

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

AUGMENTED REALITY USER EXPERIENCE STUDY IN
COMMAND AND CONTROL SYSTEMS

MUSA ALTILI

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ELECTRONICS ENGINEERING

ADVISOR: ASSOC. PROF. DR. YAKUP GENÇ

FEBRUARY 2025

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

KOMUTA KONTROL SİSTEMLERİNDE ARTIRILMIŞ
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ABSTRACT

This research explores the integration of Augmented Reality (AR) technologies into military command and control systems, focusing on their influence on operational effectiveness as measured through user experience (UX) metrics. The study began by assessing the usability of existing command and control interfaces through hands-on testing with military operators. These initial evaluations provided valuable insights into system limitations, guiding the development of an AR-based situational awareness prototype designed to improve user engagement and real-time decision-making in dynamic operational environments. To validate its effectiveness, the prototype was subjected to multiple iterative testing phases, including heuristic evaluations and cognitive walkthroughs, conducted by experienced military personnel. These assessments focused on key usability factors such as cognitive load, response efficiency, and interface intuitiveness across a range of operational scenarios. Data collected through task analyses and user satisfaction surveys were systematically examined to extract both qualitative insights and quantitative performance metrics. The findings reveal that AR integration significantly improves command and control usability, leading to notable enhancements in situational awareness, decision-making speed, and operational coordination. By streamlining complex workflows and minimizing cognitive strain, AR supports a more agile and responsive decision-making process. Ultimately, this study underscores the transformative role of AR in modernizing military command systems, improving operator performance, and establishing new UX benchmarks in high-risk operational settings.

Keywords: Augmented Reality, Command Control Systems, User Experience, Situational Awareness, Usability Testing

ÖZET

Bu araştırma, Artırılmış Gerçeklik (AR) teknolojilerinin askeri komuta ve kontrol sistemlerine entegrasyonunu inceleyerek, kullanıcı deneyimi (UX) metrikleri üzerinden operasyonel etkinliğe olan etkisini değerlendirmektedir. Çalışma, mevcut komuta ve kontrol arayüzlerinin kullanılabilirliğini askeri operatörlerle yapılan uygulamalı testlerle değerlendirerek başlamıştır. Bu ön değerlendirmeler, sistemin sınırlamalarını ortaya koymuş ve dinamik operasyonel ortamlar için kullanıcı etkileşimini ve gerçek zamanlı karar alma süreçlerini geliştirmeyi amaçlayan bir AR tabanlı durumsal farkındalık prototipinin geliştirilmesine rehberlik etmiştir. Prototipin etkinliğini doğrulamak için, deneyimli askeri personelin katılımıyla gerçekleştirilen birden fazla yinelemeli test aşamasına tabi tutulmuştur. Bu değerlendirmeler, bilişsel yük, tepki verimliliği ve arayüz sezgiselliği gibi temel kullanılabilirlik faktörlerine odaklanarak farklı operasyonel senaryolarda uygulanmıştır. Görev analizleri ve kullanıcı memnuniyeti anketlerinden elde edilen veriler sistematik olarak incelenmiş ve nitel içgörüler ile nicel performans metrikleri çıkarılmıştır. Bulgular, AR entegrasyonunun komuta ve kontrol sistemlerinin kullanılabilirliğini önemli ölçüde artırdığını ve bu sayede durumsal farkındalığı, karar alma hızını ve operasyonel koordinasyonu önemli ölçüde geliştirdiğini ortaya koymaktadır. Karmaşık iş akışlarını sadeleştirerek ve bilişsel yükü en aza indirerek, AR, daha çevik ve duyarlı bir karar alma sürecini desteklemektedir. Sonuç olarak, bu çalışma, AR'nin modern askeri komuta sistemlerini dönüştürücü rolünü vurgulamakta, operatör performansını artırmakta ve yüksek riskli operasyonel ortamlarda yeni UX standartları oluşturmaya katkı sağlamaktadır.

Anahtar Kelimeler: Artırılmış Gerçeklik, Komuta Kontrol Sistemleri, Kullanıcı Deneyimi, Durumsal Farkındalık, Kullanılabilirlik Testi

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LIST OF SYMBOLS AND ABBREVIATIONS

GTU	:	Gebze Technical University
AR	:	Augmented Reality
HoSA	:	Holographic Situational Awareness
UX	:	User Experience
UI	:	User Interfaces
C5ISR	:	Command, Control, Communications, Computers, Combat Systems, Intelligence, Surveillance and Reconnaissance
ANOVA	:	Analysis Of Variance
HAVELSAN	:	Hava Elektronik Sanayi
UCD	:	User-centered Design

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1. INTRODUCTION

1.1. Background

Command control systems serve as the backbone of modern military operations, facilitating the effective coordination of personnel, assets, and decisions in complex and dynamic environments. However, the increasing complexity of operational scenarios poses significant challenges for operators, particularly in maintaining situational awareness and processing real-time data efficiently. These challenges are further exacerbated by cognitive overload and the limitations of traditional 2D interfaces, which can hinder decision-making and operational effectiveness. In this context, advancements in augmented reality (AR) offer an opportunity to revolutionize command control systems by providing immersive and intuitive interfaces that enhance user interaction and situational understanding.

1.2. Motivation and Importance

In military operations, where precision and agility are paramount, maintaining situational awareness is crucial for effective decision-making. While legacy command and control systems have traditionally served as the backbone of military coordination, they increasingly struggle to meet the fast-evolving demands of modern warfare. Operators frequently report issues such as information overload, complex user interfaces, and difficulty visualizing real-time tactical data, all of which hinder efficiency and responsiveness in high-stakes scenarios. These challenges highlight the pressing need for innovation, particularly through Augmented Reality (AR), which has the potential to bridge the gap between operator needs and system capabilities by offering immersive and intuitive solutions.

The integration of AR technology into command and control systems represents a paradigm shift in how military personnel interact with tactical information. By providing real-time overlays of critical battlefield data, AR can reduce cognitive load, accelerate decision-making processes, and enhance overall operational effectiveness. Observations and discussions with defense industry professionals at military

exhibitions have reinforced these priorities, emphasizing the demand for user-friendly, adaptive systems that can function seamlessly in high-pressure environments. These insights further validate the practical relevance of this study and ensure that its objectives align with the real-world needs of military end users.

Despite the growing interest in AR applications for defense, a comprehensive review of existing literature reveals a significant research gap in this domain. While numerous studies explore the theoretical benefits of AR in military training, navigation, and battlefield simulations, there is a distinct lack of research focusing on the direct integration of AR-based situational awareness systems within military command and control frameworks. More specifically, no prior study has combined both the technical development of an AR prototype and an in-depth user experience (UX) evaluation in real operational scenarios.

This research addresses this gap by introducing an AR-based situational awareness prototype specifically designed for military command and control applications. Unlike existing studies that focus solely on AR's potential in defense contexts, this study conducts rigorous user testing with military operators, assessing practical usability, effectiveness, and operational relevance. By bridging technical innovation and UX-based validation, this research makes a pioneering contribution to both defense technology research and human-computer interaction (HCI) in high-risk operational contexts. The findings not only provide valuable insights into AR's real-world applicability but also lay the foundation for future advancements in UX-driven military system development.

1.3. Importance of User Experience

User experience (UX) has become a critical factor in determining the success of any technology, especially in high-risk and time-sensitive environments such as military operations. In these contexts, where split-second decisions can impact mission outcomes, an intuitive and efficient UX design plays a pivotal role in reducing cognitive load, increasing decision-making accuracy, and enhancing overall user performance. A well-designed system not only optimizes operational effectiveness but also boosts user confidence and engagement, ensuring that military personnel can interact with the technology seamlessly under pressure.

Conversely, poor UX design can result in frustration, increased error rates, and reduced efficiency, potentially compromising mission success. Complex interfaces, excessive information density, or unintuitive interactions can overload operators, leading to delayed responses and diminished situational awareness. Given these risks, UX considerations must be at the forefront of technological advancements in military applications.

In this study, UX principles are deeply integrated into both the development and evaluation of an AR-based situational awareness system. The primary objective is to ensure that the technology aligns with the cognitive and operational needs of military personnel, offering an interface that is clear, responsive, and adaptable to high-pressure scenarios. By prioritizing usability, accessibility, and efficiency, this research contributes to the development of next-generation military systems that enhance situational awareness and decision-making while minimizing cognitive strain.

1.4. Objectives of the Study

During participation in several defense industry exhibitions, direct interactions with industry professionals and military operators provided valuable insights into the limitations of existing command control systems. Feedback emphasized the need for improved situational awareness, reduced cognitive load, and intuitive user interfaces in high-pressure environments. This input played a pivotal role in formulating the research questions and objectives, ensuring they address real-world operational challenges and priorities.

The primary objective of this research is to evaluate the potential of AR technologies to enhance military command control systems. This includes:

- Assessing the usability of existing command control systems to identify key pain points and areas for improvement.
- Developing an AR-based situational awareness prototype tailored to the needs of military operators.
- Conducting rigorous usability testing to evaluate the prototype's impact on cognitive load, decision-making speed, and accuracy under simulated operational conditions.

1.5. Research Questions

Feedback gathered from industry professionals during exhibitions guided the formulation of the following research questions:

- How can augmented reality improve situational awareness and decision-making in military command control systems?
- What specific user experience design principles are essential for operational success in augmented reality-based systems?
- How do augmented reality systems compare to traditional command control interfaces in terms of usability and task performance?

1.6. Scope of the Study

This research focuses on evaluating the usability and operational impact of AR technologies within a controlled testing environment. The study is limited to specific command and control tasks, ensuring a focused analysis of performance metrics such as cognitive load, task completion times, and decision-making accuracy. Participants in the study include experienced military personnel, whose expertise ensures the reliability and relevance of the findings. The research compares an AR-based situational awareness prototype with legacy 2D systems, providing a comprehensive analysis of the advantages and limitations of AR integration.

1.7. Thesis Structure

This thesis is organized as follows:

- Chapter 2 presents a literature review of AR technologies in military applications, emphasizing their potential to improve situational awareness and user experience. The chapter also examines existing methodologies for UX evaluation.
- Chapter 3 outlines the research methodology, including the design and development of the AR prototype, participant selection, and data collection methods.

- Chapter 4 details the results of usability testing, providing both quantitative and qualitative insights into the effectiveness of the AR system.
- Chapter 5 concludes the thesis, summarizing the key contributions and outlining practical implications for military operations.

2. LITERATURE REVIEW

2.1. Command Control Systems in Military Operations

2.1.1. Historical Development

Command and Control Systems (C5ISR) have been integral to military operations, enabling effective coordination and decision-making. Early C5ISR were predominantly analog, relying on human operators to compile, interpret, and disseminate information. Over time, the digital revolution introduced systems that utilized automated data processing, advanced communication networks, and real-time updates.

C5ISR systems are crucial for providing real-time situational awareness, secure communications, and integrated combat capabilities to enhance military operational effectiveness

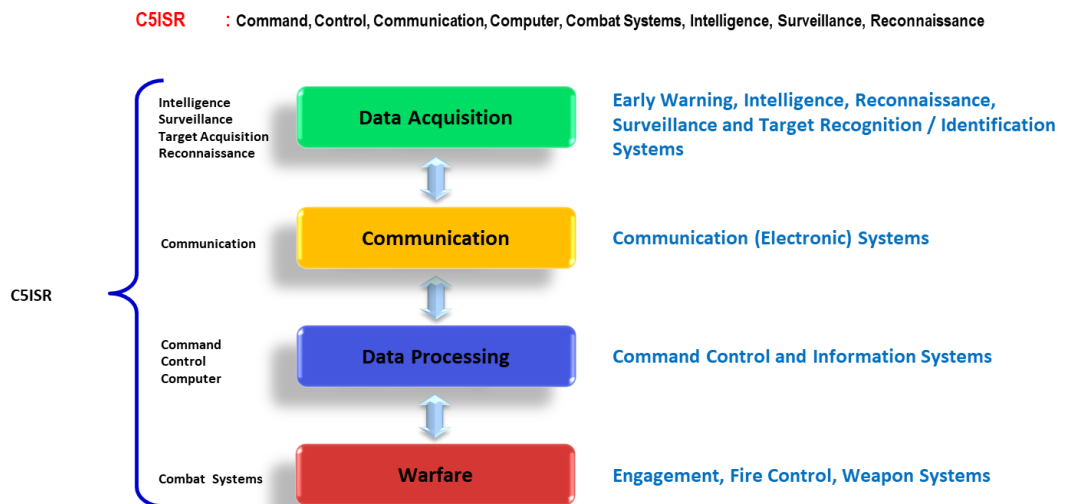


Figure 2.1: C5ISR components.

- Command: Exercise of authority and decision-making by commanders over military forces.
- Control: Directing, coordinating, and supervising military operations to achieve objectives.

- Communications: Technologies and systems for secure information transmission among commanders, units, and allies.
- Computers: Hardware and software systems for processing, storing, and managing operational data.
- Combat Systems: Integration of weapons, sensors, and technologies to support and enhance combat operations.
- Intelligence: Collection, analysis, and dissemination of information about adversaries and the operational environment.
- Surveillance: Continuous monitoring of activities, places, or persons to gather information and maintain situational awareness.
- Reconnaissance: Missions to gather detailed information about enemy activities, resources, and terrain.

Key developments include the transition to network-centric warfare in the late 20th century, emphasizing the integration of data from diverse sources to enhance situational awareness. Despite these advancements, traditional C5ISR remain challenged by the scale and complexity of modern operational environments [1]

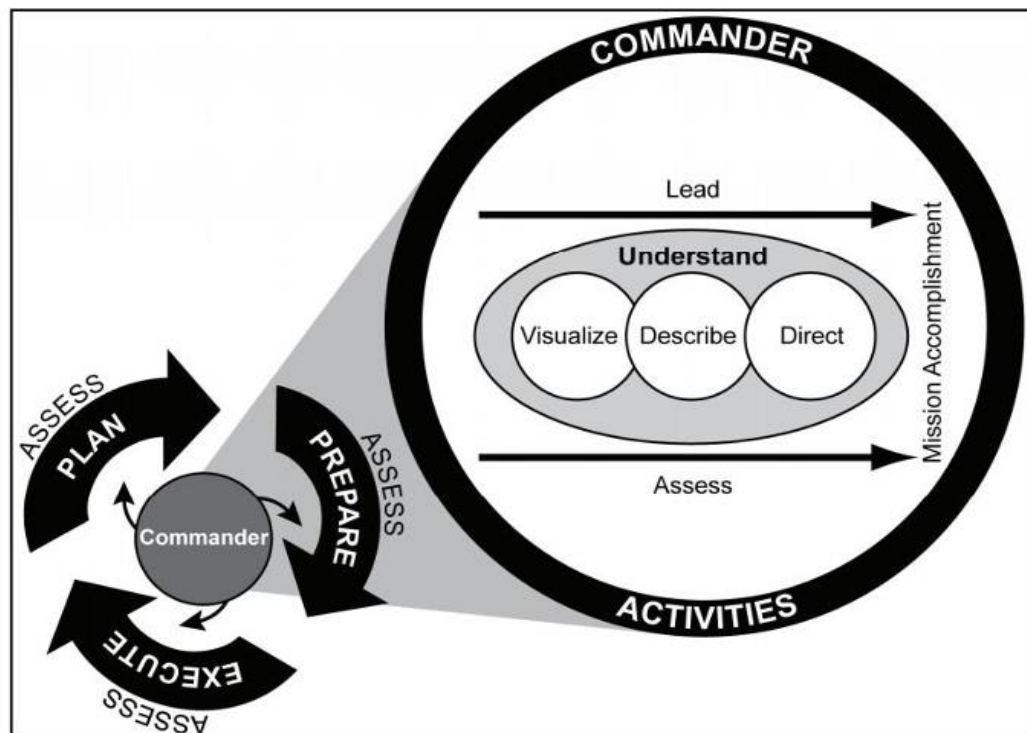


Figure 2.2: Military mission lifecycle [1].

Figure 2.2 illustrates the lifecycle of military missions, providing a structured framework for commanders and decision-makers at every operational stage. Situational awareness (SA) plays a pivotal role throughout all phases of a mission, from initial intelligence gathering and strategic planning to real-time tactical execution and post-mission evaluation.

In modern military operations, timely and accurate situational awareness is critical for informed decision-making, minimizing operational risks, and ensuring mission success. The ability to synthesize battlefield data, monitor evolving threats, and coordinate actions in real time directly impacts response effectiveness and mission adaptability.

2.1.2. Core Functions of Command Control Systems

C5ISR are designed to:

- **Facilitate Decision-Making:** Provide operators with actionable intelligence derived from real-time data streams.
- **Enhance Situational Awareness:** Integrate data across multiple domains (land, air, sea, cyber) to deliver a comprehensive tactical picture.
- **Coordinate Units Effectively:** Synchronize the efforts of distributed teams and assets for cohesive operations.

2.1.3. Importance of Situational Awareness at C5ISR

Situational Awareness (SA) is a foundational element of Command, Control, Communications, Computers, Combat Systems, Intelligence, Surveillance, and Reconnaissance (C5ISR) operations, playing a critical role in threat detection, mission planning, tactical execution, and post-mission assessment. Military operations require commanders and operators to process vast amounts of real-time data, synthesize relevant information, and make rapid decisions under time-sensitive and high-risk conditions. The effectiveness of these decisions depends on how accurately and efficiently situational awareness is maintained throughout an operation [1]

In modern warfare, situational awareness involves multiple dimensions, including spatial awareness, threat identification, operational coordination, and predictive

analysis. The ability to effectively manage and interpret data in these domains significantly influences the success of a mission. Situational awareness is not only relevant at the individual level for soldiers and operators but also at the unit, tactical, and strategic levels, impacting the overall effectiveness of command and control structures [19].

C5ISR systems are designed to acquire, process, and distribute battlefield intelligence to commanders and personnel in real time. These systems integrate multiple data sources, such as sensor networks, reconnaissance feeds, communication links, and intelligence databases, to create a coherent operational picture. The ability to track and classify enemy movements, air and naval threats, and ground-based forces is essential for preemptive decision-making [43].

