USE OF AUGMENTED REALITY FOR HYBRID MOCK-UP VALIDATION IN AVIATION MAINTAINABILITY

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Abstract

To perform maintainability and Human Factors assessment in preliminary aircraft architecture and design review, the simulation of maintenance activities is deployed inside industry. The use of augmented reality associated to a physical mock-up could be an alternative to other complementarity simulations already existing (virtual reality, physical mock-up alone). This paper introduces the first experimentation with this hybrid simulation and the results of its performance. This hybrid solution allows a reduced lead time in the development and decision process. It reduces the cost of the mock-up using only the basic shape of the model and tangible interfaces for the user. Augmented Reality increases the detail of the model and allows multiple configuration review and fosters collaboration between designers and project stakeholders.

1. INTRODUCTION

In the European Helicopter industry, Maintenance is the root cause of 6% of accidents (EASA), and it is the second source of hazards. Moreover, 62% of operators in the heavy industry consider maintenance as a hard activity (AFIM). To ensure maintenance can be achieved safely for both Helicopters and mechanics, the maintainability discipline [Ref 1] need to be considered in the design phase with a specific focus on operator ergonomics and human hazards. The integration of ergonomics in the design process has been recently formalized and standardized [Ref 2] by the use of digital simulation tools. Maintainability is defined [Ref 3] as the ability of an item under given conditions of use, to be retained in, or restored to a state in which it can perform a required function, when maintenance is performed under given conditions. In Aeronautics, one of the main contributors to maintainability is the ability to access all component candidates of a maintenance task.

2. STUDY CONTEXT

In order to minimize the risk of human hazards, maintainability studies need to be performed in the early phase of helicopter development before the design freeze.

Different methods and tools are available to verify and validate the design of the helicopter for the maintenance tasks that will be performed by customers.

Simulations need to provide objective and realistic evidence to properly assess maintenance and Human Factors criteria. As maintainability is not the only criteria to consider, among weight, performance and other safety features, we need collaborative means to interact with other stakeholders in the development process and highlight key issues that need to be improved and also ensure representativeness of the work situation to make the correct decision.

- Digital Human Modeling (DHM) (Human Builder module in CATIA V5) [Ref 4]
- Virtual Reality (VR) with digital avatar [Ref 5]
- Physical Mock-up (PMU) with mechanics [Ref 6]
- Mixed Reality (MR or XR) using tangible interface, physical parts and force feedback [Ref 7]

We propose in the following paragraph to detail the current use of each simulation tool, more specifically in the maintainability context. DHM and VR have been deployed and used for a decade in maintainability, providing very good results and allowing a better integration of HF criteria [Ref 2]. For example, it is an easy and efficient way to simulate the maintenance task of checking oil level on the Tail

Gear Box of the Helicopter before the first flight of the day (figure 1). Giving specific constraints to the designers such as an inspection hole in the cowling including size, orientation and position and checking accessibility for a wide population base to ensure this task will be achievable safely with limited effort for the customers.

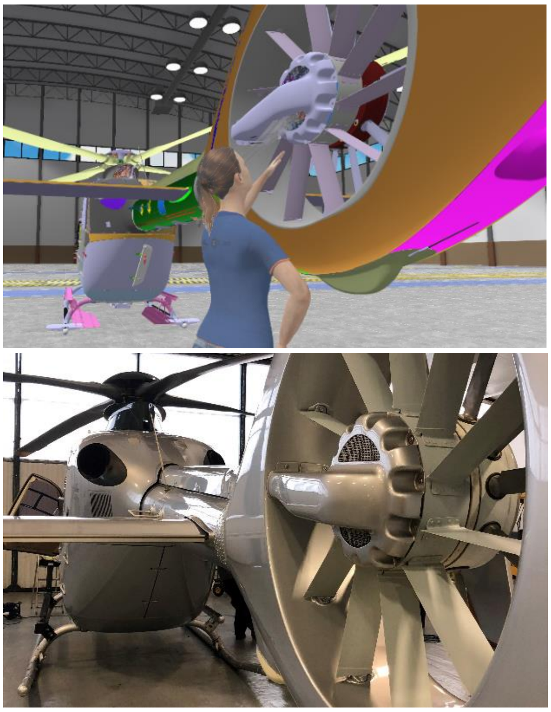

Figure 1 Tail gear box oil level check, from virtual simulation to real product to ensure maintenance feasibility

Nevertheless, there is still the need to validate some hypothesis on a physical mock-up for specific topics that cannot be simulated digitally for several reasons [Ref 18], among others:

- Complexity of the topic, depending on the number of physical interaction(s) with the environment that cannot be simulated in VR easily.
- Nature of the task with vertical motion of the operator that could endanger its safety (figure 2).

