Pilots' Considerations Regarding Current Generation Mixed Reality Headset Use in General Aviation Cockpits

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ABSTRACT

Pilots in non-commercial aviation have minimal access to digital support tools. Common 2D maps, displayed on tablets, are often the only digital information source that fails to adequately capture the 3D airspace and its surroundings, challenging the pilot's workload and awareness. In this work, we developed and tested a Mixed Reality (MR) prototype with twelve General Aviation (GA) pilots using a full-sized flight simulator environment. The prototype's demonstration showcased the capabilities of contemporary technology and its potential applications. Following the simulation, in-depth interviews were conducted with the participating pilots to discern their perspectives on integrating MR solutions into cockpit environments. The study revealed valuable insights into pilots' concerns, design prerequisites for future systems, and potential use cases. This work not only highlights the feasibility of MR implementations but also provides a foundation for the development of enhanced digital tools for GA, aiming to alleviate pilot workload and augment situational awareness.

CCS CONCEPTS

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

KEYWORDS

General Aviation, Augmented Reality, Mixed Reality, Highlighting, Workload

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1 INTRODUCTION & BACKGROUND

The aviation sector constantly transforms with steadily emerging technologies shaping how aircraft operations are conducted. Emerging pilot support systems are primarily driven by the world's few large commercial aircraft manufacturers, such as Boeing or Airbus. They initiate innovations in interactive technologies either in-house or through cooperation with their suppliers, technology innovators, or external academics. However, these developments largely ignore the safety practices and needs of General Aviation (GA) operations[1] wherein the usability, dependability, and safety constraints differ widely for new technologies. A total of approx. 211k active GA aircraft were registered in the U.S. in 2018, with around 167k ($\sim 80\,\%$) of those being motorized fixed-wing airplanes. Of those fixed-wing aircraft, over $75\,\%$ are Single Engine Piston (SEP) aircraft with an average age of 46.8 years [14]. This indicates that innovative technologies in the field of GA take decades to reach widespread use in currently flown aircraft, especially considering the age of the current GA fleet.

At the same time as *glass cockpits* emerged in commercial aircraft [13, 30], the military started to test the use of head-mounted displays for Augmented Reality (AR) applications [17]. Many years later, the potential of Mixed Reality (MR) technologies in the aviation sector has been known for decades. Both military and commercial aircraft are equipped with MR technology today [3, 9, 18, 27], successfully using MR to improve the well-established gauge- and display-based cockpits. They allow pilots to gaze outside the aircraft while simultaneously displaying vital flight information on top of the real world. However, a major part of the aviation sector does not occur in military or commercial aircraft. Most flights are operated by GA pilots [14]. Hence, recent work investigated challenges and opportunities of MR technologies for GA pilots [11, 12, 22], focusing on the potential uses and benefits of employing MR in GA cockpits. While some publications put an emphasis on the use of MR for training purposes for student pilots [26, 28], current publications rarely focus on the pilot's considerations and the general feasibility of using readily available, current generation MR technology in the cockpit.

Rather than employing MR in permanently installed avionic systems, it might be utilized as a part of the Electronic Flight Bag (EFB) instead, describing the personal electronic equipment that pilots bring along onto the aircraft. This enables GA pilots to use new MR technologies as they see fit, not being limited by the state of the technologies being available through the aircraft itself. As most GA flights are performed under Visual Flight Rules (VFR), meaning that navigation is done mainly visually and not primarily based on instrument readouts, one potential application is the visualization of traffic, airports, visual markers, and more through AR devices.

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[1] The International Civil Aviation Organization (ICAO) defines GA as any civil aircraft operation that does not entail transportation of both cargo or passengers for hire or aerial work (e.g., surveying, search and rescue operations) [19].

Table 1: An overview of the participants of the study. Next to demographic data, the attained licenses (SPL = Glider Pilot License, LAPL = Light Aircraft Pilot License, PPL = Private Pilot License, MPL = Multi-Pilot License) and the time as pilot-in-command (PIC) for both aircraft in general and motorized GA aircraft are given. Two participants, marked with an asterisk (*), had flight simulator experience but had not finished their pilots' training yet.

