up is higher fidelity compared to the wireframe. This demonstrates something closer to what a final product may appear like to the user.

3.2.4 Interface Review

Interface review is the review of the preliminary designs by stakeholders and SMEs on the project, in addition to HF engineers. This design includes how the user will interact with the system. This stage being done early provides cost savings and time savings throughout the development process. Inconsistencies between stages are addressed in this stage before the product moves on to the implementation stage.

3.2.5 Implementation

Implementation is where the behavior for the gauges is developed based on what was decided in previous stages. This is where the primary development occurs on the software/hardware side the product. This stage in the process relies heavily on the software/hardware developers, however human factors is kept in the loop as consultants. Challenges are addressed by the team as they arise during the development process.

3.2.6 Evaluation

Evaluation of the system occurs through careful testing with the aid of SMEs that assisted in the design. Task analysis that was created previously can be used as input for the creation of test plans.

This stage relies heavily on real users interacting with the product that has been developed to get a true understanding of how the system will work once deployed. This allows bugs, human factors issues, and general problems with the product to come to the surface before it becomes an issue post deployment.

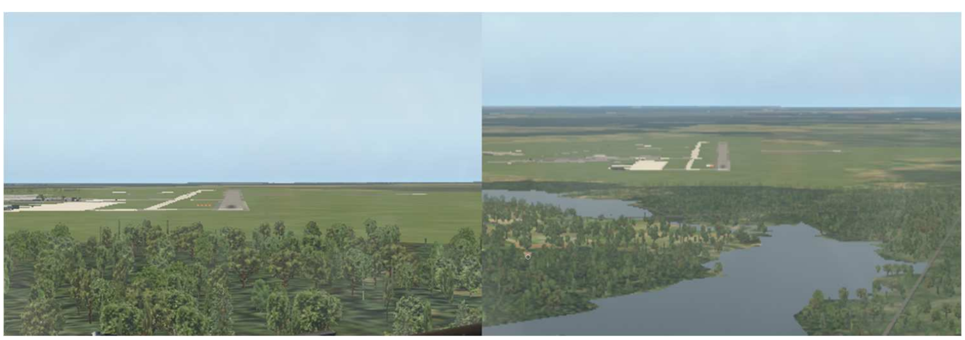
3.3 Conformality

Within a HUD environment there exist two types of conformality. Both types of conformaltiy are achieved by aligning the coordinate system of the virtual and external environment. The persisitence of this conformality is where the differences exist. The first type of conformality which is discussed in the results chapter is achieved by aligning a texture with the external environment and matching its behavior with the environment. This type of conformality can only be used when the projection visualization is not going to change shape. The FPV for example, is always a vector, and will not change shape as it moves in the HUD.

The second type of conformality is coordinate projection, in which the shape of the object in the environment continually changes. This is more difficult to achieve compared to the first type of projection. This was very critical in the design of the runway/helipad outline system. As the pilot flies the aircraft, the size of the helipad and runway changes due to the viewing location changing. SME input indicated that pilots utilize this change in sight picture to gauge their glidepath respective to the runway during the approach.

Figure 18

Change in Sight Picture Comparison: Low vs High Approach

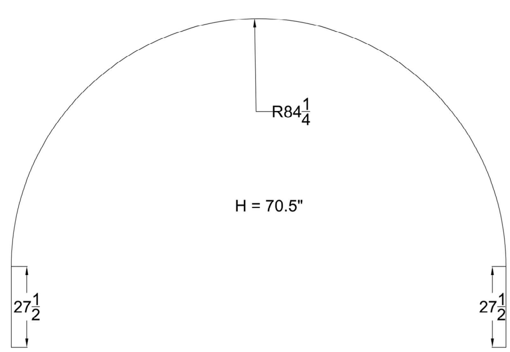


Higher altitudes cause the runway to appear smaller, whereas lower altitudes cause the runway to appear larger. The runway also changes shape based on distance. This is seen in figure 18 above by the approach into Atlantic City International Airport runway 31. The left approach is too shallow of a glidepath, versus the right which is the correct glidepath as indicated by the glidepath indicators on the left side of the runway. This change in what is known as "sight picture" is critical and must be properly represented by the HUD symbology.

As mentioned, conformality with the outside environment is critical to the pilot's situational awareness. Previous work discussed the decision to utilize the Federal Aviation Administration's (FAA) Cockpit Simulation Facility(CSF) as the simulator of choice. The screen layout for the CSF layout can be seen below in figure 19.

Figure 19

Simulator Environment FAA CSF



Three projectors are centered in the middle of the 84.24" radius curved screen. Each projector has a slight overlap that is accounted for in the CSF's projector software.

As mentioned previously, conformality with the external environment is a critical tool to increase a user's SA. To accomplish this, the device being utilized for the projection must align the virtual coordinate system it is using with the coordinate system of the real world. These coordinate systems must be aligned, and then their respective behaviors must match to maintain conformality. If the user is operating in a spherical simulator such as in this thesis, the designer must create a spherical surface within the AR application and convert any projections to this spherical surface. This can be accomplished using the following equation(s):

$$u = Point\ To\ Project - Sphere\ Origin \tag{1}$$

$$ProjectedPoint = \frac{SphereRadius}{||u||} * u \tag{2}$$

'u' is calculated by subtracting the origin of the sphere from the point that needs to be projected. This leaves a vector that indicates both direction and magnitude of that point from the origin. To project that vector, it is then normalized to the radius of the sphere as seen in the equation above.

Assuming now that all points are projected properly, the coordinate system must then be aligned with the real-world coordinate system. This can be achieved by prompting the user to calibrate the system after the HUD has successfully been loaded. The user is given an input system that allows them to align a projection with an object in the real world, or by aligning the projection with a stationary marker in the simulator such as done in this thesis. This alignment technique will be elaborated on in the results section.

Behavior of the aligned imagery must then mimic the behavior of the real-world environment to stay conformal. For example, the horizon line discussed in the results chapter must rotate opposite the rotation of the aircraft to continue to appear conformal with the outside environment. Failure to do this causes a displacement between the actual horizon and the artificial horizon.

In this chapter,

1. A methodology has been developed to identify the critical components of checklists utilized in aviation, which are amenable to adaption for heads-up displays;
2. A framework has been developed for the design of an augmented reality heads up display for pilots to integrate information provided by the checklist at the appropriate time in the flight plan;
3. Established principles of interaction design have been utilized in order to prioritize, organize and present the information to the pilot to be easily understood, without distraction;

The following platform will demonstrate the testing of the AR system on simulated flight platforms.

Chapter 4

Results

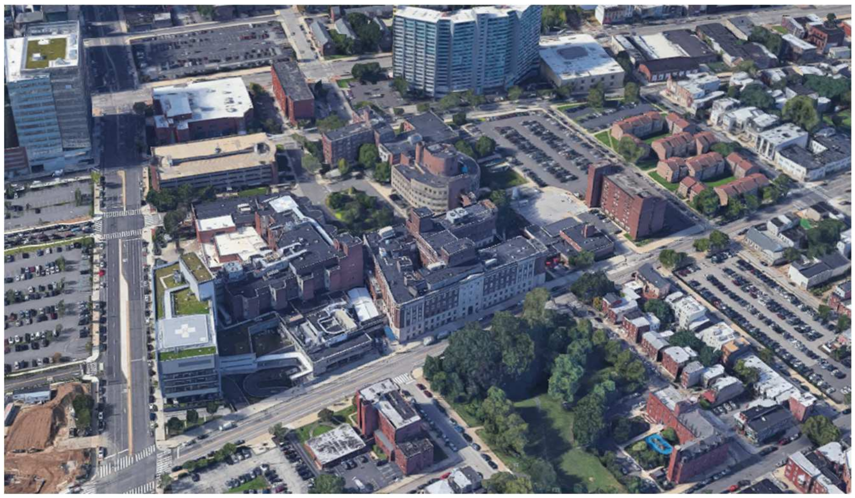
4.1 Environment Creation

As discussed in subsequent sections, the framework outlined in the approach chapter is demonstrated in a landing scenario due to the complexity involved in landing rotorcraft. This scenario required the creation of landing site models which mimic the real world, to provide a high level of immersion for the pilot when wearing the HUD and operating the rotorcraft.