Despite advancements in data acquisition and information processing, situational awareness remains one of the most challenging aspects of military decision-making. Cognitive overload, complex threat environments, and the rapid pace of engagements all pose significant challenges for operators. Studies have shown that poor situational awareness is a leading cause of battlefield errors, often resulting in delayed responses, misinterpretation of intelligence, and operational inefficiencies (Klein et al., 2018).

2.1.4. Limitations of Current Systems

While C5ISR have evolved, several limitations hinder their effectiveness:

- **Cognitive Overload:** Operators are often overwhelmed by the volume of data, particularly under high-pressure conditions. Real-time multi-domain operations require processing numerous simultaneous inputs, leading to errors or delays [2].
- **Static and Non-Intuitive Interfaces:** Traditional 2D interfaces struggle to represent dynamic tactical scenarios. Lack of spatial context complicates threat identification and prioritization [3]
- **Coordination Bottlenecks:** Information silos and delays in communication impede effective response.

2.1.5. Emerging Trends in C5ISR

Modern CCS focus on integrating advanced technologies to address these challenges:

- Artificial Intelligence (AI): Predictive analytics to anticipate threats and automate routine decisions.
- Augmented Reality (AR): Overlay critical information directly onto an operator's field of view, enhancing situational awareness and reducing cognitive load [1].
- Cloud-Based Collaboration: Enables seamless real-time data sharing across distributed units, improving coordination and responsiveness.

2.2. User Experience in Command Control Systems

User experience (UX) plays a pivotal role in the effectiveness of command control systems (C5ISR), particularly in high-stakes environments like military operations. The efficiency of these systems directly impacts operators' decision-making speed, situational awareness, and overall mission success. Poorly designed systems can lead to cognitive overload, frustration, and even mission failure.

Key principles of UX that are critical in military CCS include:

- Usability: Systems must be intuitive and easy to navigate, especially under time-sensitive conditions.
- Responsiveness: Interfaces need to provide real-time feedback to ensure operators remain aware of evolving tactical scenarios.
- Accessibility: Systems should accommodate diverse user needs and operational contexts.

2.2.1. Challenges in UX for Command Control Systems

Despite advancements, UX design in CCS faces significant challenges:

- Complexity of Information:

- Military operations involve vast amounts of data from various sources (e.g., sensors, satellites, and ground units). Presenting this data in a comprehensible format is a major UX challenge.
- Example: Traditional systems often overwhelm users with raw data, lacking prioritization or context [3]
- Cognitive Overload:
 - Operators are tasked with making critical decisions under pressure. Poorly designed interfaces can exacerbate cognitive load, leading to errors or delays.
 - Studies show that simplified, visual interfaces significantly reduce cognitive strain [4].
- Adapting to User Needs:
 - Operators have varying levels of expertise and familiarity with digital systems. UX designs must account for these differences while ensuring consistency and efficiency.

2.2.2. UX Principles for Command Control Systems

- Clarity:
 - Information should be displayed in a clear, structured manner, avoiding unnecessary clutter.
 - Example: Visual hierarchies that prioritize critical information can guide operators effectively.
- Consistency:
 - Standardized layouts and interaction models reduce the learning curve and enhance usability.
- Real-Time Feedback:
 - Dynamic updates and notifications keep operators informed of changing scenarios without overwhelming them.
- Adaptability:

- Interfaces should be customizable to suit individual user preferences or specific mission requirements.

2.2.3. Evaluating UX in C5ISR Systems

- Cognitive Load Metrics:
 - Techniques such as eye-tracking and secondary task performance can quantify the cognitive load imposed by a system.
 - Example: AR-enhanced systems have been shown to lower cognitive load by visually integrating data overlays [1].
- Usability Testing:
 - Methods such as heuristic evaluations and cognitive walkthroughs are essential for identifying pain points in system design.
 - User Satisfaction Surveys:
 - Surveys and interviews capture subjective user feedback, offering valuable insights into system performance and areas for improvement.

2.2.4. Future Directions for UX in C5ISR

The evolution of User Experience (UX) in Command, Control, Communications, Computers, Combat Systems, Intelligence, Surveillance, and Reconnaissance (C5ISR) systems is driven by the need for faster, more intuitive, and highly adaptive interfaces that reduce cognitive load while improving decision-making efficiency. As military operations become increasingly data-driven and technology-intensive, the future of UX in C5ISR will focus on personalization, automation, and immersive technologies. Below are several key areas where UX advancements are expected to shape the future of command and control operations.

Personalized Interfaces and AI-Driven Adaptability: One of the most significant advancements in UX for C5ISR will be the development of personalized, adaptive user interfaces that dynamically adjust based on individual operator preferences, task complexity, and operational context. Artificial Intelligence (AI) and Machine Learning

(ML) will play a critical role in learning user behavior patterns and customizing the interface accordingly [45][46].

Future C5ISR interfaces will be designed to optimize cognitive load, ensuring operators receive only the most relevant data without overwhelming them with unnecessary information. Real-time cognitive load assessments will enable interfaces to dynamically adjust information density, font sizes, colors, or alert frequencies, facilitating optimal information processing [47].

Additionally, AI-driven predictive UI elements will analyze past user interactions, mission priorities, and environmental conditions to anticipate an operator's needs. These predictive elements will ensure critical mission data is surfaced before the user even requests it, reducing response time and enhancing efficiency. Personalized dashboards will also provide role-based customization, tailoring information presentation based on the operator's role—whether a mission commander, intelligence analyst, or field operator—thus ensuring each user is presented with the most relevant data at any given time [48].

By minimizing the cognitive burden associated with processing large volumes of tactical data, personalized UX enhancements will allow operators to focus on decision-making rather than interface navigation, ultimately improving operational efficiency.

Advanced Usability Testing and Biometric Feedback: Traditional usability testing in military UX design has heavily relied on task performance metrics and subjective feedback surveys. While these methods provide valuable insights, future C5ISR usability testing will integrate biometric feedback mechanisms to offer a more precise understanding of user stress, workload, and engagement levels.

Physiological sensors such as electroencephalography (EEG), eye tracking, and heart rate variability (HRV) monitoring can detect changes in stress levels, alertness, and fatigue during system use [49]. Real-time UX adaptation will allow AI-powered systems to adjust system behavior dynamically, such as reducing alert frequency when stress levels are high or increasing system guidance when cognitive overload is detected.

Unlike traditional usability studies that occur at fixed intervals, biometric feedback enables real-time UX assessment, allowing developers to make iterative improvements to interfaces [50]. By incorporating biometric analytics, future C5ISR systems will not

only optimize usability in training and development phases but also adapt dynamically during live operations, ensuring that human operators remain engaged, efficient, and alert.

Enhanced Training Modules and Immersive Learning Environments: One of the primary challenges of complex military systems is the steep learning curve for new operators. Training programs must ensure that personnel can effectively operate and interpret C5ISR systems before deployment. Emerging Augmented Reality (AR) and Virtual Reality (VR) technologies are expected to revolutionize training methodologies by creating immersive, hands-on learning experiences [51].

Future UX designs will incorporate scenario-based AR training, where interactive AR overlays provide real-time guidance on tactical analysis, system operation, and decision-making in simulated battlefield environments. Mission rehearsal and stress exposure training using VR-based simulations will enable trainees to experience high-stakes, realistic operational environments without actual risk, preparing them for combat decision-making under pressure.

Moreover, AI-enhanced training customization will tailor training modules based on individual proficiency levels, focusing on areas where an operator struggles while bypassing redundant information. Research indicates that immersive training environments significantly improve knowledge retention, decision-making speed, and operational confidence compared to traditional classroom-based learning [52]. This approach will be particularly useful for complex C5ISR interfaces, ensuring personnel achieve mission readiness faster and more effectively.

Future Interaction Techniques: Future C5ISR interfaces will integrate emerging interaction techniques to further improve efficiency, accessibility, and speed. Voice-Activated Command Systems will leverage natural language processing (NLP) to enable operators to issue commands verbally, reducing reliance on manual inputs [53]. Gesture-Based Interactions will use advanced gesture recognition to allow operators to manipulate 3D tactical displays, zoom into maps, or highlight enemy positions using hand movements rather than clicking through menus.

Brain-Computer Interfaces (BCIs) are being actively developed to enable direct brain-to-system interactions, where operators can control interfaces simply through thought patterns, significantly reducing response times in critical situations [54].

These emerging interaction techniques will increase operational efficiency, particularly in hands-free or high-mobility scenarios, such as pilots, vehicle operators, or dismounted soldiers operating in real-time combat environments.

2.3. Augmented Reality

2.3.1. Definition and Key Characteristics of AR

Augmented reality (AR) is a technological innovation that incorporates virtual elements into the real-world environment in real time, enhancing the user's experience and interaction. As defined by Azuma et al., AR systems should fulfill three key criteria: (1) seamlessly combine virtual and physical objects in a real-world setting, (2) provide real-time interactivity, and (3) ensure alignment between virtual and real-world elements [24], [25]. Unlike virtual reality (VR), which immerses users in an entirely artificial environment, AR enriches reality by overlaying virtual objects on the physical world, enabling a more integrated perception and interaction [26].

2.3.2. Applications of AR

AR enhances user interaction with real-world environments by integrating digital content, such as live video streaming or virtual overlays, into physical surroundings. AR aims to improve user understanding by contextualizing virtual data within the real world, offering significant advantages in various applications. For example, AR can simplify complex information visualization during military operations by aligning real-time data with the physical environment [24].

2.3.3. Tracking Techniques in AR

Tracking methods in Augmented Reality (AR) applications help place virtual objects correctly in the real world by finding the user's position and direction. These methods ensure that digital elements stay aligned with real surroundings, improving accuracy and usability in AR systems.

One common method is sensor-based tracking, which uses gyroscopes, accelerometers, magnetometers, and laser sensors to measure movement and

orientation [27]. For example, gyroscopes track rotation and direction, while magnetometers detect magnetic fields to help with positioning. Laser sensors measure distances very accurately, which is useful in fast-moving environments. These sensors work together to help AR systems adjust as users move or the surroundings change.

Another important method is vision-based tracking, which uses cameras and image processing to understand the position of the user and objects in the real world. This method detects features like edges, corners, and patterns to match virtual and real-world elements [27]. Vision-based tracking is helpful in indoor areas or places where GPS does not work well. More advanced tracking methods improve AR accuracy even further. One example is Simultaneous Localization and Mapping (SLAM), which creates and updates 3D maps of unknown places while also tracking the user's movement. Another technique, model-based tracking, uses pre-made digital models to recognize objects and place virtual elements correctly. These advanced tracking methods are very important for military applications, where precise positioning and fast updates are necessary for situational awareness and decision-making [26].

2.3.4. Interaction Techniques in AR

Augmented Reality (AR) systems use modern interaction methods to help users easily engage with virtual content. One method is Tangible User Interfaces (TUIs), which let users control virtual objects by using physical items. This approach combines real-world touch with digital interaction, making the experience more natural and immersive. TUIs give users a better sense of control, improving their connection with the virtual world.

Another important way to interact with AR is gesture-based and body movement interactions. These allow users to zoom, drag, or tap on virtual elements using hand movements instead of buttons or controllers. TUIs also support collaborative interactions, meaning multiple users can work together in the same AR environment, improving teamwork and communication [29].

Hand and eye tracking are also key interaction methods in AR. Hand tracking allows users to move and adjust virtual objects without using a physical controller. Eye tracking follows where the user is looking and adjusts the content to keep the most

important information clear and in focus. By working together, these methods make AR interactions smooth, easy, and more realistic [30].

2.3.5. AR Display Types

The Augmented Reality (AR) display systems help combine virtual elements with the real world in a seamless way. Different display types allow users to experience AR in various ways, depending on the application.

One common type is transparent head-mounted displays (HMDs), such as Microsoft HoloLens and Magic Leap. These devices use optical pass-through technology, allowing users to see both real and virtual objects at the same time. This creates a mixed environment, where digital content blends naturally with physical surroundings.

Another method is projection-based displays, which project virtual images onto real surfaces. This allows users to interact with AR content without wearing a headset or special device. Such systems are useful in collaborative workspaces and large-scale visualizations. Handheld devices, like smartphones and tablets, offer a more accessible way to experience AR. These devices use built-in cameras and sensors to place virtual objects on live camera feeds, making AR widely available to the public.

Each type of AR display has unique advantages, making them suitable for different uses. Choosing the right display depends on the application, whether for military training, industrial design, or everyday consumer experiences [32].

2.3.6. Challenges in AR Implementation

Although Augmented Reality (AR) offers many advantages, several challenges limit its widespread use. One major issue is hardware limitations—many AR devices have short battery life and can be bulky or uncomfortable, making them difficult to use for long periods, especially in demanding environments.

Another challenge is integration with existing legacy systems. Many traditional military systems were not designed to work with AR platforms, making compatibility and data synchronization difficult. This slows down the adoption of AR technologies in operational settings.

Additionally, some operators may be hesitant to use AR due to lack of familiarity or concerns about its reliability during critical missions. In high-risk military operations, personnel need to trust their equipment completely, and any uncertainty about AR's performance under pressure can create resistance to its adoption.

To successfully implement AR in military applications, these challenges must be addressed. Improvements in hardware efficiency, system integration, and user training will be essential to ensure that AR becomes a reliable and widely accepted tool in defense operations.

2.3.7. Emerging Trends in AR

The Augmented Reality (AR) technology is constantly evolving, with new developments aimed at overcoming current challenges. One major trend is the integration of Artificial Intelligence (AI) into AR systems. AI helps analyze and filter data in real time, allowing users to process information faster and make quicker decisions.

Another important advancement is the use of multi-modal interaction methods. These systems combine voice commands, hand gestures, and eye tracking, making AR more accessible and user-friendly. By allowing users to interact in multiple ways, these methods improve efficiency and ease of use, especially in high-pressure environments.

Additionally, cloud-based AR platforms are becoming more popular. By processing data remotely, these platforms reduce system lag and enhance data sharing between users. This is especially useful for collaborative applications, where multiple users need to access and interact with the same AR environment.

These emerging trends are shaping the future of AR technology, making it more efficient, adaptable, and widely applicable across various fields, including military operations, healthcare, and industrial training.

2.4. Augmented Reality in Military Applications

2.4.1. Introduction to Augmented Reality (AR) in Defense

Augmented Reality (AR) is becoming an important technology in the defense sector, providing immersive solutions that improve situational awareness, decision-making, and training effectiveness. By displaying digital information directly onto the real world, AR allows military personnel to access critical data in real time. This reduces cognitive workload and helps operators make faster and more accurate decisions.

The growing use of AR in defense shows its potential to solve longstanding challenges in command and control systems. By improving information delivery and visualization, AR helps military teams operate more efficiently and respond quickly to dynamic situations. As AR technology continues to evolve, its role in modern defense strategies is expected to expand even further [1].

2.4.2. Applications of AR in Military Operations

The use of Augmented Reality (AR) in military operations has brought major advancements in situational awareness, combat training, equipment maintenance, and decision-making. Many military forces around the world are adopting AR-based systems to improve efficiency, reduce cognitive workload, and create more intuitive user interfaces.

Recent studies highlight how AR enhances real-time data visualization by overlaying digital information onto physical environments. This feature helps simplify complex command and control operations, allowing military personnel to process information faster and make better decisions under pressure. As AR technology continues to improve, its role in modern military strategy is expected to grow even further. [1].



Figure 2.3: Usage of AR in military operations [41].

- **Situational Awareness and Command Control**

Situational awareness is one of the most important factors in military operations. It refers to an operator's ability to observe, understand, and predict battlefield conditions. In traditional command and control centers, personnel rely on 2D digital maps, sensor feeds, and text-based reports. This requires them to manually analyze and combine information from different sources, which can slow down decision-making.

Augmented Reality (AR) significantly improves situational awareness by displaying critical data directly within the operator's field of view. Instead of relying on separate screens or reports, military personnel can see real-time intelligence, enemy positions, and battlefield analytics overlaid onto their surroundings. This allows for faster information processing, better coordination, and improved decision-making in high-pressure situations [2].

The HAVELSAN ASGER Holographic Command & Control System is a key example of how Augmented Reality (AR) is transforming military decision-making. By integrating interactive 3D holographic interfaces into command environments, this system allows military personnel to visualize and manipulate battlefield information in a spatial format. This creates a 360-degree operational picture, as shown in Figure 2.3 [41].

By overlaying tactical elements, threat markers, and real-time geospatial intelligence, AR improves multi-domain coordination, ensuring smooth

synchronization between land, naval, and air forces. Recent studies highlight that AR-based command and control tools help reduce cognitive workload, allowing operators to process battlefield data more quickly and respond more effectively to emerging threats. [1],[2].

Augmented Reality (AR) also enhances real-time collaboration between military units operating in different locations. For example, a naval combat team using an AR-enhanced interface can monitor submarine movements and detect incoming missile threats in an interactive 3D space. This dynamic visualization allows teams to analyze threats quickly and take faster, more effective countermeasures [42].

- **Training and Simulation**

Augmented Reality (AR)-based training systems have become an essential part of modern military education and combat preparation. Traditional training methods rely on physical equipment, live exercises, and simulated battlefields, but these approaches often face logistical, financial, and environmental challenges. AR helps overcome these limitations by creating immersive virtual training environments, allowing military personnel to practice real-world combat scenarios without physical constraints [1].

For example, AR-enhanced flight simulators provide pilots with realistic mission scenarios, such as emergency landings, enemy engagements, and multi-aircraft formations. These simulations allow pilots to develop critical decision-making skills in high-risk situations, without the danger of real combat or the risk of damaging expensive aircraft. Similarly, ground troops benefit from AR-driven urban warfare simulations, where they can interact with virtual enemies, experience changing battlefield conditions, and engage with advanced AI-controlled adversaries.

In addition, special forces and navy personnel use AR-based mission rehearsal tools to analyze terrain, assess enemy fortifications, and plan tactical maneuvers before deployment. By integrating digital twin technology, these AR systems enable real-time adaptation of combat strategies, ensuring that military forces train under conditions that closely replicate actual battlefield environments [2].