PID	Age	Gender	Licenses	PIC Hours (Overall)	PIC Hours (Motorized GA Aircraft)
P1	28	M	SPL	100	10
P2*	31	M	-	0	0
P3	28	W	SPL	50	1
P4	26	M	SPL, LAPL	300	30
P5	30	M	SPL, LAPL	500	200
P6	27	M	SPL, LAPL	700	60
P7	30	M	PPL	650	650
P8*	24	M	-	0	0
P9	30	M	PPL, MPL	200	140
P10	27	M	SPL, LAPL	7	4
P11	26	M	SPL, PPL	350	200
P12	29	M	SPL, LAPL	15	0

Further previous work investigated the utility of AR applications in GA. For example, the "CAVOK display" developed by Lenhart [25] in 2006 is one of the first systems which brought the Head-Mounted Display (HMD) technology into the civil sector. A HMD was successfully tested in a stationary flight simulator test, displaying the usual flight information in conjunction with flight guidance information, baring similarities to the much later proposed *AeroGlass* [15]. In 2017, interviews with a total of 24 pilots were conducted to gain a better understanding of GA pilots' concerns, desires, and thoughts regarding the use of novel flight data visualizations in the cockpit [17]. After preliminary tests of four prototypes, the novel "Lateral Guidance Line Display Format" was chosen to be investigated further, yielding promising preliminary results. Yet, no further development has been reported.

Another factor to consider is exceptionally high workloads in the cockpit, which is not uncommon [23], and situational awareness is crucial for a successful flight. Previous research has already been conducted in the field of displaying current flight information via AR [16, 17, 25] and highlighting relevant Points of Interest (POIs) in the real world via MR [22] in flight simulator studies.

This work is a first step in bridging the gap between potential MR uses in the GA cockpit as envisioned by some of the aforementioned papers and the current state of available technology. For this, a prototype using current MR technology was tested by GA pilots in a full-sized flight simulator, offering an insight into the state of current research. Yet, the aim of this was not to quantify the effect of a prototype on the users but rather to offer a common understanding of the technology at hand, fostering an interview setting that is not grounded on vague ideas but on tangible experiences and impressions. In total, twelve GA pilots were interviewed in order to gather pilot expectations, concerns, and wishes towards MR technologies for use in GA aircraft cockpits. The results of this qualitative study were then used to answer the following research question:

RQ What considerations do pilots currently hold regarding the use of current generation MR headsets inside GA cockpits?

2 METHODOLOGY

The methodology employed in this study aimed to first showcase the integration of current-generation MR technology into the cockpit environment of GA to the participants. Based on prior research [16, 22] and military use cases [3, 9], a prototype was designed to extend the real-world experience by overlaying information about Points of Interest (POIs). The prototype employed a *Microsoft HoloLens 2*[2] to project information within the three-dimensional space of the cockpit and its surroundings, allowing the accurate tracking of relevant POIs (i.e., other aircraft and airports in the vicinity) regardless of both the aircraft's and the pilot's head's attitude in space. A recreation of the view provided by the prototype is given in Figure 1a.

It is crucial to emphasize that the primary objective of this approach was not to assess the prototype's performance nor to conduct a formal usability evaluation. Instead, the focus resided on providing GA pilots with a visionary glimpse into the potential of next-generation MR applications tailored for their sector. By immersing pilots in a simulated environment that leveraged MR's spatial augmentation, the study sought to stimulate discussions and elicit insights into the feasibility, concerns, and potential benefits of such technology.

2.1 Procedure

Initiating the landing process is a cognitively demanding task that includes several factors to consider (e.g., maintaining radio contact, monitoring surroundings and flight parameters, and following the flight pattern) [10]. Thus, the landing process is one of the most demanding moments in aviation operations, requiring the pilot's full attention, who has to carefully manage their workload and attend to the many operations at this time. This is reflected by the aviation accident statistics by the NTSB [1, 2], with more than a third of all accidents in the civil sector happening during the approach and landing phase alone.