The creation process utilizes RenderDoc, an open-sourced graphics debugger provided by the Massachusetts Institute of Technology(MIT). This tool allows for process injection, which enables the user to download high polygonal 3D models from any online mapping tool. Penn Presbyterian Medical Center was designated as a testing location due to the complexity of the surrounding area and the existence of two helipads on the building. Seen below in figure 20 is an image of the Penn Presbyterian Medical Center using the online mapping service.

Figure 20

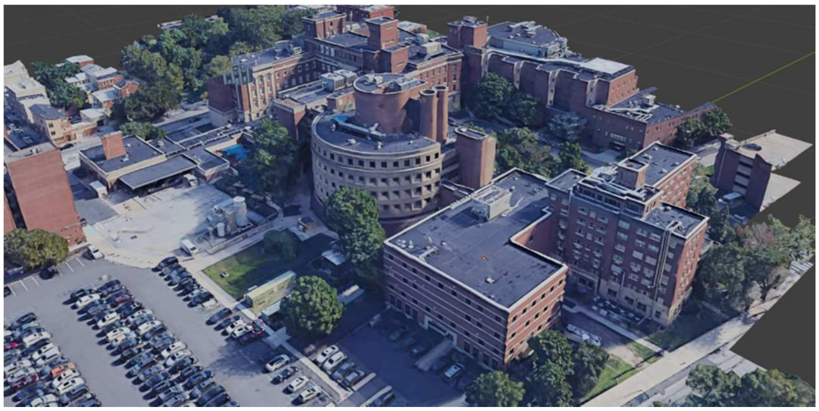
Penn Presbyterian Medical Center (PA39)



Shown below is the model taken from the online mapping software that has been extracted using the RenderDoc graphics debugging software and imported into Blender, an opensource 3D modeling tool.

Figure 21

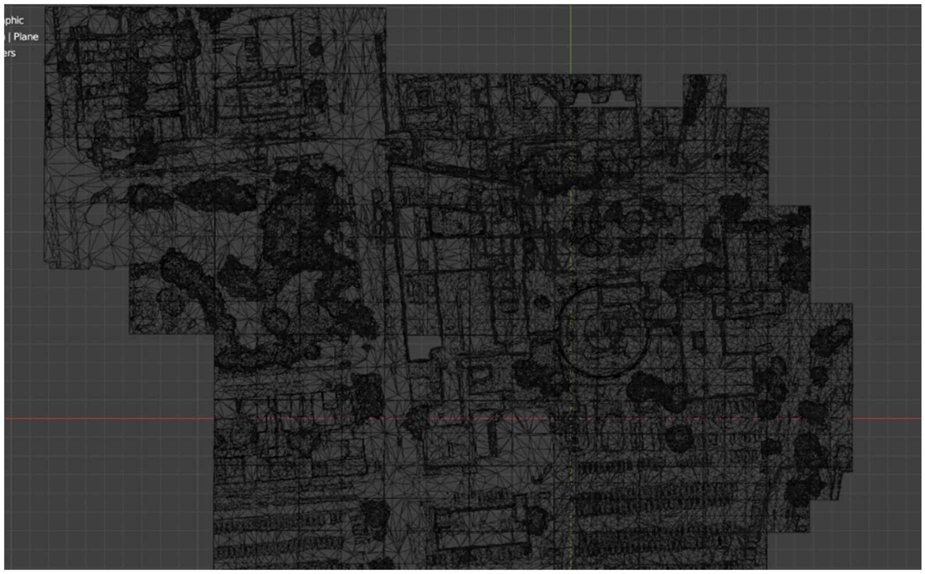
Penn Presbyterian Medical Center (PA39) Extracted



The extracted model contains a high amount of detail as well as a high amount of noise which is visible within the extracted model. The noise is a result of the 3D models being generated from height data captured via aircraft, which is then combined with 2D satellite imagery. A large amount of polygons present in the model extracted from RenderDoc are artifacts that result from noise. In addition to noise is unnecessary detail that is present within the model. The more detail present, the more polygons that are necessary to display that detail which exerts a larger load on the system rendering the model. A factor that had to be considered was which details were necessary and which were not. For example, signage that indicates to pedestrians that the building is an emergency room does not need to contain as many polygons as the features on the top of the building that the pilot will view when performing a landing. Shown below is a wireframe of the PA39 model prior to being optimized. This illustrates the dense clusters of polygons that are present in both detail and artifacts.

Figure 22

Penn Presbyterian Medical Center (PA39) Polygon Wireframe View

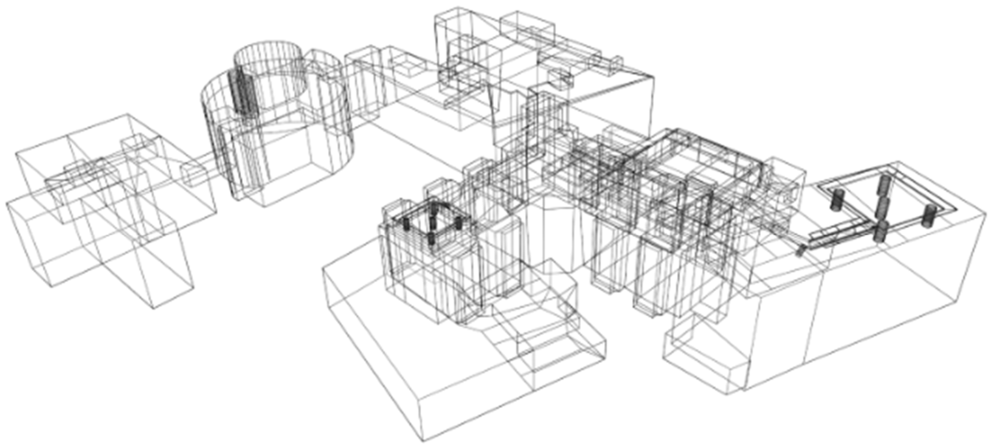


To run effectively in the simulation environment, models cannot exceed 20,000 polygons. This is a limitation of the computer that performs the X-Plane simulation rendering at the FAA's CSF. The model shown above has approximately 150,000 polygons which is over seven times the permissible limit.

Blender's high to low polygon baking functionality was used to reduce the amount of polygons present in the model. This was done in addition to the removal of non-critical scenery comprising the trees and roads. Shown below is a wireframe of the reduced polygon model.

Figure 23

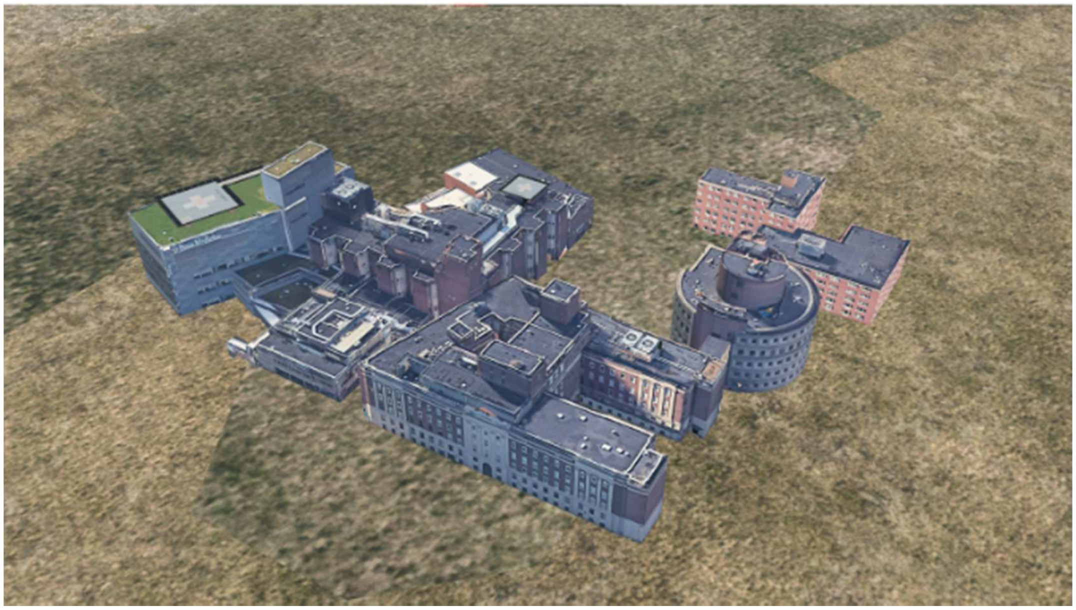
Penn Presbyterian Medical Center (PA39) Reduced Polygon Wireframe View



The completed model contains approximately 5,000 polygons, compared to the original extracted model which contained 150,000. This optimized model is also shown below after being imported into the X-Plane flight simulation platform. This import process is where the building is properly scaled and configured to fit into the surrounding scenery.

