CLASSIFICATION OF EXTENDED REALITY BASED HUMAN MACHINE INTERFACES SCENARIOS FOR URBAN AIR MOBILITY

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Abstract

Uban Air Mobility is a new concept of air transportation system that include platforms with different specifications, mainly vertical take-off and landing vehicles, aiming to transport goods and people within urban settings by alternatively managing traffic in congested ground mobility. To ensure the operability of Urban air Mobility, some challenges and objectives in terms of public acceptance and effective design of operational scenarios still need to be achieved before its full integration and deployment. Extended Reality technologies can contribute to the successful realization of these goals as they offer immersive human-machine interfaces that can improve the implementation of such innovative transportation systems. This paper explores Extended Reality-based scenarios and their potential applications for Urban Air Mobility within the framework of the Reality Virtuality Continuum and end user of Urban Air Mobility are elicited. The most promising applications of the proposed approach are discussed, focusing on the main feature that can be enhanced though the adoption of Extended Reality-based technologies.

Keywords: Sustainable Mobility, UAM, U-space services, UTM, XR.

1. Introduction

In recent years, urban context has experienced an increase in its population and traditional terrestrial commuting has been facing some congestion impasses. Mobility is, therefore, promoted along the third dimension and Urban Air Mobility (UAM) is the subset of Advanced Air Mobility (AAM) solutions operating at a very low level to guarantee a new safe, secure and more sustainable cargo and passenger air transportation system in urban environments [1]. Particularly in the Italian airspace, electric Vertical Take-Off and Landing aircraft (eVTOL) – the most promising vehicles of this new aerial mobility – operations are expected to become real in 2024 [2]. First air taxi services in the city of Rome are expected to be activated by the end of 2024 so to make the service available during the Jubilee year [3][4]. However, in order to fully integrate new mission profiles in everyday life some operational conditions such as public acceptance, safety and security assurance, regulatory bodies' assessment, route identification and integration with local traffic and network still need to be met [5]. In this context, Extended Reality (XR) technologies outstand as enabling technologies that are potentially capable of boosting the development and deployment of such complex systems by forecasting and foreseeing potential future UAM scenarios [6].

In fact, seamless integration of advanced Unmanned Aerial Systems (UASs) in civil aerospace for UAM applications needs the development of specific solutions to guarantee adequate reliability and robustness levels. The application of XR Technologies can support, for example, the design process of the new UAM concept for systems and procedures as well as the operative state for different end-users. Considering the new concept design, the requirements definition of the so-called *vertiports*, i.e. properly designed infrastructures for safe take-off and landing operations of the new concept aircraft, can be preliminary validated including simulated data in an interactive Human Machine Interface (HMI) to allow a more efficient and effective design process.

With respect to the operative state, both strategic and tactical phases must be evaluated to define the main application fields. Specifically, the strategic phase can be supported by developing adequate scenarios for mission planning purposes. On the other hand, the tactical phase can be aided by including critical flight parameters information in the displayed environment. The operative state can also be improved by introducing advanced risk assessment procedures thanks to XR Technologies that allow for more intuitive and efficient management of contingencies. Moreover, the integration with traditional Air Traffic Management (ATM) must be evaluated to reduce the impact on the traditional system.

In the UAM context, several end-users can be identified, such as UAS operator, UAS remote pilot, ATM specialists, UAM passengers and uninvolved people. The specific need of the mentioned users must be analyzed in order to identify the best strategy to be applied according to the presented Reality-Virtuality continuum. To fully exploit the advantages of XR Technologies, a systematic classification of scenarios that can be adapted to different states of UAM operations and to different users must be developed, together with the expected benefit for each case and each user.

To this aim, this paper proposed a taxonomy of the so called XR-UAM scenarios founded on the theory of the Reality-Virtuality Continuum theory followed by considerations on Extended Reality Technologies and the classification proposed by the authors. Subsequently, a set of scenarios are analyzed and discussed, and some potential applications and end-users are suggested.

