No Margin for Errors: Using Extended Reality to Augment Users in Safety-Critical Environments

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Fig. 1. In the XR application shown, Augmented Reality displays relevant information about surrounding points of interest (e.g., other traffic, airports). Pilots, for example, can benefit from these information. In this context, cognitive workload, user experience, and flight performance are augmented.

XR is getting integrated more and more into work and daily life. This includes safety-critical environments that require to display information accurately as well as precise interaction without overwhelming the user. In this workshop paper, we discuss our lessons learned from using XR in General Aviation (GA) to support pilots during their flight routine. We describe the encountered challenges for safe interaction in safety-critical environments and propose future research directions for XR environments, aiming to improve safety and security.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; **Mixed / augmented reality**; • **Applied computing → Avionics**.

Additional Key Words and Phrases: Extended Reality, Safety, Highlighting, Workload, General Aviation

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1 INTRODUCTION

Extended Reality (XR) proliferates into daily life through smaller and more affordable wearable devices. For example, recently released Augmented Reality (AR) glasses, including the Microsoft HoloLens 2 [1] or the Magic Leap One [2], can be used to augment the user's view in different environments. As human cognition and the interaction space are limited in nature when interacting in XR [4], these applications aim to support users in their work during times of increased demand. The supposed results are lower error rates, higher productivity, and life satisfaction.

To achieve these advantages, XR technologies must provide a minimum level of *reliance*. Factors including tracking accuracy [5], detection of context, the considerations of supporting the user without distracting them, and kind of provided visualization are pivotal design aspects when implementing XR applications for safety-critical environments. In the worst case, misaligned cognitive assistance through XR applications can even deteriorate the user's performance instead of giving aid [6]. While the XR applications come with numerous advantages, possible negative influences on the user must also be considered. With this in mind, XR technologies must be applied thoughtfully, reflecting upon the potential shortcomings and dangers to the user. This is especially true in the case of hazardous environments where inattentiveness, distractions, and other issues can quickly become a threat to the user's well-being.

In the following, an assortment of possible errors that can occur during XR application usage is listed below. This collection does not aim for completeness; instead, the upcoming reasons for potential threats were identified during a pilot study of an AR prototype for General Aviation (GA) pilots [3]. The field of aviation is a prime example of an environment where new technologies can be highly advantageous and dangerous to users. In the US alone, around half a million GA pilots fly close to 200.000 planes and generate an annual economic activity surpassing 150 billion US dollars [2]. At the same time, and in stark contrast to commercial aviation, GA contributes a far more significant number of accidents per flight than any other aviation branch [1]. Pilots have to keep track of many tasks and constantly changing surroundings simultaneously. Therefore, supporting them in their work can make it much easier for them to accomplish their tasks. Yet, unforeseen consequences and oversights during development can quickly turn an initially helpful technology into a catalyst for undesired outcomes.

[1]https://www.microsoft.com/en-us/hololens
[2]https://www.magicleap.com/en-us

Context: XR for GA Pilots

In the study, twelve participants with pilot skills of varying degrees were instructed to land at airports unknown to them before the study. During parts of this, they were instructed to use an XR prototype utilizing the Microsoft HoloLens 2 to display additional information about other traffic in the vicinity. The experiments took place in a full-size flight simulator at the Institute of Flight Systems and Automatic Control at the Technical University Darmstadt. The participants' performances were evaluated through various quantitative measures (e.g., flight path recordings, task completion times, flight data logging), and qualitative data was gained via interviews and questionnaires (e.g., NASA-TLX, User Experience Questionnaire, custom questionnaires).

In the following, potential causes for errors that can quickly become danger factors are split into three distinct categories. At first, issues that stem from the supplied data itself are presented. This is followed by a selection of user errors and other human factors that can negatively influence XR applications' experiences. Lastly, a closer look at display and interaction modalities is given.

2 DATA-RELATED AND TECHNICAL LIMITATIONS

This section focuses on the data quality and trustworthiness necessary for reliable data assessments when using XR applications. Based on the experiences of our previous showcase, we elaborate on how different data anomalies compromise the accurate representation of XR experiences.

2.1 Missing Data

Irregular data loss leads to inaccuracies when displaying XR applications. Here, missing information can lead to inconsistencies in XR interaction, such as glitching hands, and incorrectly detected objects, such as nearby airplanes or runways. Safety-critical content not displayed to the user can lead to dangerous situations, especially when objects are nearby and close to collision. The reliability of the application is directly tied to the reliability of the data source(s).

2.2 Faulty Data

Besides altogether missing data, available data has to be generated, transferred, and stored correctly. Defect data is, for example, the result of tracking inaccuracies or a partial data transfer between systems, which can lead to the incorrectly displayed information. In the example of augmenting pilots in the aviation area, traffic shown with incorrect information can lead to severely dangerous situations (e.g., the augmented airplane icon being more distant than the actual plane, incorrect information about the aircraft model).

2.3 Latency

Latency is an expression of how long a data packet takes to travel from one designated point to another. Ideally, latency will be as close to zero as possible. However, this is generally unrealistic, and milliseconds of latency can be expected. This is often the case when two systems (e.g., a pilot XR system and an aircraft control element) communicate. While latencies in milliseconds are acceptable to display or update information, seconds of delayed information transfer can lead to life-threatening situations. For example, the position of surrounding airplanes might be displayed significantly later, leading to airplanes coming dangerously close to a collision before the pilots realize it. This ties closely into incorrect data, as formerly correct data can quickly become stale and therefore out of sync with current circumstances, not representing the current surroundings as they currently are. Therefore, it is not only data that arrived too late but also data that has not been updated in a reasonable time frame which can pose a threat if not handled cautiously.