Figure 24

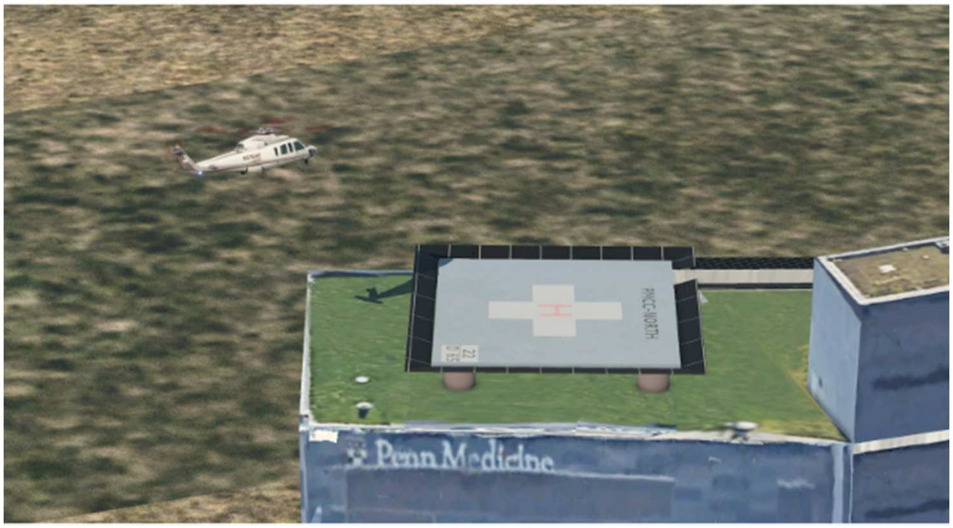
Penn Presbyterian Medical Center (PA39) Final Model



Below in figure 25 is an exterior view of an S-76 aircraft conducting an approach to the helipad on the completed Penn Presbyterian Medical Center building.

Figure 25

Penn Presbyterian Medical Center(PA39) Approach Exterior View



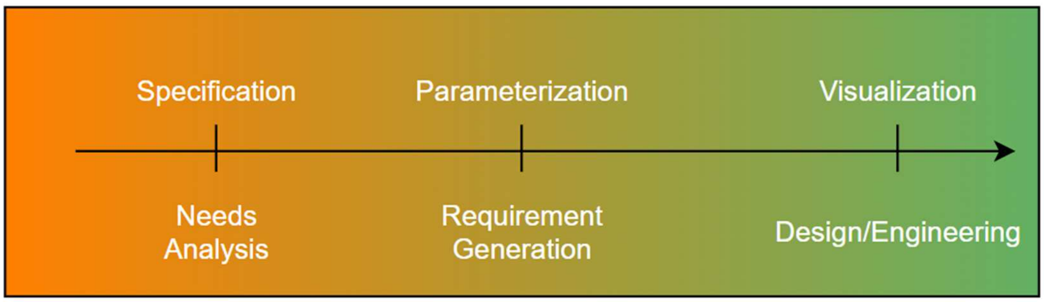
This process was also applied to the Golden Nugget casino and helipad which is located along the coast in scenic Atlantic City, NJ. This secondary location was chosen due to its proximity to already developed testing platforms at the Steel Pier and Atlantic City International Airport.

4.2 Incorporating Human Systems Engineering (IDEAS)

The framework designed in this thesis, described in section 3.1, relies on the IDEAS methodology for the entire process. Outlined in the following subsections is how the IDEAS framework persists throughout the visualization of information from checklists to HUD environments. Shown below in figure 26 is an overview of how the IDEAS framework is integrated in this thesis. The IDEAS framework is shown on the bottom of the figure, while the thesis framework methodology is depicted on the top portion where each category resides within IDEAS.

Figure 26

IDEAS Framework and HUD Visualization Techniques



4.2.1 Needs Analysis

Needs analysis is accomplished in this thesis during the specification stage, which overlaps slightly with the parametrization stage.

Needs analysis involves the gathering, or generation, of information about the user and contexts in which they operate. This thesis integrates the analysis technique of Goal Directed Task Analysis (GDTA) to identify information that is relevant for the user from the checklist to be visualized. GDTA enables the designer to segment the checklist information into SA levels which provides the designer with a better understanding of both the user as well as the environment being designed for. An established GDTA can be adopted from other sources, or an original GDTA can be conducted in this stage.

Domain experts are also identified in this step, as they are crucial guides throughout the parameterization stage of the project.

4.2.2 Requirement Generation

This stage relies heavily on the GDTA framework that was either created or adapted in the previous stage. As seen in figure 26, this stage is completed by the parameterization stage outlined in the approach chapter.

SME input is necessary in this stage, as the designer may not be familiar with the environment or may be unaware of external information not present in a checklist item. The GDTA previously identified is used to assign information from the checklist an SA level (I, II, or III) which informs the designer of how this information impacts a user. With assistance of an SME and the framework outlined in this thesis, the designer takes the information from the checklist and begins develop the user interface for the HUD. This begins the transition into the design/engineering phase of IDEAS which is where preliminary layouts for the visualizations are designed.

4.2.3 Design/Engineering

The process of design/engineering is the main component of this thesis, in which the type of visualization for every piece of information in the checklist is developed. The visualization stage accomplishes this portion of IDEAS. Information obtained from both the SME and the checklist is filtered through the framework detailed in the approach chapter and is designed for the HUD environment. This process, in addition to that of interface review, is a cyclical process that may take several iterations. A result found that is discussed later in greater detail pertains to the heading display. This display has already undergone multiple reviews and based on results found in this thesis may be changed once more before the project is ready for the final deployment.

4.2.4 Interface Review

The interface review process was conducted weekly with the FAA sponsor, where parameters such as size and location of gauges were adjusted as needed. Interface review involves user testing of the HUD and is the most time intensive phase of the project.

Pilots have specific expectations for how data is presented to them due to several factors, including training and previous experience. This also affects how they interact with systems in the cockpit. The HUD developed has undergone several interface reviews, including for example, user interaction with the HUD in previous work. During this previous work, the user interacted with the HUD using voice commands at one point. Unfortunately, it was discovered that voice commands posed multiple issues when operating in a noisy cockpit. A physical number pad was suggested as a solution. The mapping of these keys to commands went through the IDEAS process to provide the best experience for the user. After multiple interface reviews, a final design for the number pad was designated.

4.2.5 Implementation

Implementation is where the behavior for the gauges is developed based on decisions made in previous stages. Secondary displays, such as the heading for example, are animated based on design specifications set out by SMEs in earlier stages. As mentioned in the approach, implementation is covered by previous work and will not be discussed in detail here.

4.2.6 Evaluation

Evaluation of the framework developed in this thesis has been done using the SAGAT testing methodology discussed in later sections. This evaluation needs to be tested further by human factors engineers, but findings suggest that the preliminary work addressed by this thesis may increase the SA of a user in a head worn, HUD environment.

4.3 Goal Directed Task Analysis

Goal Directed Task Analysis is the main driving force for the needs analysis aspect of the IDEAS framework. As mentioned previously, the GDTA process was designed by Mica R. Endsley. This analysis technique was primarily used for analysis of commercial aviation pilots. This thesis uses the SA information created by Dr. Endsley for commercial aviation and applies it to the realm of rotorcraft and Head Up Displays. This is possible due to the large overlap that exists between fixed-wing aircraft and rotorcraft.

Outlined below in table 1 is the categorization of gauges that were implemented in the HUD, in addition to their corresponding SA levels as adapted by Endsley's work.