2. The Reality-Virtuality Continuum

The concept of Reality-Virtuality was firstly introduced by Milgram and Kishino and sustains that reality and virtuality are not two separated entities but rather opposite ends of a continuum, as reported in Fig.1. In one side of the spectrum there are fully modelled environments called Virtual Environments (VEs), consisting solely of virtual content where users have no contact to real worlds. Opposed to it, there are Real Environments (REs) or rather any sort of model environment not computer generated [7]. In between these two extremes, real and virtual worlds are mixed and categorized under a broader term called Mixed Reality (MR). Covered by this category lies Augmented Reality (AR), when real world has somehow been enhanced by means of superimposed computer graphics and also Augmented Virtuality (AV), when the enhancement of virtually generated worlds is done through real components.

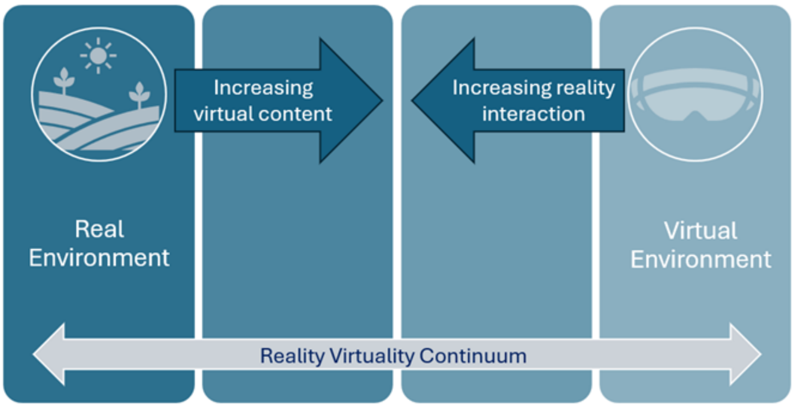

Fig. 1 Simplified illustration of the Reality-Virtuality Continuum framework, adapted from Milgram [7].

However, one dimension is not enough to distinguish Augmented Reality from Augmented Virtuality. In his taxonomy to mix real and virtual worlds, Milgram sustains that a three-dimensional framework is, therefore, required. The environment – to which he called hyperspace – contains three different properties:

- Reality: it refers to whether the environment is actually real or virtual.
- Immersion: this property is related to how the environment is displayed to the user. It refers to whether subjects need to be immersed in the displayed environment or not.
- Directness: this property considers how the world is viewed by the user; if it is viewed directly

or synthetically, through screens or head-mounted displays.

While the RV Continuum stands as a unique framework for synthetic environments visualization, its actual implementation is based on the hardware devices and systems that are available on the market and/or under development. Lighter and higher-performance devices are being developed in a rapidly growing market. Besides their maturity level, such devices may be classified as head attached, hand-held or screen projection based. The head attached displays are also known as Head Mounted Displays (HMDs) and they can be totally immersive or allow for an overlapping of virtual content onto the real content that is captured by a camera, in the case of optical see through or directly combined onto the real view, in the case of optical see-through displays. The video-based combination is also implemented on hand held devices and is very popular as a huge number of Augmented Reality applications for tablets and smartphones have been developed. Finally, the projection-based displays detach de display technology from the user's body [8]. The most popular system is the Cave Automatic Virtual Environment (CAVE), which is a system based on the projection of the scene onto a variable number of screen, usually three or four, arranged as a large box within users can interact with real scale models.