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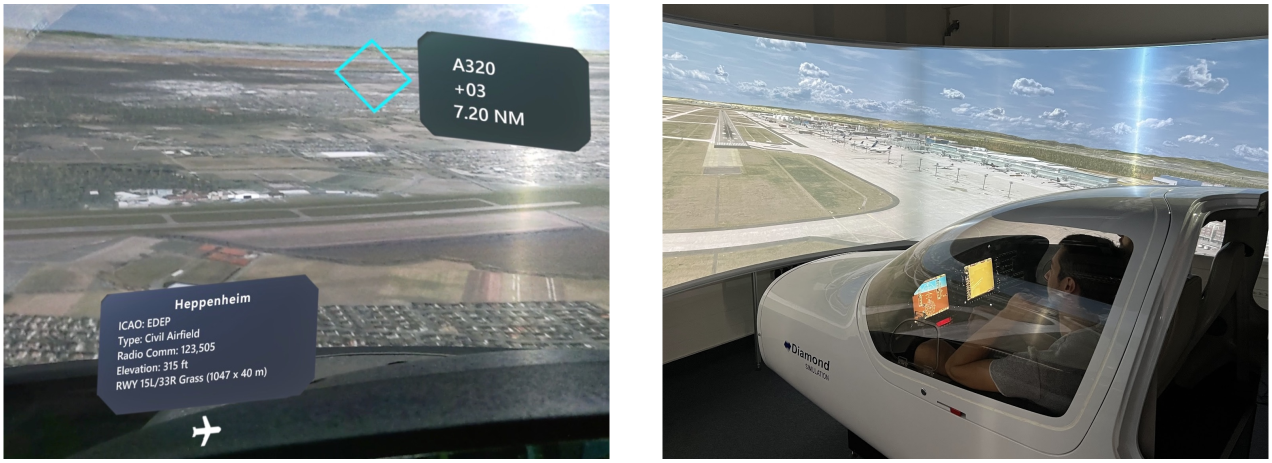
[2] www.microsoft.com/en-us/hololens



(a) Exemplary virtual components displayed by the prototype to accompany an aircraft (upper right) and an airport (lower left) in the vicinity.

(b) Pilots were flying in a full-size Diamond DA40 aircraft flight simulator. The cockpit resembles the full functionality of a real cockpit.

Figure 1: This figure shows the experimental setup employed in our study to offer the participants an insight into the potential use cases of current- and next-generation MR applications specifically designed for the GA cockpit.

For this reason, two landings were conducted per participant, once while using the prototype and once without it. The study began by explaining the general procedure to the participants. After consent was given, an initial questionnaire was filled out to record demographic data and the participant's stances toward technology and GA. The participants were then allowed to independently test the *HoloLens 2* and the flight simulator. The *HoloLens 2* was calibrated to the user's eyes, and a sample interaction scene was loaded so familiarization with the holographic display and the interaction modalities of the device could happen. For the flight simulator test, participants were allowed to fly wherever and however they wished, except at the airports chosen for the subsequent landings. Before each landing, participants received a short briefing informing them of their current position and heading. We assumed that landing permission had already been granted, requiring the pilot to follow the airport traffic pattern before initiating the landing. A sectional chart of the region was available to the participants, and no radio communication was required.

Afterward, one Likert Scale Questionnaire was filled out after the experiments to assess the participant's overall opinions about their experiences and the use of MR in GA cockpits. The questions are depicted in Figure 2. A semi-structured interview followed to gather qualitative insights into the participant's thoughts towards using MR in GA.

2.2 Participants

Overall, 12 participants (11 male, 1 female) aged between 24 to 31 years ($\bar{x} = 28$, $s = 2.09$) were recruited for the study. The study was advertised through a mailing list of the institute where the flight simulator is located and by sending direct invitations to regional flying clubs. One participant reported a moderate amount of experience ($\sim 20\,\text{h}$) with VR technology, six reported little experience ($< 20\,\text{h}$), while the rest reported no previous experience with VR. Regarding AR and its applications, all participants had little ($n = 7$) to no ($n = 5$) prior experience with such technology. The number of experiences regarding GA operations and amassed flight time differed significantly. The mean flight time as pilot-in-command was $239.34\,\text{h}$ ($s = 259.44\,\text{h}$) for all types of aircraft and $107.92\,\text{h}$ ($s = 187.56\,\text{h}$) for SEP aircraft specifically. An overview of all participants is given in Table 1.

2.3 Analysis

A thematic analysis, based on the suggested procedure by Blandford et al. [6], was used to approach the qualitative data from the interviews. At first, the audio recordings of the interviews were transcribed verbatim, and two coders conducted an initial coding round where a subset (25 %) of the interviews was open-coded. This initial set of codes was then refined in a code adjustment session, and the authors coded the final interviews based on this coding tree. Common patterns were classified afterward during axial coding, after which four significant themes could be established.

3 RESULTS

The results of the concluding questionnaire, consisting of two Likert scale questions, showed generally favorable views towards both the prototype and MR in general in GA. As for the interviews, four overarching themes could be identified: Reliability, Ergonomics, Information Adaptability and Modality, and Interaction.