Table 1

HUD Gauges, Corresponding SA Level, and Display Types

Gauge	SA Level	Gauge Type
Altitude	Level 1	Indication
Groundspeed	Level 1	Indication
Airspeed	Level 1	Indication
Engine Torque	Level 1	Indication
Navigation Mode	Level 1	Indication
FMA	Level 1	Indication
Skid/Slip	Level 1	Indication
Heading	Level 1	Indication
Rotor RPM	Level 1	Indication
Radio Altitude	Level 1	Indication
Glideslope	Level 1	Indication
Localizer	Level 1	Indication
Enhanced Vision System	Level 1	Projection
Attitude(Pitch and Roll)	Level 2	Projection
Waypoint/Distance/Time	Level 2	Indication
Horizon Line	Level 2	Projection
Vertical Speed	Level 2	Indication Auditory
FPV	Level 3	Projection

A large subset of the gauges developed for the HUD are categorized as Level I SA information according to the GDTA for commercial aviation. This is indirectly addressed by Endsley in her 1998 study. For Level 2 SA information, it is necessary to go further than simple awareness of the elements that are presented. This level is based on knowledge of Level 1 information, but includes synthesis of multiple sources of information to determine the impact of this information on the system. A designer can provide the pilot with attitude information for instance; However, the pilot is responsible for interpreting and acting upon this information. How the pilot consumes this information reflects many factors, including training and prior experience. Another factor which potentially could affect pilot comprehension is current workload, which is an area of research that may be explored in future work. Therefore, most of the information displayed within the HUD environment is generalized Level I information, as the ability to design for a specific pilot is not possible at this time. Level III information is the highest level of SA and builds on both Level I and Level II. This level is achieved through full understanding of the status and dynamics of the elements, in addition to comprehension of the situation. This level projects the future actions of the environment, and as such, visualization of Level III information is incredibly difficult. The only gauge that is presented that can be categorized as Level III is the Flight Path Vector(FPV) gauge. This gauge relies on the pilot understanding the complex gauge behavior and being able to use this comprehension correctly. Due to this, training is required for the pilot to be able to fully synthesize and utilize this gauge in the cockpit environment. This gauge is considered Level III due to the projection the pilot can do with this gauge. If the gauge is aligned with the runway, the pilot knows they will intersect at that point in the future.

4.4 Checklist Implementation

The FAA operates a Sikorsky S-76 simulator at the William J Hughes Technical Center (WJHTC) located at the Atlantic City International Airport. This high-fidelity simulator is currently being developed by the FAA Cockpit Simulation Facility (CSF) and plans for flight testing are in place for Summer of 2022. The cockpit of the simulator is pictured below in figure 27.

Figure 27

FAA CSF S-76 Simulator

The CSF S-76 exterior was retrieved from the body of an S-76 helicopter that was in an accident that rendered the helicopter unable to fly. The new interior and interface have been designed by the CSF team at the WJHTC. Custom-bult screens were integrated with aircraft equipment already present in the wreckage, such as the collective and yoke controls.

The CSF S-76 simulator has the exterior of an S-76 aircraft; however, the interior and physics models are closer to the competing Augusta Westland AW-139 model. The pilot operates in the virtual flight simulator platform X-Plane 11, which is highly integratable with custom software and high-fidelity. The X-Plane 11 simulation performs with a physics model similar to an AW-139 aircraft. In essence, the aircraft is visually similar to an S-76 aircraft, however the operational experience within the simulation environment is closer to the Augusta Westland model of the aircraft. Due to this, the AW-139 operating handbook has been utilized in this section to demonstrate the efficacy of the framework previously mentioned.

A Category B landing checklist for the AW-139 rotorcraft is shown in the following table. This checklist has been chosen to illustrate the process outlined in the approach chapter due to the complexity involved within the landing procedure of a rotorcraft.

Table 2

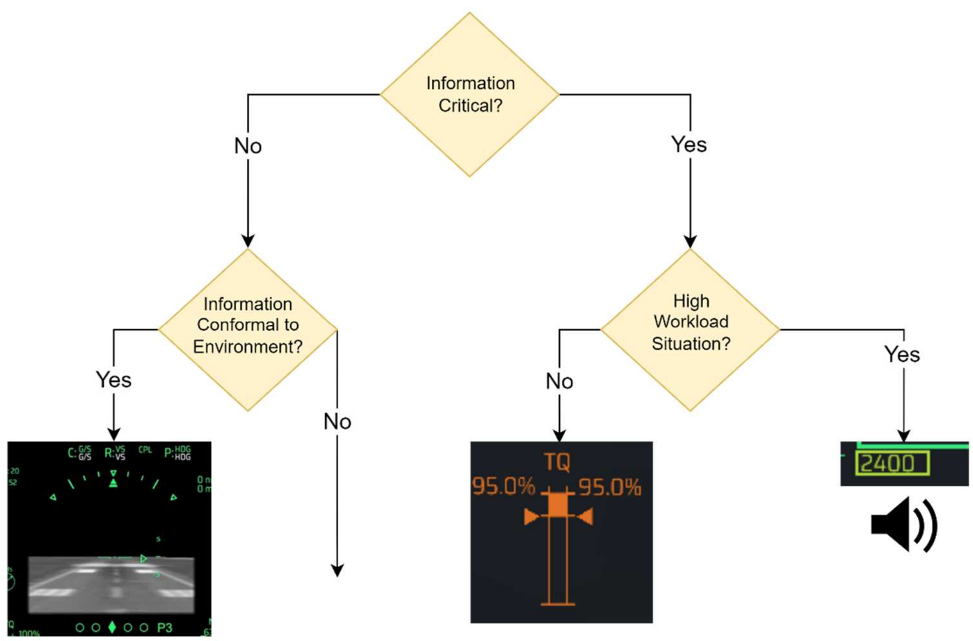
AW-139 Category B Landing Checklist

Checklist Item	Procedure
Pre-landing checks	Complete.
AWG switch	Normal.
Landing direction	If possible, orientate the aircraft for an approach into the prevailing wind.
Initial point	During the approach, reduce airspeed gradually to arrive at a position 200ft above touchdown point with a rate of descent of no more than 500fpm. Initiate a deceleration to achieve 30 KIAS at 50ft. At 50ft rotate nose up to approximately 20° to decelerate.
Landing	Continue the deceleration and descent to hover.
MFD PWR PLANT page	In hover check all parameters within normal operating limits and confirm no engine matching abnormalities.
Touch down	Maximum nose up attitude at touch down 15°. Apply wheel brakes, as required.
NOSE WHEEL lock	UNLK if ground taxiing is required.

Implementation of the procedure outlined above is shown below in figure 28 and figure 29. This flowchart is identical to the one shown in the approach chapter; however, it has been populated with the gauges from the HUD. Some gauges included, such as the skid slip indicator and altitude gauge, were developed in previous work and will not be discussed further in this thesis. They are included below to demonstrate the efficacy of the framework.

Figure 28

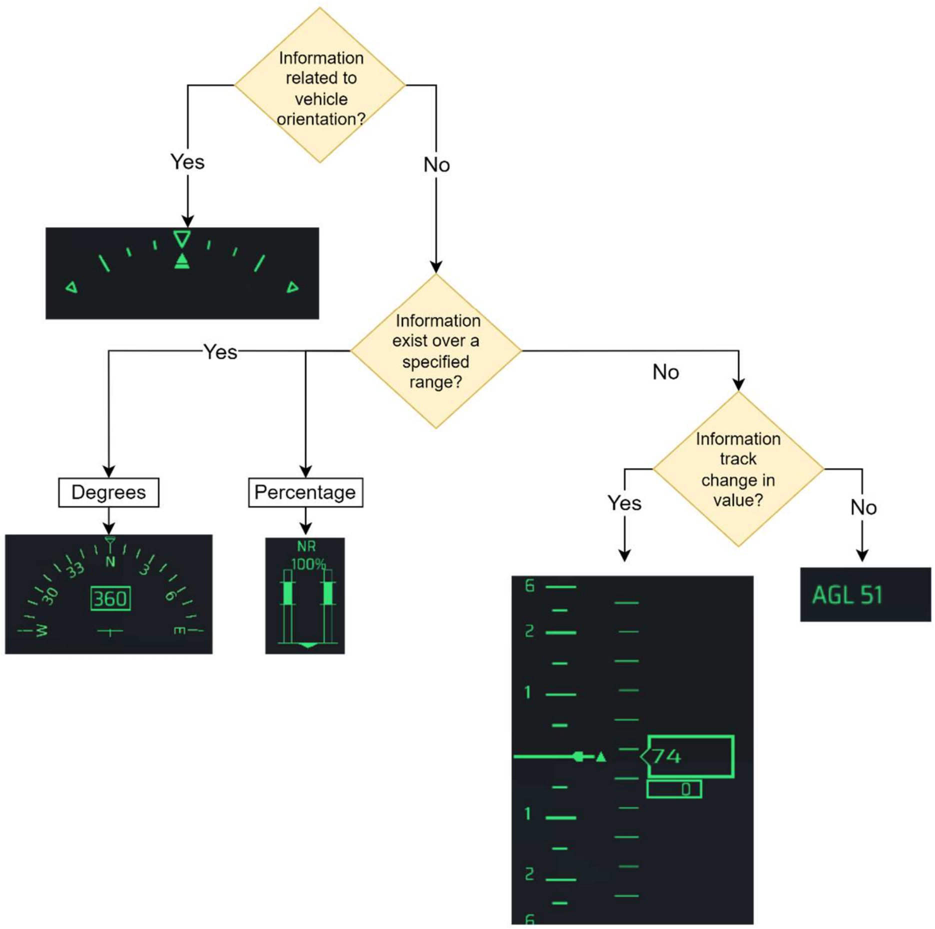
Results Within Flowchart: Critical/Non Critical