Figure 2 limits of Virtual Reality for complex use case involving vertical movement of the operator

Finally, even if solutions exist to overcome those limits in simulation tools such as a haptic device or tangible interfaces [Ref 9], DHM and VR requires special training and skills to perform such simulations and are less adapted to collaborative sessions without several VR headsets [Ref 10].

PMU provides tangible interfaces to the operator with real dimensions, mass and balance of fixed or moving components [Ref 6]. This allows assessing all the dimensions of ergonomics (physics, cognitive and organizational), [Ref 8] if weight is added to the mock-up and the overall mock-up is representative of real environment [Ref 11].

Physical Mock-up (PMU) are frequently built in the Helicopters development process to review some key mission capacities in the cockpit, cabin and to verify some manufacturing or maintenance topics [Ref 12].

The previous example mentioned the simulation of vertical motion for assessing accessibility to the rotor area of the helicopter for the daily check this is generally performed on a wooden mockup (figure 3) during the early phase of the design.

Figure 3 Helicopter Physical Mock-up in development phase

PMU generally does not require any training for the operators to perform HF assessment. The operator only requires a briefing for the purpose of the simulation and safety measure regarding risk of injury and work at height rules.

Nevertheless, the Physical Mock-up requires long time to manufacture and it is complex to modify if a change is identified during a simulation or through the design phase [Ref 7].

Using PMU also requires special care to ensure representativeness for its targeted purpose, as it requires a significant lead-time for its manufacturing (between 2 weeks for a small area to 3 months for a complete area of a helicopter). Details of the mock-up (e.g. harness, connectors, and small items) can be missing compared to the DMU due to a manufacturing limitation or if the DMU is updated [Ref 7].

For these reasons, AR have been identified as a potential solution to overcome the limits of existing simulation tools.

When using Augmented Reality, a digital layer is superimposed onto the physical world, integrating the physical, real environment with virtual elements to enhance or "augment" the real-world experience [Ref 13].

This experience can be done with smartphones, tablets, smart glasses and other head-mounted displays [Ref 14]. For a maintenance simulation use case, the use of smart glasses or head-mounted displays are adapted to provide the user a scale view of the model with the ability to interact with its hand and body in the virtual environment. The following figure shows the operator able to move and interact with a 3D model of a helicopter in the nose avionic bay to assess maintenance feasibility (figure 4).

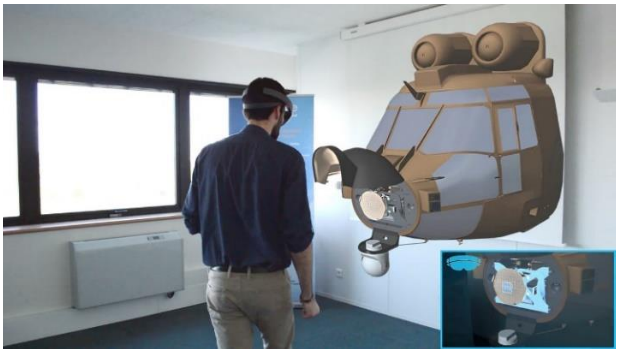

Figure 4 Augmented Reality simulation

Since a few years now, Augmented Reality devices have been evaluated and deployed in the aeronautics industry [Ref 15].

AR devices are deployed in multiple areas for different use case types:

- Providing instructions on the floor shop for manufacturing or maintenance [Ref 16].
- Perform design review of a modified system on an existing physical aircraft [Ref 17].
- Remote assistance for customers or operators located in a different location [Ref 18]
- Sales and marketing demonstration to improve product perception [Ref 19].

The interaction capability of the AR device is different than with a VR set-up due to the absence of controllers. It relies mainly on standard hand gestures (pinch, grasp, push, swipe) limiting sometimes the complexity and precision of the inputs. Nevertheless, it provide an easy solution for both engineers and workers giving a highly collaborative perspective (figure 5).