- **Equipment Maintenance and Support**

Maintaining military-grade equipment, including armored vehicles, fighter jets, and naval warships, is a complex and resource-intensive process. Traditional maintenance procedures often require specialized expertise, extensive technical manuals, and on-site diagnostics, leading to longer downtimes and increased operational costs. AR revolutionizes military equipment maintenance by providing real-time, interactive repair guidance through augmented overlays.

Additionally, AR-enabled remote assistance features allow field operators to receive expert guidance from off-site technicians, ensuring that critical assets remain combat-ready at all times [42].

- **Collaborative Decision-Making**

Military operations rely heavily on synchronized, real-time collaboration between command centers, field operatives, and intelligence analysts. AR enhances collaborative decision-making by allowing multiple users to interact with a shared, interactive battlefield model. This fosters joint planning, synchronized execution, and efficient visual communication among military leaders at Figure2.4 [2].

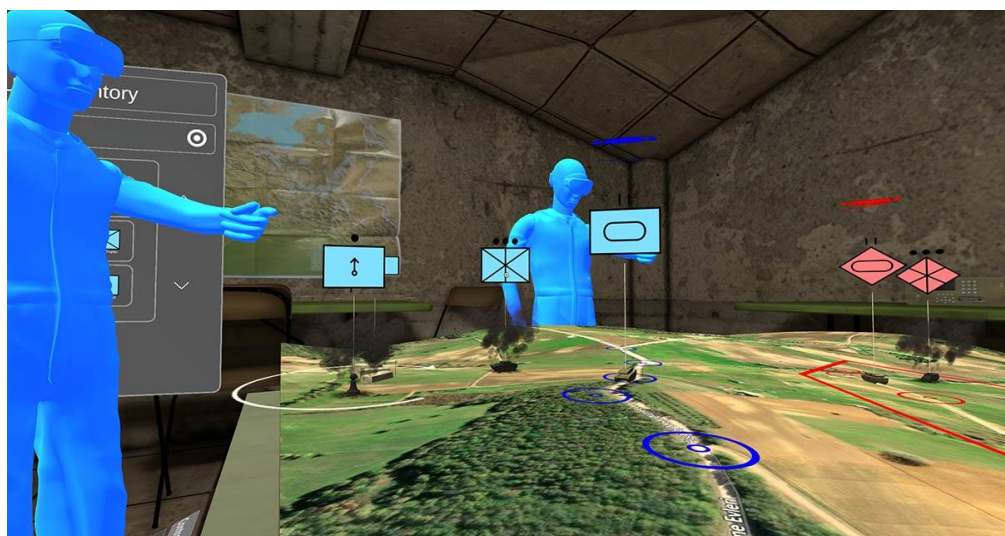


Figure 2.4: Collaborative decision making with AR application [42].

The HAVELSAN ASGER Holographic Command & Control System, for example, enables multiple commanders across different locations to interact with the same holographic battle map, providing a shared, real-time operational picture. This multi-user AR collaboration system allows military leaders to assign tasks, monitor real-time mission execution, and adjust strategies instantaneously, ensuring seamless cross-domain coordination [42].

2.4.3. Benefits of AR in Military Applications

The integration of Augmented Reality (AR) in military command and control systems has greatly improved how battlefield data is visualized and interpreted by operators. Traditional interfaces, such as 2D tactical maps and multi-screen setups, require personnel to analyze large amounts of information while making split-second decisions. This fragmented approach can cause delays, cognitive overload, and errors in battlefield intelligence. However, AR-based visualization systems provide a more intuitive and efficient alternative by displaying real-time, spatially aware data overlays that help operators quickly assess and respond to mission-critical information.

One of the biggest advantages of AR in situational awareness is that it eliminates the need for operators to switch between multiple screens and interfaces. Instead of relying on static 2D maps, separate sensor feeds, and text-based reports, AR integrates all these elements into a single 3D holographic battlespace. This system allows military personnel to see enemy positions, friendly unit movements, terrain hazards, and real-time intelligence updates in one interactive display. By combining information sources, AR helps reduce decision-making time and improves the accuracy of threat detection and mission planning. Research shows that AR-driven visualizations not only make battlefield intelligence easier to understand but also lead to faster and more accurate decisions, especially in high-stress combat environments [2].

Another key benefit of AR is its ability to reduce cognitive load on military personnel. Traditional command systems often overload operators with large amounts of raw data, forcing them to filter out irrelevant details while identifying important information. This constant mental strain can affect performance, particularly during long missions that require continuous focus. AR improves information delivery by displaying only the most relevant data, helping operators concentrate on critical

intelligence without being overwhelmed. Studies suggest that AR-assisted decision-making improves both speed and accuracy, as users spend less time interpreting information and can react more efficiently [2].

Beyond improving situational awareness, AR also increases operational efficiency by enhancing responsiveness and adaptability in fast-changing combat environments. Conventional military interfaces require manual input, which can create delays when adjusting battle strategies. In contrast, AR-based systems provide real-time updates, gesture-based controls, and interactive 3D displays, allowing operators to quickly analyze threats, modify mission objectives, and coordinate with allied forces with minimal effort. For example, an AR-enabled battlefield management system can display live drone surveillance footage onto a commander's augmented display, allowing real-time adjustments to troop movements and tactics. These features improve unit coordination and ensure that military forces respond to threats immediately.

In summary, AR is transforming military decision-making by enhancing data visualization, reducing cognitive workload, and improving operational efficiency. By revolutionizing how information is displayed and processed, AR boosts situational awareness, speeds up decision-making, and increases accuracy, leading to more effective mission execution. As AR technology continues to evolve, its integration into next-generation command and control systems will further enhance battlefield operations, joint force coordination, and real-time intelligence sharing, ultimately providing military forces with a strategic advantage in modern warfare [2].

2.4.4. Challenges and Limitations of AR in Defense

While Augmented Reality (AR) offers numerous advantages in enhancing situational awareness and decision-making in military operations, its widespread adoption is hindered by several technical, operational, and logistical challenges. These limitations primarily stem from hardware constraints, integration issues with legacy systems, resistance to adoption among military personnel, and the substantial cost associated with deployment and maintenance. Addressing these challenges is crucial to ensuring the effective implementation and long-term sustainability of AR-based solutions in defense applications.

- **Hardware Constraints and Durability Issues**

One of the biggest challenges in adopting Augmented Reality (AR) in military operations is the current limitations of AR hardware. Many AR devices, including head-mounted displays (HMDs) such as Microsoft HoloLens and other military-grade AR goggles, are often bulky, power-intensive, and not rugged enough for battlefield conditions. Military operations require lightweight, durable, and weather-resistant equipment that can function in extreme temperatures, dusty terrains, and wet environments. However, most commercial AR devices are not designed for long-term field use, making them less practical for combat and reconnaissance missions.

Another major concern is battery life and power management. Current AR systems require high power consumption due to high-resolution displays, real-time data processing, and constant wireless connectivity. This short battery life creates a serious risk, as soldiers rely on AR for situational awareness and cannot afford for their devices to lose power during a mission. To make AR more effective for military use, developers must focus on energy-efficient solutions that provide longer battery life, ensuring that these systems remain operational during extended missions.

- **Integration Challenges with Legacy Command Systems**

Integrating Augmented Reality (AR) technologies into existing military infrastructure presents a significant challenge. Traditional command and control systems (C5ISR) were designed for 2D interfaces and proprietary architectures, which often lack compatibility with modern AR applications. As a result, integrating AR requires major system upgrades, including new data transmission protocols, real-time synchronization algorithms, and advanced sensor fusion techniques. The complexity of adapting AR to existing command and control (C2) networks can lead to latency issues, data inconsistencies, and cybersecurity risks.

One of the biggest technical challenges is ensuring real-time data synchronization between AR-enabled devices, battlefield sensors, unmanned aerial vehicles (UAVs), and centralized command hubs. Military operations require instant and highly accurate data processing, but AR systems must

collect information from multiple sources, such as satellites, radar systems, and geospatial intelligence (GEOINT) platforms. Any delay or mismatch in data transmission could result in incorrect battlefield assessments, potentially putting missions at risk. Therefore, developing secure, low-latency, and encrypted communication protocols is essential for the successful deployment of AR in defense operations [42].

- **Resistance to Adoption Among Military Personnel**

Despite advancements in AR technology for defense, there is still resistance to adoption among military personnel and decision-makers. Operators and commanders may hesitate to switch from traditional command and control (C2) interfaces to AR-based systems, especially if they view AR as unreliable, difficult to operate, or overly complex. This skepticism often stems from concerns about system stability, real-time performance, and possible interference with critical operations.

Additionally, human factors play an important role in AR adoption. Some users may experience discomfort, dizziness, or cognitive strain when using AR headsets for long periods, making them less willing to rely on the technology. Another challenge is training requirements—introducing new AR systems requires extensive user training, which can increase operational downtime and require additional resources. Without well-structured training programs and gradual onboarding, military personnel may struggle to integrate AR into their daily workflows, reducing its overall effectiveness in high-pressure environments.

- **High Cost and Resource Investment**

The development, deployment, and maintenance of AR systems for military use require significant financial and resource investments. Unlike consumer-grade AR applications, military AR solutions must meet strict security, durability, and performance standards, leading to high research and development (R&D) costs. The production of custom-built AR hardware, secure software platforms, and real-time battlefield simulation environments requires substantial funding, which can put pressure on defense budgets. This

is especially challenging when military spending must also cover cybersecurity, unmanned systems, and next-generation weapons development.

In addition, the long-term success of AR in military operations depends on its ability to evolve with emerging technologies. As sensor technology, AI-driven decision-making, and edge computing continue to improve, military AR systems must be regularly updated to stay effective. This constant need for upgrades and system refinements increases operational costs, making large-scale adoption a financial challenge for defense organizations

While Augmented Reality (AR) offers significant advantages in situational awareness, decision-making, and operational efficiency, its widespread adoption in military environments is still limited by several challenges. Issues such as hardware limitations, integration difficulties, user resistance, and high costs make it difficult to fully implement AR in real-world defense operations.

To overcome these challenges, continued investment is needed in lightweight and durable AR hardware, seamless system integration, and comprehensive training programs for military personnel. Although these obstacles remain, the potential benefits of AR in modern warfare are substantial. As technology advances, AR is expected to become a transformative tool for enhancing military operations, improving battlefield coordination, and optimizing real-time decision-making.

2.4.5. Emerging Trends in AR for Defense

- **AI-Enhanced AR Systems:**
 - Artificial intelligence is being integrated with AR to automate data filtering and highlight critical information dynamically.
 - Example: AI-powered AR systems can predict enemy movements and suggest optimal countermeasures.
- **Multi-Modal Interfaces:**
 - Combining AR with voice commands, haptic feedback, and gesture controls is expanding its usability and accessibility.
 - Example: Operators can interact with AR interfaces hands-free while managing other tasks.

- Cloud-Based AR Platforms:
 - Cloud computing enables real-time updates and data sharing, reducing latency and improving scalability for large-scale operations.

2.5. Evaluation Methods in UX and AR Systems

2.5.1. Introduction

Evaluating the effectiveness of Augmented Reality (AR) systems and user experience (UX) in military command and control environments is essential for ensuring their operational success. Unlike traditional evaluation methods that focus only on technical performance, modern UX assessments aim to balance efficiency with usability, considering both cognitive and emotional aspects of user interaction. In high-stakes military operations, where quick and accurate decision-making is critical, strong evaluation methods are needed to understand how AR systems impact operator performance and situational awareness.

AR systems introduce both opportunities and challenges in evaluation. While they offer immersive and intuitive interfaces that can reduce cognitive load and improve task efficiency, they also present design challenges, such as information overload and hardware usability limitations. Therefore, evaluating AR requires a multifaceted approach that combines quantitative methods—such as task completion time and cognitive load metrics—with qualitative insights from user feedback, heuristic evaluations, and thematic analyses.

This section explores the methodologies used to evaluate UX and AR systems, focusing on their importance in military command and control settings. By integrating traditional and advanced techniques, such as biometric monitoring and virtual reality simulations, evaluations can provide valuable insights to enhance system usability and effectiveness. The following subsections will discuss quantitative and qualitative evaluation methods, comparative testing approaches, and recent advancements in UX assessment for AR-based military systems.

2.5.2. Quantitative Evaluation Methods

Quantitative methods provide measurable insights into system performance, focusing on aspects such as task efficiency, cognitive load, and user satisfaction.

2.5.3. Task Performance Metrics

- Completion Time:
 - Measures the time taken to complete specific tasks using the system.
 - Example: Comparing task completion times between legacy systems and AR-enhanced prototypes to assess efficiency gains [3].
- Error Rates:
 - Tracks the number of mistakes made by operators.
 - Example: Monitoring misclassifications in air track identification tasks to determine system reliability [4]
- Decision-Making Accuracy:
 - Evaluates the precision of decisions made under time constraints, providing a direct measure of system usability in high-stakes environments.

2.5.4. Cognitive Load Measurement

- NASA Task Load Index (NASA-TLX):
 - A subjective, self-report measure that evaluates workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration [5].
- Eye-Tracking:
 - Tracks gaze patterns, fixation duration, and saccades to infer cognitive effort.
 - Example: Eye-tracking studies on AR systems show reduced visual search times due to intuitive data overlays [1].

- Secondary Task Performance:
 - Participants perform an additional task (e.g., pressing a button when a light flashes) while using the system. Performance on this secondary task reflects the cognitive load imposed by the primary task.

2.5.5. User Satisfaction Surveys

- System Usability Scale (SUS):
 - A widely used 10-item scale that provides a quick and reliable measure of usability [6].
- Likert Scales:
 - Captures user ratings on various dimensions such as ease of use, intuitiveness, and satisfaction.
 - Example: Surveys comparing user satisfaction with AR systems versus legacy systems [2] .

2.5.6. Qualitative Evaluation Methods

Qualitative methods complement quantitative approaches by providing deeper insights into user preferences, challenges, and overall experiences.

- Heuristic Evaluations
 - Experts evaluate the system against predefined usability principles, such as Nielsen's heuristics.
 - Example: Identifying design flaws in AR interfaces, such as cluttered overlays or non-intuitive controls [10].
- Cognitive Walkthroughs
 - Simulates a user's thought process when interacting with the system for the first time.
 - Example: Evaluating the intuitiveness of task workflows in AR-based situational awareness systems [3]
- User Interviews

- Semi-structured interviews capture detailed feedback on system usability and functionality.
- Example: Gathering insights from military personnel who tested the AR prototype during simulated missions.
- Thematic Analysis
 - Analyzes qualitative data from interviews, observations, and open-ended survey responses to identify recurring themes and insights.
 - Example: Highlighting user frustrations with AR headsets that are too bulky for prolonged use.

2.5.7. Comparative Testing

Comparative methods are essential for evaluating the relative performance of AR systems against traditional solutions.

- A/B Testing
 - Compares user performance between two systems, such as legacy and AR-enhanced systems.
 - Example: Assigning participants randomly to either system and measuring task performance metrics like completion time and error rates.
- Benchmarking
 - Establishes performance baselines for traditional systems and compares them with AR prototypes.
 - Example: Setting a benchmark for task completion times in air track classification tasks and comparing it to the AR system's performance.

2.5.8. Emerging Trends in UX and AR Evaluation

- Biometric Data Integration
 - Combining physiological and behavioral data offers a comprehensive understanding of user stress, engagement, and cognitive load.

- Example: Monitoring brain activity using EEG during AR system use to quantify mental effort [7].
- Virtual Reality (VR) Simulations
 - Using VR environments to simulate battlefield conditions and evaluate AR systems under realistic scenarios.
 - Example: Testing how AR overlays impact decision-making in high-pressure environments with simulated threats [3].
- Machine Learning for UX Analysis
 - Leveraging AI to analyze user interactions and identify patterns that indicate usability issues or areas for improvement.
 - Example: Predicting task performance based on interaction data collected during usability tests.

2.5.9. Summary of Evaluation Methods

The evaluation of UX in AR systems for command control environments requires an integrative approach that combines:

- **Quantitative Methods:** Provide objective performance metrics, such as completion time and cognitive load.
- **Qualitative Methods:** Capture user-centric insights through interviews, walkthroughs, and heuristic evaluations.
- **Emerging Technologies:** Biometric monitoring and VR simulations enhance the evaluation process, ensuring systems are both practical and user-friendly.

These methods form the foundation for assessing the usability and operational impact of AR-based systems, ensuring they meet the demands of modern military operations.

2.6. Summary and Research Gaps

2.6.1. Summary of Key Findings

The literature review highlights the following critical insights:

- **Command and Control Systems (C5ISR) (2.1):** C5ISR systems are essential for coordinating complex military operations. However, traditional CCS face significant limitations, including cognitive overload, static interfaces, and challenges in multi-domain coordination [1], [2]. Emerging technologies such as augmented reality (AR) and artificial intelligence (AI) offer promising solutions to address these limitations by enhancing situational awareness and decision-making processes.
- **User Experience in C5ISR (2.2):** UX plays a pivotal role in the effectiveness of CCS, particularly in reducing cognitive load and improving operator performance. Evaluation methods like heuristic evaluations, task performance analysis, and user satisfaction surveys provide valuable insights into system usability and areas for improvement [3], [4].
- **Augmented Reality in Military Applications (2.3):** AR has demonstrated significant potential in enhancing situational awareness, training, and real-time decision-making. Applications range from battlefield visualization to equipment maintenance. Despite these advantages, challenges such as hardware constraints, integration with legacy systems, and user resistance remain prevalent [1], [3].
- **Evaluation Methods in UX and AR Systems (2.5):** Effective evaluation of AR and UX systems requires a combination of quantitative and qualitative approaches, including cognitive load metrics, usability testing, and biometric data integration. Emerging trends, such as VR simulations and machine learning analysis, further enhance the robustness of UX evaluations [5], [6].

2.6.2. Research Gaps

While existing studies provide valuable insights, several gaps remain unaddressed:

- **Limited Research on AR Integration into CCS:** Most studies focus on AR's theoretical potential rather than its practical integration into command control systems. Gap is addressed by developing and evaluating an AR-based situational awareness prototype, specifically designed for military C5ISR.