The figure above is populated with gauges from the framework outlined in the approach chapter. The conformal gauge shown above is a snapshot of the Enhanced Vision System, or EVS sensor which is a projection gauge. To the right of this is the torque and vertical speed gauges. As previously mentioned, the gauges that are presented in a high workload situation require auditory cues to capture pilot attention. Vertical speed is best displayed by changing the color and providing an auditory alert based on the current checklist being run by the pilot. During landing scenarios, 500 feet per minute was the threshold used as explained in subsequent sections.

Figure 29

Results Within Flowchart cont.



Shown above is the second part of the framework populated with additional gauges. Vehicle orientation is best depicted with a circular gauge. Shown above is the skid slip indicator which provides the pilot with an understanding of the tail of their rotorcraft with respect to the forward axis of flight. Information that exists over a certain range is depicted with either a circular or bar display. The circular display shown above is the magnetic heading, while the bar display is the engine RPM. Non bounded information, or information that does not exist over a specified range, is then either categorized as trend information or non-trend information. Trend information is best displayed using a tape display. Feedback from pilots indicates that a majority of pilots believe a tape display is essential for a pilot to have a full understanding of altitude information. Trend information provides a deeper understanding of the altitude, pushing the display from a simple level I to a level II source of information. Non trend information leaves only the simple indication displays such as the altitude above the ground as shown in figure 29.

The first stage in the pipeline is the development or utilization of an already designed GDTA to understand the information needs of the pilot. This step is crucial in the visualization of any checklist item. Utilization of the GDTA enables the designer to filter out what information is necessary to be presented, and what information is less critical for operations. For example, the second checklist item: "AWG – Normal". The designer follows the specification flowchart with SME assistance, and determines that this is considered a Level 1 information need.

The parameterization stage would lead the designer to providing a simple primary indication display to the user. This information, however, is not critical to operational safety of the rotorcraft. The designer is not aware of this until feedback is obtained from the SME. The SME informs the designer that the status of the AWG is considered auxiliary information and will not impact the safety of the landing procedure. With this iterative process, the designer can successfully narrow down what information is critical for display from the checklist.

Explained in the subsequent sections is the specific application of the framework to individual gauges and the resultant gauge type.

4.4.1 EVS System

During preliminary discussions with the project sponsor and SMEs, it was determined that during the landing phase of flight the pilot would need continuous reference to the ground. While not critical for landing, the system would need to be conformal to the environment to provide the pilot with an appropriate sense of distance from the ground.

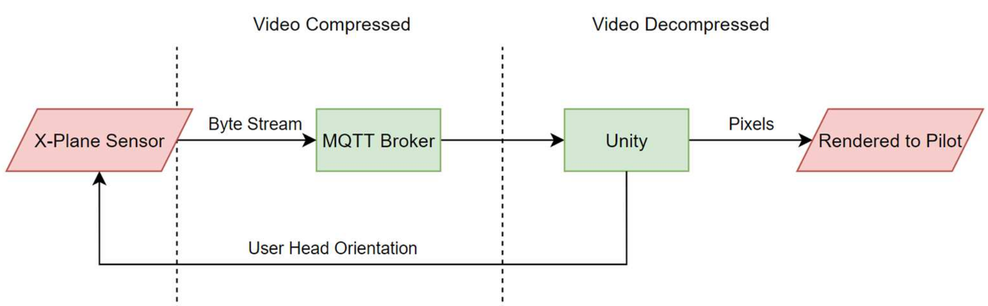
Figure 30

EVS Visualization

Seen above in figure 30 is a capture of the pilot taking off the runway and the associated imagery generated by the model. Utilization of the framework determined that the best mode of notification for this information would be projection due to the requirement of environmental conformality. The EVS system developed in this project is very similar to the concept of NVGs discussed previously. However, due to the simulated environment, the sensor providing the information is simulated. Therefore, the EVS imagery depicted in figure 30 has both a grain and grayscale modification to mimic the noise expected in a true EVS sensor. The modularity of the system allows real world sensors to be integrated into the system when the HUD is deployed in a non-simulated rotorcraft.

Figure 31

EVS Implementation Overview



The implementation for the EVS system is shown above in figure 31. As mentioned, EVS sensors are a combination of one or more sensors mounted on the outside of the aircraft similar to the concept of NVGs. To mimic this in a virtual environment, a model of an aircraft sensor must be simulated. A client was created with another version of X-Plane running identical to that of the original simulation. This simulation changes viewing angle based upon the viewing angle of the user's head orientation. The head orientation is provided by the internal tracked pose driver of the HoloLens 2 and is communicated over a broker identical to the one that transfers the sensor data. The imagery viewed by the second version of X-Plane is then compressed and transferred through an MQTT broker to the HoloLens, where it is decompressed and processed before being displayed.

Transferring video data from X-Plane 11 to the the HoloLens 2, presents a unique set of challenges. One such challenge is the need for asynchronous loading. Unity processes data at fixed intervals and has difficulty receiving messages that do not align with this interval. Two options were available, align the interval of the data being sent with the interval of unity, or enable unity to load this data asynchronously outside of its normal interval. The asynchronous method was implemented to prevent latency in the lens. If the video stream is slowed due to network issues, asynchronous data will not slow down the lens while it waits for the data to be sent. This method enables the environment to load the data it has available and pause until new data is present for loading.

The second issue that arose is that of data transfer speeds. One of the reasons the HoloLens was chosen is due to the wireless connection which would enable the user to be untethered compared to similar devices on the commercial market. The HoloLens experienced latency when attempting to process over the wireless network due to the large amount of data that must be transferred to update both the gauges as well as the video stream. This was prior to the introduction of the head orientation tracking system. To address this problem, an ethernet adapter was connected to the USB-C port on the HoloLens which provided the appropriate data rate needed to support the live video and data streams.

4.4.2 Vertical Speed

Vertical speed measures the trend information of the pilot's change in altitude. The vertical speed indicator is a critical gauge when conducting any landing in a rotorcraft. Maintaining a constant vertical speed enables the pilot to conduct a safe, controlled, stable landing.

Checklist item 3 is conducted by the pilot when they begin to set up for their landing zone. This is the "set-up" stage of the landing. This checklist item is shown again below for reference:

During the approach, reduce airspeed gradually to arrive at a position 200ft above touchdown point with a ***rate of descent of no more than 500fpm.*** *Initiate a deceleration to achieve 30 KIAS at 50ft. At 50ft rotate nose up to approximately 20° to decelerate.*

The pilot configures the aircraft and begins to reduce airspeed anticipating the need to begin their descent.

The checklist item indicates that the pilot can descend no faster than 500 feet per minute. SME input on the development of this checklist item indicated that a descent faster than 500 fpm is considered an "un-stabilized approach". It is critical that this is avoided. Knowing this information that was found during the specification process, the designer now knows that the pilot should be alerted of descent that is faster than 500 feet per minute.