Figure 5 Mixed Reality using Augmented Reality on aircraft

A key advantage of AR usage in the frame of the design phase is the ability to invite several stakeholders and share the same understanding of a design and work situation in a collaborative mindset (figure 6). [Ref 20]

This innovative approach is in line with the new way of working deployed in many industries in recent years. [Ref 21]

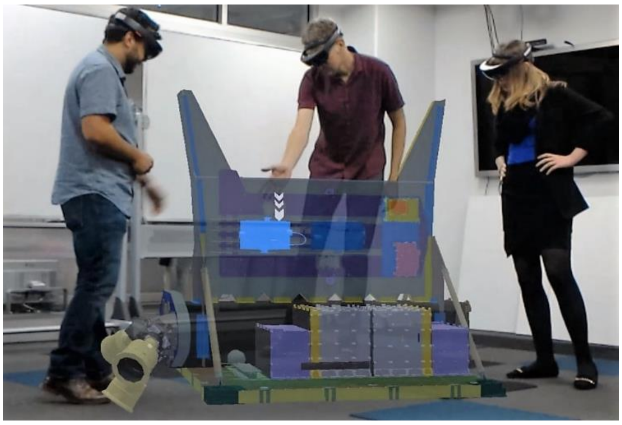

Figure 6 Collaboration review using Augmented Reality device

In the frame of a new development project, we had to specify, verify and validate a stepping concept definition to allow the access to the engine and rotor area of a helicopter during a preflight check.

This maintenance function allows the mechanics and flight crew to perform any daily check or servicing tasks on the aircraft using integrated handles and footsteps on the helicopter without the need of external access means. Our hypothesis will be to explore the usage benefit of Augmented Reality to complete a simplified physical mock-up in order to assess ergonomic and Human Factors criteria for maintenance tasks.

3. OBSERVATION

3.1. Method

As we have developed previously, the constraints of this project does not allow to use former simulation means such as a complete physical mock-up of the helicopter to assess the accessibility and Human Factors criteria.

Cost and delay to build such a detailed mock-up are not compliant with the planning of the development. Moreover, we have seen the limit of such physical mock-ups such as small details that cannot be reproduced with a good representation and up to date with the latest design status.

To overcome the limits and constrains of the project identified in the existing validation and verification means, the combination of AR and PMU has been assessed to respect delay constraints with a higher representation of the simulation. This simulation will have to respect a rigorous protocol with a representative sample of the world population, with appropriate skills and observing objective criteria regarding ergonomic, performance and safety.

3.2. Participants

The participants have been selected for their anthropometric characteristics to get a representative sampling of the real population. The experience of the participant have also been considered to involve maintenance mechanics knowing the tasks that will be simulated on a similar helicopter type.

Some of them are working in the prototype shop on a similar helicopter type and regularly perform these tasks. We had sixteen participants of 42(±7.8) years old, and an average stature of 179(±6.8) centimeters.

3.3. Means

An existing physical Mock-up of the cabin layout has been adapted for the purpose of our simulation.

Additional handles and steps have been added to the external surface based on the characteristics of the preliminary design proposal. To complete the physical mock-up with all necessary systems such as rotor, flight controls, drive system, engine and cowlings, an extract of the digital mock-up has been done using the Augmented Reality kit. The augmented reality kit allows perfect alignment of both the digital and physical parts, allowing the operators to perform a simulation with the same accuracy and performance as on a real helicopter (figure 7).

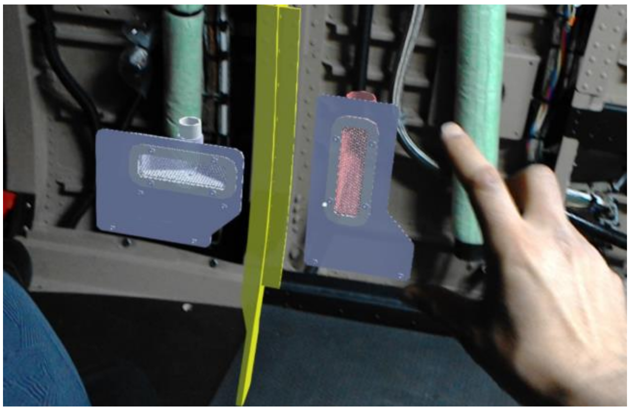

Figure 7 Augmented Reality user positioning 3D model on a mock-up

2 AR device where available:

- 1 for the operator doing the access and inspection check: seeing the 3D part overlaid over the PMU.
- 1 for the ergonomic specialist to assess HF criteria, being able to move around the operator and talking with him about precise and detailed technical topics (ease of access, need to change the design, risk of injury or safety concerns)

In addition to this AR set-up, an external large TV screen was connected to the AR device held by the operator, giving the rest of the audience a better understanding of the operator's point of view. Indeed, different stakeholders from the helicopter design office were invited to this simulation as a collaborative design review.

