Implementing Augmented Reality in the Flight Deck for Single Pilot Operations

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Abstract

Single Pilot Operations is a current topic with the potential to significantly affect the future of commercial aviation. While financially attractive for airlines, Single Pilot Operations bring forth important safety concerns, especially regarding the lack of human redundancy in the flight deck, an increased workload for the single pilot, reduced situational awareness and a higher risk of human error.

It is assumed that potential problems affecting Single Pilot Operations could be addressed by implementing an Augmented Reality (AR) device in the flight deck, by presenting additional information and supporting hints within the pilot's field of view. Concretely, AR could be used to help reduce the single pilot's workload, improve situational awareness and reduce the risk of human error.

This paper sets out to demonstrate two use cases for augmented reality in the flight deck. A system, called Pilot Assist, was developed that allows pilots to conduct checklists interactively with a Microsoft HoloLens. The system also provides a holographic Head-up-Display. Pilot Assist was developed and demonstrated with a fixed base Airbus A320 simulator at the Technical University of Wildau.

With the HoloLens' spatial mapping capabilities – scanning and recognizing the environment around the user – it was possible to create a system that guides the pilot through the conduction of checklists. This is done by prompting the user towards the location of each checklist item in the cockpit, where information regarding necessary actions is projected. Furthermore, Pilot Assist is integrated with the aircraft systems, making it possible to obtain aircraft status data in real time, thus allowing error-checking of the pilot's actions as well as automating the progress through checklists.

The holographic Head-up-Display allows the user to look at the surrounding environment while presenting critical flight data within the user's field of view. The holographic Head-up-Display is intended to contribute to the pilot's situational awareness.

Experts in the aviation field, including pilots, researchers and engineers had the chance to qualitatively assess the Pilot Assist tool. They pointed to limitations of both Pilot Assist and the HoloLens itself, but shared optimism as to how this technology and similar applications could indeed impact the future of flight operations. Concerns regarding the HoloLens' weight, comfort and narrow field of view were expressed. However, continued development of head mounted devices (e.g. HoloLens 2) is expected in the coming years.

Further research into augmented reality applications in the flight deck is needed to advance this and other use cases. Nonetheless, the experts agreed Pilot Assist provides beneficial support during single pilot operation considering the current prototypical nature of the system.

I. Introduction

Since the early days of the aviation industry, technological advances have brought significant improvements in automation and operations that allowed the reduction of the flight crew from five to two members, while constantly maintaining high safety standards.

In recent years, continuing the process of "de-crewing", which started in the 1950s has been in the mind of airlines and manufacturers, since crew costs make up a very large portion of an airline's expenses. There have already been efforts within the aviation industry to pave the way towards Single Pilot Operations (SPO) [1], [2]. The vision of only one crew member in the cockpit is, however, disruptive and certainly brings forth many safety concerns. What if the pilot becomes incapacitated? Who will relieve them of some of their duties when the workload increases? How to counteract the effects of exhaustion during long journeys with only one technical crew member on board? These are some of the questions that must be answered before even thinking of performing commercial aviation with SPO.

These challenges also affect General Aviation. It is not unusual that pilots fly alone or with passengers who cannot be counted among the flight crew. In such cases, pilot incapacitation can be a life-threatening scenario.

Mixed reality has some characteristics that might prove to be very helpful in the flight deck, especially under certain circumstances, such as the reduction of the flight crew or off-nominal situations, which usually involve a higher work load.

This article presents an Augmented Reality (AR) system designed to improve the pilot's situational awareness with a Head-up-Display (HUD) and assist the pilot during the execution of procedures in the flight deck. The system, referred to as the Pilot-Assist-System (PAS), makes use of a Microsoft HoloLens as an input/output device and was developed and tested at the Airbus A320 flight simulator at the Technical University of Applied Sciences Wildau (THW).

The remainder of this section will first offer a brief introduction to AR, the HoloLens and the A320 flight simulator where the holographic assistant was developed. Thereafter, the theoretical background for the creation of the holographic checklist assistant will be discussed. This is followed by a description of the holographic checklist assistant's, including high-level technical details. The article is concluded by the feedback provided by professional pilots who tested the PAS and the possible ramifications of future developments.

A. Augmented Reality and Microsoft HoloLens

Augmented Reality can be understood as a region in the so called "virtuality continuum" (see Figure 1), where reality occupies a place to the left side of the spectrum and virtuality — where the real environment is completely replaced by a virtual one — a place to the right.