- **Insufficient Focus on UX Metrics in AR Systems:** Many evaluations of AR systems prioritize technical performance over user experience, neglecting critical aspects like usability and cognitive load. Gap is addressed by employing a mixed-methods approach, this study evaluates both quantitative (e.g., task performance, cognitive load) and qualitative (e.g., user satisfaction) metrics.
- **Lack of Real-World Testing Scenarios:** Existing studies often rely on laboratory settings, which may not fully capture the complexity of military operations. Gap is addressed by getting feedback from experienced military personnel and simulations reflecting real-world conditions.
- **Challenges in Comparing Legacy and AR Systems:** Few studies provide comprehensive comparisons between traditional CCS and AR-enhanced systems in terms of usability and task performance. Gap is addressed by doing study systematically comparing legacy and AR-based systems across multiple tasks, highlighting key differences and potential advantages.

2.6.3. How This Study Addresses These Gaps

This research bridges the identified gaps by:

- Developing a functional AR prototype tailored to the needs of military operators.
- Conducting usability testing that integrates both heuristic evaluations and task performance metrics.
- Comparing the prototype to legacy systems to quantify improvements in cognitive load, decision-making speed, and user satisfaction.
- Incorporating real-world feedback from defense industry exhibitions and experienced personnel to ensure practical relevance

While this study addresses critical research gaps through the development and evaluation of an AR-based prototype, persistent challenges within command control systems must also be recognized to contextualize the importance of these efforts. These challenges are outlined below.

2.6.4. Identified Challenges in Command and Control Systems

The review of existing literature and practical observations highlights several persistent challenges in C5ISR Systems. These challenges underscore the limitations of current systems and the urgent need for innovative solutions to enhance operational effectiveness. The key challenges identified are:

- **Perception of the Tactical Environment:** Operators face significant difficulty in rapidly and effectively perceiving the tactical environment due to the reliance on traditional 2D interfaces and complex military symbology. Research highlights that static interfaces hinder quick interpretation of critical data, leading to potential delays in situational awareness [1], [3].
- **Classification of Low-Resolution Tracks:** Existing systems require operators to classify tracks with limited or low-resolution information, which makes timely and accurate decision-making a challenge. Studies indicate that this is particularly problematic in multi-domain operations where real-time decisions are critical [2].
- **Intent Analysis for Airborne Tracks:** Operators must interpret complex airborne maneuvers, such as diving and climbing, to perform intent analysis. This task imposes a substantial cognitive burden, complicating the assessment of potential threats, particularly when data is sparse or ambiguous [7].
- **Improving Situational Awareness:** Traditional systems lack advanced visualization tools capable of providing operators with a comprehensive understanding of operational environments. AR technologies have been shown to mitigate this issue by overlaying critical tactical data in real-time, thus enhancing situational awareness [1], [3].
- **Enhancing Decision-Making:** Legacy systems do not offer the high-resolution data and advanced analytics necessary for improving decision accuracy and operational planning. Research into AR-enhanced systems demonstrates their potential to support faster and more precise decisions, especially in high-pressure environments [4].

Addressing these challenges requires the integration of innovative technologies, such as augmented reality (AR), to bridge the gaps in usability, situational awareness, and

decision support. By focusing on these areas, this study seeks to contribute to the modernization of C5ISR through the development and evaluation of an AR-based situational awareness prototype. Moreover, this effort provides a foundation for future research into the integration of AR with other advanced technologies, such as machine learning and predictive analytics, further enhancing the capabilities of military operations.

3. METHODOLOGY

In this section, the application part of the study will be explained. The stages of the study is shown in Figure 3.1.

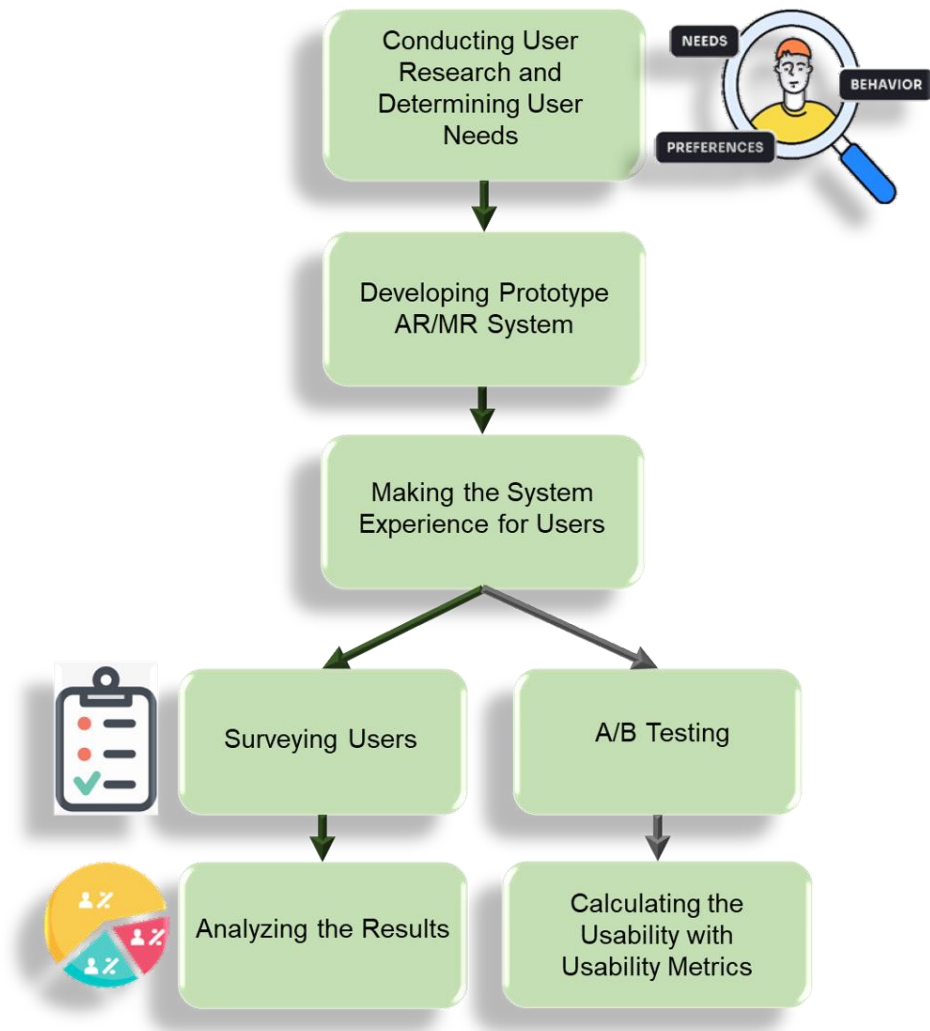


Figure 3.1: Parts and flow diagram of the study.

3.1. Overview

The methodological framework for this study is designed to systematically address the research objectives, focusing on the development, testing, and evaluation of an AR/MR-based situational awareness system. This framework incorporates both qualitative and quantitative approaches to ensure a comprehensive understanding of the system's usability, functionality, and overall effectiveness in improving decision-

making processes in military command and control settings. Figure X provides a visual representation of the methodology, outlining the sequential phases undertaken in this study.

3.1.1. Phase 1: Conducting User Research and Determining User Needs

The first phase of the methodology involves extensive user research aimed at identifying the specific needs and challenges faced by military operators. User-centered design (UCD) principles, as outlined by [8] are integral to this stage, ensuring that the system design aligns with user expectations and operational requirements. Feedback from experienced personnel at defense exhibitions was gathered through structured surveys and interviews, a practice aligned with the recommendations of [9] for understanding user behaviors and preferences. These interactions highlighted critical limitations in existing systems, such as difficulties in tactical perception, track classification, and intent analysis. These findings formed the basis for the design objectives of the AR/MR system.

3.1.2. Phase 2: Developing the Prototype AR/MR System

Based on the insights gathered during user research, the prototype AR/MR system, termed the Holographic Situational Awareness (HoSA) system, was developed. The prototype integrates holographic displays and mixed reality technologies to address the limitations identified in legacy systems. According to Azuma et al [11] AR systems that combine virtual objects with real-world environments can significantly enhance user engagement and situational awareness. Tools such as Unity and C# were employed to create the prototype, consistent with best practices for AR development [27]. The HoSA system's design focused on providing an intuitive interface and reducing cognitive load, echoing the principles outlined by Nielsen (1993) [15] for usability optimization.

3.1.3. Phase 3: Making the System Experience for Users

In this phase, the HoSA system was tested in a controlled environment with experienced military operators. The tasks were designed based on real-world

operational scenarios to ensure ecological validity, following the approach recommended by [6] for usability testing in high-stakes environments. The system's ability to enhance situational awareness and decision-making was evaluated through predefined tasks that simulated dynamic operational conditions.

3.1.4. Phase 4: Surveying Users

During defense exhibitions, the HoSA system was presented to a broader audience of 26 participants to collect preliminary user feedback. Surveys were structured to assess factors such as usability, intuitiveness, and perceived impact on operational performance. This phase aligns with the survey methodologies discussed at [4] in their systematic review of UX in AR systems. User feedback provided valuable qualitative and quantitative insights into the system's design and functionality.

3.1.5. Phase 5: A/B Testing

A controlled A/B testing framework was employed to compare the HoSA system with the existing legacy system. Each of the 16 participants performed identical tasks using both systems, allowing for direct comparisons of task completion times and usability metrics. A/B testing, as discussed by Kohavi [12], provides a robust framework for evaluating system performance under controlled conditions. The tasks were crafted to highlight the strengths and weaknesses of each system, providing a comprehensive comparison of their usability and effectiveness.

3.1.6. Phase 6: Analyzing the Results

The final phase involved analyzing the data collected during the survey and testing phases. Quantitative data, including task completion times and satisfaction scores, were analyzed using statistical methods such as t-tests, Wilcoxon Signed-Rank tests, and ANOVA, as recommended by Field [13]. Additionally, effect sizes, such as Cohen's d [14], were calculated to quantify the magnitude of differences between the systems. These analyses provided a rigorous assessment of the HoSA system's impact on usability and operational performance.

3.2. General Survey Design

The general survey was conducted to gather insights into user perceptions of the HoSA system, identify potential usability issues, and validate its relevance for situational awareness tasks in military operations. A total of 26 participants, primarily professionals from military and defense industries attending defense exhibitions, took part in the survey. Their expertise ensured familiarity with situational awareness systems.

The survey was structured with a combination of closed-ended and open-ended questions. Closed-ended questions measured usability, ease of use, and satisfaction using a Likert scale, while open-ended questions captured qualitative feedback on user impressions and potential areas for improvement. Participants engaged with the HoSA system exclusively during live demonstrations at the exhibitions.

Data collection and analysis involved both quantitative and qualitative approaches. Quantitative responses, such as Likert-scale data, were analyzed using descriptive statistics to identify patterns and trends in user satisfaction and usability perceptions. Open-ended responses were analyzed thematically to extract common feedback themes and highlight potential usability challenges. This comprehensive approach provided both numerical insights and contextual understanding of user experiences.

3.2.1. Demographic and Experience Questions

- Questions:
 - Q1: Have you ever experienced augmented reality (AR) goggles before?
 - Q2: Have you ever experienced an augmented reality-based system before?
- Objective: To understand participants' prior familiarity with AR technologies and systems.
- Analysis: Descriptive statistics are calculated by the percentage of respondents who answered "Yes" or "No" to each question. This helps determine how prior exposure might influence usability and adaptability. Research indicates that

prior experience with AR significantly impacts user performance and satisfaction [17], [18].

3.2.2. Adaptation and Discomfort Questions

- Questions:
 - Q3: How long did it take you to get used to the AR glasses in this system?
 - Q4: How long time later did glasses make you annoyed in this system?
 - Q5: What kind of discomfort occurred? (if any)
- Objective: To evaluate user adaptation to AR hardware and identify potential discomfort. Previous studies highlight adaptation challenges with AR systems, such as motion sickness, fatigue, and visual strain [15],[16].
- Analysis: Frequency distribution is calculated by using the frequency of responses (e.g., "immediately," "little time later," "long time") to analyze how quickly users adapted.

3.2.3. Usability and Learning Questions

- Questions:
 - Q6: Clicking object is...
 - Q7: Track (battleship, airplane, boat, etc., icon) selection process is...
- Objective: To assess the usability and learnability of core functions in the HoSA system. Usability evaluations often reveal barriers in interaction design that impact task performance [6][15].
- Analysis: Usability evaluation is measured the ease of use and learning for each interaction (e.g., clicking objects, selecting tracks).

3.2.4. Effectiveness and Situational Awareness Questions

- Questions:
 - Q8: Track information levels (are)...

- Q9: 3D track icon holograms (are)...
- Q10: 3D track representative hologram models (are)...
- Q11: 2D virtual screens (are)...
- Q12: 3D tactical hologram map (is)...
- Q13: Multi-user collaboration...
- Objective: To evaluate how the system supports situational awareness and operational effectiveness. Situational awareness is critical for decision-making in dynamic military environments [19][20].
- Analysis: Effectiveness evaluation is assessed user responses to elements like track information, holograms, and collaboration to gauge their contribution to situational awareness.

3.2.5. Application and Platform Questions

- Questions:
 - Q14: Which forces can this system (HoSA) contribute positively to situational awareness?
 - Q15: In which navy platforms can this system be used?
- Objective: To identify the most suitable military applications and platforms for the HoSA system. Research suggests that AR applications in military operations can be tailored to specific forces and platforms for enhanced relevance [17],[18].
- Analysis: Descriptive statistics are calculated the percentage of responses favoring different forces (e.g., Navy, Land Forces) and platforms (e.g., frigates, corvettes).

3.2.6. Comparative and Feature Questions

- Questions:
 - Q16: Which features of HoSA are better than conventional C5ISR situational awareness system features?

- Objective: To compare the perceived advantages of the HoSA system over traditional systems.
- Analysis: Comparative analysis studies on AR indicate the importance of feature-specific evaluations to understand user preferences [16], [21].

3.2.7. Perception and Satisfaction Questions

- Questions:
 - Q17: This system is...
 - Q18: The experience feeling was...
- Objective: To evaluate user satisfaction and overall perception of the HoSA system. User satisfaction often correlates with perceived system efficacy and usability [6], [22].
- Analysis: User Perception Evaluation analyzed responses to determine if the system was perceived as effective or more like a simulation/game.



Figure 3.2: General survey participants.

Figure 3.2 and Figure 3.3 show that attendees are experiencing the HoSA and giving survey feedbacks.



Figure 3.3: Participant feedbacks.

3.3. Controlled Experiment Design

The controlled experiment was designed to rigorously evaluate and compare participant performance using the HoSA and legacy systems. This section outlines the objectives, participants, task design, experimental setup, and performance metrics used in the study.

3.3.1. Objectives

The controlled experiment sought to:

- Compare participant task performance between the HoSA and legacy systems.
- Evaluate the impact of HoSA on task completion times and situational awareness, which aligns with previous findings on the importance of AR in improving decision-making in operational environments [11].
- Validate the effectiveness of HoSA in a controlled operational environment, following principles of usability testing outlined by Nielsen [10].

3.3.2. Participants

The study included 16 experienced participants with prior knowledge of command control systems. Each participant performed identical tasks on both the HoSA and legacy systems to allow for within-subject comparisons. Such within-subject designs are recommended in usability studies to minimize individual variability [23].

3.3.3. Task Design

Three standardized tasks were developed to evaluate participant performance across both systems:

- **TASK-1. Perception of the Tactical Environment:** Participants assessed the tactical environment to identify and interpret situational elements, as suggested by the operational frameworks of situational awareness studies [19].
- **TASK-2. Classification of Low-Resolution Tracks:** Participants classified tracks based on limited kinematic data, such as speed, position and altitude. This aligns with cognitive load theory in decision-making environments [28].
- **TASK-3. Intent Analysis for Airborne Tracks:** Participants analyzed airborne maneuvers, such as climbing or diving, to infer intent. This follows methodologies employed in prior intent recognition studies [3].

3.3.4. Participant Test Workflow

This flow represents the **step-by-step workflow** for each participant during the experiment. It ensures clarity in understanding the individual interaction process with both the HoSA and legacy systems. The workflow begins with an empty map for orientation, proceeds to task declaration, and measures the task completion time as participants perform specific situational awareness tasks. By systematically organizing the participant's experience, the flowchart highlights the consistency of the testing protocol across all participants.

Each step of the workflow minimizes potential variability by clearly defining:

1. **State of the System:** Starting with an empty map ensures that all participants begin from a neutral setup, eliminating prior knowledge effects [30].

2. **Task Declaration:** Declaring the task before showing tactical units ensures participants understand the objective before engaging with the system.
3. **Timing Mechanisms:** Using specific start and stop points ensures the accurate measurement of task performance, a key metric in usability studies [5], [6].