The protocol is based on the following aspect:

- 16 participants including mechanics familiar with the daily check on similar helicopters ;
- A preliminary survey to collect participant background and anthropometric size ;
- A check-list to be filled by each participant during the simulation for all inspection areas and associated step/handle positions to collect direct feedback and observe behavior ;
- A final survey to assess global participant performance and their feelings about safety ;
- Cameras were used from different points of view to evaluate posture and accessibility ;
- Augmented Reality was used to complete the wood mock-up for representativeness of the study.

3.4. Process

Participants were invited in small groups of 5-6 people over the course of several days to ease the observation for both mechanics and Human Factors specialist. A safety briefing and introduction to the test with the context of the study was performed to avoid any accidents and ensure the understanding of the goals of the simulation. Then they have completed the preliminary survey to ensure the population representativeness. The observation was then performed by a Human Factor specialist whose task was assessing with each operator the different objective criteria and collecting additional remarks such as balance and performance level. Pictures and video were taken during the entire simulation to enable data post-treatment. The two augmented reality kits were provided to the operator and Human Factor specialist for the simulation with a live streaming on a large screen beside the mock-up for all other participants.

We have taken the existing maintenance task for a preflight on a similar helicopter as a reference for our study (Fig 8).

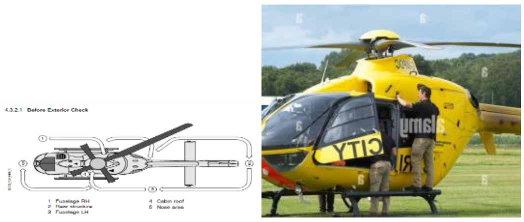

Figure 8 Extract of helicopter preflight check

All areas to be inspected and sequence of the tasks where shown and described to all participants before starting the test. This description included a detail of the steps and handles available to ensure a homogenous understanding among all attendance (figure 9).

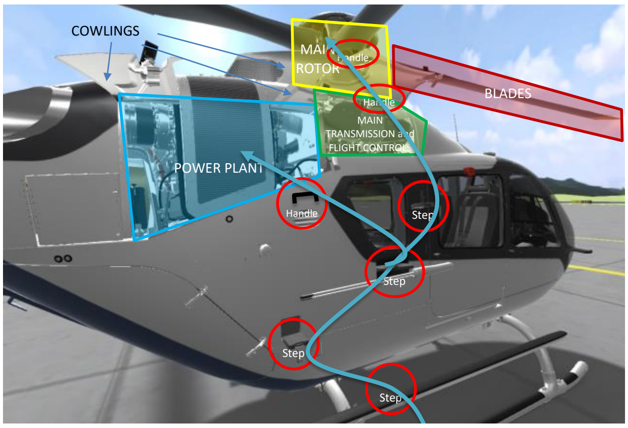

Figure 9 example of Helicopter system and access means

3.5. Observed indicators

Participants will have to complete a preliminary survey to collect their anthropometric data and experience back-ground. During the observation, they are asked to verbalize their perception related to the physical and visual access, balance and safety risks. At the end of the observation, each participant will then complete a final survey to get the overall result of their performance to achieve the task on selected indicators and based on a Likert scale [Ref 22]:

- This task can be done easily with a flashlight and a soft rag in hands
- I am satisfied to fulfill the task properly
- I was able to conduct the access safely
- The condition to perform inspection is safe
- The access position and posture and movement comfortable

During the observation, a Human Factors specialist will identify all risks related to worker safety and potential errors that could lead to a catastrophic consequence for the helicopter using a Cox Matrix [Ref 23]. Any remarks and comments of the participants are also recorded at each step of the procedure; picture and video recording will also help to further detailed analysis:

- Step description and area of inspection
- Ergonomic criteria (Physical and Organizational) with associated indicators (dimensions)

Those indicators and the observed criteria have been assessed using a hybrid mock-up mixing PMU and AR and results are similar to a real helicopter simulation.