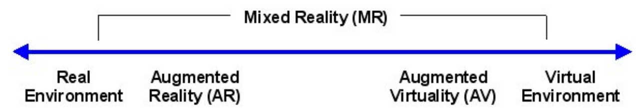

Figure 1. The virtuality continuum [3]

An AR system "augments" the real environment by means of virtual objects [3]. The following conditions have been formulated in order to categorize an audiovisual system as an AR system [4]:

1) Combines real and virtual
2) Is interactive in real time
3) Is registered in three dimensions

The Microsoft HoloLens (see Figure 3Figure 2) can be counted among the AR devices currently available in the consumer market. It is a head mounted computer with a holographic display. It counts with a total of four environment understanding cameras, which constantly scan the user's surroundings, and a depth sensing camera. The depth sensing camera measures the distance from the HoloLens to the surrounding objects. The vast amount of data provided by the five cameras and other sensors is processed by the Holographic Power Unit, one of the custom parts equipped in the HoloLens, in order to place holograms in the environment around the user in a convincing, reality-like manner.

Figure 2. The Microsoft HoloLens [4]

Figure 3 offers a glimpse of an Augmented Reality scene captured with the HoloLens. As the user moves around the room, the holograms (dinosaur, space shuttle, globe, etc.) keep their designated position and are not projected in unrealistic ways, for instance, penetrating real objects in the room or with unusual orientations.

Figure 3. HoloLens mixed reality capture

Spatial Mapping and Spatial Understanding are the key features that allow the HoloLens to, respectively, “perceive” and subsequently “understand” the world around it. The HoloLens is thus capable of scanning objects and surfaces in its immediate surroundings and then, making decisions about what those objects might be, either walls, floors, ceilings, or, a chair, a door, etc. Figure 5 offers a glimpse of how HoloLens perceives the world, showing the so called “spatial mapping mesh”. A human being sees something similar to the image in Figure 4. The spatial mapping mesh is made up out of volumes and thousands of triangles that recreate the world around the HoloLens’ user. “World anchors” allow referencing specific triangles in the mesh, so they can be used, for instance, to place holograms in space. Spatial mapping data can be persistent. The HoloLens can thus recognize rooms it has already scanned and place previously created holograms in their original positions.

Figure 4. Mixed reality capture

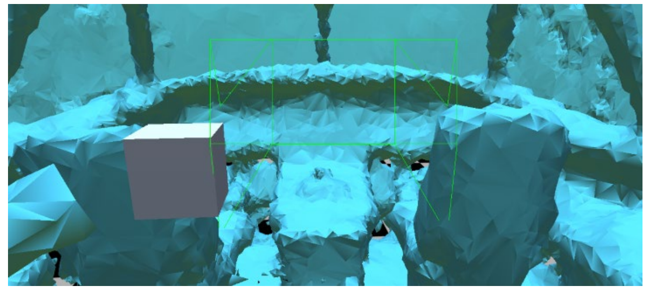

Figure 5. HoloLens' spatial mapping mesh

B. The Airbus A320 Procedure Trainer

The AR applications demonstrated in this article were developed at the Airbus A320 flight simulator at the THW. The interior of the simulator, with most of the haptic and visual components found on the real aircraft, largely resembles a true A320 cockpit (refer to Figure 4). However, none of the components are original A320 equipment and the avionics and aircraft systems are simulated by third party software.

The simulation environment is provided by Lockheed Martin’s Prepar3D (P3D). An Application Programming Interface (API) called SimConnect, part of P3D, allows third party software to read and write simulation data. It is possible to create add-on components for P3D by using SimConnect.

C. Theoretical Background

The theoretical background for the development of the holographic checklist assistant has its foundations in some of the problems posed by the introduction of SPO. Any two-crew-cockpit is faced with a high workload during certain flight phases, especially during ground operations, takeoff, approach and landing. Crew Resource Management (CRM) techniques are in place to help the pilots cope with an increasing workload. In a single pilot cockpit, high workload situations could have detrimental effects on the pilot’s performance [5].

Off-nominal situations are also likely to cause an extraordinary workload increment. An off-nominal situation, apart from the resulting workload increment and the physical and psychological burden it can cause on the crew, is usually also accompanied by the necessity to execute procedures that are not routinely performed. These procedures often require using aircraft systems that are otherwise rarely used, whose operation might not be so well engraved in the pilots' mind – in contrast with the operation of other aircraft systems that constitute nominal flight missions. During SPO, an off-nominal situation could become especially troublesome.

A further concern regarding SPO is the lack of human redundancy in the cockpit. Human redundancy is especially important if crew members became incapacitated. Current solutions proposed to mitigate this special case involve a ground station and a remote pilot, who could eventually take control of the crew-less aircraft. The human redundancy in the cockpit is, however, also manifest through crosschecking and monitoring activities. One crew member, who usually assumes the role of Pilot-not-Flying (PNF), or Pilot Monitoring (PM), is aware of the Pilot Flying's (PF) actions and can provide feedback and recommendations whenever faulty actions are carried out, a mechanism that is meant to work both ways.

