



EXTENDED REALITY IN AIRPORT CONTROL TOWERS: FROM CONCEPT DESIGN TO PRELIMINARY ASSESSMENT OF AN INNOVATIVE HUMAN-MACHINE INTERFACE FOR AIR TRAFFIC CONTROL OPERATORS

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Abstract

The global increase in air travel presents airports with the challenge of ensuring safety and efficiency amid growing traffic volumes. Current Air Traffic Management systems in control towers often diminish situational awareness by requiring operators to alternate between head-down monitors and direct head-up observations. This paper investigates the integration of extended reality technologies, specifically augmented reality, to enhance safety and efficiency in control towers. It outlines studies conducted to assess the potential of these technologies in supporting air traffic control operations and the development of an extended reality-based Human-Machine Interface. Evaluations were conducted in both simulated and real environments, demonstrating that extended reality can significantly improve situational awareness and operational efficiency in airport control towers, especially in low visibility conditions. While showcasing promising results, this study also identifies limitations and proposes a layer-based approach as a viable solution for further refinement.

Keywords: Airport Control Tower, Air Traffic Control, Extended Reality, Human-Machine Interface, Artificial Intelligence

1. General Introduction

As global air travel demand continues to escalate, airports are required to balance this increase with the imperative of maintaining operational safety standards. The limitations of existing Air Traffic Management (ATM) systems, especially within control towers, have become increasingly apparent. While technological advancements have been exploited to enhance operational safety, the deployment of instrumentation tools, particularly A-SMGCS-based solutions, introduces complexity. Current systems, including conformance monitoring, movement maps, and conflict detection, operate through monitor interfaces in the controller working position (CWP). However, these systems divert the focus of control tower operators from the primary out-of-the-window view. This paradoxically diminishes situational awareness, as increased head-down time and continuous shifting between head-up outside view and head-down CWP contribute to the potential risk of not detecting unpredictable events [1]. Recognising the pivotal role of direct head-up observation in Air Traffic Control (ATC) operations and following the successful use of Virtual/Augmented Reality and Synthetic Vision in piloting and pilot training activities, the possibility of transferring these technologies in the control tower has been considered [2] to address the inherent trade-off between increased capacity and operational safety. A few experiments, such as those explored in [3, 4, 5], have investigated the integration of eXtended Reality (XR) technologies, particularly Augmented Reality (AR) in control towers to provide air traffic controllers with spatially conformal information [6], leading to a positive evaluation of the overall potential of AR technology to benefit control tower operations. In this framework, two different collaborative projects *RETINA* - *Resilient Synthetic Vision for Advanced Control Tower Air Navigation Ser-*

*vice Provision*¹ and *DTT - Digital Technologies for Towers Solution 97.1-EXE002*², have assessed, at different maturity levels, the potential and applicability of Virtual/Augmented Reality technologies for the provision of Air Traffic Control service by the airport control tower and the possibilities offered by these technologies in eliminating the trade-off between airport safety and efficiency of operations and in improving the controller's workload and situational awareness. The investigation was led by the *Digital technologies and Design Methods for Aerospace Applications* research group of the University of Bologna, which tested different techniques in a simulated environment to later develop a first application assessed in a real Control Tower.

This paper discusses the development of the proposed eXtended Reality-based Human-Machine Interface for Air Traffic Control operations. It covers the entire process, starting from the initial concept design and validation in a simulated laboratory environment to the preliminary development and assessment in a real environment of the real-world Augmented Reality airport control tower platform (Figure 1). Moreover, a refined layer-based approach is proposed as a possible solution to improve



Figure 1 – Extended Reality in airport control tower: from concept design representation (*RETINA concept*) to Real-Time Human-in-the-Loop simulation (*DTT Sol97.1-EXE002 Validation exercise*) and preliminary assessment in real Control Tower environment (*Shadow Mode technical test*).

the platform and address the gaps identified during the preliminary assessment of the XR HMI.