4. RESULTS

Three aspect where raised by this experiment:

- Identification of recommendations with objective criteria based on a representative population
- Provide collaborative tools to discuss these recommendations with stake holders
- Reduce lead time to provide our recommendations and improve the confidence level of the simulation

More than 15 participants could attend to the test campaign, 1/3 of them were mechanics involved in daily checks on similar helicopter types and they could reproduce what they do in real situations. The others participants were stakeholders in the project without preliminary experience in an operational maintenance activity, they discovered for the first time how to access and perform inspections on the helicopter. Participant size were almost conform to the initially expected targeted population. We initially identified the need to cover the widest part of the world population, starting from the 5th female percentile to 95th male percentile (French population considered). Smallest operator was 164cm and the tallest operator was 191cm, which is considered as acceptable for our study. Participants have never used AR device before.

Having such a representative population for this test allows strengthening the result of the study. We have identified several design improvements to increase human performance and reduce hazards.

- Reduce distance between 2nd and 3rd step for small operators
- Improve design of 1st Handle to step on it for all operators
- Add a new handle to reach rotor area for all operators

The figure 10 shows an example of helicopter and access means improvement (compared to the figure 9).

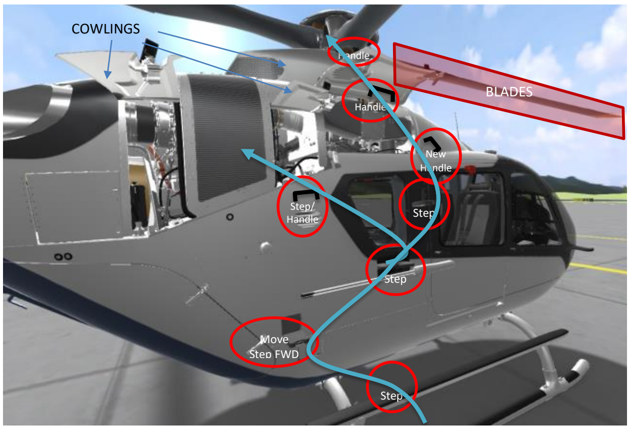

Figure 10 example of Helicopter system and access means

Main outcome shows a uniformity of the feedbacks and need for design improvements. Small operators faced issues to move from 2nd to 3rd step, due to the distance that is too far compared to their anthropometric data. All operators have clearly identified the need to improve the 1st handle to allow stepping on it while accessing the rotor area, criteria raised for this improvement were comfort and balance issue.

The most important design change recommendation concern one additional handle identified based on the entire operator's behavior when grabbing an area of the wood mock-up that was not initially identified as a handle.

As this additional handle will have an impact on weight for the helicopter design, we need strong argumentation to ensure our recommendations are taken into account. We have then asked all operators to complete the final survey twice on the following criteria without and with this additional handle.

- This task can be done easily with a flashlight and a soft rag in hands
- I am satisfied to fulfill the task properly
- I was able to conduct the access safely
- The condition to perform inspection is safe
- The access position and posture and movement comfortable

An interpretation of the survey shows significant improvement in the safety and performance of the task (5 criteria of the final survey) when taking into account the additional handle (figure 11).

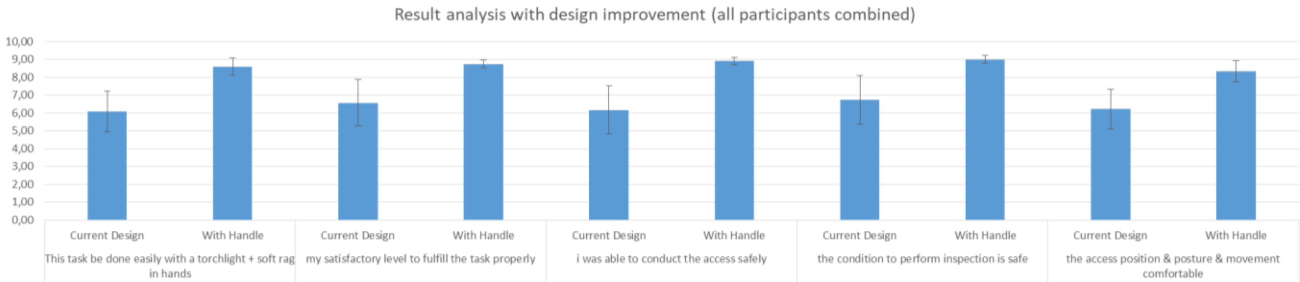

Figure 11 tendency of survey to compare improvement of worker safety with the introduction of a new access handle