Landing and take-off are task-saturated scenarios for rotorcraft pilots. Vertical speed must then be alerted to the pilot in two different manners, a color change to obtain the pilot's attention and auditory as a second means of notification due to the task saturation. This is seen below in figure 32. In addition to the color change is the inclusion of an auditory alert which is directed to the left and right ear of the user wearing the HoloLens. One of the many beneficial features of this compared to the already established cockpit auditory indication is that only the user wearing the lens can hear the alert. If a pilot and co-pilot were wearing different lenses, one user can be indicated while in landing mode while the other user is not notified if they are conducting a different task.

Figure 32

Vertical Speed Coloration

To obtain the non-critical visualization method, the flowchart must be followed for a non-task saturated and non-critical situation. In doing so the designer determines that a tape indication display is the best method of visualization for a non-critical situation. This is seen to the left of the text as denoted by the arrow which tracks the trend information for the change in vertical speed. This is combined with the primary indication of the numerical value to the right of the tape display.

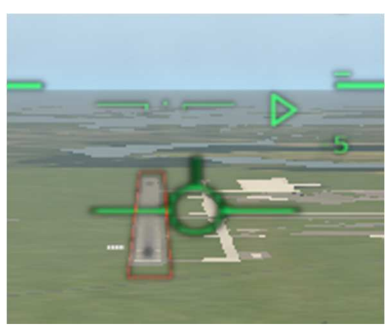
4.4.3 Flight Path Vector

As mentioned previously, all information that may be necessary to conduct a checklist item may not be apparent during the initial investigation. The category B landing checklist makes no mention of utilizing the FPV to conduct a landing, as it is not information that is directly necessary. SME input during the specification stage of previous items indicated that having a visualization of the velocity of the aircraft would be immensely useful when landing. The specification stage of the design of this gauge indicates that it must be a projection technique.

The Flight Path Vector(FPV) informs the pilot of the velocity vector of their aircraft. This provides information such as the glidepath of the rotorcraft, which is a critical piece of information during the landing stage of flight. The pilot will fly direct to the runway if they align the FPV instrument with the runway. The specification stage for the FPV determines that the FPV is considered Level 3 information due to it being utilized for future projections.

Figure 33

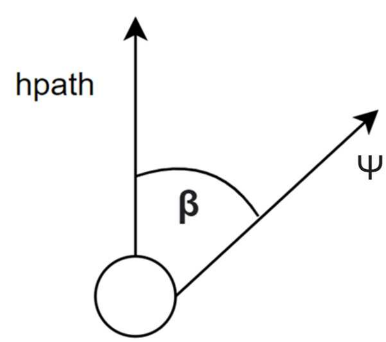
Flight Path Vector During Landing Phase



The SMEs indicated that conformality of the FPV is critical for the pilot to fully utilize the element. The FPV unlike other conformal imagery does not have external information in the environment that it must align with, as the velocity is not visually apparent to the user. The FPV must rotate around the user, unlocked from the user's head orientation unlike that of the indication gauges.

Figure 34

Flight Path Vector Data References



The behavior of this projection element is like that of the horizon line. A spherical object was created in the virtual environment like the generation of the aforementioned horizon line. Data references provided from the external simulator provided the necessary information to calculate the FPV orientation. Seen in figure 34 is an overhead view of the rotorcraft. Two variables are utilized to calculate the FPV rotation. The vertical rotation, or pitch, of the FPV is provided by a single variable known as 'vpath' which is measured in degrees from the z axis. The horizontal rotation shown above is calculated using "psi" and “hpath”. “hpath” is the heading the aircraft is currently flying. Psi is a measure of the true heading of the aircraft, which is measured in degrees. Subtraction of “hpath” from “psi” gives the beta value, which is the rotation from the current heading of the aircraft’s horizontal velocity.

The sphere object in the virtual environment is then rotated in both the vertical and horizontal directions by the hpath and beta variables respectively. This generates a conformal FPV for conducting a landing in the rotorcraft.

4.4.4 Horizon Line

During the needs analysis stage of development, SMEs noted that reference to the horizon is an information need required to conduct a landing in a rotorcraft. It was also indicated that this is critical when a pilot is operating in deteriorated conditions.

4.4.4.1 Horizon Line Conformality. To obtain a conformal horizon line, the environment designed in Unity must be equivalent in both shape and behavior.

Figure 35

Top Down View of Horizon Line in Unity

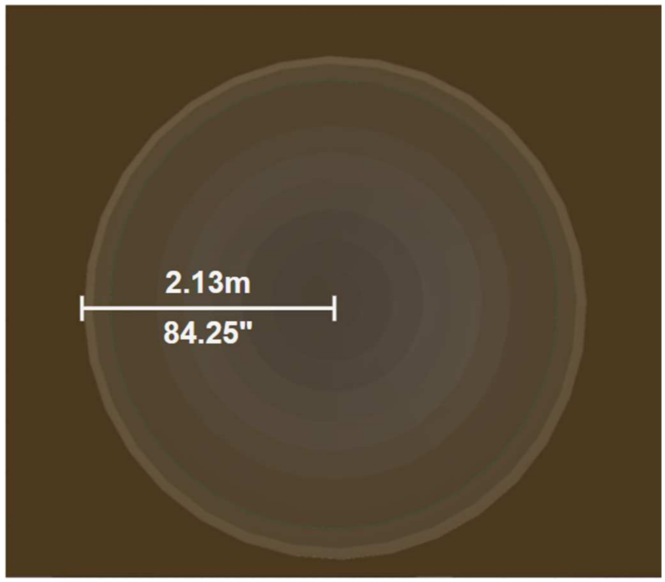


Figure 35 denotes the top-down view of the horizon line in Unity. This sphere is created in Unity by assigning a texture to a sphere with inversed 71ormal, which enables the camera that resides inside of it to render the object. The sphere created in the virtual environment is the same size as the outside environment that the user will operate in.

The system must be calibrated by the user to line up the coordinate systems of the virtual environment and the outside simulator environment. This is done using a wireless number pad connected to the Microsoft HoloLens. The user is given a set of controls that enables translation, rotation, and pitch offsets to be added to the conformal imagery spheres in the Unity environment. When the HUD first loads, the user utilizes the provided controls to align the virtual coordinate system with that of the external cockpit environment. It is critical that this is done when the user is level and stationary.

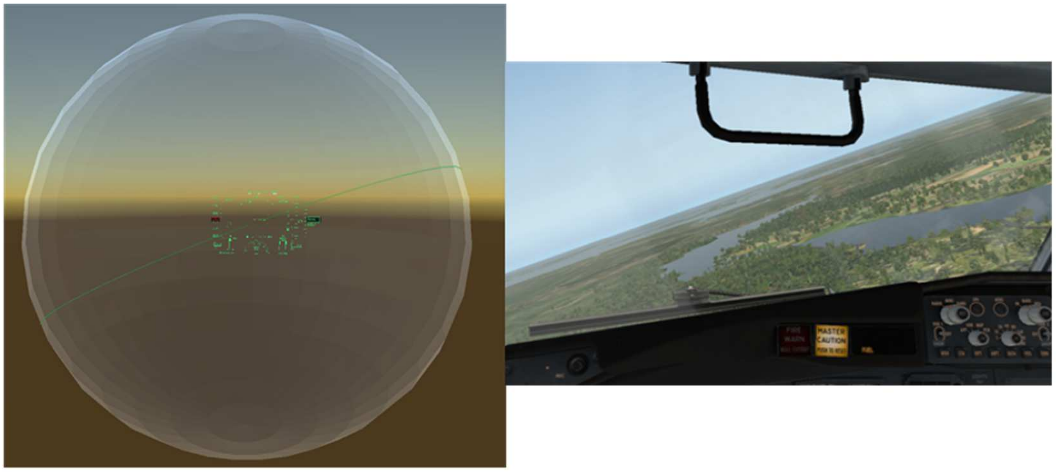
Figure 36

HUD Display with Conformality

As mentioned, the behavior of this object in the Unity environment must match that of the outside environment to maintain the established conformality. To achieve this, the horizon line object is manipulated in the x, y, and z axes. This data is provided from the data broker which is outlined in previous work. When the aircraft changes pitch, this correlates to a change in pitch in the x environment. The y axis is correlated with the heading of the aircraft, and the z is correlated to that of aircraft bank.

Figure 37

Horizon Line and X-Plane Simulation Conducting Right Bank



As seen above in figure 37, the aircraft is performing a right bank. This bank is then translated to the sphere object in Unity to ensure conformality is kept. When the aircraft performs a bank, this rotation is applied in an equal and opposite direction. This is done by negating the value being provided to the Unity environment within the HoloLens.