This detailed structure aligns with best practices in usability testing, where standardized workflows are essential to ensure repeatability and reliability [23]

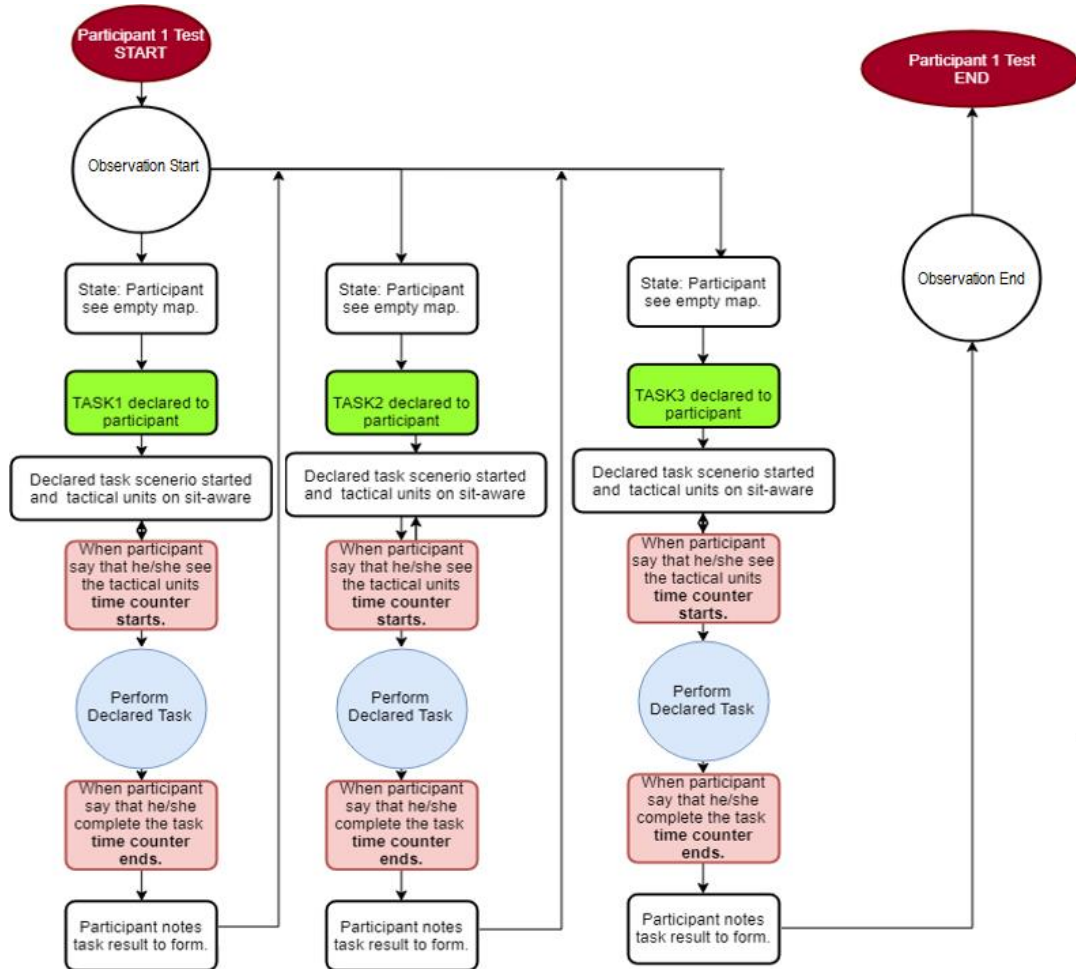


Figure 3.4: Participants task execution workflow.

- **Observation Start:** The participant enters the testing environment. An empty map is displayed on the system interface.
- **Task Declaration:** The test administrator announces each task (Task 1, Task 2, Task 3) to the participant. A scenerio is loaded into the system, displaying tactical units relevant to the declared task.

- **Task Execution:** The participant indicates when they recognize tactical units on the situational awareness interface (time counter starts). The participant performs the assigned task (e.g., tactical environment perception, classification, or intent analysis). The participant signals task completion (time counter ends).
- **Recording Results:** The participant's performance metrics, including time taken and task-specific notes, are logged into the form.
- **Repetition for Each Task:** The process is repeated for Tasks 1, 2, and 3 to collect comprehensive data.
- **Observation End:** The participant completes all tasks, and the experiment concludes.

3.3.5. Experimental Setup

- **Holographic Situational Awareness System (HoSA):** Participants utilized Microsoft HoloLens to visualize tactical elements in an interactive 3D environment. Such systems have been shown to enhance operator performance by reducing cognitive overload [1]
- **Legacy System:** The 2D interfaces presented tactical elements on a conventional monitor. Tasks were randomized to minimize potential learning effects, adhering to experimental design best practices in UX research [6].

3.3.6. Performance Metrics

- **Task Completion Times:** The time required to complete each task was recorded in seconds for both systems. Measuring task time is a key usability metric in evaluating interface effectiveness [31].
- **Error Handling:** Minimal errors observed during the study were excluded from analysis as they did not significantly impact task performance. Error rates are often used in usability research to complement time-based performance measures [10].

This experimental design ensured a robust comparison of the two systems, emphasizing task performance and situational awareness. The integration of AR technology follows recent trends in situational awareness enhancement [27].

3.4. Experimental Setup

The experimental setup plays a critical role in validating the comparative performance of the Legacy Situational Awareness System and the Holographic Situational Awareness (HoSA) System. This section provides an overview of the test environment and systems involved, designed to emulate real-world operational conditions for military command and control scenarios.

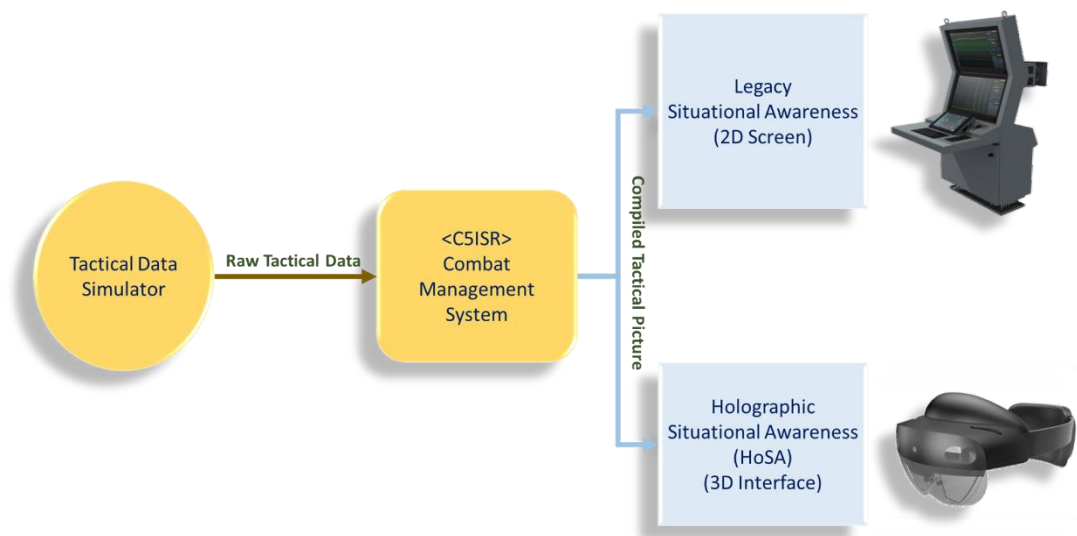


Figure 3.5: Experimental setup overview.

The setup leverages a combination of advanced tools to create a controlled environment for accurate data collection and analysis. The Tactical Data Simulator generates realistic tactical scenarios by providing dynamic raw data on tactical elements, including their positions, velocities, and maneuvers. This raw data is processed by the C5ISR Combat Management System, which compiles it into a meaningful tactical picture.

The compiled tactical picture is then visualized through two systems:

- **Legacy Situational Awareness System:** Displays tactical information on a 2D screen interface, adhering to traditional design paradigms with standard military symbology.
- **Holographic Situational Awareness (HoSA) System:** Presents tactical information in a 3D augmented reality environment using Microsoft HoloLens.

This system is designed to enhance spatial awareness and decision-making through immersive visualization.

This dual-system setup enables participants to perform identical tasks on both systems, ensuring a fair comparison. The flow of data between components, as depicted in the diagram (Figure 3.5), underscores the integration of simulation, processing, and visualization technologies, reflecting the workflow of modern combat management systems.

The results from this experimental setup provide a basis for evaluating system usability, effectiveness, and their impact on situational awareness and task performance.

3.4.1. Tactical Data Simulator

The Tactical Data Simulator is a commercial system designed to generate tactical objects on operational maps tailored to specific scenarios. These tactical objects are configured with attributes such as position, altitude, and velocity, enabling realistic and dynamic movements. The system allows the creation of realistic operational scenarios, which can be recorded and replayed with varying parameters to provide consistent data input to command systems like the Naval Combat Management System (C5ISR). By simulating real-world conditions, this system ensures repeatability and accuracy, which are essential for controlled experiments [11].

3.4.2. Naval Combat Management System (C5ISR)

The C5ISR system processes data from the simulator and presents it meaningfully to end-users. This mockup version of an operational military system adheres to military symbology standards, displaying tactical unit traces on a 2D geographic map. The system provides real-time kinematic data such as 3D positions, orientations, velocities, accelerations, and actions like diving or climbing. Additionally, its 2D interfaces support various critical tasks, including:

- Analyzing the operational field.
- Extracting and correlating information.
- Classifying tracks and identifying potential threats.

- Determining the intent behind detected tracks.

These capabilities replicate the features of modern combat management systems used in military operations, offering a baseline for comparison against the Holographic Situational Awareness System (HoSA) [1].

3.4.3. Legacy Situational Awareness System

The legacy system represents tactical data on a 2D map using traditional monitors or projectors. While functional, it relies on static and linear interfaces that can limit user interaction and situational awareness. Its representation of tactical units plays a foundational role in operational decision-making by displaying spatial and kinematic information on 2D surfaces. However, these systems lack depth, leading to potential cognitive overload in complex scenarios [3].



Figure 3.6: Legacy system display type.

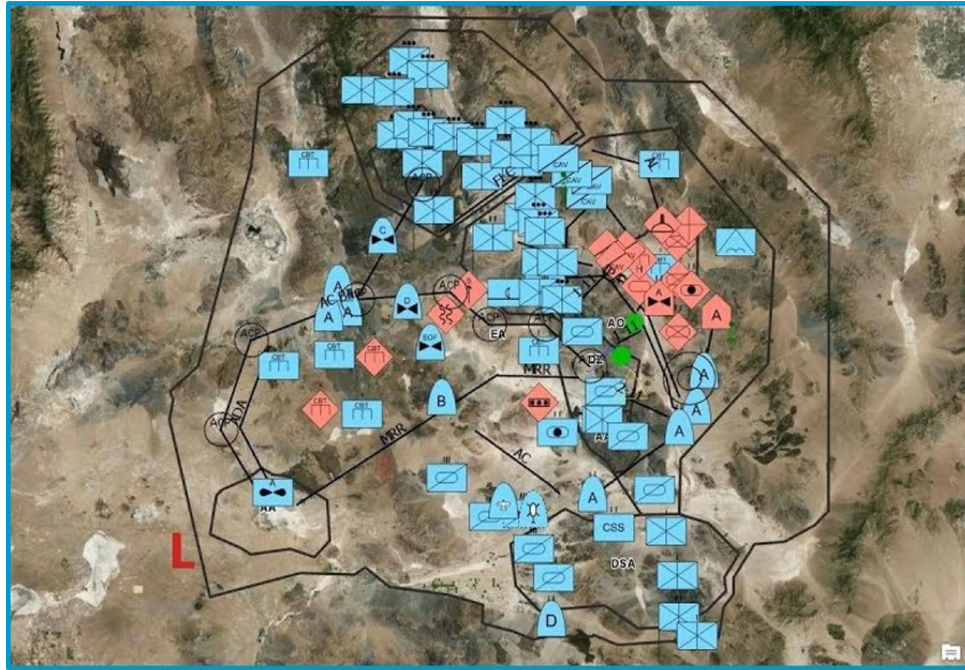


Figure 3.7: Legacy system symbology.

3.4.4. Holographic Situational Awareness System (HoSA)

The Holographic Situational Awareness (HoSA) system is a next-generation mixed-reality platform designed to improve situational awareness through advanced 3D visualization techniques. The system leverages Microsoft HoloLens to display tactical units as interactive 3D holographic icons, providing a multi-dimensional view of battlefield environments. Developed in Unity using the C# programming language, HoSA integrates multiple software modules to ensure real-time data processing, seamless interaction, and collaborative capabilities.

Key Features of HoSA:

- **3D Holographic Maps:** The system integrates geographic coordinates with real-time tactical data, allowing users to interpret battlefield conditions more intuitively.
- **Real-Time Data Processing:** HoSA displays unit positions, movements, and kinematic details (e.g., velocity, acceleration, and maneuver patterns) with minimal latency.

- Collaborative Capabilities: While testing was conducted in a single-user environment, HoSA supports multi-user collaboration, enabling shared decision-making and synchronized battlefield visualization.
- Dynamic User Interfaces: HoSA features three-tiered UI options (mini, midi, and mega 2D interfaces) that provide detailed information on tactical units, mission parameters, and operational contexts.

Software Architecture and Key Components:

The HoSA system architecture consists of multiple software units designed to enhance performance, usability, and scalability in military applications:

- Data Integration Engine: Aggregates real-time battlefield intelligence from radar systems, UAV feeds, GPS data, and sensor networks, ensuring a unified tactical overview.
- 3D Rendering Module: Developed in Unity, this module optimizes holographic asset generation and real-time rendering of tactical environments.
- User Interaction Framework: Implements gesture-based controls, voice commands, and gaze tracking to create a hands-free, intuitive user experience.
- AI-Assisted Decision Support System: Uses machine learning algorithms to analyze tactical movements, predict enemy maneuvers, and provide adaptive recommendations based on historical combat data.
- Network Synchronization Module: Ensures secure, real-time data transmission across multiple AR users, enabling synchronized command and control operations.
- HoSA's Core Objectives:

The HoSA system is specifically designed to address challenges in military command and control environments, focusing on reducing cognitive load, improving situational awareness, and accelerating decision-making [2]. The key objectives include:

- User-Centered Design Optimization: Collecting user feedback to identify usability issues and refine the interface for improved operator efficiency.

- Comparative A/B Testing: Evaluating various interface designs and interaction models to determine the most effective configurations for military applications.
- Iterative System Enhancement: Continuously refining the software framework based on empirical data, ensuring long-term adaptability to evolving military needs.

By integrating real-time tactical data and intuitive AR interfaces, HoSA represents a transformational leap in military situational awareness. Its modular software architecture ensures adaptability, while its multi-layered visualization system enhances operational efficiency. As AR technology continues to evolve, HoSA is expected to further refine its capabilities, making it a cornerstone of future command and control systems.

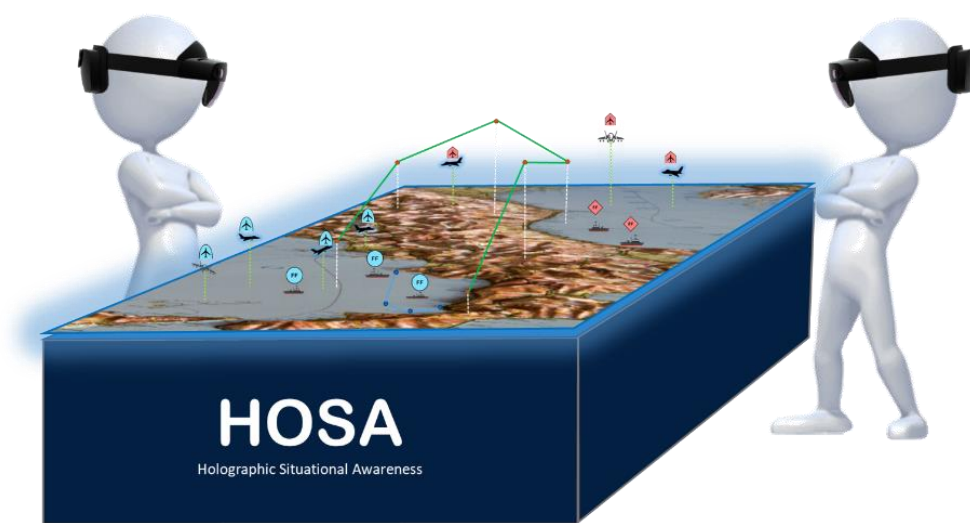


Figure 3.8: HoSA system concept.



Figure 3.9: HoSA controlled experiment.

3.4.5. Comparative Setup

The comparative setup employed a robust within-subject design to evaluate the performance of the Holographic Situational Awareness (HoSA) system and the Legacy Situational Awareness System. This design ensured a fair and unbiased comparison by systematically addressing potential confounding variables, such as learning effects and participant fatigue.

- **Key Features of the Comparative Setup**
 - **Task Randomization:** Tasks were presented in a randomized order for each participant to prevent task-order effects from influencing the results. This method ensured that performance differences were due to the system interfaces rather than task familiarity.
 - **System Alternation:** Participants alternated between the HoSA and Legacy systems. The sequence of systems was counterbalanced to minimize order effects, with half the participants starting with HoSA and the other half with the Legacy system.
 - **Rest Periods:** A minimum one-hour rest period was implemented between sessions to prevent participant fatigue and ensure unbiased task performance evaluations. This break reduced carryover effects,

where the experience with one system might influence performance on the next.

- **Performance Metrics:**

- Task completion times were recorded to measure efficiency.
- Situational awareness and task accuracy were assessed to determine the effectiveness of each system in supporting operational decision-making.

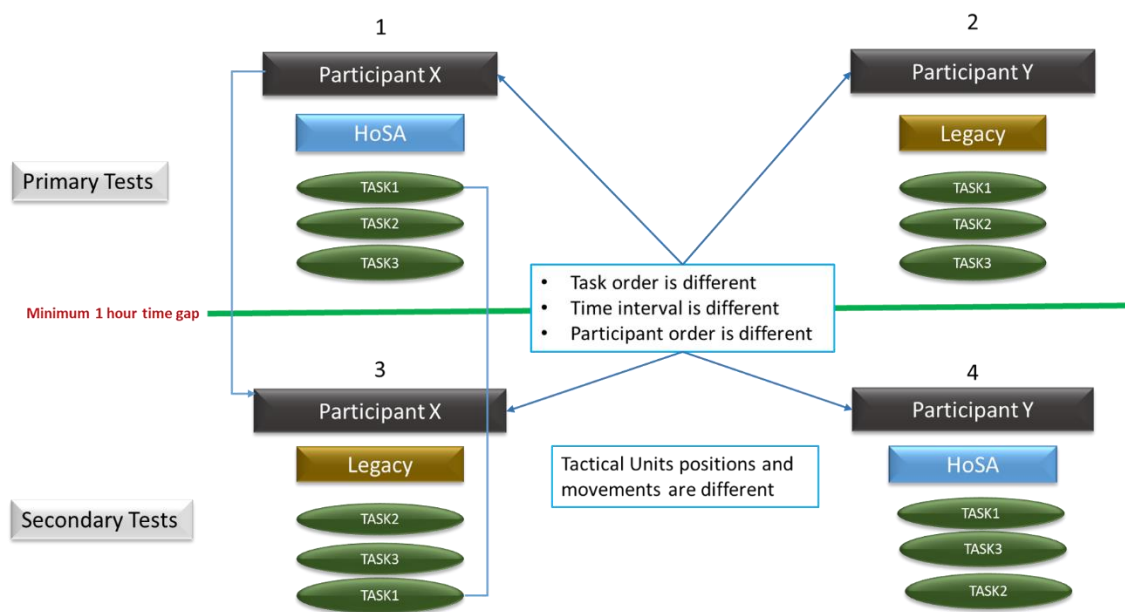


Figure 3.10: Experimental design overview.