This overall set-up was key to the collaborative aspect, giving every stakeholder of the project the same information at the same time and giving each operator and decision maker the same understanding of the issue, it means that if the decision maker was not able to understand an issue he could experiment the check by himself immediately. This feature is decisive for the success of such a project, and the integration of HF and maintainability consideration in the design process. Every stakeholders of this simulation and test campaign have shared the same conclusions and decisions to improve design on the aircraft have been agreed without any doubt.

Finally, the key success factor of this hybrid simulation was the lead time that allows such results, in less than 3 weeks we were able to achieve our goals instead of 2 or 3 months with a full scale and detailed mock-up. This aspect is essential to integrate our recommendations in the design.

5. DISCUSSION

This study was initiated to foster our efficiency and the quality of maintainability analysis while considering all dimensions of human factors in the design phase of a helicopter. We have identified the augmented reality as a potential complementary means to a physical mock-up for hybrid simulation of the stepping concept to perform daily check on the helicopter. A group of 16 operator's representative of world population has contributed to a robust protocol to assess their performance and identify potential risks. All recommendations were identified and discussed with the design office responsible based on the analysis of a human factors specialist.

- We have been able to provide design recommendations with objective criteria based on a representative population, thanks to a robust protocol built with Human Factors specialist to define the objective criteria for the observation. The participant list were selected for their qualification and anthropometric data to complete the protocol.

- The collaborative way of working using the hybrid mock-up helps to integrate these recommendations. The use of several Mixed Reality kits together combined with the Physical Mock-Up allowed us to increase the accuracy of the simulation and reach a common understanding of the situation, risks and recommendations required. Other studies already show the efficiency of collaborative dimensions in maintainability through augmented reality [24], but this kind of study does not take into account Human factors criteria.

- We have reduced the time to provide our recommendations to the design and improve the confidence level of the project compared to previous methodologies

Compared to previous verification and validation means (DHM, VR), the use of Mixed Reality combined to Physical Mock-Up has unlocked several barriers in the efficiency of our analysis process.

Simple Physical mock-up, without detail, can be quickly built at low cost providing only the tangible interface for the operators (main physical contacts). This lead time is a key in the aeronautic development process as several systems are designed in parallel and must be studied by the maintainability department in a limited amount of time [Ref 25]. Moreover, the design and architecture of the Helicopter is changing and evolving every day in the early phase of the development [26], to refine assumptions, consider all stakeholders and assess criteria for trade-offs [27].

The cost and lead-time to build a Physical Mock-up is directly related to the level of detail required. Indeed, reducing the cost of manufacturing process is also a key aspect to avoid continuous update of the Physical Mock-up to keep it align with Digital Mock-Up [2] or to perform trade-offs to compare two design solutions in the same simulation.

Rapid Manufacturing process have been improved in the last years (3D printing) and it can be used in our industrial context [28]. However, to reach a level of detail with all mechanical functionalities (moving parts, different colors for each system, harness and very small item) a huge effort is required for limited benefit. This state can be easily managed thanks to Augmented Reality. The 3D, providing all detail from the most recent Digital Mock-Up status model, is superimposed on the physical Mock-up during the simulation.

In accordance with the literature [29; 30], AR device have been developed by major digital company and user interface was one of the main criteria to ensure its success and acceptance level in all area from the office to the workshop. Augmented Reality device and software does not require intense training [31], control is done by pushing virtual buttons with fingers or grabbing a 3D hologram with the hand (figure 12).

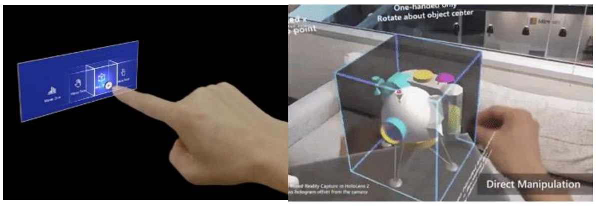

Figure 12 Augmented Reality user interfaces

But one of the main assets is the collaborative aspect. AR device allows several users to see the same data and discuss technical topics without the need to remove the device. All users are able to understand what the operator is doing and explaining via another AR device or by display on a large screen in the room. This ability to see the same data and other stakeholders ensure the success of the action plan defined in the simulation, none of the required change have been challenged after these sessions compared to previous experience in the past not using this new approach.