The location of any environment -or any world- along the RV Continuum must coincide with another location along a parallel continuum called the Extend of the World Knowledge (EWK) as reported in Fig.2. The latter spectrum, in its turn, relates along a continuous scale how much is known about the world being displayed. In one end, fully modelled worlds lie, in which everything is known about them and opposed to it there unmodelled worlds, conditions in which nothing is known about what is displayed. In the range in between these two extremes the world is partially modelled, that is, virtual and real contents are merged within the same display and in order to somehow augment what is being visualized it is needed to know exactly *what* this object is, e.g. dimension, and *where* it is location, e.g. orientation, in the real world [8]. Objects contained inside world belonging to the left end of the continuum, thus, belonging to unmodelled worlds, can be viewed directly in see-through displays.

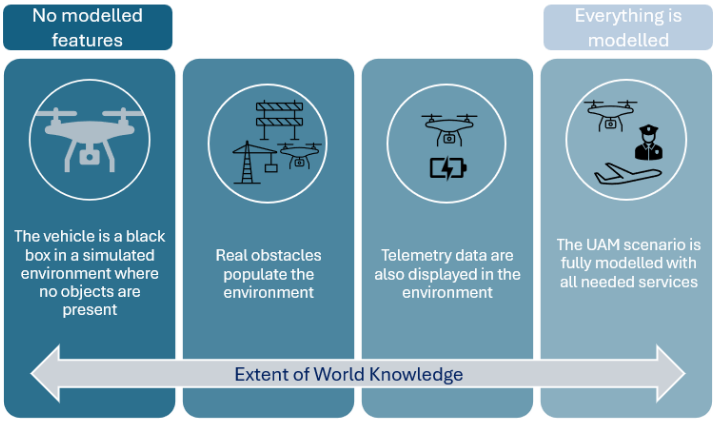

Fig. 2 Extend of the World Knowledge (EWK) spectrum adapted from Milgram [9].

A further axis of Milgram's classification was called Reproduction Fidelity (RF) and is related to the image quality of the objects being displayed for both real and virtual objects. As one moves to the right within the RF continuum, displayed computer graphics should be indistinguishable from viewing reality directly. Moreover, Milgram argues that in some see-through situations the viewer can be already immersed in the real environment but may be provided with only relatively low-quality visual aids called holograms. In addition to the correlation between the ability to blend additional visual information to real worlds (and vise-versa) on the fidelity of both what is being displayed on the environment.

The last proposed axis is called Extend of Presence Metaphor (EPM) and it refers to the extent to which the observer is intended to feel present within the displayed scene. In the far left, there are monitor-based human-machine interfaces and within those HMIs the sense of presence is poor, since the user experience is not of immersive type. As one moves along the EPM continuum this perceived level of immersion increases, until sensations are ideally no different from those of unmediated reality [9].

Usually in the real world, an unknown situation where the modelled environment cannot be developed, the interaction between humans and machines is made via traditional input devices such as computer keyboards, screens and remote controls. Instead, moving along the Continuum, HMIs are elevated to higher degree technologies capable of more advanced interaction techniques, reaching the opposite extreme in which all the information about the displayed world is available. Only recently the Extended Reality term has been introduced as a macro-term encompassing Virtual Reality, Augmented Reality and Mixed Reality and any other technology that can still be developed situated at any point in the RV Continuum and works by enabling users to exploit immersive and interactive environments reported in Fig.3. These innovative solutions have paved the way toward advanced HMIs since they build the gap between humans and machines allowing for more intuitive and seamless interaction with digital content [10].

Fig. 3 Extended Reality Technologies as an umbrella term encompassing all immersive technologies.

3. XR – UAM Scenarios Taxonomy

The aim of this section is to provide a classification of Extended Reality-based Human Machine Interfaces of Urban Air Mobility scenarios within the framework of the Reality-Virtuality Continuum theory. As described in the previous section, in every XR application what is experienced by the users is composed of a modelled world component and of an unmodelled world component. Such components are combined depending on the EWK of the single scenario. The modelled world in UAM applications may be the set of three-dimensional assets replicating those contained in a typical urban environment such as streets, construction sites, vegetation and topography data. For simplification reasons, it will be called the environment or urban environment, and it refers to the location where the UAM mission is expected to take place. In addition to the environment asset, a three-dimensional model of one or more electric eVTOLs -commonly referred to as drones- will also be presented and its flying trajectory is also considered. The source and the transmission mode of trajectory-related data can be defined according to one of the following items:

- Simulated flight trajectory data: the flying vehicle will follow an entirely simulated path that can be created based on existing records or on a mix of simulations with recorded flight data.
- Real flight recorded telemetry data: the obtained trajectory is a trajectory that was executed in the real world, and it is available by means of recorded telemetry data.
- Real-time telemetry: the flight will thus be real-time updates and the aircraft will then fly along a real time path, unless there is any sort of communication delay.

In addition to the replica of real-world components, in XR applications the scenario can be populated by a layer of information displayed through the specific device. Such layer is populated with computer generated data, in form of alphanumeric strings or specifically designed graphics, such as arrows or other geometries, to provide information with the aim of supporting the user in performing operations or in decision making. Such a layer is usually referred to as *Overlay layer* and must be designed considering the entire spectrum of the human factors dimensions to allow a safe and respectful interaction of the operator with the system. Overlays may be displayed onto the screen maintaining a static position in the viewport, for example the battery level displayed at the bottom of the screen or may need to maintain a certain position with respect to the object in the scene, for instance a flight tag attached to a flying obstacle that displays information related to the object. Hence, we distinguish the registered from the not registered objects in the overlays. Moreover, the overlays will be designed depending on the position of the user with regards to the aircraft, since it may be egocentric, i.e. aligned to the pilot's point of view, or exocentric, i.e. located outside the aircraft. The overlay layer's layout depends on the specific scenario and data available. In Fig.4 some examples are provided in the framework of a generalized taxonomy for XR-UAM Scenario model.

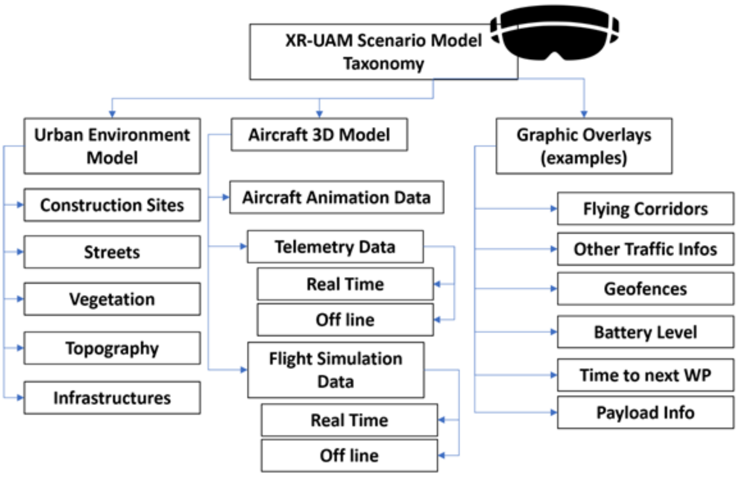

Fig. 4 Generalized overlays' taxonomy for XR-UAM Scenario model.

3.1 The *XR-UAM Continuum* concept

In previous sections it was introduced XR-based HMIs as Human Machine Interfaces that implement XR technologies realizing specific applications and each of such applications can be classified according to the VR-Continuum theory. Hence, each application conceived for this purpose can be located closer to one or the other extreme point of the continuum according to the ratio of synthetic content on real perceived environment. Applying this theory to UAM Scenarios one can move along the continuum depending on the Extend of the World Knowledge of the environment and on the specific requirement that, in this case, are related to safety of the operations of user requirements. For instance, considering an application aiming at training an UAS operator to perform specific tasks in urban environments, it can be designed to work in an immersive environment if a totally modelled urban environment is available or in a Mixed Reality environment where the operator manages a three-dimensional model of the aircraft in a real urban scenario. In both cases the level of safety is the same, but we may consider the advantages and drawbacks of the two approaches. In the first case, the operator can perform the exercises in any location, with no need for the trainer or trainee to be located at the exercise site. Moreover, not only the repeatability of exercises can be achieved by controlling the light and weather conditions, but also disruptive events can be simulated to increase the resilience of operators and train the operator to be prepares to non-nominal situations. On the contrary, if training sessions are performed in Mixed Reality environments, the trainee is physically located in the urban environment and therefore the level of presence is maximum. In order to include all the possible combinations of applications in a unique classification criterion, the XR-UAM concept is introduced as depicted in Fig.5.