From the considerations regarding the increased workload and reduced redundancy in a single pilot cockpit, AR use cases were developed with the general aim of reducing the pilot's workload, providing an extra layer of redundancy and improving the pilot's situational awareness.

One of the conceived ideas was that of a holographic checklist assistant, designed to take over tasks usually reserved for the PM in a two-pilot crew. The intended effect is a workload reduction for the single-pilot. The HoloLens' spatial mapping capabilities would be used to associate physical locations in the cockpit to aircraft variables. HoloLens' speech recognition would allow the pilot to interact with the device in a similar manner as they would with a second crew member: through oral commands.

The following section will show the implementation of the holographic checklist assistant and give further details about its constitution.

II. Implementation

A. Holographic Head-up-Display – Use Case Description

A HUD is designed for the pilots to see flight-relevant data within their field of view. This allows looking at the environment outside the aircraft while still having an overview of information that is critical for the task of aviating.

The data displayed by a HUD can range from simple – for instance just a few important parameters such as airspeed, altitude and heading – to more complex information, such as a "tunnel in the sky" or synthetic vision, where the terrain is rendered as a virtual mesh. As a starting point for this use case, the data presented by the HUD will be limited to the basic data from a PFD, namely: (1) orientation data (roll, pitch and heading) (2) airspeed (3) altitude (see Figure 6).

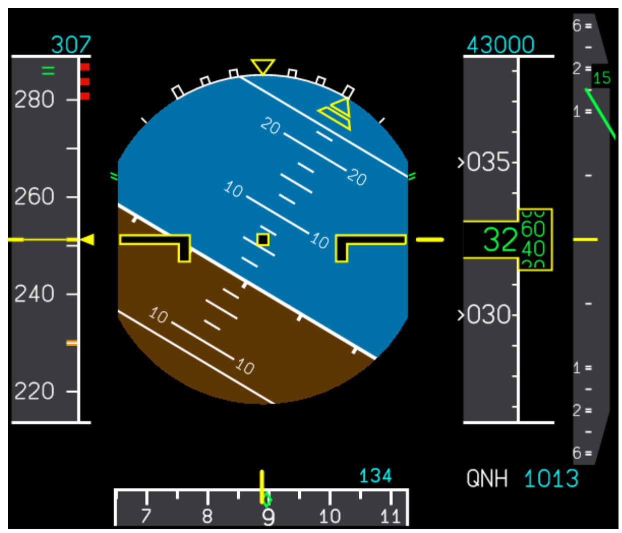

Figure 6: Primary Flight Display of an Airbus A320

This information is sufficient to fly under good weather conditions. Further information that would allow the pilot to rely on instrumentation data is not yet provided by the HUD. Therefore, it is assumed that the current version of the holographic HUD is to be used under Visual Flight Rules (VFR). The HUD is not yet equipped to allow the pilot to fly under deteriorating weather conditions where Instrument Flight Rules (IFR) apply.

The holographic HUD here presented runs on a Microsoft HoloLens and receives the required orientation and instrumentation data from the simulation computer. The data from the simulation computer is used to update the orientation, position and textual elements of the various HUD components.

The usage of the HUD is simple. The following scenario describes the usage of the HUD:

A pilot in command of an aircraft will perform a VFR flight. The Pilot Assist System and a HoloLens headset are available. Before taxiing to the runway, the pilot puts on the HoloLens and opens the Pilot Assist HoloLens application. Initially, no HUD is displayed. The pilot decides to taxi to the runway without the HUD, as it will only clutter its field of view with non-relevant information. Once the pilot gets the take off clearance and lines up on the runway, he issues the oral command “show primary flight display”. The HUD is now displayed in the pilot’s line of sight. The pilot can issue the oral command “new position” to reposition the HUD to ensure a better alignment with the airplane’s longitudinal axis. Once a satisfactory position has been found, the pilot initiates the takeoff by increasing the engine power. The pilot sees the airspeed increasing as the aircraft accelerates. Upon reaching the rotation speed, the pilot starts pulling on the yoke and the aircraft’s nose rises from the ground. Meanwhile, the artificial horizon in the HUD is continuously updated so the pilot can see the aircraft’s changing pitch. The pilot is then also able to see the changes in altitude as the aircraft climbs away from the runway. Further maneuvers can be performed using the HUD as instrumentation to make turns, climb, descent, level off, etc.

When the cruise phase is reached, the pilot might opt to hide the HUD by issuing the oral command “hide primary flight display”. With the command “show primary flight display” the pilot can activate the HUD again for performing the approach and landing.

Figures 7 and 8 can be used as examples to compare a traditional HUD (Figure 8) and a holographic one (Figure 7) where the projection device is worn by the user.