2. Virtual/Augmented Reality Human-Machine Interface for Air Traffic Control Operations

The idea of an augmented reality human-machine interface (AR HMI) for airport control towers, aimed at providing air traffic controllers (ATCOs) with operational information, was initially investigated by Reisman et al. [6] during the early 2000s. In the development of this first AR system prototype, issues arose regarding the unreadiness of the technology, primarily related to collimation performance, which led to a consequent lack of confidence in the system. A few years later, leveraging technological advancements, the concept of an AR HMI to support ATC operations was further explored in the *RETINA* research project [7, 8]. This study evaluated the potential benefits of transferring Enhanced Vision Systems and Synthetic Vision Systems to air traffic control, particularly in terms of improving controllers' situational awareness and reducing workload. The *RETINA* concept involved overlaying synthetic auxiliary information onto the real view seen by air traffic controllers, Figure 2.

The information currently displayed on the head-down CWP could be displayed on AR tools and, therefore, superimposed on the controller's line of sight. Since the project focused on overlaying information onto the actual window view, ensuring accurate alignment between the displayed information and the user's perspective was a significant challenge [9]. To achieve this, the AR systems tracked the controller's head position and gaze direction, ensuring the interface properly displayed the most useful information while avoiding unnecessary clutter. Within the project, two different AR systems were investigated: Conformal-Head-Up Displays (C-HUDs), potentially coinciding with the tower windows, and See-Through Head-Mounted Displays (ST-HMDs), Figure 3.

¹Resilient Synthetic Vision for Advanced Control Tower Air Navigation Service Provision, <http://www.retina-atm.eu/index.html>

²DIGITAL TECHNOLOGIES FOR TOWER Solution 97.1, <https://www.remote-tower.eu/wp/project-pj05-w2/solution-97-1/>

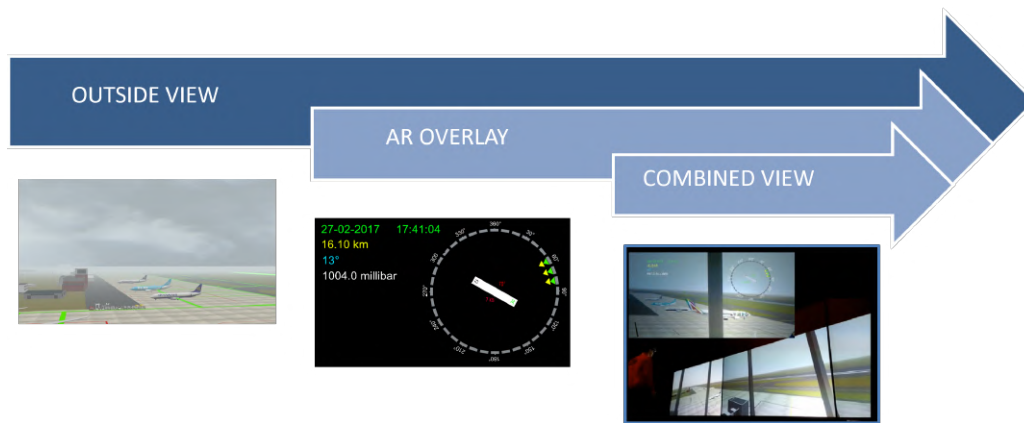


Figure 2 – AR HMI concept for airport control towers: synthetic overlays are displayed over the control tower outside view to provide the ATCOs with auxiliary information.