The situation depicted in the far-left part of the XR-UAM Continuum corresponds to a totally real scenario in which UAS flight is executed in real environments. Such situations could be part of specific UAS flying routes or as part of a leg in a broader and more complex multi-modal urban transport scenario. With respect to the Extend of the World Knowledge, that region corresponds to the world being entirely unmodelled and nothing is, therefore, known, at computer level, about what is being perceived by the subjects. In these cases, the user perceives the world with their natural senses. We will refer to this XR-UAM type with the letter "a".

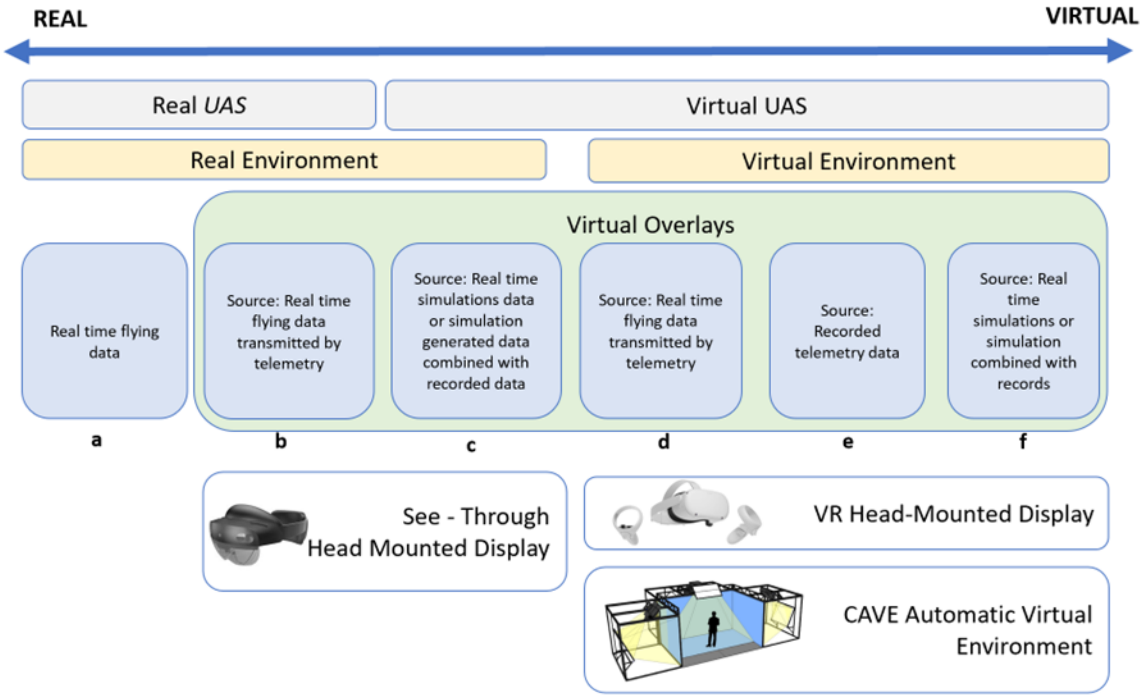

Fig. 5 The XR-UAM Continuum concept.