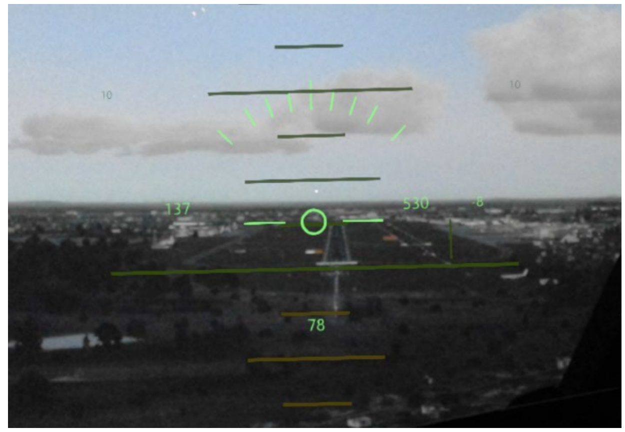

Figure 7. Holographic HUD with Microsoft HoloLens

Figure 8: Traditional Head-up Display on a Boeing 787 [6]

B. Checklist Assistant - Use Case Description

The present section describes a concrete scenario, used to exemplify the intended functionality of the checklist assistant.

The scenario consists of a pilot in command of an aircraft during final approach, with an AR device at their disposal. The pilot must, shortly before landing, conduct the landing checklist. The landing checklist used in this example consists of the following items[1]:

1) Landing gear: down
2) Flaps: full
3) ECAM[2] memos: LDG, no blue

When the time comes to perform the checklist – the aircraft is established on the localizer, flaps have been set to three or full according to the desired landing configuration, etc. – the pilot issues the oral command "landing checklist". The command is detected by the AR device, the Microsoft HoloLens. The headset then projects an arrow-shaped or conical hologram that points towards the landing gear lever. The pilot's gaze follows the hologram until it meets a holographic marker in the vicinity of the landing gear lever (Figure 6). Besides the marker, the pilot finds a textual instruction that says, "Gear Down". The pilot complies to the instruction and lowers the gear level.

After the landing gear is deployed, the same holographic guide appears before the pilot's eyes, this time pointing towards the element in the cockpit that corresponds to the second checklist item: the flaps handle. Again, the pilot finds a holographic marker next to the flaps handle with the textual instruction "flaps full" (Figure 7).

After setting the flaps to full (or four on the A320), the process is repeated for the last item in the checklist, the ECAM memos. In this case, the pilot sees the marker next to the systems display, accompanied by the text "ECAM Memos, LDG, no blue" (Figure 8). If there are any blue items in the ECAM memos, the pilot needs to take appropriate action until all items are green. Once all items are green, the pilot issues the oral command "checked", with which the current item, as well as the checklist is completed. The pilot is then notified by holographic text that the checklist has been completed.

It is worth noting that the transitions between steps 1 and 3 were automatic. The PAS monitors the variable that corresponds to the currently active checklist item. If the variable assumes the target value defined in the checklist, the next item will be automatically activated. Some variables, however, cannot be monitored by the PAS, which explains the introduction of the "checked" keyword, used to transition from step 2 to step 3.

The "checked" keyword was introduced to handle checklist items, whose value cannot be obtained from the aircraft systems, but from the crew directly. Some checklists might include items such as "Cockpit preparation: completed", or "Cabin crew: advised", etc. In these cases, the "checked" keyword allows the pilot to progress through the checklist.

With the current simulator's setup, where aircraft systems are simulated by third party software, the "checked" keyword is also useful as a workaround to handle variables that cannot be monitored by the PAS due to technical limitations. Variables that are declared within third party software are not accessible through SimConnect, and therefore, it is not possible to automate the transition through these. The "ECAM Memos" variable serves as an example.

Figure 9. "Gear down" holographic instruction

[1]The checklist used in this article is to be interpreted solely as a mechanism to illustrate the function of the checklist assistant. A real A320 landing checklist usually takes a different form.

[2] ECAM: Electronic Centralized Aircraft Monitor

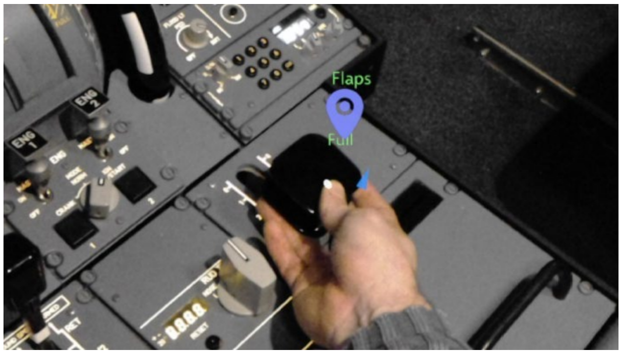

Figure 10. "Flaps full" holographic instruction

Figure 11. ECAM Memos holographic hint

Note that since the checklist assistant was developed to be used in an A320 simulator, it contains items that mostly Airbus pilots would be familiar with. Nevertheless, the principle could be transferred to any other type of aircraft with an electronic monitoring system, where the values of various system variables can be obtained and monitored.