3.1 Reliability: "I See No Holograms; Hence There Is No Traffic"

The most important topic was the reliability of the prototype and the inherent trust in it. Only two participants reported that they could recognize traffic they previously could not identify after seeing the corresponding holograms. All remaining participants were only able to see the corresponding traffic holograms, though not the traffic itself. Still, they trusted the holograms to furnish correct information about the existence of traffic: "*I just assumed that everything that [the prototype] displayed was correct and accurate. (P2)*". For the participants, redundant or incorrect data trumps the alternative scenario in which no information is supplied.

They furthermore stated that it is the pilot's task to evaluate and, therefore, potentially ignore information that they do not deem reasonable or helpful in their current situation. However, this feeling was not mutual. P5 called it a "*blissful ignorance when not using the prototype*", mentioning that they felt tenser when using MR. The majority of participants reported that they instinctively trusted the prototype to be reliably able to highlight all traffic in the vicinity. They reported that the absence of holograms was providing valuable information as well: "*With seeing some [traffic holograms], [I assumed] that's all of them that could be dangerous to me. [...], I assumed that there were no more aircraft there in any case because there weren't any additional holograms. (P5)*". Most of them reflected on this confidence afterward, voicing concerns that the absence of holograms does not indicate an absence of traffic for certain, with system faults or missing transponder technology being just some of the many possible reasons why holograms might be missing for aircraft in the vicinity.

Participants agreed that the prototype offered a net positive regarding their flight operations. However, the concerns above indicate that participants felt that the initially assumed reliability of the device might negatively influence their actual performance in real-life scenarios.

3.2 Ergonomics: "Fine in the Simulator, Questionable for Real Cockpits."

All participants agreed that the comfort of the *HoloLens 2* was acceptable, albeit not great. It did not negatively impact their movement. However, concerns about its potential use in real GA cockpits were still raised. For one, P11 wished "*that it would fit a bit more firmly against my head*", as the naturally occurring g-forces during actual flights could involuntarily shift or even pull off the device from their head. Three participants noted that the strap of the *HoloLens 2* would probably interfere with their over-ear headsets, which they usually use during their flights. Most deemed the possibility of flipping up the front part of the *HoloLens 2* crucial feature. P1 mentioned that they "*in no way would want to take [the HoloLens] off and then put it on again during a flight*". Being able to stop using the prototype without completely taking it off, combined with the possibility of resuming its use, were noted as significant factors in the acceptance of the prototype.

At the same time, the field of view through the *HoloLens 2* was unanimously regarded as "*good enough*", and four participants reviewed the edge of the holographic lenses as annoying and irritating. Reasons for this were the bezels of the lenses and the different refraction of light through the acrylic lens cover compared to the uninterrupted air around it. As the roof already limits the outside view and the instrument panel in a cockpit, comments about potential improvements in the field of view were mainly concerned about the horizontal dimension: "*A larger field of view would, of course, be beneficial, but I'm talking specifically about the horizontal field of view, that is, more to the left and right. Vertically, everything was already visible; you could see [the holograms] through the windshield from top to bottom. (P1)*".

One participant (P4) mentioned that they perceived MR as one more layer to keep track of, inducing a context shift when consciously observing the displayed holograms: "*Sometimes you have this moment where you're "in the HoloLens", and then you're back in the cockpit, and then you're outside the cockpit again. (P4)*"

3.3 Information Adaptability and Modality: "It Depends on the Situation."

All participants agreed that clutter was not an issue during the study, but various situations that could pose problems were mentioned, such as the following: "*I could, for example, imagine issues at gliding competitions or the like, if ten gliders are hanging under a cloud and in thermals, then it can certainly be a bit overloaded, but that hasn't been the case here yet. (P1)*". The airport holograms were deemed helpful for navigation in unknown regions to find the airport of interest but annoying during the final phases of the approach when already following the airport traffic pattern: "*Especially during the final descent, it was instead a hindrance to having all the information permanently superimposed in your view, obstructing parts of it. (P3)*". Furthermore: "*Sure, it made [the airport] much easier to find, but at some point, it got in the way, too, because [the hologram] was right above it. (P6)*". As the text was rather hard to read for some participants, a few wished for a mode wherein no text was shown, and only the symbols would be displayed. Four participants liked the explicit information about distance and type of aircraft, and half agreed that location markers for the airports alone would be preferable. Generally, participants wished for more adaptability of the displayed information, either controlled manually (see the following theme) or automatically.