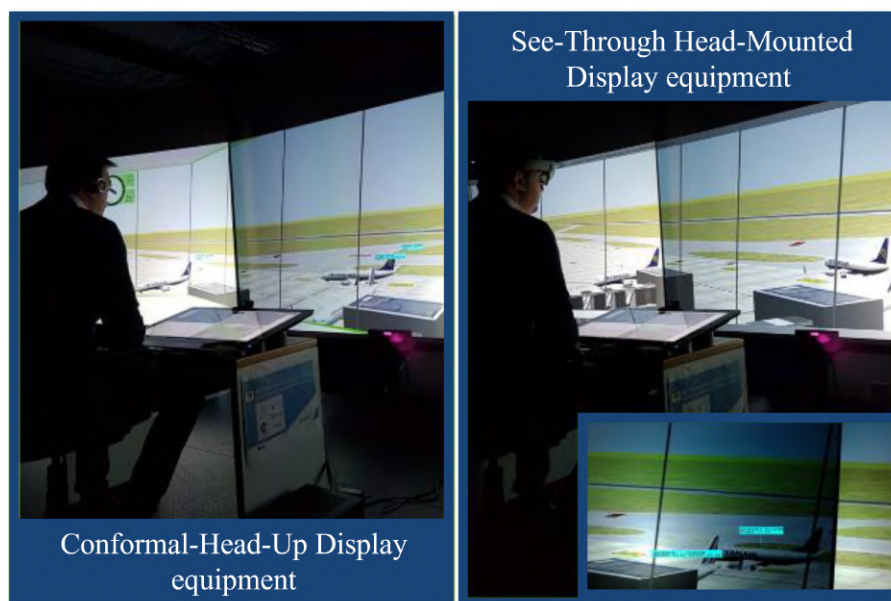


Figure 3 – *RETINA* AR systems: Conformal-Head-Up Displays (C-HUDs), and See-Through Head-Mounted Displays (ST-HMDs).

A proof-of-concept of both systems has been implemented and validated through human-in-the-loop real-time simulations in a laboratory environment to assess the proposed solutions. The simulated external view of Guglielmo Marconi International Airport in Bologna, Italy (LIPE) was provided to the user through a high-fidelity 4D model in an immersive environment replicating the out-of-the-tower view. Additional digital data overlays were placed over the actual out-of-the-window view through an AR application and were tailored and displayed on the AR interface according to the user's gaze orientation, phase of flight, and visibility condition. In particular, the displayed information was tailored for three distinct visibility conditions defined by operational needs. Whilst information related to aircraft traffic, ground vehicles, and Environmental Information (MET REPORT data) were present in each visibility condition, details about Airport static features were specifically adapted according to visibility requirements. Under CONDI VIS 1 (sufficient visibility for taxiing and collision avoidance), controllers were provided with essential airport static features such as basic aerodrome layout and critical areas: RWY status (Occupied, closed), Restricted areas (Taxiway closed). During CONDI VIS 2 (sufficient visibility for taxiing but insufficient for full visual surveillance), the display included additional detailed information on the aerodrome layout (apron and manoeuvring area), RWY status, restricted areas and stopbar. Addressing CONDI VIS 3 (visibility conditions severely limiting taxiing and surveillance capabilities, typically RVR below 400 meters), the AR interface expanded to encompass comprehen-

sive aerodrome layout details, multiple closed taxiways, and detailed stopbar information at critical holding points. Each condition was studied independently without transitions between them, ensuring a thorough system performance assessment under varying visibility scenarios. Providing controllers with augmented reality overlays tailored to each condition demonstrated significant advantages for ATCOs' decision-making and operational safety, particularly in low visibility conditions [10]. As a matter of fact, when low visibility conditions were applied, the use of *RETINA* tools providing the ATCO with a head-up conformal view of all needed information, led to improved operational efficiency and the reduction of restrictions due to Low Visibility Procedures, with consequent increased throughput. The concept also identified see-through HMD displays as the best technology, with spatial displays still lacking the maturity needed to handle multiple users. Moreover, the results of *Retina Project* were further explored in the *Digital Technologies for Towers - DTT* industrial research project. Within the *DTT*, the objective of one of the exercises of the solution *Virtual/Augmented Reality Applications for Tower solution (Solution 97.1-EXE002)* [11, 12] was to refine and expand upon the findings of the *RETINA* validation campaign, addressing the identified research gaps. These included the need for multi-user operations, understanding the impact of the shift in visibility conditions on ATCOs tasks, exploring various interaction modalities, and visualising safety nets for attention guidance and capturing. With this aim, the simulation platform, already exploited in the exploratory research stage (Figure 4), was integrated with additional functions.