3 HUMAN FACTORS

Human reliance on novel technology contributes to user errors in safety-critical environments. The following section focuses on user-related issues when using XR in such environments.

3.1 Overconfidence in Technology

Technologies can create the impression of a reliable and secure environment, feigning a false sense of safety. In aviation, pilots rely on sensing technologies and visual displays (traditionally electromechanical gauges) to obtain critical information about the airplane's state and surroundings as humans cannot reliably ascertain the state of the airplane by sense alone. Herein, pilots are always instructed to crosscheck all available information, ensuring that all sensors show reasonable values, indicating a safe flight attitude. Consequently, XR technologies are becoming increasingly integrated into the cockpit, which has to work reliably to avoid overreliance on the interpretation of the pilot. Even though no warnings are shown, pilots must ensure that the current situation is safe. For example, the absence of a traffic warning cannot lead to a disregard for looking out. Instead, the pilot must ensure that the system works as expected.

3.2 Dismissing Previous Technologies in Favor of XR

Established technologies supporting users in safety-critical environments are continuously tested and validated to maintain a specific level of safety. Consequently, these technologies are constantly innovated to increase the level of safety while minimizing the error margin. XR technologies will likely increase safety by displaying holographic real-time information to the user that is spatially aligned with the environment. Here, XR technologies should not replace the established technologies; instead, XR technologies should utilize the established technologies and extend them in XR. For example, the traffic collision avoidance system (TCAS) commonly found in airplanes can be visualized in XR to improve the pilots' awareness of danger. Herein, the tried and tested symbology known by generations of pilots can be used instead of "reinventing the wheel", possibly causing misapprehensions in critical moments. An apt tradeoff between innovation and further use of established technologies has to be found.

3.3 Reliance on New Technologies

Novel technologies should work with existing safety support systems, including introducing both systems to the user. Relying on novel technologies (i.e., in their prototyping phase) can lead to dangerous situations that require established technologies to serve as a backup. Everyday situations are technical malfunctions, such as overheating, that reduce the level of assistance for the user. Designers of XR applications must remember that technologies might fail and how a transfer to another assistive technology can be seamlessly paved. Another example is recognizing an excellent approach to an airport by eye. Pilots typically learn what a runway looks like when the correct glideslope (vertical angle between flight path and runway) is flown. An XR application could potentially help in identifying a well-flown approach. However, pilots still have to be able to do that by themselves, should the application suddenly fail to work correctly.

4 INTERACTION

Interacting in XR remains a research challenge. Therefore, we briefly describe intuitive implicit and explicit interaction pitfalls compromising a user's safety.

4.1 Visual Clutter

Displaying too many elements at inconvenient positions in XR will likely distract the user rather than support them. Hence, valuable information can be easily missed while a lot of unnecessary information is displayed. For example, in general aviation, an XR system can display nearby airplanes to avoid collisions. However, when too many elements are displayed at once, it isn't easy to distinguish between the relevant airplanes requiring the pilot's immediate attention. Therefore, XR technologies must assess the user's context to display the correct information at the right time. Users should also be able to control the detail of the supplied information (if applicable), making it possible to immediately stop showing anything to ensure a distraction-free view if needed.

4.2 Choosing the Right Input Modality for the Right Job

Interacting in XR still poses a challenge for interface designers. There is no one-size-fits-all interaction modality that is suitable for every use. Specific interaction concepts are necessary depending on the use case, required interaction efficiency, and interaction accuracy. For example, voice interaction is not ideal in loud environments, and gesture interaction may be inefficient in areas with limited space. XR environments for pilots affected by a loud environment and limited interaction space need to consider novel multimodal interaction concepts. Haptic interaction modalities might pose advantages, as they give feedback to the user by default and can often be interacted with while preoccupied. However, further research is needed to identify relevant interaction modalities for safety-critical environments.

5 CONTRIBUTION TO THE WORKSHOP

We presented challenges of current XR applications for safety-critical environments. Then, using the example of General Aviation, we highlight where a precise design of XR environments is critical to maintaining a safe environment for pilots. While research into XR applications already has shown many advantages in a multitude of use cases, potential threats and hazards introduced by them have to be considered as well. This is especially true for safety-critical environments where small mistakes can quickly become dangerous.

6 AUTHORS' BIOGRAPHIES

Christopher Katins recently finished his degree in Information Systems Technology at the Technical University of Darmstadt, and currently, he is a student pilot. His research interests are human-computer interaction, ubiquitous computing, and communication systems, focusing on mixed reality interaction in the cockpit.

Sebastian Feger is a Postdoc at LMU Munich, conducting research across a broad spectrum of HCI. He greatly enjoys designing smart objects and teaches electronics and physical computing with great enthusiasm. Sebastian perceives XR as an excellent opportunity to transform how the wider society engages in making and digital fabrication. Recognizing the importance of configuring and navigating increasingly complex and data-rich mixed reality environments, Sebastian decided to focus on designing intelligent objects for XR in his habilitation. Holding a US pilot license, he identified general aviation as one of the most interesting data-rich environments in which augmentations can increase safety.

Thomas Kosch is a professor in the Human-Centered Computing Group at Utrecht University. His research uses AI-driven sensing to anticipate user states and actions for subsequent interface adaptations. With more and more XR technologies interweaving with the human body and perception, Thomas is interested in how the interaction and design of XR technologies can use the user's behavioral patterns and physiological data. This includes utilizing the user's context and physiological responses analyzed and used by adaptive XR environments.

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