The flowchart provides a visual representation of the experimental design, emphasizing its counterbalanced structure. The diagram illustrates task randomization, participant alternation between systems, and the systematic flow of the experiment.

- **Design Strengths**

- **Counterbalancing:** This approach minimizes potential biases from learning effects, fatigue, or order effects that might arise during repeated measures [33].
- **Primary and Secondary Tests:** Participants first interacted with one system and then switched after a rest period. This alternation ensured that no single system benefited from the order of testing [34].

- **Within-Subject Comparison:** All participants interacted with both systems, allowing the study to isolate the effects of the system interface while reducing variability caused by individual differences [36].
- **Purpose and Outcome**

The comparative setup enabled a direct evaluation of 2D and 3D interfaces across identical tasks. By integrating systematic task randomization and participant alternation, this design ensured that any observed differences in usability and performance could be confidently attributed to the systems themselves. The robust methodological approach highlights the strengths and weaknesses of both systems in supporting situational awareness and operational effectiveness.

3.5. Data Analysis

This section explains the statistical methods used to analyze the collected data. The study used both parametric and non-parametric methods to ensure robust and reliable results. These quantitative analysis techniques were chosen based on the nature of the data and the objectives of the analysis.

3.5.1. Paired t-Test Analysis for UX Data Comparison

The paired samples t-test is a parametric statistical method used to compare two related groups, such as the same participants performing tasks under different conditions. This test evaluates whether the mean difference between paired observations is statistically significant, making it a widely used method in within-subject experimental designs [13], [35].

- **Application in the Study:** In this study, the paired t-test was employed to compare task completion times and error rates between the Holographic Situational Awareness (HoSA) system and the legacy system. Participants performed identical tasks under both systems, allowing for direct comparisons of performance metrics.
- **Hypotheses:**

- **Null Hypothesis (H_0):** The mean difference in task performance (e.g., completion times) between the legacy and HoSA systems is zero.
 - **Alternative Hypothesis (H_1):** The mean difference in task performance between the legacy and HoSA systems is not zero.
- **Assumptions:** The paired t-test relies on several key assumptions:
 - **Normality of Differences:** The differences between paired observations should be approximately normally distributed.
 - **Independence of Pairs:** Each pair of observations (e.g., one participant's performance on both systems) must be independent of other pairs.
 - **Interval or Ratio Scale Data:** The data should be measured on an interval or ratio scale to ensure meaningful computation of means and differences.
- **p-Value and Significance:** The t-statistic is compared to a critical value based on the degrees of freedom ($n-1$) and the chosen significance level ($\alpha=0.05$). The corresponding p-value indicates the likelihood of observing the mean difference under the null hypothesis. A p-value less than 0.05 suggests a statistically significant difference [14].
- **Rationale for Use:** The paired t-test was chosen for this study because:
 - It accounts for individual variability by comparing participants to themselves under two conditions.
 - It provides a straightforward method for identifying significant differences in performance metrics.
 - Its assumptions were deemed reasonable based on the characteristics of the collected data.
- **Results Interpretation:** The resulting p-values were interpreted as follows:
 - **$p < 0.05$:** The null hypothesis was rejected, indicating a significant difference in task performance between the legacy and HoSA systems.
 - **$p \geq 0.05$:** The null hypothesis was not rejected, suggesting no significant difference in performance.

The paired t-test ensured robust statistical analysis by leveraging the within-subject design of the study, reducing variability caused by individual differences, and isolating the effect of the system on task performance.

- **Advantages and Limitations:**

- **Advantages:** The paired t-test is highly efficient in detecting differences because it controls for variability between participants, making it more sensitive to treatment effects [34]
- **Limitations:** It assumes normality of differences, which, if violated, can lead to inaccurate results. In such cases, the Wilcoxon Signed-Rank Test serves as a suitable alternative.

3.5.2. Wilcoxon Signed-Rank Test for Non-Parametric Data

The Wilcoxon Signed-Rank Test was employed as an alternative to the paired t-test for analyzing task completion times and error rates when data did not meet normality assumptions. This test is non-parametric, making it suitable for small sample sizes or skewed data distributions. It evaluates whether the median differences between paired observations are significantly different from zero, focusing on ranks rather than raw values [37].

- **Application in the Study:**

- **Paired Observations:** Each participant performed the same tasks under both the legacy and HoSA systems, creating paired data.
- **Ranking Differences:** The absolute differences between paired observations were ranked, with positive or negative signs assigned based on whether HoSA outperformed or underperformed the legacy system.

- **Hypotheses:**

- **Null Hypothesis (H_0):** The median differences between the legacy and HoSA systems for task completion times or error rates are zero.
- **Alternative Hypothesis (H_1):** The median differences between the legacy and HoSA systems for task completion times or error rates are non-zero.

- **p-Value Interpretation:** The p-value was compared against a threshold of 0.05 to determine significance. A p-value below 0.05 indicated a rejection of the null hypothesis, suggesting significant differences between the two systems [13]

The Wilcoxon Signed-Rank Test complemented the paired t-test, providing robust results even when data deviated from parametric assumptions.

3.5.3. ANOVA Analysis for Multiple Comparisons

Analysis of Variance (ANOVA) was used to compare task performance across multiple groups, specifically the three tasks and two systems. ANOVA is a statistical method designed to test for differences among group means by examining variance within and between groups [38].

- **Application in the Study:** ANOVA was applied to:
 - Analyze differences in task completion times across tasks (Task 1, Task 2, Task 3).
 - Evaluate performance differences between the legacy and HoSA systems.
- **Hypotheses:**
 - **Null Hypothesis (H_0):** There are no significant differences in task completion times across tasks or systems.
 - **Alternative Hypothesis (H_1):** At least one group mean differs significantly.
- **ANOVA Process:**
 - **F-Statistic:** ANOVA computes the ratio of between-group variance to within-group variance. A higher F-value indicates greater differences between groups [39].
 - **Post Hoc Analysis:** If the ANOVA results were significant, post hoc tests were conducted to pinpoint specific group differences.
- **Benefits:** ANOVA was critical for evaluating interaction effects between tasks and systems, ensuring a thorough understanding of performance variations [36].

3.5.4. Cohen's d for Effect Size Analysis

Cohen's d was used to quantify the effect size, providing a measure of the magnitude of differences between the legacy and HoSA systems. Unlike p-values, which assess statistical significance, Cohen's d evaluates practical significance [14].

- **Interpretation:**
 - **Small Effect:** $d=0.2$
 - **Medium Effect:** $d=0.5$
 - **Large Effect:** $d=0.8$ or greater
- **Application:**
 - **Task Completion Times:** Cohen's d provided insights into the practical impact of observed differences, highlighting the effectiveness of HoSA in reducing task completion times.
 - **Usability Impact:** A larger effect size indicated meaningful improvements in user experience and situational awareness.
- **Importance:** Cohen's d helped contextualize the statistical findings, ensuring that significant results also had real-world relevance [40].

3.5.5. Why These Techniques Were Used?

- **t-Test:** Robust for paired comparisons when data are normally distributed.
- **Wilcoxon Signed-Rank Test:** Ensures validity for non-normal data distributions.
- **ANOVA:** Identifies differences across multiple tasks and systems, capturing interaction effects.
- **Cohen's d:** Measures practical significance, translating statistical differences into actionable insights.

This comprehensive analytical approach combined the strengths of parametric and non-parametric methods to ensure accurate and reliable results. The integration of these techniques provided both statistical and practical perspectives, essential for evaluating the effectiveness of the HoSA system.

3.6. Ethical Considerations

Ethical integrity was a cornerstone of this study, ensuring that all research activities complied with established ethical guidelines and standards for human subject research.

3.6.1. Informed Consent

Participants were fully informed about the study's objectives, procedures, and their rights as participants before providing their consent. A detailed briefing was conducted to explain:

- The purpose of the research and its relevance to enhancing situational awareness systems.
- The voluntary nature of participation, with the option to withdraw at any point without repercussions.
- The specific tasks participants would undertake and the data to be collected.

Written consent forms were provided, ensuring that participants explicitly acknowledged their understanding and agreement to participate.

3.6.2. Anonymity

To protect participants' privacy, all collected data were anonymized. Each participant was assigned a unique identifier, ensuring that individual responses could not be traced back to their identity. This measure was crucial to maintaining confidentiality and fostering trust.

3.6.3. Data Security

Survey and experimental data were securely stored in encrypted formats on password-protected devices. Access to the data was restricted to authorized researchers only, and the data were used exclusively for research purposes. Additionally, compliance with data protection regulations, such as GDPR, was ensured throughout the study.

3.6.4. Ethical Review

The study protocol underwent an ethical review process to ensure that it adhered to the principles of respect, beneficence, and justice as outlined in the Declaration of Helsinki and other relevant ethical guidelines.

3.7. Limitations

While this study provided valuable insights into the usability and effectiveness of the HoSA system, several limitations should be acknowledged to contextualize the findings and guide future research.

3.7.1. Sample Size

The study included 26 participants for the general survey and 16 participants for the controlled experiment. While sufficient for initial insights, these sample sizes are relatively small, limiting the generalizability of the findings to broader populations. Larger, more diverse samples would enhance the robustness of the results.

3.7.2. Error Data Exclusion

Errors were excluded from the analysis due to their infrequency. While this approach simplified the analysis, it may have overlooked subtle usability issues or patterns that could provide additional insights into system performance. Future studies could explore errors in greater detail to identify areas for improvement.

3.7.3. Simulated Environment

The controlled experiment was conducted in a simulated environment rather than real-world operational conditions. While the simulation was designed to closely replicate actual scenarios, it may not fully capture the complexities and pressures of real-world military operations. This limitation affects the external validity of the findings.

3.7.4. System Familiarity

Participants' prior familiarity with traditional command and control systems might have influenced the results. While efforts were made to minimize learning effects, participants' experience levels could still introduce bias in favor of the legacy system.

3.7.5. Single-Task Focus

The controlled experiment focused on three specific tasks: perception of the tactical environment, classification of low-resolution tracks, and intent analysis for airborne tracks. While these tasks are representative, they do not encompass the full range of activities required in operational contexts. Future research could expand the scope to include more diverse tasks.

3.7.6. Hardware Constraints

The HoSA system relied on AR hardware, such as Microsoft HoloLens, which has inherent limitations, including field of view and potential discomfort during prolonged use. These factors might have influenced participants' performance and perceptions.

3.7.7. Enhanced Insights for Future Research

Recognizing these limitations provides a foundation for refining future studies. Expanding sample sizes, incorporating real-world environments, and exploring additional performance metrics would strengthen the validity and applicability of findings. Ethical rigor and a focus on minimizing bias will remain critical as the research evolves.

4. RESULTS

4.1. General Survey Results

4.1.1. Participant Demographics

The general survey included a diverse group of 26 participants, primarily drawn from military and defense sectors. As shown in Figure 4.1, the participants represented various professional domains:

- Navy professionals accounted for the largest group at 35%, emphasizing the strong relevance of the system to naval operations.
- Land Forces (15%) and Air Forces (11%) personnel provided critical perspectives from their operational contexts.
- Additional participants included representatives from specialized fields such as Aviation ATC, AWC, engineers, and even medical professionals, which highlights the system's potential adaptability to various scenarios.

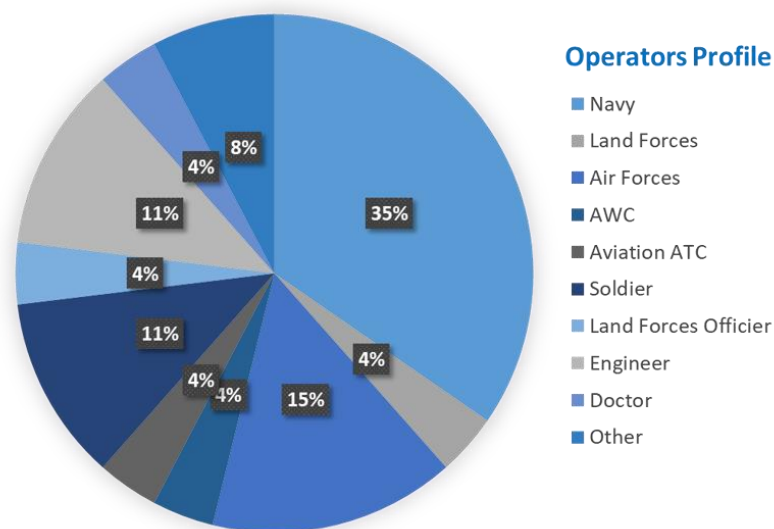


Figure 4.1: Profile of operators in the general survey.

This diverse representation ensures that the survey results are not only relevant to a single domain but provide a broad understanding of the potential applicability of the HoSA system across various operational environments. The feedback gathered from

these participants reflects a comprehensive evaluation of the system's usability and situational awareness features.

4.1.2. Participant Satisfaction

Participant satisfaction with the HoSA system was assessed through the survey, with results depicted in Figure 4.2. The distribution of responses demonstrates overwhelmingly positive feedback:

- 76% of participants rated the system as "Very good, amazing, great, wow!" indicating strong approval and enthusiasm for the system's design and functionality.
- 12% rated it as "Good, cute," reflecting general satisfaction.
- 8% found the system to be "Average."
- A small percentage, 4%, rated it as "Not bad," while no participants rated it as "Bad."

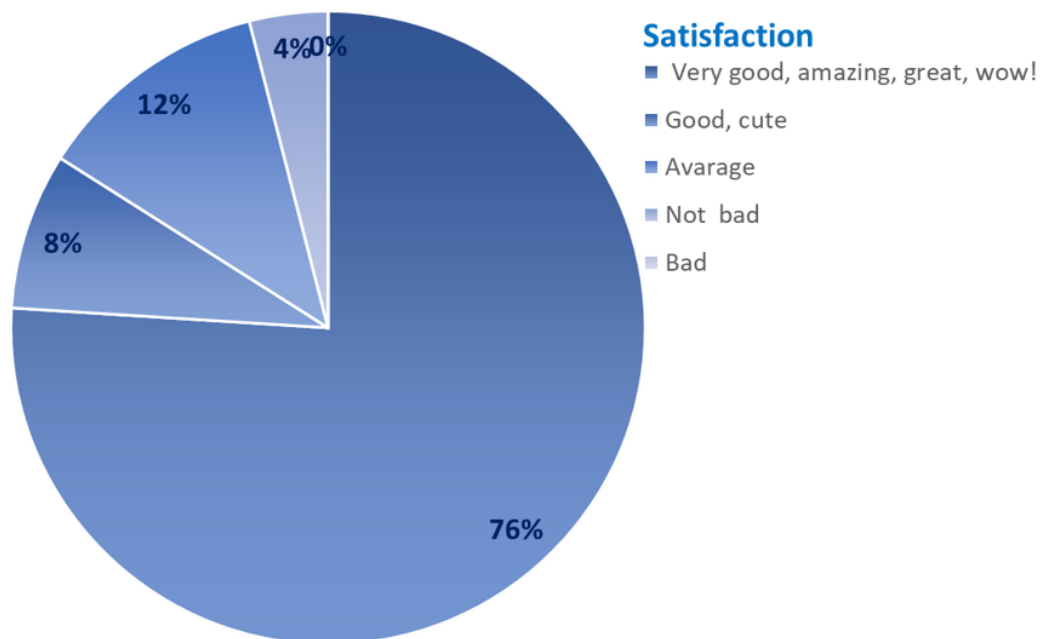


Figure 4.2: Participant satisfaction levels.

The overwhelmingly positive feedback supports the conclusion that the HoSA system provides a highly satisfactory user experience. The minimal percentage of lower ratings indicates potential areas for minor improvements but overall highlights the system's success in meeting user expectations.

4.1.3. Adaptation and Discomfort

The survey included questions aimed at understanding the ease of adaptation to the HoSA system and any discomfort experienced by participants. The results are summarized in Figure 4.3, highlighting three key aspects of user experience.

- **Adaptation Time:**
 - 65% of participants reported adapting to the AR glasses "immediately," indicating a high level of usability.
 - 31% adapted "a little time later," showing that the system required minimal learning for most users.
 - Only 4% took "a long time later" to adapt, suggesting the system's overall accessibility.
- **Onset of Annoyance:**
 - 77% of participants stated that the AR glasses "did not annoy" them at any point.
 - Smaller portions of participants reported annoyance:
 - 8% at the "beginning of the experience."
 - 8% "in the middle of experience."
 - 7% "long time later."
- **Types of Discomfort:**
 - 62% of participants did not experience any discomfort.
 - Among those who experienced discomfort: 19% cited "physical weight" as an issue. 19% reported a "reduced field of view."