Moving towards the right side of the spectrum, aircraft and environment still exist and are physical but XR applications may be designed to superimpose a synthetic layer of overlays on such a real scenario. In this case, both the UAS and the environment positions must be known in order to manage the interface. We will refer to this XR-UAM type with the letter “b”. Considering that we are the region of the RV Continuum in which the world is partially modelled, what is known is thus the location or *where* that object is in the real world. In this scenario, human-machine interaction can be elevated to a more immersive interface by means of HMDs and this additional information is, therefore, visualized without completely obstructing the outside view. For example, in recent studies, see-through devices have been used in conventional aviation to provide air traffic controllers with additional overlayed flight information and it has proved to be an effectful solution towards digital control towers [11][12][13].

As the center of the RV continuum is reached the aircraft is now virtual. The environment, on the other hand, is still unmodelled and thus real and the trajectory followed by the aircraft is a combination involving simulated data, that is, somewhat virtual. We will refer to this XR-UAM type with letter “c”. Such situation provides ideal scenarios for drone operator training [14] and foster integration of current air traffic scenario with novel UAM. The next three potential scenario types provide the same combination of environment and UAS states and, since they are both virtual, what distinguishes them among themselves is the nature of the data sources for the overlays’ construction.

The XR-UA type “d” is animated by real time transmitted telemetry data, suggesting that even if the user is immersed in a fully virtual scenario the knowledge of the extend of the world related to the real time data illustrates a correspondent real aerial flight that is happening at some point in the real world. A possible application of such scenario could be remote control of sensed systems including remote digital towers or any sort of activities which require surveillance [15][16] or system controls by Digital Twins.

The XR-UAM of type “e” is still composed of the virtual UAS and virtual environment, but the trajectory followed by the aircraft is then recorded: it is not real-time updated but runs on recorded telemetry data. As a consequence, what is perceived about the real world by the user in this situation is, to some extent, real, considering the fact that the trajectory is a real one that had previously happened. This could be potentially used to either validate autonomous UAS flying trajectories and thus assess human's trust in artificial intelligence, one of the conditions of operations presented by EASA on its report on Urban Air Mobility or as an asset for improvement of Risk Analysis [17][18]. This XR-UAM type can be used to validate the developed concept with technology and investigate public acceptance. In the last XR-UAM type, type "f", at the right end of the continuum, both the environment and the aircraft are fully modelled, meaning that, to the computer, everything is known about those two objects such as the type and position. In this situation the trajectory followed by the aircraft can be created based on simulations or a combination of simulated data with recorded data: the knowledge of the real world is non existing, but it could potentially be used as a first step of new concept validation.

Table 1 summarizes the XR-UAM types identified along with the potential applications proposed and the type of XR-System-Device to be used.

Table 1 Scenarios classifications and their potential applications.

XR-UAM types	Potential applications	XR – System – Interface - Device
a	Real UAM operations; conducting experiments in real settings	No XR Systems implementation
b	Integrated Air Traffic Control Operators; Maintenance activities	See-Through Head Monted Device
c	Drone operation activities; supporting the integration of current air traffic scenario with simulated UAM	See-Through Head Monted Device
d	Remote Control Tower; surveillance activities	Virtual Reality Head- Mounted Device / CAVE (Cave Automatic Virtual Environment)
e	Validation of developed concept with technology; development of strategies to increase trust in Artificial Intelligence; Construction of studies on public acceptance; Visualization of risk analysis	Virtual Reality Head- Mounted Device / CAVE (Cave Automatic Virtual Environment)
f	First step of new concept validation	Virtual Reality Head- Mounted Device / CAVE (Cave Automatic Virtual Environment)

4. XR-UAM Continuum potential implementations

In the framework of MOST National Project on sustainable mobility, the state of the art of Italian UAM operations have been discussed and possible scenarios for XR-UAM Continuum have been identified. Such scenarios have been scouted with the aim of understanding the impact of such technology on the further development of UAM concepts and scenarios that are of interest at national level.