Only showing information about the airport at which the landing is planned during normal operations and still being able to quickly display the airports closest to them in case of emergency was requested multiple times.

3.4 Interaction: "Less Explicit Interation is Better"

While the possibility to control what information is displayed was wished for by most, a majority also concluded that they would rather interact with the device as little as possible: "*I would argue that one requirement has to be that I don't have to put so much effort into operating that other system as well now. It should work by "plug-and-play", and I don't want to set up, configure, or adjust much. (P3)*". While all participants liked the possibility of interacting with the *HoloLens 2* via gestures, none would like to use this modality in the cockpit. The tight spaces inside an aircraft, the constant movement during flights, and "*tapping around in the air without any hard target to hit (P12)*" were some of the reasons given against gestures. Over half of the participants were curious about the potential of controlling the device by voice, ranging from suggested commands like "*Show me the closest airports. (P9)*" to "*What airplane is in front of me? (P5)*".

One participant (P6) commented that he would like to set the device up as needed before the flight, loading his flight plan onto the device and manually deciding what kind of information he would

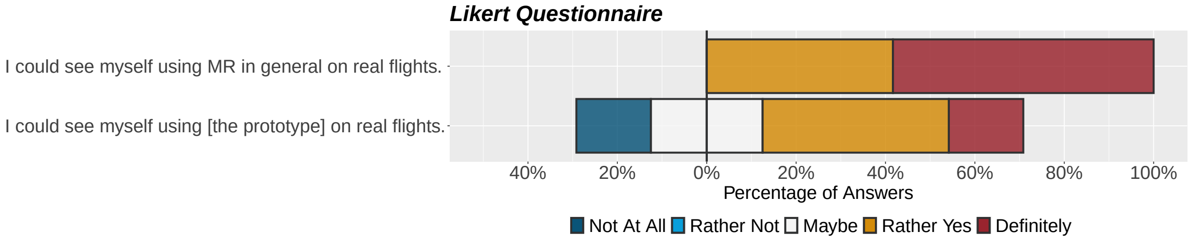


Figure 2: The results of the Likert scale questionnaire. The participants generally favored both the prototype and MR as a whole.

like to have displayed per flight and not interacting with it anymore as soon as the aircraft is airborne. In the end, P3 commented on the topic of interaction as follows: "*It's always like that, you test out something new, and then you first constantly look at it, interact with it, focus on it. But if you were to fly around with it all day, at some point, you just "get" it, you get used to it. (P3)*"

4 DISCUSSION

The following discussion section provides a summary of the insights given by the pilots throughout this study. It concludes our examination of using a current generation MR headset in the context of GA, addressing concerns, proposing design considerations for MR interfaces in GA cockpits, exploring potential future applications, and acknowledging the study's limitations.

4.1 Implications for Using a Current Generation MR Headset in GA Operations

Participants were much more aware of their location regarding the approached airport. However, most participants agreed that even with the prototype, they could not distinguish an actual aircraft from the sky and relied on the correctness of the traffic holograms. The issue of reporting aircraft for which only a hologram can be seen might, however, be regarded as controversial as it leads to regulatory concerns that have not yet been addressed by current legislation. Is an aircraft in sight if a virtual object is shown at its precise location, even if the naked eye cannot distinguish the aircraft? Incorrect data can lure the users into a false sense of security, as many participants acknowledged themselves in the interviews.

This result matches some of the comments of the participants, such as the quote regarding "another layer" to be aware of (P4 in Section 3.2) when wearing the *HoloLens 2*. For some participants, the device and its displayed holograms merge with the real world, giving additional information about POIs without distracting from other sources of information. For them, this might lead to a reduced workload as scanning their environment, navigating, and being aware of other aircraft are supported by the prototype. For the remaining part of users, however, this familiarization with virtual components in their field of view does not happen, or at least not as quickly as for the others. As the novelty of the user experience was reported as rather high when using the prototype, this might be a temporary factor that decreases as the experience with the prototype increases.