C. The Pilot Assist System

The holographic checklist assistant and HUD make part of a broader construct called the Pilot-Assist-System (PAS). The PAS is a "platform" to exchange data between the simulator and the Microsoft HoloLens. Furthermore, the PAS also has a Graphical User Interface (GUI) which can be used by a system administrator to manage the data necessary for the execution of checklists. The first part of this section will present the PAS, its architecture and some of the features necessary to implement the use case described above. The second part will present the cockpit mapping procedure, necessary to display information with a spatial context in the cockpit.

Pilot-Assist-System Overview

The PAS is composed of two main elements: The Pilot Assist Control Center (PACC) and the Pilot Assist HoloLens (PAHL). A high-level abstraction of the PAS' architecture is shown on Figure 9.

The PACC runs on the simulation computer and allows retrieving "dynamic data" from the simulation software – i.e. data regarding the various simulation variables, subject to changes in time. The holographic HUD relies only solely on dynamic data, specifically, the simulation variables that describe the aircraft's orientation in space (roll, pitch and yaw), as well as the variables for the airspeed, altitude and vertical speed. As soon as the data is available through SimConnect, a data package is sent to the PAHL via MQTT, the data exchange protocol used by the PAS. When a dynamic data package is received by the PAHL, the HUD is updated with the new information. Data is available on each simulation frame, which is limited to 30 frames per second – due to performance optimizations on the flight simulator. This means that if the bandwidth allows, the HUD can be updated synchronously with each simulation frame at 30 Hz.

All "static data" necessary for the holographic checklist assistant – for instance, the data structures that represent checklists – can be managed through a Graphical User Interface (GUI) inside the PACC. The static data is saved in a document-based database. The PACC was developed using the C# programming language and .NET framework.

The PACC counterpart is the PAHL. It is a HoloLens application, also developed using the C# programming language. It is the PAHL which is directly experienced by the pilot, it contains all graphic (holographic) elements used to guide them through the conduction of checklists. Furthermore, as illustrated in Figure 9, pilot issued speech commands (e.g. checklist invocations by the pilot) are processed by the PAHL and forwarded to the PACC.

Figure 9 shows an intermediary between the PACC and PAHL under the name "MQTT broker". The Message Queuing Telemetry Transport (MQTT), is a light-weight client-server, publish/subscribe messaging transport protocol. It is ideal for contexts where a small code footprint is necessary, and the network bandwidth is limited [7]. The MQTT broker allows the data to be exchanged between two or more client machines. Each client, in this case the PACC and PAHL, can subscribe or publish to specific topics. The messages *published* on a given topic are forwarded by the MQTT broker to all clients *subscribed* to that topic.

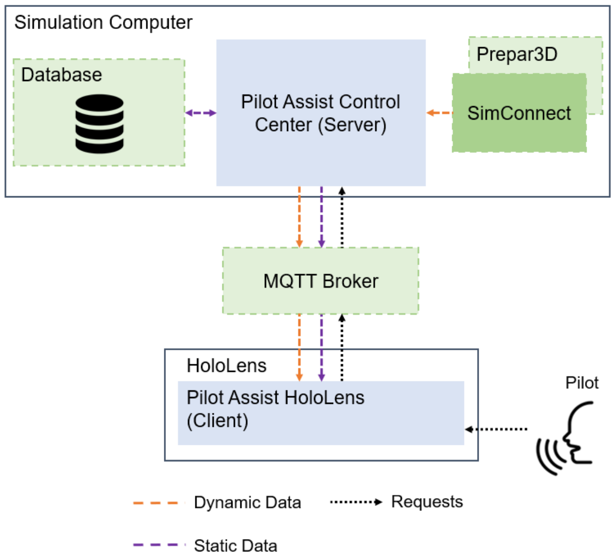

Figure 12. Pilot-Assist-System high-level architecture

By working together, these components create the experience described in the previous section. Several speech commands are registered on the PAHL, which correspond to specific checklists or procedures. After one such command is detected, the PAHL sends a message to the PACC via MQTT, indicating the procedure invoked by the pilot. This triggers the procedure's execution on the PACC. The PACC first retrieves the necessary data from the database. Put simply, the representation of a procedure in the database is a list of items, each item containing a simulation variable to be monitored and a target value. Each simulation variable contains, among other attributes, the identifier for its "world anchor", which used to position the holographic markers in the cockpit (as illustrated in Figures 6 to 8). World anchors and the cockpit mapping process are explained in the next section.