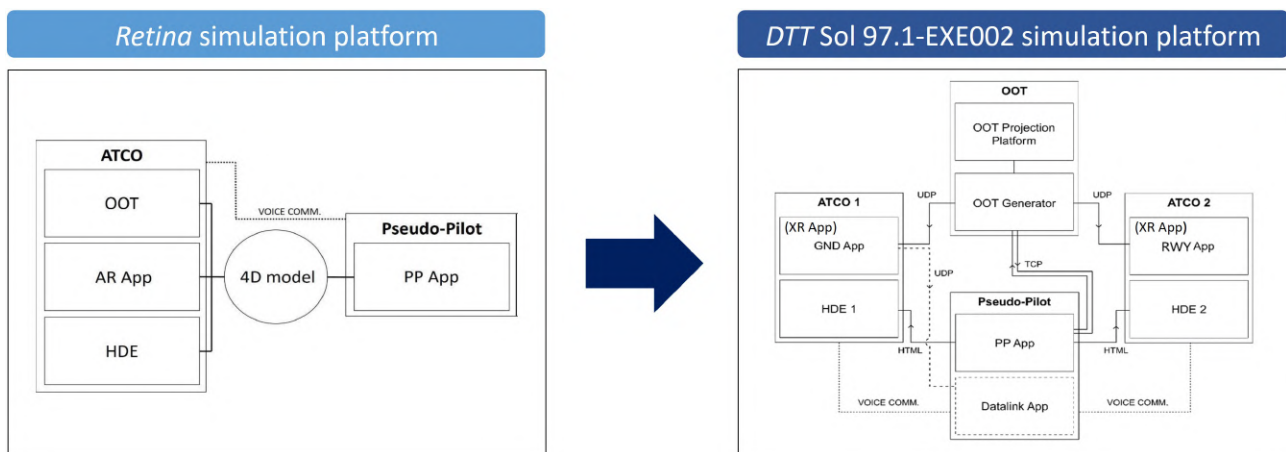


Figure 4 – Evolution of the University of Bologna simulation platform for the implementation of XR HMI in Airport Control Tower.

In particular, this exercise explored three specific features: adaptive HMI and CWP, multimodal interaction, and safety net visualisation for attention guidance on the Bologna International Airport (LIPE) simulated scenario. Differently from *RETINA*, the simulation involved two different CWPs, namely Tower Ground and Tower Runway, meaning that to fully customise the type of information delivered and the view of each one of the two users, the system had to track two different points of view. In this case, the C-HUDs were not a viable solution, and the only system assessed was the ST-HMD. Moreover, the *EXE002* eXtended Reality applications (XR App) enabled, on the one hand, the users to interact with the system by a combination of voice and gestures to deliver datalink-like messages issuing not-time-critical clearances [13] and, on the other hand, to display safety warnings regarding conflicting clearances and runway incursions [14], as can be seen in Figure 5.

A real-time human-in-the-loop validation campaign was conducted to confirm the previous project's positive outcomes and assess the additional functions introduced. As expected, the results showed that the virtual/augmented reality HMI developed and implemented on the platform was feasible from both an operational and technical perspective. The solution proposed proved to support the ATCO in working in a head-up position more than head-down even with low-visibility operational scenarios, and to lower the time to react in critical or alerting situations. The positive impact of the HMI implementation on ATCOs' human performances underscored its potential to mitigate workload, reduce the potential for human error, and enhance trust, acceptance, job satisfaction, and perceived safety. However, several limitations and challenges emerged while developing this study that must