Overall, the prototype was deemed helpful by some participants but not all. Hence, using MR in aviation is highly individual. **As the experience of MR environments was new to most of them, the novelty and unfamiliarity of this approach to present information are assumed to be the leading factor as to why some participants perceived a higher workload instead. Parallel to including tablets into EFBs, future research must investigate the long-term effects of MR in aviation by, for example, including them in supervised training scenarios.**

4.2 Designing MR Interfaces for Applications Inside GA Cockpits

The participants unanimously agreed that they could imagine using MR devices during actual flights (see Figure 2). With the qualitative results of the expert interviews, specific design considerations for future MR applications for GA cockpits can be made. The *HoloLens 2* was seen as primarily unfit for use in a real cockpit. Its heavy weight and size, as well as potential interference with over-ear headsets, were relevant problems during the study. These issues could pose even more significant problems, mainly when used for longer flights and under the influence of g-forces. While the work of Gorbunov [16] already showed that using HMDs is feasible in GA, the prototype in this work showed that current devices could be used for much more than just presenting already available flight information. The study participants agreed that they felt confident using the prototype and that such a device could be a reliable part of their future operations.

Most wished for less interaction with the MR device instead of more. The reason for this is the already demanding workload they have to handle, requiring most of their attention for flying the aircraft. The need to interact with yet another device might mitigate any improvement it could offer. Ideally, the device should automatically adapt to the current situation of the aircraft and its pilots, changing the kind of information supplied depending on the current needs. Participants agreed that they have an inherent trust in such a device, assuming it reliably presents helpful and, most importantly, correct information. The potential to use current devices like the prototype in this work does not imply that it is safe or even recommendable. For some, it reduced their workload and supported them in navigation and awareness of other traffic. For others, it increased their workload and distracted them from their tasks. The participants also highlighted certain significant challenges that overlap with relevant related work, such as issues related to visual clutter [20] and data accuracy [21], which were perceived as potential factors with substantial influence on their receptiveness towards the proposed MR tools.

The performance of MR technologies that go beyond what conventional avionics can display during real-world GA operations remains open for future research. **The design of MR interfaces influences flight performance and must be considered carefully in future research.**

4.3 Limitations and Future Work

A significant study limitation is the controlled environment in which it was conducted. No significant weather or potentially dangerous traffic situations were programmed to occur herein. Furthermore, no radio communication was required, and the participants were aware that no actual aircraft was flown. Supervised testing of MR while operating a real aircraft will probably yield many new findings, as a truly realistic environment cannot be reliably achieved in a simulator. For example, using MR with an adaptive interface for the first time in the cockpit might trigger novelty effects, where pilots rate the utility of MR better in lab environments than it would be in real long-term settings [24]. Furthermore, HMDs can sense pilot context for advanced measures. In this context, measures such as emotions [4, 5], frustration [7, 8], or mental workload [23, 29] has been researched in driving scenarios and could be transferred to the GA context.

Next, the prototype has not been tested for performance with actual real-world data. While the connection to live databases has been achieved, the influence of a non-steady flow of information and its natural inaccuracies remains to be tested. Next, implementing one of the many ideas collected during the interview could provide valuable insights into what MR can be used for in GA. This includes, but is not limited to, the illustration of airspaces, flight paths, airport traffic patterns, or weather information. Participants had the idea of using MR as a means to learn and training for novice and student pilots.

Another step is to adapt this prototype for other aircraft as well. For example, rotorcraft pilots probably have much less need for highlighting airports and their runways, but helipads and similar places could be shown instead. Pilots of gliders and other unmotorized aircraft could be interested in current wind conditions and the thermals around them. Lastly, interaction is a big part of such a system that was only touched on in this work. Enabling the users to interact with the holograms freely, adding and removing data sources as desired, or even controlling it via voice commands are all potential developments that could be tested.

5 CONCLUSION

In a qualitative user study, twelve participants tested a prototype for GA pilot support using a current generation AR headset in a full-sized flight simulator. They gave feedback about their experiences and considerations regarding the utility of MR in the GA cockpit in general. Based on the analysis of post-test interviews, we defined design considerations for using MR in GA. We identify the themes RELIABILITY, ERGONOMICS, INFORMATION ADAPTABILITY AND MODALITY, and INTERACTION. Future designs must critically consider novelty effects, clutter, distractions, and more issues that might arise when using MR in GA environments.

At the same time, our results show that overreliance on such technologies might pose severe threats to the safety onboard. While the use of MR technologies has already been proven to be a helpful addition in commercial and military aircraft, the oftentimes wildly differing environments of GA operations open up new challenges to be considered. Our research lays the foundation for pursuing MR in the aviation sector to increase the awareness and safety of GA pilots.

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