Once the procedure's data has been retrieved the checklist execution starts. The PACC will, at this stage, start to monitor the simulation variable that corresponds to the first checklist item. Parallelly, the PACC will send a message back to the PAHL with the simulation variable's target value, in textual form, and its associated world anchor identifier – with these steps the procedure invoked by the pilot is now active.

After receiving this data from the PACC, the PAHL locates the world anchor that corresponds to the procedure item. This allows the HoloLens to identify the exact location in the cockpit where the marker is to be displayed accompanied by the target value in text form.

Meanwhile the PACC will continuously monitor the simulation variable's state until it matches the target value. The next item in the checklist will be activated then[3]. Alternatively, if no value can be obtained from the simulator for the current variable, the pilot must trigger the transition to the next item by using the "checked" keyword. In this case, a message is sent to the PACC to activate the next item in the procedure. This process is repeated until the procedure is completed.

Cockpit Mapping Process

One of the challenges involved in the creation of the checklist assistant was to assign the simulation variables behind each checklist item a physical location in the cockpit, so the corresponding marker and textual instruction can be shown with a spatial context.

The concept of "world anchors" provided a suitable solution for this problem. A world anchor can be understood as a reference to a specific polygon in the spatial mapping mesh (Figure 5), which is saved locally for each HoloLens application. A specific world anchor can be retrieved from the anchor store by using its identifier; the world anchor's location in the mesh can be used to place holograms with a spatial context.

The cockpit mapping process consists of creating an identifier for a new world anchor using the PACC GUI. The identifier, a *unique* chain of characters, is saved along with a label for the world anchor in the document-database. Each world anchor document can be sent to the PAHL via MQTT, say,

[3] In order to reduce the chance of "false positives" the variable's value keeps being monitored for a short time period after the target value is reached.

on the topic “new_world_anchor”, to which the PAHL is subscribed. When data is received through this topic, the PAHL shows a marker similar to those in Figures 6, 7 and 8. This marker follows the user’s gaze until it is placed on the correct position using the HoloLens’ air-tap gesture (see Figure 10).

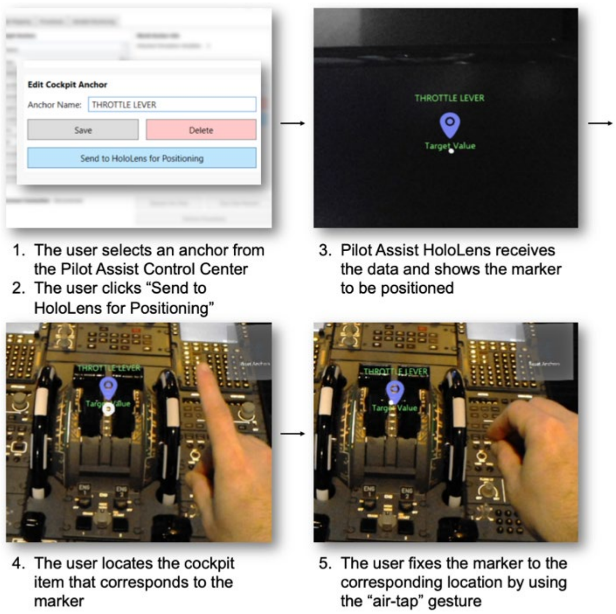

Figure 13. PAS cockpit mapping process

III. Evaluation from Pilots

Several subject matter experts (SME), in this case professional airline pilots, were invited to take part in simulator sessions and experience the checklist assistant and the holographic HUD.

The checklist assistant, as well as the HUD, as presented in this article, are in their early infancy and initial iterations. Therefore, the aim of the simulation sessions was to gain insights from the SMEs and make an initial feasibility assessment regarding the implementation of both applications.

A. Participants

The SMEs for the simulator sessions were six (6) professional airline pilots with varying number of fly hours, namely between1700 to 11.000.

Five (5) were Airbus A320 pilots, currently in service with various European airlines. Since the simulator sessions were conducted at the THW Airbus A320 simulator, this set of pilots experienced a very familiar environment. However, in order to get more general insights, agnostic to the aircraft type, it was attempted to have at least one non-A320 pilot. In this case, a 737NG pilot, also in active service with a European airline. Because no off-nominal situations were to be simulated, and each pilot was given enough time to become familiar with the simulator, the Boeing pilot reported to be comfortable enough to perform the short, planned routes.

Apart from the SMEs, the author participated as a second crew member, who assumed the role of PM during the sessions with a two-pilot crew.