Adaptation and Discomfort

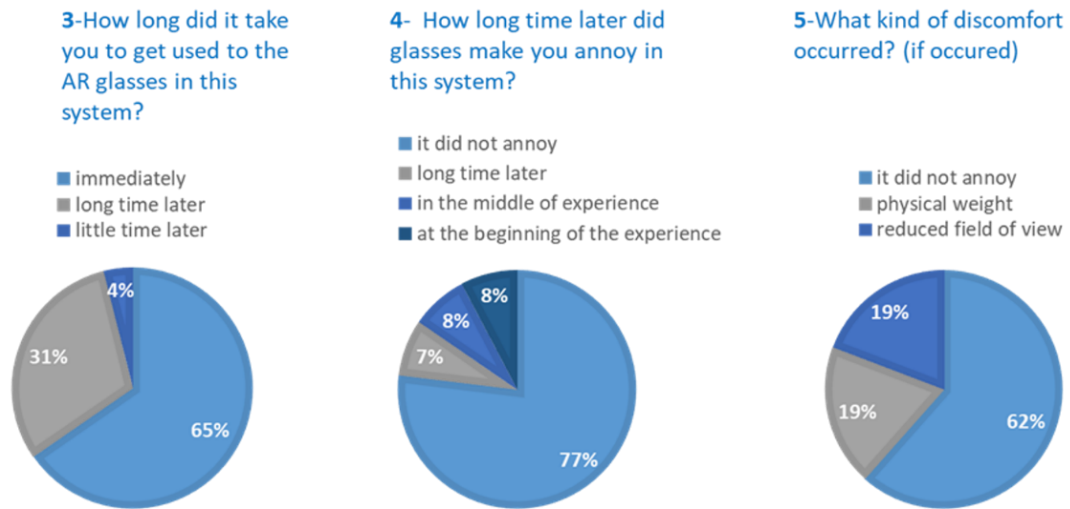


Figure 4.3: Adaptation and discomfort metrics.

These findings demonstrate that the majority of participants found the HoSA system easy to adapt to and largely free of discomfort. The small percentage of reported issues, such as physical weight and field-of-view limitations, provide valuable insights for potential hardware improvements in future iterations.

4.1.4. Effectiveness and Situational Awareness

The survey aimed to evaluate the HoSA system's effectiveness and its impact on situational awareness. Figure 4.4 illustrates participant feedback across six key aspects of system usability and understanding:

- **Track Information Levels:** 26 participants reported that track information levels were easy to understand and perceive, emphasizing the system's clarity in presenting tactical data.
- **3D Track Icon Holograms:** 25 participants found the 3D track icon holograms intuitive and easy to understand. Only 1 participant faced challenges in perceiving this feature.
- **3D Track Hologram Models:** 23 participants perceived 3D track hologram models as easy to understand and interpret. A minor portion (3 participants) found these models challenging, suggesting room for refinement in holographic representations.

- **2D Virtual Screens:** 23 participants rated the 2D virtual screens as easy to perceive and use. Similarly, 3 participants reported difficulty with the screens, aligning with feedback from traditional interface users.
- **3D Tactical Hologram Map:** 24 participants acknowledged the 3D tactical hologram map as an effective tool for situational awareness. A smaller subset (2 participants) faced minor challenges in interpreting this map.
- **Multi-User Collaboration:** 24 participants found the multi-user collaboration feature beneficial for enhancing situational awareness. 1 participant expressed difficulty, likely due to limited exposure to collaborative functionalities in real-time environments.

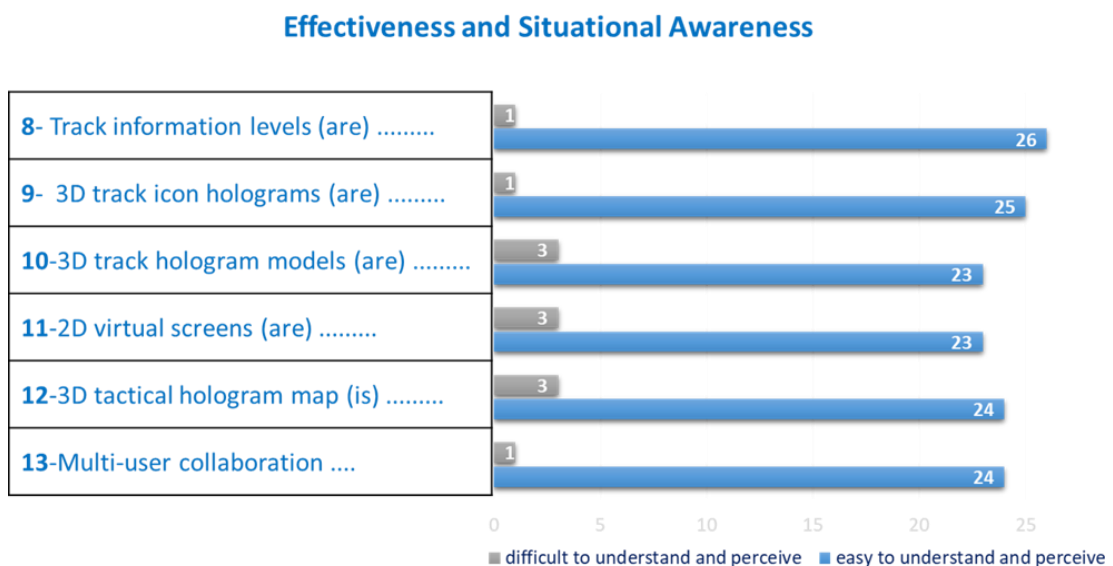


Figure 4.4: Effectiveness and situational awareness.

The findings strongly support the HoSA system's capability to enhance situational awareness through features like intuitive 3D holograms and maps. While most participants found the system effective and user-friendly, the feedback highlights areas, such as 3D models and collaborative features, for potential improvement. This analysis underscores the significant role of innovative visual interfaces in advancing decision-making in complex tactical environments.

4.1.5. Application and Platform

The survey explored the potential application areas and platforms for the HoSA system to determine its versatility and relevance in military operations. Figure 4.5 provides insights into the participants' feedback regarding the system's application across forces and naval platforms.

- **Application Across Forces:**
 - 40% of participants identified the Navy as the primary beneficiary of the HoSA system due to its tactical and operational requirements.
 - 33% believed the system would significantly benefit the Land Forces, highlighting its adaptability to ground-based C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) systems.
 - 27% acknowledged its potential for Air Forces, particularly in aviation control and situational awareness tasks.
- **Platforms for Navy Utilization:**
 - Among naval platforms, the following preferences were noted:
 - Aircraft Carriers (29%) emerged as the most suitable platform for deploying HoSA, emphasizing its role in complex, high-stakes operations.
 - Landing Helicopter Docks (25%) and Landing Ship Tanks (22%) were also identified as key platforms where HoSA could enhance tactical operations and coordination.
 - Frigates (13%) and Corvettes (11%) were recognized as potential platforms, albeit with slightly lower emphasis due to their specific operational scopes.

Application and Platform

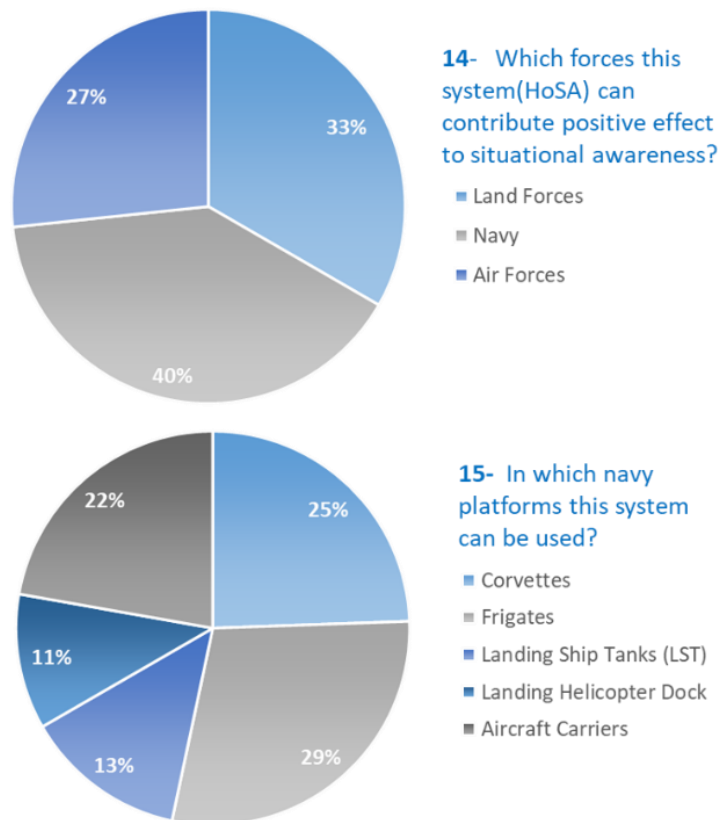


Figure 4.5: Application and platform preferences.

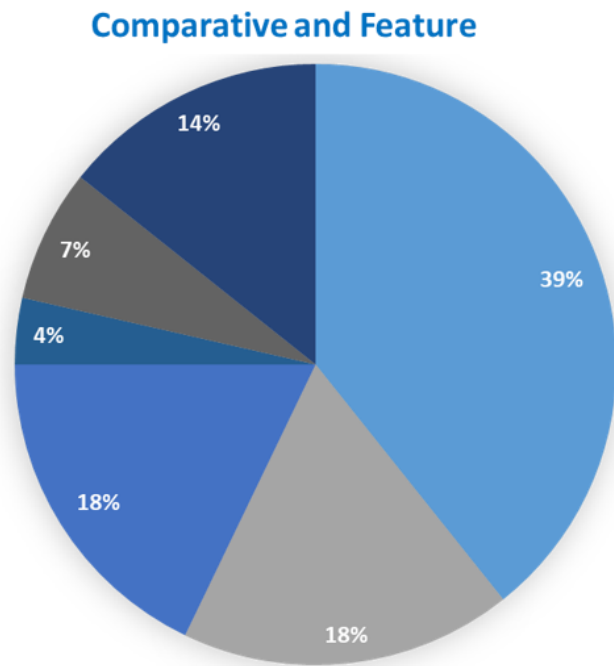
The feedback highlights the HoSA system's adaptability across diverse military forces and its potential to enhance operational capabilities on various naval platforms. The strong preference for naval applications aligns with the system's design and focus on 3D situational awareness in maritime environments. This insight is critical for refining the system's features and prioritizing its deployment in relevant operational scenarios.

4.1.6. Comparative Features of HoSA

The survey sought to identify the features of the HoSA-C4ISR system that participants deemed superior to conventional C4ISR situational awareness systems. Figure 4.6 presents a breakdown of participants' preferences regarding specific features.

- **3D Hologram Track Icons vs. Traditional APP(6) 2D Icons (39%):**
 - The majority of participants highlighted the advantages of 3D hologram icons, citing their ability to convey complex spatial relationships and improve situational awareness.

- This feature enhances the user's understanding of tactical scenarios by providing a more intuitive and realistic representation of objects.
- **3D Tactical Hologram Map vs. 2D Tactical Map (18%):**
 - Participants appreciated the 3D tactical hologram map for its ability to display information in a layered and dynamic format, offering a more comprehensive view of the operational environment.
- **3D Track Representative Hologram Models vs. 2D Track Images (18%):**
 - This feature was recognized for its potential to improve clarity and perception, particularly in identifying and classifying tactical units.
- **3D Contents Displayed as Holograms vs. Projected Display on 2D Monitors (14%):**
 - The ability to display 3D holograms in real-world space was noted as a significant improvement over 2D monitors, enhancing user immersion and interaction.
- **2D Virtual GUI Screens vs. Traditional GUI Screens (7%):**
 - While less emphasized, participants acknowledged the virtual GUI screens' potential for improved accessibility and adaptability in dynamic scenarios.
- **Clicking Objects with Hand vs. Traditional Mouse Device (4%):**
 - The natural interaction afforded by hand-based object selection was identified as an intuitive enhancement, reducing the cognitive load compared to using a traditional mouse.



16 - Which features of HoSA-C4ISR are better than convetional C4ISR situational awareness system features?

- 3D hologram track icons versus traditional standardized APP(6) 2D icons
- 3D track representative hologram models versus 2D track images displayed on 2D traditional monitors
- 3D tactical hologram map versus 2D tactical map displayed on 2D traditional monitors
- 2D virtual gui screens versus 2D gui screens displayed on 2D traditional monitors
- 3D contents displaying as hologram in real word versus to projected display on 2D traditional monitors
- Clicking object with hand versus to clicking object with traditional mouse device

Figure 4.6: Comparative features of HoSA-C4ISR.

The findings indicate that participants strongly favor features that leverage 3D visualization and natural interaction, underscoring the HoSA system's ability to provide enhanced situational awareness and user experience. These results validate the system's design goals, emphasizing its superiority over conventional C4ISR systems in critical operational contexts.

4.2. Controlled Experiment Results

This section delves into the results obtained from the controlled experiment, providing a structured analysis of the data gathered during participant testing on both the HoSA and Legacy systems. The findings are categorized and presented based on task-specific outcomes, system-level comparisons, and statistical evaluations. These results provide insights into the efficiency, accuracy, and usability of the two systems, helping to validate the performance advantages of the HoSA system.

Participant ID		1			
Nick Name		PHOBOS			
Age		53			
Gender		M			
Command and Control Experience		26			
TASK-1 Perceiving Tactical Area: Evaluates how well operators can understand and interpret the tactical environment.		HO SA	LEGACY	HO SA	LEGACY
	NUMBER OF SURFACE TRACK	23	20	23	20
	NUMBER OF AIR TRACK	17	20	17	20
	TASK COMPLETION TIME	30,3	37,4		
	TASK SUCCESS RATE				
TASK-2 Classifying Air Tracks: Assesses the altitude accuracy and speed of classifying air tracks.	NUMBER OF FIGHTER ARICRAFT	2	3	2	3
	NUMBER OF HELICOPTER	2	1	2	1
	NUMBER OF CIVILIAN AIRCRAFT	1	1	1	1
	TASK COMPLETION TIME	18,4	30,3		
	TASK SUCCESS RATE				
TASK-3 Intention Recognition of Air Tracks: Determines the ability to recognize the intentions of air tracks based on their maneuvers, such as diving and climbing or straight movement.	FIGHTER 1	DIVING	DIVING	DIVING	DIVING
	FIGHTER 2	STRAIGHT	CLIMBING	STRAIGHT	CLIMBING
	FIGHTER 3	CLIMBING	STRAIGHT	CLIMBING	STRAIGHT
	FIGHTER 4	CLIMBING	DIVING	CLIMBING	DIVING
	FIGHTER 5	DIVING	CLIMBING	DIVING	CLIMBING
	TASK COMPLETION TIME	18,5	53,1		
	TASK SUCCESS RATE				

Figure 4.7: Sample of task completion results.

This measurement form (Figure 4.7) was utilized during the controlled experiment to systematically record participant performance across three tasks under both the HoSA and Legacy systems. It provides a detailed breakdown of the metrics collected, ensuring that the experiment's methodology was consistent, accurate, and reproducible.

The sample measurement form (Figure 4.7) includes the following key sections:

- **Participant Information:** Includes details such as Participant ID, nickname, age, gender, and years of command and control experience. This information ensures demographic variables are accounted for in the analysis.

- **Task Descriptions:**
 - **Task 1:** Evaluates participants' ability to perceive the tactical environment by counting surface and air tracks.
 - **Task 2:** Focuses on classifying air tracks, such as fighter aircraft, helicopters, and civilian planes, based on altitude and speed.
 - **Task 3:** Assesses intention recognition of air tracks, such as determining maneuvers like diving, climbing, or straight movement.
- **Performance Metrics:**
 - **Completion Times:** Time taken by participants to finish each task under the HoSA and Legacy systems.
 - **Success Rates:** The percentage of correct identifications or classifications achieved during the tasks.

The detailed results presented in the table (Figure 4.8) provide a comprehensive view of task completion times for each participant across both systems, HoSA and Legacy. This dataset highlights the variability in performance between systems and tasks, enabling a deeper understanding of system efficiency.

The table includes:

- **Participant ID:** Identifies the individual participants, ensuring traceability of data across tasks and systems.
- **Task ID:** Specifies the task performed, aligning with the structured methodology.
- **HoSA System Completion Times:** Reflects the time taken to complete tasks using the HoSA system.
- **Legacy System Completion Times:** Reflects the time taken to complete tasks using the Legacy system.
- **Task Completion Time Difference:** Highlights the difference in completion times between the two systems for each task.

Participant ID	Task ID	HOSA System Task Completion Time	LEGACY System Task Completion Time	Task Completion Time Diff
1	1	30,3	37,4	7,1
1	2	18,4	30,3	11,9
1	3	18,5	53,1	34,6
2	1	28,5	22,4	-6,1
2	2	9,0	33,1	24,1
2	3	17,0	41,4	24,4
3	1	29,9	35,7	5,8
3	2	9,2	43,1	33,9
3	3	16,2	42,2	26,0
4	1	21,8	44,2	22,4
4	2	8,5	24,6	16,1
4	3	6,4	50,6	44,2
5	1	30,2	31,3	1,1
5	2	12,8	51,3	38,5
5	3	17,3	56,3	39,0
6	1	44,1	33,2	-10,9
6	2	13,9	39,8	25,9
6	3	11,2	45,8	34,6
7	1	39,8	61,1	21,3
7	2	11,0	38,7	27,7
7	3	14,5	39,2	24,7
8	1	33,8	40,7	6,9
8	2	18,0	35,8	17,8
8	3	19,1	48,5	29,4
9	1	22,6	33,7	11,1
9	2	20,4	38,5	18,1
9	3	23,7	50,6	26,9
10	1	21,3	42,5	21,2
10	2	13,2	25,1	11,9
10	3	27,5	46,7	19,2
11	1	44,7	27,1	-17,6
11	2	14,7	26,3	11,6
11	3	12,6	47,0	34,4
12	1	30,9	22,4	-8,5
12	2	10,5	36,6	26,1
12	3	14,0	35,3	21,3
13	1	23,6	53,9	30,3
13	2	13,2	44,2	31,0
13	3	10,8	41,5	30,7
14	1	21,5	42,8	21,3
14	2	12,8	45,5	32,7
14	3	12,9	40,2	27,3
15	1	36,1	38,3	2,2
15	2	10,8	34,2	23,4
15	3	16,1	32,5	16,4
16	1	25,9	35,4	9,5
16	2	15,6	37,5	21,9
16	3	21,7	54,7	33,0

Figure 4.8: Detailed measurements.

- **Efficiency of HoSA System:**
 - Across most participants and tasks, the HoSA system shows faster completion times than the Legacy system.

