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Maturity-based taxonomy of extended reality technologies in aircraft lifecycle

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Abstract. EXtended Reality (XR) is a fast growing and rapidly evolving technology. In the aeronautical sector, XR can be exploited for the entire aircraft lifecycle, however, different levels of maturity can be identified for applications in each one of the lifecycle's phases. This paper, by outlining the TRL of current XR applications over the aircraft lifecycle, aims to be a foundation to identify the possible future improvements and applications of immersive technologies in the aeronautical sector.

Introduction

EXtended Reality (XR) is a fast growing and rapidly evolving technology, a comprehensive term given to all computer-generated environments that either merge the physical and the virtual worlds or create an entirely immersive experience for the user. Even if XR technologies such as Virtual (VR) and Augmented Reality (AR) have already reached maturity as they are considered mainstream for a few domains of application, in the aeronautical sector this is not yet entirely true. XR can be exploited for the entire aircraft lifecycle, however, different levels of maturity can be identified for applications in each one of the lifecycle's phases (Figure 1).

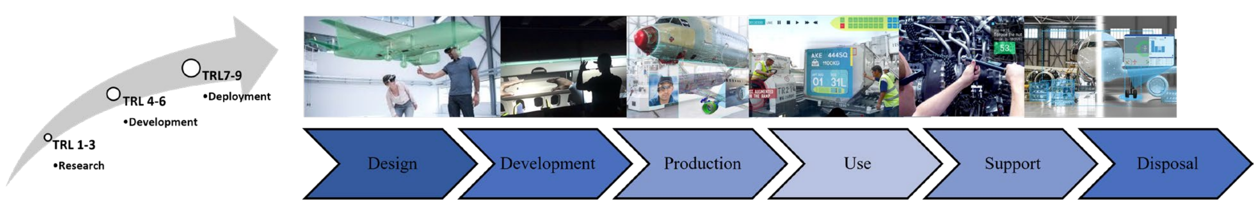

Figure 1: Aircraft lifecycle's phases and Technology Readiness Level (TRL).

This paper, by outlining the TRL of current XR applications over the aircraft lifecycle, aims to be a foundation to identify the possible future improvements and applications of immersive technologies in the aeronautical sector.

Extended Reality in Aircraft Lifecycle

Extended Reality technologies can find a number of applications in aeronautics. Synthetic visualisation and multimodal interaction tools target almost all aircraft lifecycle phases. From design to manufacturing and maintenance, passing through training and operations [1] and since the early stages of industrialisation, the main aeronautical companies are relying on those technologies [2].

Figure 2: Industry-first concept based on Mixed Reality technologies for Cabin Customisation and Design for the A320 Family (courtesy of Airbus[1]).

In the design and development phases, rather mature applications are established in the field of synthetic visualization which allow for a better understanding of the performance achieved by a certain design solution[2]. Furthermore, XR has proven to be beneficial for collaborative design, design reviews and user assessment throughout the product development process [3]. This application is still in the early stages of research, begin now developed as a proof of concept [4]. One of the biggest opportunities provided by XR is the one of including user feedback in the design process, as proved in a study conducted to virtually test the comfort of newly conceived aircraft cabin designs. Not only the project exploited V/AR technology to validate the proposed design approach and strategy in the design of aircraft cabins, but it demonstrated how XR can be a useful tool, starting from the very early stages, to the entire process which results to be more open and flexible, time efficient and cost-effective [5]. As a matter of fact, early stages of design, when prototypes are still in the digital phase, are ideal for leveraging eXtended Reality technologies. Recent research[3,4] [6], makes use of advanced VR technologies to enable the different stakeholders to experience and be immersed in the full scale design, allowing them to be involved in the process starting from the Inspiration and Ideation Phase [7-8].

In view of the production phase, a number of applications are developed within the framework of Industry 4.0 which aim at exploiting XR to make aircraft systems production and final assembly more efficient in terms of time, quality and dependability. In particular, if VR is mainly applied during the design phase, AR is mostly used in the production line. The usage of synthetic visualisation tools leading to early detection of non-conformities allows not only to avoid expensive corrections but also to improve the quality control process and reduce inspection time. Nevertheless, users' familiarity and training with the specific devices and technology are crucial aspects and must be considered to achieve the best possible results [9].

Airbus, among other companies such as Boeing and Embraer, foresaw the potential and applicability of digital technologies since the early 2000s, and in 2009 the European company collaborated to create an AR solution (*MiRA - Mixed Reality Application*) consisting of a tablet PC and related sensor pack to scan parts and detect errors. On the A380 MiRA allowed to check 80.000 brackets in the fuselage reducing the time needed from weeks to hours and the late discovery of mispositioned or damaged brackets by 40% [10]. Currently, Airbus is industrializing a first application to be deployed across various sites either to help with the drilling and fitting of brackets or to support quality control activities[1].

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1 https://www.airbus.com/en/newsroom/stories/2023-06-mixed-reality-to-meet-future-challenges
2 https://www.holoforge.io/en/project/safran-marketing/
3 https://www.dlr.de/as/en/desktopdefault.aspx/tabid-18135/28809_read-74794/
4 https://www.dlr.de/en/images/2020/1/indicad-fuselage-designs-for-the-future

AR devices such as head-mounted displays, can be used not only to assist the assembly procedure, but also for communication purposes in human-autonomy system teams as proved by a recent research in which the hybrid team has to rivet stringers onto a fuselage [11]. Hazardous and physically demanding tasks were assigned to the mobile robotic system, while the human workers performed tasks requiring experience, knowledge and multi-sensory sensitivity.