4.4.5 Runway/Helipad Outline

Runway and helipad outlines are extremely similar to that of the FPV and EVS systems. To land on a runway, especially in deteriorated conditions, pilots must have awareness of where is runway is located. SMEs indicated during the needs analysis stage that this system would need to be conformal to the environment for it to be of use to the pilot. This led for the designer to create a projection display for the information, specifically that of a polygon overlay. These can be seen in figure 36 above as the outline surrounding the runway.

4.4.5.1 Runway/Helipad Conformality. Runway and Helipad conformality fall under the secondary type of conformality which involves the projection of coordinates onto a surface. As mentioned, this is due to the continually changing shape of the indication.

First, a list of coordinate points are generated for each line that must be drawn to the user. In the case of runway and helipad outlines, a table of latitude, longitude, and altitude are stored for each point. Google earth was used to obtain this data alongside information provided by FAA Airport/Facility Directories.

A vector is calculated by taking the great circle distance from each of these points and the location of each runway coordinate. In addition to this, the bearing to this coordinate is calculated with the rotorcraft considered as the origin.

The altitude of this point must then be considered. The rotorcraft altitude is subtracted from the altitude of the point to treat the user in the virtual environment as the zero point. This value is used as the y value of the vector mentioned previously, which is then rotated around the y axis to generate a vector in the virtual environment which is aligned with the outside environment.

As with the previous method of conformality, this point is then normalized to the spherical object to be completely conformal with the outside environment. These points are drawn utilizing Gl.Lines which is a lightweight way to quickly render lines in the Unity engine.

The result is a conformal runway outline which changes shape as the user moves around in the simulation environment.

4.5 SAGAT Testing

As discussed in the background chapter, SAGAT testing is a form of testing designed by the creator of the GDTA framework, Mica Endsley. SAGAT is a testing framework for evaluating the effect of a tool or system on a user's SA. This thesis integrated a modified version of SAGAT analysis to determine the efficacy of different forms of gauge visualization.

This testing was conducted with three pilots and seven students. The results for each group are kept separate due to the difference in experience and background knowledge. One critical difference in group two is the lack of knowledge regarding operating aircraft. Due to this constraint, only one gauge was visualized for the participants in group two during each trial, aiming to reduce the cognitive overhead required during testing.

Participants in group one were placed in the FAA CSF's S-76 simulator, and instructed to conduct a landing at the Penn Presbyterian Medican Center helipad(PA39) from a 3nm final approach. Participants in group two were placed in front of a laptop running the same software. Group two was started on a 3nm final into ACY runway 31, and instructed to perform a standard landing. Students were given a fixed-wing model to fly due to the lack of experience operating aircraft.

During testing, participant's screens and the simulator were randomly paused and hidden, and they were probed with questions to gauge their current SA for different visualization methods as outlined by the SAGAT analysis framework. The measurement of a participants SA was estimated by calculating the percent difference between the ground truth value of a gauge, and the participant's current estimate for what the gauge value currently is during the paused period when the screens were hidden. Compiled below in table 3 is the average of the seven participant's percent differences between the ground truth and their understanding of the current gauge value. Compiled in table 4 is the average of the three pilot's percent differences. These results suggest that the lower the average error, the more likely that the visualization may increase a user's SA.

Table 3

Results from Modified SAGAT Testing – Students

Visualization Test	**Mean Percent Difference**
Coloration of Vertical Speed with Audio Cuing	7.8
Coloration of Vertical Speed without Audio Cuing	55.1
Altitude with Tape	29.2
Altitude without Tape	16.6
Rectangular Heading Display	1.8
Circular Heading Display	30.2
Bar Display Engine RPM	3.2
Dial Display Engine RPM	8.3
Heading without Circular Display	6.9

Table 4
Results from Modified SAGAT Testing – Pilots

Visualization Test	Mean Percent Difference
Coloration of Vertical Speed with Audio Cuing	2.5
Coloration of Vertical Speed without Audio Cuing	13.3
Altitude with Tape	1.4
Altitude without Tape	12.6
Rectangular Heading Display	1.6
Circular Heading Display	2.1
Bar Display Engine RPM	1.8
Dial Display Engine RPM	14.5
Heading without Circular Display	2.6

Pilots showed an overall lower error compared to that of the students that participated in the testing. All pilot percent differences are below 20%, while the student differences go as high as 55%

The results found a lower average percent difference between the coloration of vertical speed with audio cuing than the vertical speed without. This is supportive of the framework design in which critical information would be displayed to operators during task saturated scenarios. In addition to this, 67% of of the pilot surveyed stated that they would likely pay attention to auditory alerts when dealing with task saturated scenarios such as those experienced during this testing. These two results suggest that audio cuing may be beneficial for notifying a pilot of critical information.

The next result was not as expected, a larger difference existed with the altitude display that utilized a tape vs the altitude display that did not use a tape. A possible reason for this is due to the inexperience of student participants with regards to piloting aircraft. Input from the human factors experts on the project hypothesize that the additional information provided by the tape display likely provides more clutter than benefit to the participants.

Figure 38

Altitude Tape Display vs non-Tape

Pilot feedback during the survery favored the tape display, citing the decades of industry use on primary flight displays (PFDs) and pilot familiarity with the presentation of trend information. The pilots that participated in the testing demostrated a difference of approximately 12.6% for the non tape display, and a difference of only 1.4% with the tape. This more closely aligns with the pilot feedback that suggests the tape display provides benefit to SA.

A surprising result was that of the rectangular display compared to the traditional circular heading display currently being presented at the bottom of the HUD. Currently, the HUD displays a circular gauge for the heading due to SME provided suggestion on the design during the requirements generation portion of the project.

Figure 39

Circular vs Rectangular Heading Visualization

The testing conducted for this thesis found a percentage difference of approximately 2% with rectangular magnetic heading, versus an average of 30% with the circular heading. This finding aligns with the testing done with the pilots, in which the circular heading showed an error of 2.1% while the rectangular heading only showed an error of 1.6%.

One potential factor that may be influencing the difference is the location of the visualization. The circular display is located at the bottom of the user's FOV while the rectangular display is located at the top of the user's FOV. Future work may test the location of the visualization to verify if it is the rectangular display, or if it is the location of the rectangular display that appears to increase a user's SA. This is an extremely interesting finding however further research is necessary to make conclusions regarding the effect of circular versus rectangular displays on a user's SA.

Bar displays proved to be superior to that of dial displays, as was expected from SME feedback conducted earlier in the design process. SMEs noted that the dial design was difficult to read compared to the bar display.

Figure 40

Dial vs Bar Display

Multiple participants in the trials noted that they were "Unsure which part of the display I should be looking at" when using the dial display versus that of the bar display.

Finally, the difference between the heading display with a circular display or without a circular display. Heading with and without the circle seems to have had a similar issue as that with the tape display, students were unsure of what they were supposed to be looking at. The percent difference for the heading without a circle was better compared to that of the heading with a circle. This is believed to be the same as with the tape display, the more information that is displayed to someone unfamiliar with a HUD, the lower their SA appears to be.

Figure 41

Heading with Circular Display vs No Circular Display

The pilots had a difference of 2.1% for the heading with a circular display, versus 2.6% for the heading without. It is likely that an individual trained on HUD systems and with knowledge of aviation is more likely to be aware of gauges that display trend information, i.e, information that shows how quickly a parameter is changing.

More trials are necessary to definitively answer the question of what visualization is most appropriate for each information type. This thesis lays the groundwork for the framework of visualization of information from a checklist to the final HUD environment. It then suggests, based on prior development and a small subset of trials, some findings that may hint towards the visualization that may be appropriate for different information types. The sample size used is not nearly enough to make a conclusive argument and only suggests that some correlation may exist between visualization methods and effects on a user's SA. In addition to the sample size is the background of the participants. All of the participants were students, and while some had experience wearing AR HUD displays, none of them had experience operating aircraft. Finally, is the lack of a full fidelity simulator which would further the user's immersion and likely increase the reliability of the results. Future work is required in order to concretely make these claims previously stated and would be an excellent area for experimentation in collaboration with human systems engineers.