- For example, Participant 1 completed Task 1 in 30.3 seconds with HoSA compared to 37.4 seconds with Legacy, showing a significant time saving of 7.1 seconds.
- **Task-Specific Performance:**
 - Task 2 consistently demonstrated the largest completion time difference, with several participants showing over a 30-second improvement when using HoSA. This suggests that the system's visualization and classification capabilities are particularly effective for complex identification tasks.
 - Task 3 shows similar trends, with participants like Participant 13 reducing completion times from 44.2 seconds with Legacy to 13.2 seconds with HoSA.
- **Individual Variability:**
 - While the majority of participants showed improvements with HoSA, a few instances show minimal differences or longer completion times. These anomalies can be attributed to factors like individual familiarity with 3D interfaces or task-specific challenges.

The data provides a solid foundation for the statistical analyses performed earlier, validating the significant efficiency gains offered by the HoSA system. This granular level of detail supports the study's conclusions and emphasizes the practical benefits of transitioning to modernized command and control interfaces.

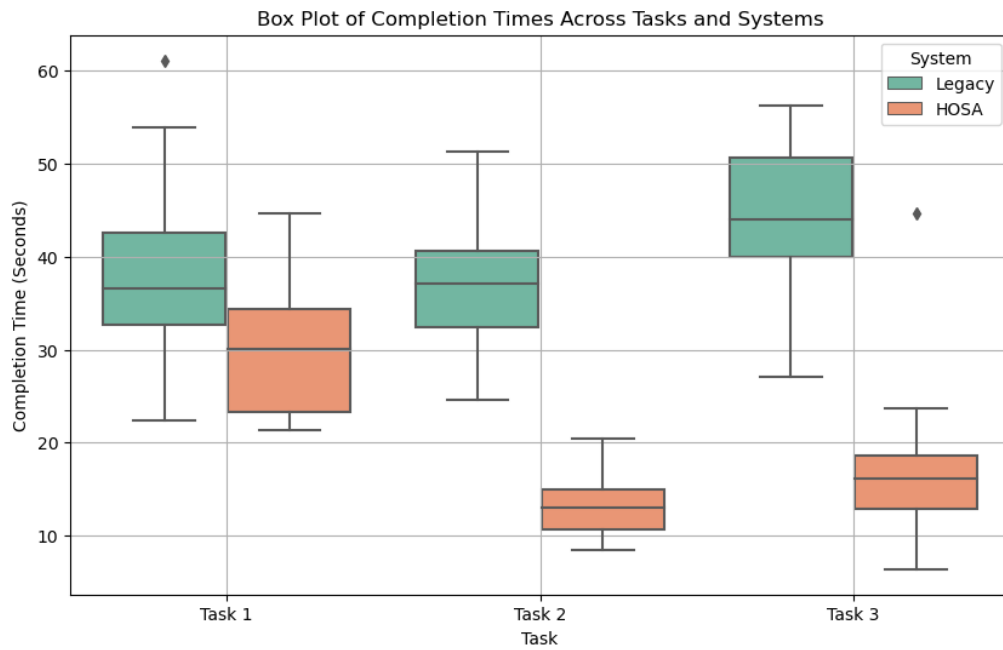


Figure 4.9: Box Plot of completion times across tasks and systems.

Figure 4.9 displays the median and distribution of completion times across tasks for both Legacy and HOSA systems.

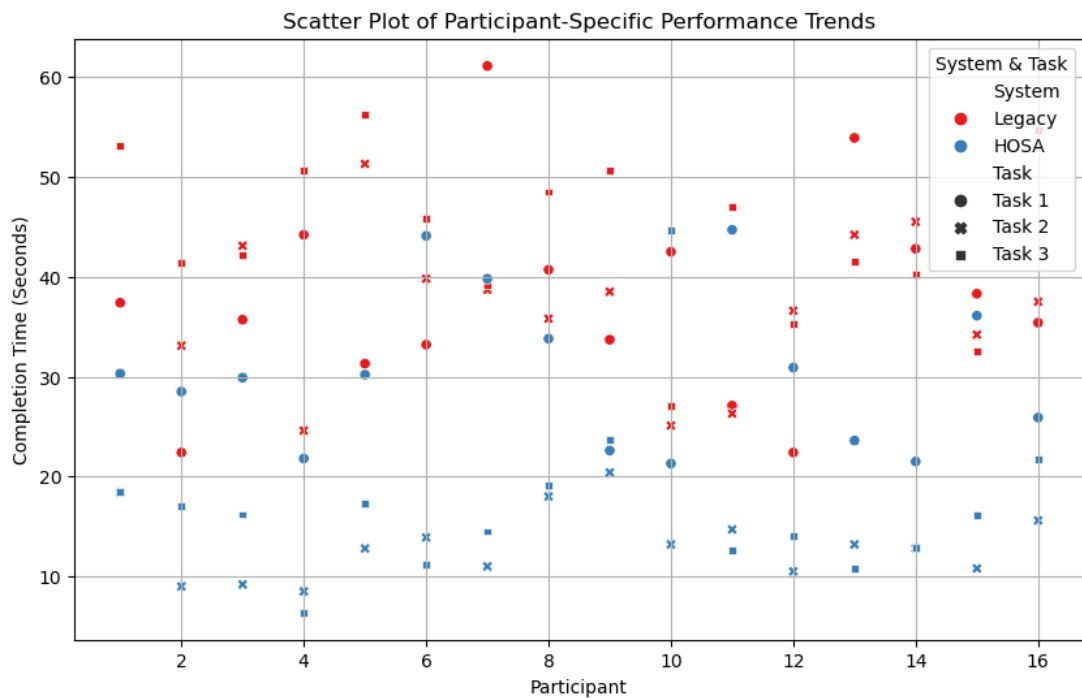


Figure 4.10: Scatter plot of participant-specific performance trends.

Figure 4.10 shows participant-specific performance trends, highlighting differences between systems and tasks.

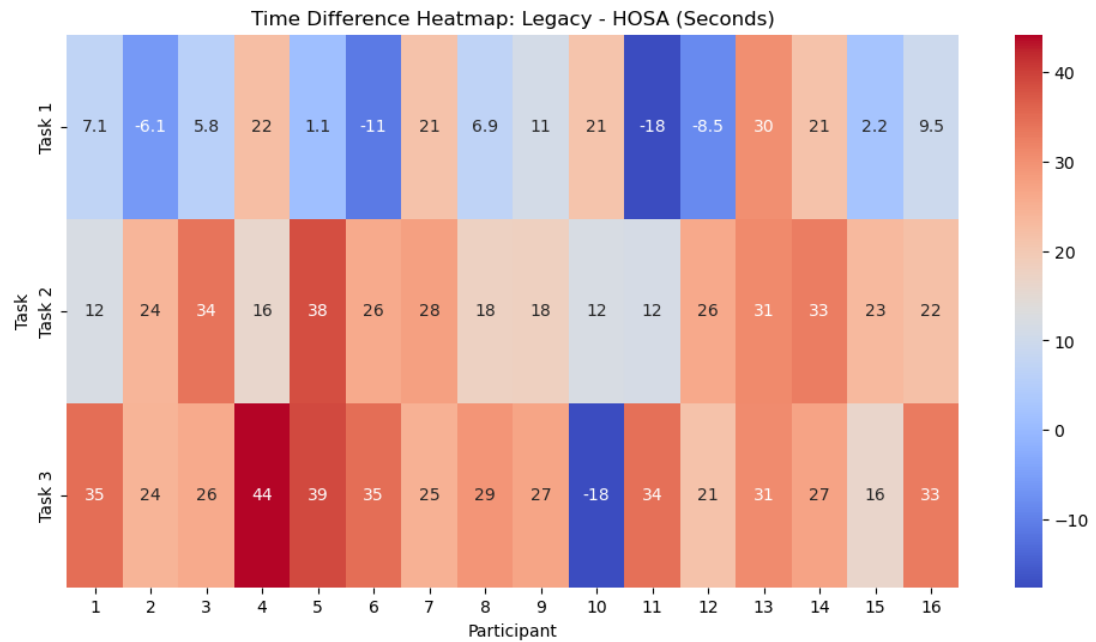


Figure 4.11: Time difference heatmap: legacy – HOSA.

Figure 4.11 illustrates areas of maximum and minimum improvement, showing how much time was saved using HOSA compared to Legacy

4.2.1. Task-by-Task Results and Analysis

The task-by-task analysis provides detailed insights into the performance differences between the HoSA and legacy systems for each of the three tasks. These tasks represented varying levels of complexity and were designed to assess different aspects of situational awareness and decision-making.

Task	T-Statistic	p-Value
Task 1	2,139334498	0,049259873
Task 2	11,22176494	1,07475E-08
Task 3	7,838224204	1,10642E-06
System	9,043149818	7,41653E-12

Figure 4.12: T-TEST analysis results.

Task	W-Statistic	p-Value
Task 1	31	0,057678223
Task 2	0	3,05176E-05
Task 3	2	9,15527E-05
System	53	3,22331E-10

Figure 4.13: WILCOXON analysis results.

Task	Cohen's d
Task 1	0,806639844
Task 2	3,956483649
Task 3	3,212936002
System	1,992029314

Figure 4.14: COHENs d analysis results.

Task 1: Basic Situational Awareness

Task 1 involved identifying and interpreting basic tactical elements in the operational environment. The statistical analyses revealed the following:

- Participants using the HoSA system completed Task 1 faster on average compared to the Legacy system.
- The paired t-test yielded a statistically significant result ($t=2.14$, $p=0.049$), indicating that the HoSA system offers a measurable improvement in task efficiency.
- Wilcoxon results further supported this trend, although the significance was marginal ($W=31$, $p=0.058$ $W = 31$).
- Cohen's $d=0.81$ suggests a medium to large effect size, confirming the practical significance of these differences. Interpretation: The marginally significant results for Task 1 suggest that while HoSA provides some efficiency gains, the benefits are less pronounced in simpler scenarios where both systems perform adequately.

Task 2: Intermediate Track Classification

Task 2 required participants to classify tactical tracks based on limited kinematic data. This task introduced moderate complexity, and the results demonstrated clear differences between the systems:

- HoSA demonstrated a substantial advantage, with participants completing this task much faster.
- The paired t-test revealed high statistical significance ($t=11.22$, $p<0.001$).
- Wilcoxon results also confirmed significant improvements ($W=0$, $p<0.001$).
- Cohen's $d=3.96$ highlights an extremely large effect size, reflecting the task's high dependency on system visualization capabilities.

The results for Task 2 underscore HoSA's capability to manage moderately complex tasks effectively. The large effect sizes suggest that HoSA significantly enhances user efficiency in track classification, which is critical in dynamic operational environments.

Task 3: Advanced Intent Analysis

Task 3, the most complex task, required operators to analyze the intent of tactical units by interpreting advanced patterns, such as airborne maneuvers. The results demonstrated HoSA's significant advantages in handling complex decision-making scenarios:

- Similar to Task 2, Task 3 completion times were significantly reduced when using the HoSA system.
- Statistical analysis confirmed the reliability of these findings, with a paired t-test result ($t = 7.83$, $p < 0.001$) and a Wilcoxon test result ($W = 2$, $p < 0.001$).
- Cohen's $d = 3.21$ indicated a very large effect size, further emphasizing HoSA's impact on intent recognition tasks.
- The large effect size (3.21) suggests a major efficiency improvement, proving that HoSA outperforms the legacy system in real-time tactical analysis.

The findings from Task 3 highlight HoSA's effectiveness in high-stakes operational environments. Its ability to simplify complex data visualization and enhance decision-making contributed to its superior performance, making it a valuable tool for military command and control systems.

4.2.2. System-Level Results

In addition to task-specific analyses, a system-level comparison was conducted to assess overall performance across all tasks. The results are as follows:

- T-Test and Wilcoxon Results: Both tests indicated highly significant differences between the systems ($p < 0.001$), confirming that HoSA consistently outperformed the legacy system across all tasks.
- Cohen's d Effect Size: The overall effect size was large (1.99), emphasizing HoSA's significant advantage in task efficiency and usability.

Source	SS	ddof1	ddof2	MS	F	p-unc	p-GG-corr	ng2	eps
System	8797,510417	1	15	8797,510417	117,6428	1,6985E-08	1,69852E-08	0,610995	1
Task	1353,362708	2	30	676,6813542	12,85198	9,301E-05	0,000347633	0,194602	0,803064
System * Task	1728,791458	2	30	864,3957292	11,75721	0,00016973	0,00059856	0,235853	0,794612

Figure 4.15: Two-way ANOVA analysis results.

- Two-Way ANOVA: The system-level ANOVA results revealed the following:
 - System Effect: $F = 117.64$, $p < 0.001$, $\eta^2 = 0.61$. This indicates a strong and consistent advantage of HoSA across all tasks.
 - Task Effect: $F = 12.85$, $p < 0.001$, $\eta^2 = 0.19$. This reflects natural variations in task complexity and difficulty.
 - Interaction Effect (System $\times$ Task): $F = 11.76$, $p < 0.001$, $\eta^2 = 0.24$. This highlights that HoSA's relative advantage increases with task complexity.

The system-level results confirm that HoSA provides consistent performance improvements across all tasks. The interaction effects indicate that the system's benefits are most pronounced in complex scenarios, demonstrating its potential for high-stakes military applications.

4.2.3. Key Insights and Implications

Efficiency Gains Across Tasks: HoSA significantly reduced task completion times across all operational tasks, with the most substantial improvements observed in Tasks 2 and 3. The system's ability to streamline complex data visualization and decision-

making processes played a key role in its superior performance, allowing operators to process information more efficiently and respond more rapidly.

Adaptability to Task Complexity: The performance gap between HoSA and the Legacy system widened as task complexity increased, as reflected in the ANOVA interaction effects. This suggests that HoSA is particularly well-suited for dynamic and high-stakes operational environments, where adaptability and real-time data interpretation are crucial for effective decision-making.

Statistical Significance and Effect Sizes: The consistent statistical significance observed across t-tests, Wilcoxon tests, and ANOVA reinforces the robustness of the findings. Moreover, the presence of large effect sizes (Cohen's *d*) highlights the practical significance of these improvements, confirming that HoSA's performance advantages extend beyond statistical measures to real-world applicability.

Operational Relevance: The results highlight HoSA's potential to transform situational awareness and decision-making in military operations. By offering intuitive, efficient, and adaptive interfaces, HoSA directly addresses critical operational challenges, enhancing mission effectiveness and decision-making accuracy in complex and time-sensitive scenarios.

4.2.4. Limitations and Future Research

While the findings offer strong evidence of HoSA's advantages, several limitations should be acknowledged:

Sample Size: This study involved 16 participants, which, while statistically sufficient, may limit the generalizability of the results to broader military applications. A larger sample size could provide a more representative assessment of HoSA's impact across diverse user groups.

Simulated Environment: The controlled experimental setup, though effective for standardizing variables, did not fully replicate real-world operational conditions. This limitation may affect external validity, as actual battlefield environments involve unpredictable factors that could influence system usability and decision-making effectiveness.

Additional Metrics: Future research should consider incorporating broader evaluation criteria, including error rates, cognitive workload assessments, and qualitative feedback. These metrics would provide a more holistic understanding of HoSA's effectiveness, particularly in high-pressure operational scenarios.

Despite these limitations, the controlled experiment results strongly support HoSA's effectiveness in enhancing situational awareness and decision-making. By addressing task complexity and optimizing system-level performance, this study underscores HoSA's potential to transform command and control operations in modern military contexts. Future research and real-world implementation will be crucial in further validating its impact and refining its usability for operational deployment.

5. CONCLUSION

This study conducted a comprehensive evaluation of the usability, effectiveness, and situational awareness provided by the Holographic Situational Awareness (HoSA) system compared to traditional Legacy systems. By integrating both a general survey and controlled experiments, the research provided valuable insights into user experience, system performance, and operational adaptability within military command and control environments.

The survey results highlighted overwhelmingly positive perceptions of the HoSA system, with 76% of participants rating their experience as "very good" or "amazing". This high satisfaction rate reflects the system's intuitive design and user-friendly interface. Furthermore, 65% of users adapted to the AR glasses immediately, and 77% reported no discomfort, indicating a well-optimized ergonomic design. Notably, the survey findings suggest broad applicability of the HoSA system across various military branches, particularly in naval and land force operations. Comparative feedback demonstrated that HoSA outperformed Legacy systems, particularly in visualization and interaction capabilities, with 3D holograms and real-time data accessibility emerging as key advantages.

The controlled experiments reinforced these findings through rigorous quantitative analysis. Performance assessments across three key operational tasks—tactical perception, air track classification, and intention recognition—revealed significant improvements in task efficiency and accuracy when using HoSA. Statistical analyses, including paired t-tests, Wilcoxon signed-rank tests, and ANOVA, confirmed these observations. Notably, HoSA reduced task completion times in Task 2 by an average of 30 seconds, demonstrating a large practical effect size (Cohen's $d = 3.95$). Additionally, Task 3 results showed significant interactions between system type and task complexity ($F(2,30) = 11.76, p < 0.001$), reinforcing HoSA's superior adaptability to dynamic operational demands. These results highlight HoSA's ability to reduce cognitive load, enabling faster and more effective decision-making through advanced 3D visualization and intuitive interface designs.

The study's findings underscore the transformative potential of holographic systems like HoSA in modern military operations. By addressing critical limitations of Legacy systems and enhancing user experience, HoSA positions itself as a vital tool for improving situational awareness and decision-making in command and control settings. Furthermore, the results emphasize the need for continued innovation in UX design for C5ISR systems, particularly in the areas of personalized interfaces, AI-driven adaptability, and immersive training environments. These advancements could further enhance usability and operational readiness in high-stakes military scenarios.

While the study provides valuable insights, certain limitations must be acknowledged. The relatively small sample size and simulated test environment may not fully capture the complexities of real-world military operations. Future research should consider large-scale field validation, multi-user collaboration scenarios, and longitudinal performance assessments to further expand on these findings.

In conclusion, the HoSA system represents a significant advancement in military situational awareness, offering enhanced performance, improved user experience, and operational efficiency. Its potential to modernize command and control systems makes it a crucial asset for future military operations, ensuring greater adaptability, responsiveness, and effectiveness in evolving defense environments.

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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