In order to mimic ATC, a pseudo-controller was present during the simulations, sitting behind the pilots at the instructor’s station.

B. Independent Variables

For the simulation sessions there were two parameters that were varied, namely the presence of a second crew member assuming the role of PM and the use of the holographic checklist assistant. The influence of these two parameters was to be assessed by the pilots after finishing all simulator sessions.

C. Simulation Sessions Design

The simulator sessions to test the checklist assistant were conducted in three phases after an initial familiarization flight.

A separate session was conducted in which the holographic HUD was used by the SMEs.

The familiarization consisted of a free flight around Berlin Tegel (EDDT), in order to allow the pilots to familiarize themselves with the simulator. The length of this flight was left to the pilot’s judgement. Furthermore, during this phase, the pilots were introduced to the holographic checklist assistant. They could experience it during flight, were briefed about how to use it and about the currently available checklists.

The first phase involved a short, planned flight with a two-pilot crew, starting and arriving at (EDDT). The pilots were given a flight plan and received instructions from ATC.

The second phase was an SPO scenario, using the same flight route as in the previous phase.

The third phase followed the flight plan from phases one and two. It was also an SPO scenario but this time, using the holographic checklist assistant. The pilots were already briefed about the assistant's usage and the checklists to be performed with it, namely: (1) after takeoff checklist; (2) approach checklist; (3) landing checklist.

In order to increase the nominal workload without bringing forth a non-normal situation, the weather was set to include strong, gusting winds, moderate turbulence, moderate precipitation and visibility of 3km. It was assumed that under these weather conditions, more concentration is directed to the task of flying and controlling the aircraft.

After completing the sessions, the pilots were asked to report about specific aspects of their experience using a questionnaire with four (4) questions. The exercise was finalized with discussions pertaining the holographic checklist assistant and using the HoloLens in the flight deck. The questions included in the questionnaire were:

1. Did you experience a workload reduction during the session with the checklist assistant compared to the SPO session without it?
2. According to your (simulator) experience, did the checklist assistant, to any extent, help to reduce the risk of human errors and improve your performance?
3. Did the usage of the checklist assistant in any way affect the experienced mental stress?
4. Did the usage of the checklist assistant, to any extent, compensate for the absence of a second crew member?

After the holographic checklist assistant session was finished, there was a final session in which the pilots used the holographic HUD for a short VFR flight around EDDT. This last session was followed by a discussion where the pilots reported about their experience and gave feedback regarding the holographic HUD.

D. Results

All sessions were completed successfully, i.e. the planned flight route was completed without any incidents. Regarding the questionnaire, the pilots' answers tended to be very consistent among the pilots, the answers are summarized in Table 1.

The subsequent discussions with the pilots provided insights which stand in line with some of the original suppositions. The discussions mainly focused on the value of a tool such as the checklist assistant during high-workload, and more significantly, during off-nominal situations in an SPO context.

It was argued that the holographic assistant's value could be more conspicuous during off-nominal situations. As most commercial flights are completed with total normality, checklists become routine for both young and seasoned pilots. However, if a failure occurs and the conduction of an abnormal procedure becomes necessary, its content is unlikely to be very fresh in the pilot's memory. Furthermore, the muscular memory which allows pilots to perform normal procedures quickly and accurately is usually not so thoroughly developed for abnormal procedures, even if they have already been trained in the flight simulator.

Therefore, it was pointed out that a system like the Procedure Assistant, could help in mainly two ways. First, it could help reducing the pilot's workload by loading the correct procedure for the arising abnormal situation, eliminating the need to resort to the reference handbooks. It was then suggested to save procedures within the PAS that correspond distinct abnormal situations. In the initial iterations the pilot would be able to invoke a specific procedure that is thought to be appropriate. Consulting the reference handbook can still be necessary, as the pilot might not instantly remember the name of the correct procedure to be invoked. However, in a more mature version of the PAS, individual procedures could be associated with specific failures detected by the aircraft. Thanks to the PAS partial integration with the (simulator) aircraft, it could be notified about emerging failures. Upon failure detection, the pilot could be offered a list of the possible courses of action and be subsequently guided through them by the checklist assistant.

The second advantage from the Procedure Assistant is the crosschecking of the pilot's actions. The checklist assistant offers a very basic mechanism for crosschecking: if the pilot acts inappropriately, the checklist won't automatically advance. Although this should be perceived by the pilot as an indication that the action performed was incorrect, there is no direct feedback about eventual wrongdoings. A more refined and mature system could give direct feedback to the pilot, for example by pointing out the exact actions that weren't carried out appropriately.