4.6 Pilot Information Survey and SME Feedback

A survey was sent out to a group of pilots through the FAA project sponsor, and 7 responses were received. There was over 60,000 hours of flight time across the group of pilots, spanning over 50 years of service. These surveys were focused on notification methods for a head worn HUD system. Participants were asked to rate a series of questions with 1 indicating *do not agree*, and 5 indicated *agree strongly*. Pilots were also requested to give any input or feedback they felt pertinent to the design and application of a head worn, HUD within an aviation cockpit. Outlined below in table 5 is a summary of the average results. Some select questions were asked twice, the second question ensuring confirmation that the information questioned is accurate. The results discussed below assume that an answer less than three indicates *do not agree*, while an answer greater than three indicates *do agree.*

Table 5

Summary of Survey Results

Question	Mean Response
Pilot total time	19,300 hrs
Horizon line must be conformal	4.8
Auditory alerts are the best way to alert a pilot of a problem	3.9
A pilot must be aware of rate of descent(vertical speed) when landing	4.9
Critical information being displayed takes priority over noncritical information	4.7
Likely to pay attention to auditory alerts when dealing with task saturated situations	3.9
Head worn HUDs have use in the cockpit	3.9
Heading is best displayed using a circular gauge	3.4
Altitude display is useful without a tape that displays how quickly altitude is changing	2.9
I often use checklists when operating an aircraft	5
During landing, I'm more likely to ignore auditory alerts from the aircraft	2.4
During a task saturated situation, I'm more likely to remove the head worn display to better focus on the task	3.2
Red is the best color to indicate a critical problem with an aircraft instrument/system	4.1
Pilots should be notified of localizer deviations when landing the aircraft	3.9

Question	Mean Response
Pilots should be able to quickly disable the HUD when flying	4.8
Rate of descent is not important when landing an aircraft	1.4
Pilots should be notified of glideslope deviations when conducting a landing	4.3
Visualization of terrain and obstacle sensors on a head worn display would provide benefit to a pilot	3.8
Aircraft roll should be displayed using a circular gauge	3

The first and arguably most critical question asked is regarding the use of checklists in the cockpit. The average result for all pilots surveyed was a five, indicating that checklists are always used in the cockpit. This supports the intial research and information provided by SMEs regarding checklist use.

The conformality of the horizon line had a very positive result at an average result of 4.8. This indicates that for the horizon line to be useful to the pilot, it must be conformal to the pilot's environment.

Pilots indicated that altitude display without a tape display does not have much use in the cockpit. The survey provided an average result of 2.9. One pilot indicated in the comments that current convention uses a tape display on aircraft primary flight displays, and pilots are already accustomed to the display. This supports the findings with the pilot trial, in which the pilot had a larger percent difference without the tape display than with.

A surprising result found from the surveys is that pilots reported they are likely to pay attention to auditory alerts during landing. This question was repeated twice to ensure the reliability of the answer. When questioned about this result, SMEs indicated that pilots receive auditory warnings for critical dangerous flight characteristics such as a stall, in which the aircraft is no longer producing enough lift to fly. Another system, known as the Terrain Avoidance and Warning System(TAWS), provides auditory alerts when the aircraft is within dangerous proximity to terrain. These two systems are critical for a pilot to be aware of and so an audible alert is issued when required.

In regards to alerting the pilot of critical flight characteristics, pilots indicated that red is one of the best colors to use. The average result for this was 4.1. One pilot left a comment on his survey referencing the federal code 14 CFR 25.1322. This code refers to three alerting levels: warning, alert, and and advisory. For the highest level of notification, red is to be used to alert the pilot to what issue is occuring. This supports the framework developed in this thesis.

One of the most interesting findings is that four of the seven (57%) pilots surveyed, when prompted about heading being best displayed with a circular gauge, rated a 3 which is the neutral/indifferent rating. This aligns closely with the results found from the student trials in which rectangular display may have provided a higher SA for the user compared to the currently implemented circular display. One pilot who provided feedback on his survey mentioned that “Other huds have [a] horizontal number line with heading and that works fine”.

This pilot also left comments on the survey he completed. He noted that HUDs he has used previously self decluttered, meaning that depending on the phase of flight he was in the HUD changed appearance or hid unnecessary information. This area has potential to be extremely useful for some form of AI to toggle gauges based on the current environment/user workload.

Finally, vehicle orientation has provided numerous results in this thesis. The framework developed in this thesis suggests using a circular display to indicate to the pilot of their vehicle orientaition. This survey asked the participants if the best way to display orientation is with a circular gauge. The average answer was 3 which is interpreted as neither supporting nor dislikling this visualization method. This result, combined with the results about the heading, suggest that a circular visualization method is not the best suited method for visualization of vehicle orientation. Additional research is needed to determine the optimal visualization method for this.

Chapter 5

Conclusions

Nearly a hundred years have passed since the checklist method that began as a necessity in the aviation industry, has reached almost every human endeavor that requires complex, sequential and routine tasks that have significant consequences to health and human safety if mistakes are made. Within the scope of developing a checklist embedded in a head mounted display for rotorcraft pilots, this thesis has examined formal methods for determining the requirements for situational awareness and adapted them into a human-systems engineering framework to create an appropriate environment for visual display.

The specific objectives of the research work are revisited below:

1. Identification of the critical components of checklists utilized in aviation, which are amenable to adaption for heads-up displays;
2. Development of a framework for designing an augmented reality heads up display for pilots that can integrate information provided by the checklist at the appropriate time in the flight plan;
3. Utilization established principles of interaction design in order to prioritize, organize and present the information to the pilot to be easily understood, without distraction;
4. Testing the AR system on simulated flight platforms.

The specific contributions outlined in this thesis are:

1. Integration of previously created human system engineering framework and analysis techniques, specifically that of IDEAS and GDTA.
2. The development of a framework for the presentation of checklist information to a rotorcraft pilot, compromising the stages of specification, parameterization, and visualization adapted from previous work conducted.
3. Visualization of checklist information at the appropriate time to enable the pilot to operate the rotorcraft effectively.
4. Testing and verification of the methodology outlined in the approach using a modified version of SAGAT testing.

A survey was conducted with a group of pilots with over 60,000 hours of combined flight experience. Pilots provided feedback related to the framework designed in this thesis. The survey indicated that:

1. Altitude display is not useful without a tape display to show trend information
2. The horizon line must be conformal for it to be of use to the pilot
3. Pilots are likely to pay attention to auditory cues
4. Red is an adequate color to indicate system abnormalities to pilots
5. Vehicle orientation is not best displayed with a circular gauge

Using the framework developed in the approach, a landing checklist for an AW-139 aircraft has been reconstructed within a HUD environment. These visualizations were then tested on a group of undergraduate students and an FAA pilot with positive results that suggest it may positively benefit a user's situational awareness.

Results found during the testing are the following:

1. Audio cuing appears to increase a user's SA
2. Trend information being displayed with a primary indication appears to increase a user's SA
3. Vehicle orientation may not be best displayed using a circular gauge
4. Rectangular heading displays appears to provide better SA for a user than circular heading displays
5. Bar displays may provide better SA than dial displays

A recommendation for future work is the integration of artificial intelligence for the selection and display of visualization methods. Level II and Level III situational awareness information relies heavily on user comprehension, which reflects background experience and training. This is an excellent area for a system to be designed that changes the visualization methods and what is being displayed based on the current flight scenario the pilot is experiencing.

The next step in this research work is the rigorous exercise of human factors testing to ensure that the heads-up display of a checklist does add to the overall safety of the pilot's mission. Certain visualizations such as the rectangular gauge may also be affected by which portion of the display the visualization is being presented in and further testing is required to determine which portion of the display is the best for each visualization method.

Following this, the methods developed in this thesis can be expanded to numerous other applications where critical operator decisions have significant consequences: Turret gunners, military infantry, crane operators, ship captains, and space exploration are a few primary examples.

And so, Dr. Atul Gawande makes a profound observation of the checklist manifesto, the acceptance of human fallibility against the “complexity of the world” [38]. He writes:

> *When we look closely, we recognize the same balls being dropped over and over, even by those of great ability and determination. We know the patterns. We see the costs. It’s time to try something else.*
>
> *Try a checklist*

This thesis attempts to take the first step in re-imagining the checklist method for the dawn of the age of the metaverse.

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