The operational environment is benefiting a lot from the application of XR, both in training and real-life operations. One of the first applications of Augmented Reality is the cockpit head-up display (HUD), which enables the pilot to get synthetic information collimated with the real view (Figure 3). This is the only optical-based XR application that already reached complete maturity in the aeronautical sector.

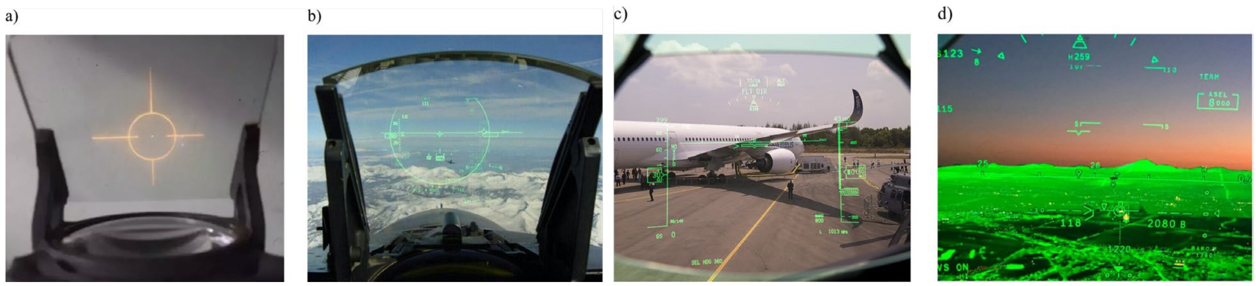

Figure 3: Technological advancement of the cockpit HUD [14].

More recently, different research projects explored a similar operational concept applied to airport control towers [12-13] reaching the development phase. The projects demonstrated how XR technologies in control towers are beneficial for the situational awareness of the controllers especially when the aerodrome is affected by low visibility conditions. The capability to make degraded visual information visible during low visibility and low-altitude operations given by XR can also enhance spatial awareness and safety during low visibility helicopters or ground operations [14-16]. Furthermore, ground operations are good candidates for technical solutions that make use of XR technologies.

Moving on to the support phase, a few quite mature applications of XR in maintenance, [17] inspection and repair operations are possible to identify. In 2015, Boeing adopted AR technology to reduce the impact of assembly harness errors. In 2017, General Electric used AR technology to communicate to mechanics whether they are properly tightening and sealing jet engine B-Nuts, and the working efficiency increased by 8-12% [18]. Maintenance is of paramount importance in the aviation industry therefore inspection and maintenance personnel have to be trained with appropriate tools. Training methods need to keep up with advanced technologies while ensuring safety and cost-effectiveness. Exploiting eXtended Reality as a training tool can overcome this issue providing a safe learning environment drastically reducing the risks that may occur during training with reduced costs, and improving labor efficiency [19].

The presented immersive technologies solutions are only a few of the numerous ones already available in the aeronautical sector. The proposed preliminary assessment of maturity-based taxonomy of XR technologies in aircraft lifecycle (Table 1) aims to serve as a base to identify the future possible improvements and applications of these technologies in the aircraft lifecycle. Furthermore, serves as a useful tool in understanding and addressing the number of challenges, ranging from technology to human factors, the aeronautical sector will face while maturing XR solutions in specific phases of aircraft lifecycle.

Table 1: Preliminary taxonomy assessment of XR technologies in aircraft lifecycle.

Lifecycle Phase		Taxonomy assessment		Reference
Design & Development	Scientific visualisation	Development	TRL 4-6	^2
	Collaborative design	Research	TRL 1-3	[3-4]
	Human-centered design	Research	TRL 1-3	[5-8] - ^3-4
Production	Assembly	Deployment Development	TRL 7-9 TRL 4-6	[9-10] ^1
	Human-autonomy teaming	Research	TRL 1-3	[11]
Operation	Cockpit HUD	Deployment	TRL 7-9	[14]
	Airport Control Tower	Research	TRL 3	[12-13]
	Ground Operations	Development	TRL 4-6	[14-16]
Support	Maintenance	Deployment	TRL 7-9	[17-19]
	Digital Twin interaction	Research	TRL 1-3	[20]

Conclusions

As a matter of fact, most of the presented solutions may reach maturity in the next 20 years. The vision is that, in the future, XR will be an extension of the human senses necessary to understand, interact, control, and command complex systems belonging to the digital era.

In the context of aeronautics, a more advanced level of development would regard XR as a means to visualize and interact with digital twins throughout the entire aircraft lifecycle [20]. EXtended Reality will be the technical enabler to interact with such systems that will be more autonomous and enhanced by artificial intelligence. Nevertheless, a number of challenges and barriers are still limiting the evolution of such technology in aeronautics, making its development slower than expected. XR still relies on cumbersome equipment, previous attempts to overcome this obstacle have proven unsuccessful. Incremental improvements are being made to enhance the wearability of hardware. Additionally, more automated solutions are needed to fully exploit the potential of such technology. Whilst a few Mixed Reality devices are already mainstream, non-intrusive solutions are not mature enough. The cost of equipment along with some big company trends are also acting as barriers to the deployment of business solutions based on XR technology. Although Industry 4.0 was expected to boost XR growth, it has also introduced some standardization issues in a number of application domains. Lastly, human factors and user acceptance are considered among the main risks for eXtended Reality massive use in safety-critical environments.

A maturity-based taxonomy of immersive technologies aims to be a tool to understand and overcome the number of challenges, ranging from technology to human factors, the aeronautical sector will face while maturing XR solutions in specific phases of aircraft lifecycle.

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