Limits of the study are identified in two categories:

- Representativeness of the simulation
- Capacity of the simulation tools

The population that could attend our simulation allows us to identify the main risks and provide recommendations, nevertheless they were not in operational working conditions with potential external influence on their performance such as time pressure, poor environmental condition (figure 13), fatigue or stress. Such factors are difficult to reproduce and the assumption taken was to keep optimal condition to allow proper comparison between each participant over time.

We also need to improve representativeness on the configuration of the aircraft, to show the cowlings opened or closed, to display potential optional equipment such as a hoist or search light that could affect accessibility.

Figure 13 real operating condition for daily check

Capacity of the simulation means have also shown some limits in this study.

Ability for the operator to interact with 3D model to simulate a removal/installation of a component or a cowling opening was not facilitated by the mixed reality device (figure 14).

Clash detection between operators and the 3D model where not possible to detect potential risk of injury.

The mixed reality devices used during that simulation were not fully connected together, requiring higher preparation time to perfectly align the 3D model on the mock-up on both mixed reality devices.

Finally, the last limit remained the physical mock-up that needed adaptation or modification to consider the potential recommendations, that will lead to additional delay to update and complete the study with a final check for verification of the performance.

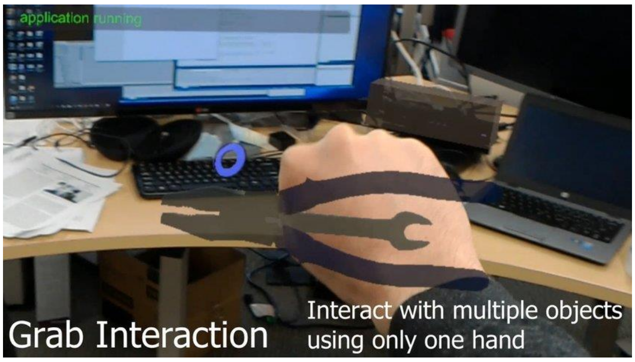

Figure 14 Limit of AR for object handling

Globally**,** this new approach has changed the way we collaborate in design office to assess maintainability and ergonomic criteria.

Perspective of the study can be grouped in two categories:

- Efficiency and accuracy of the analysis.
- Integration in a streamlined process to facilitate digital connection and iteration loop.

To improve the efficiency and accuracy of such a simulation, we could combine with the augmented reality kit a motion capture capability to track operator movement. This would provide to the human factors specialist a live analysis of the posture and allow a record of the activity to refine the ergonomic indicators. Such detailed results could ensure we comply with relevant ergonomic standards and reduce the risks for operator health and safety.

To improve the integration of such simulations in the design process, we could provide features in the augmented reality kit to interact with the digital mock-up and send those proposal back to the design office, ensuring a more accurate reporting and reducing loops to exchange with designers. The physical mock-up needs also to be easily reconfigurable to allow shortened iteration loops to reassess the criteria after recommendations are implemented.

6. CONCLUSION

The Aviation industry has since a few years entered in a new era of complex challenges. The market is evolving fast, competitiveness modifying industry leadership models, safety all becomes a priority, along with many other criteria. To cope with such various and contradictory constraints, industry needs to improve its productivity, efficiency, collaboration and raise its standards to a higher level. This is valid also in the maintainability department of the design office to consider maintenance in the development of a new helicopters.

We have identified limits of existing ways of working to perform maintenance simulation using the physical mock-up, digital mock-up or Virtual Reality. Even if they still provide value individually, we have proposed a new approach to combine simplified physical mock-up to augmented reality in the frame of an accessibility check for daily inspection of a helicopter.

Using a robust protocol combining representative population and objective ergonomic and human factors criteria, leaded by a human factors specialist and supported by a simplified wood mock-up build in a couple of week, we have assess the value of the augmented reality to complete the simulation with all detail of the digital mock-up. This collaborative session between operators, human factors specialist and designers allows us to validate the design and identify potential risk and mitigation with a higher accuracy, reduce lead-time and cost with a better confidence between each stakeholders.

The limits of the study have been identified to work on method and tool improvement and perspectives have been discussed to prepare a safer helicopter maintenance operation future.

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