The first discussed scenario is related to passenger transport limited to a selected corridor to accelerate mobility and decongest on-ground wheeled traffic. An example of this mission is identified in the experiments conducted in the Rome Airport of Fiumicino in 2022 where the first crewed eVTOL test flights in Italian airspace has been performed [19]. Passenger services in this airport are expected to be delivered in the next future. Several potential XR-UAM applications could be considered, such as XR for the design of accession procedures, XR for the management of the vertiport itself in compliance with the regulations, XR for personnel training, XR for the support in the management of vertiports operations and XR for the coordination with ATC traffic.

Moreover, considering Unmanned Traffic Management (UTM) requirements, it could be necessary to control the connection area between two different vertiports. Several XR-UAM applications could support vertiport development and operations and training needs and in the management of vertiports. A Virtual Reality application (XR-UAM of type f) could support in the development of the vertiport's architecture and procedures and also in understanding the capability of the vertiport and UAS operators in maintaining the adequate level of situation awareness under specific design conditions. For the training phases, immersive reality simulations (XR-UAM type f) could be designed to train vertiport operators under different conditions. Furthermore, Mixed Reality interfaces (XR-UAM of types c, d or e) could foster familiarization with unknown environments. Finally, to manage vertiports type b interfaces could support in the control of vertiport areas by using overlays so to augment the comprehension of the situation in all weather and light conditions.

The second identified example discusses ad-hoc transport solutions for collective events, such as the need to develop efficient connections to serve the Milano Cortina during the Winter Olympics in 2026 [20]. In this case, different vertiports are foreseen along the route's pathway and an immersive interface would aid in the control of such airspace connection of such vertiports through a VR immersive interface for remote control (XR-UAM of type d), for example, from a Virtual Control Room.

The third analyzed scenario involves the use of the proposed XR-UAM concept to support a more sustainable air mobility. An immersive interface (XR-UAM of type f) for social acceptance can be supported by the visualization of the flying platforms to increase the consciousness of overflown uninvolved people. Consumption and noise related features can be properly simulated and displayed to developers to better achieve the environmental impact of the designed vehicles. Extended Reality solutions can improve the current state of the art of UAM platforms.

Finally, the last discussed scenario regards the use of XR-based Human Machine Interface for a multi-vehicle management system for the Last Mile delivery [21]. This solution can support challenging connections to transport goods and people to islands, such as from land to Procida isle in the south of Italy. The planning phase could be supported by Mixed Reality interface (types b and c) regarding an interactive visualization of flight data and risk level as the mission's boundary conditions change. During the control flight phase, on the other hand, a Virtual Reality scenario (type d) can be utilized to remote interaction of the mission's environment.

5. Conclusion

This study presents potential use-case scenarios to be exploited and simulated using XR Technologies to support Urban Air Mobility operations. The aim is to categorize such scenarios within the framework of the Reality-Virtuality continuum theory. A short discussion of the theoretical basis is provided, and the developed scenarios are contextualized, explained highlighting the most promising applications. The discussed scenarios aim to improve risk analysis, develop strategies to increase trust in artificial intelligence, apply remote control tower solutions and surveillance activities, aid traffic management and perform personnel training and drone operations. This study was produced as part of MOST – *Mobilità Sostenibile* national project and presents the discussion of XR-UAM Continuum concept in the state of the art of UAM activity. Possible applications of the concept include XR-UAM solutions to aid the development of vertiport architecture and also to assist as immersive interfaces during operator's training phases and procedures. Moreover, applications of different categories of XR-UAM are analyzed for virtual control towers, to support in the control of vertiport areas and interactive visualization of flight data. At the end, an additional XR-UAM category was identified to improve risk analysis operations and support virtual control rooms. Nevertheless, this paper contains the early steps towards the implementation of an Extended Reality - based Human Machine Interface for Urban Air Mobility applications.

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7. Copyright Statement

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