The feedback regarding the holographic HUD was mostly positive. Pilots remarked an advantage of a head-mounted HUD as opposed to traditional HUDs in that no precise adjustments on the seat position must be made to properly use the HUD. Therefore, a head mounted HUD should be in principle more user friendly than the fixed HUDs currently found in commercial aircraft.

One common suggestion was to display some pieces of information constantly within the pilot's field of view, namely airspeed, altitude, vertical speed and heading. This would allow pilots to look at their surroundings without loosing sight of these critical parameters. A specific instance where this would result useful is during a circular approach, where the runway must be kept in sight.

There was general consensus that the HUD could improve the situational awareness by allowing pilots to monitor their surroundings while still having access to critical flight data. However, once again, there was a certain amount of criticism regarding comfort while wearing the HoloLens after long time periods. By the time the holographic HUD was tested, the pilots had already worn the headset for approximately 15 to 20 minutes. Conclusions

Table 1. Questionnaire Answers Summary

Question	Answer Summary
1	Very slightly. No off-nominal or particularly high-workload situations were simulated. Furthermore, the simulated situations were very familiar for all pilots, as were the procedures involved.
2	Slightly. Once again, the experienced Airbus A320 pilots found themselves in not particularly demanding situations and had familiarity with their environment. However, it was reported that the appearance of items that require the "checked" keyword, encouraged them often to re-check the status of the corresponding item before advancing through the checklist.
3	Yes, both positively and negatively. All pilots reported that their cognitive abilities might have been affected negatively by wearing a device they aren't familiar with. Wearing the HoloLens for longer time periods also started to become uncomfortable for all pilots, due in part because of its weight and pressure on the head, as well as the eyestrain caused by the HoloLens' visual system. On the other hand, the Boeing pilot reported that despite of the physical discomfort caused by wearing the HoloLens, the guidance towards the checklist items was slightly beneficial, as very little mental effort was required to find the correct control in an unfamiliar cockpit.
4	Partially. During certain sessions, the pilots were conducting checklists while being "interrupted" by ATC. The most common strategy was to first finish the checklist and then take care of communications. However, using the checklist assistant allowed pilots to communicate with ATC without losing track of the procedure being executed. Some of the pilots suggested that such functionality would be especially valuable to preserve the quality and efficiency of communication with ATC during departure/approach procedures in busy airspace. On the other hand, it was suggested that the checklist assistant would not be all that useful during high-workload situations, where procedural omissions can take place (e.g. checklists are not carried out due to the high workload) and the checklists are not invoked.

IV. Conclusions

This article presented a concept for a holographic checklist assistant and a holographic Head Up Display using the Microsoft HoloLens.

Simulator sessions and discussions with professional pilots shed some light regarding the potential and limitations regarding the usage of an AR-device in a cockpit environment. The participation of pilots in the simulator sessions focused on assessing the benefits from using the checklist assistant during Single Pilot Operations and the holographic HUD on VFR flights.

The absence of the second crew member is by no means compensated by using the checklist assistant. Therefore, the implementation of the checklist assistant is not feasible as an isolated solution for enabling SPO. However, it is not unrealistic to depict the integration of tools such as the checklist assistant within other frameworks to enable SPO, which include ground stations for remote assistant. In these scenarios, more mature versions of headsets like the Microsoft HoloLens could be implemented as human-machine, human-human interfaces. Within this picture, the checklist assistant could provide a good complement in the pilot's (and remote pilot's) toolbox.

The simulator sessions and the later discussions revealed that the checklist assistant has the potential to be beneficial, especially during high-workload and off-nominal situations. However, the still prototypical nature of the checklist assistant, its yet very basic functionality, and the HoloLens' shortcomings are current limitations to properly assess the potential of the concept here presented. Therefore, further experimentation with a more mature Pilot Assist System, as well as hardware upgrades in the near future, is necessary to explore the potential of tools like the holographic checklist assistant and AR technologies in the flight deck.

In order to enhance the checklist assistant's value in the near future, the development work will be focused on specializing the checklist assistant for off-nominal situations – with the goal of alerting the pilot of emerging failures and suggesting courses of action.

Regarding the holographic HUD – a head-mounted Head up Display running on the Microsoft HoloLens, the pilots reported that even it's basic functionality, satisfactory to be used under VFR, has the potential to improve the pilot's situational awareness. Feedback regarding the HUD's design will be useful for further developing the HUD according to pilots' needs. Furthermore, increasing integration with the aircraft systems will potentially enhance the HUD's capabilities and value in the flight deck.

Continued work with pilots, researchers and engineers will be paramount for a meaningful and successful development the Pilot Assist System. In parallel with mixed reality technologies, systems such as the one here presented, shall one day mature and make their own contribution to more efficient and, more importantly, safer aviation.

V. References

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4th Automobile Symposium Technische Hochschule Wildau

March 6, 2019