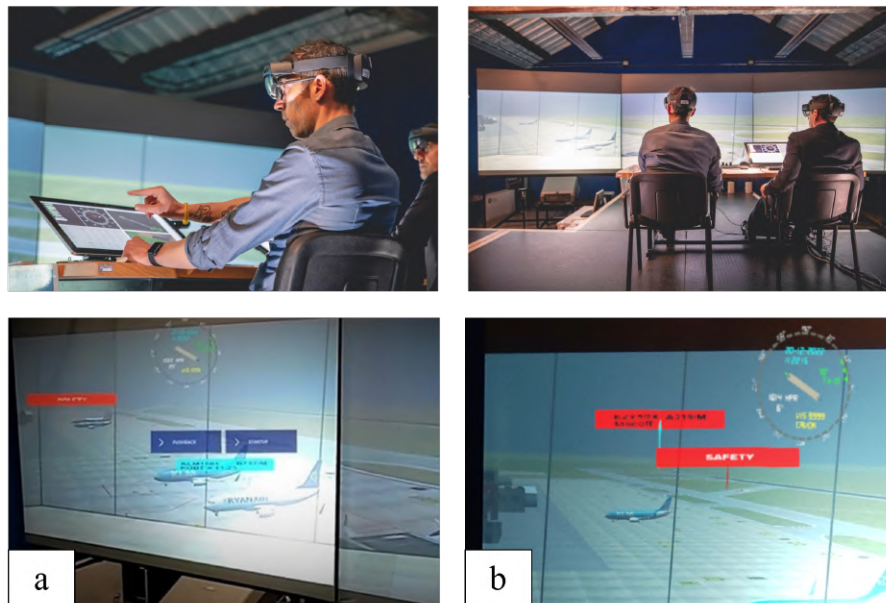


Figure 5 – ATCOs can simultaneously see both the out of the tower view and the AR overlays through the ST-HMD. (a) Personal view of the GND ATCO, the blue buttons allow the ATCO to issue Push back and Start-up clearances to the pseudo-pilot. (b) Personal view of the RWY ATCO visualising the safety warnings triggered by a runway incursion.

be addressed to realise its full potential. The current implementation was constrained by the limited field of view of the AR device, potentially hindering the ATCOs' awareness of peripheral information crucial for decision-making. While augmenting object identification, the design and positioning of Tracking Labels might require refinement to better align with user preferences and operational needs. Finally, while the system was successful in simulated environments, transitioning to real-world scenarios presents unique challenges, including regulatory compliance, infrastructure integration, and user acceptance.

3. Real-World Augmented Reality Airport Control Tower Platform

The results obtained during the validation campaign of the proposed concept solution confirmed the positive impact of a virtual/augmented reality HMI in supporting the controllers' operations. Nevertheless, they highlighted the necessity of progressing and assessing the solution in a real control tower rather than in a safe, non-critical, and fully controllable environment such as the laboratory one.

This necessity led to designing a real-world, live augmented reality platform based on some of the concepts validated in the two previous projects: aircraft tracking labels, aerodrome layout overlays, and weather interface. The developed platform could visualise and track operative aircraft and acquire their surveillance information in the airport traffic zone [15]. Utilising live ADS-B data, the system processed information on aircraft positions, decoded data, and organised it into a dynamic database. This database, constantly updated, enabled the calculation of holograms' positions and the real-time rendering of information to be visualised through a C-HUD. Additionally, the application incorporated essential overlays such as a weather interface, utilising actual METAR data, and a runway layout overlay designed explicitly for low-visibility conditions triggered by visibility distances indicated by the METAR. A representation of the AR application architecture can be seen in Figure 6; two different layer components are identified, a data and a visualisation one.

The developed application is thus capable of detecting aircraft movement and correctly collimating the holographic aircraft pointers and the surveillance information with the user's and aircraft's respective positions. The application can filter airport-relevant traffic among all the signals detected by the ADS-B antenna. It can also distinguish landing and departing aircraft, recognise their position in the airport and current flight status, and detect when they have parked. An on-site validation of the concept developed was performed as a shadow mode technical test at the Bologna airport control tower.

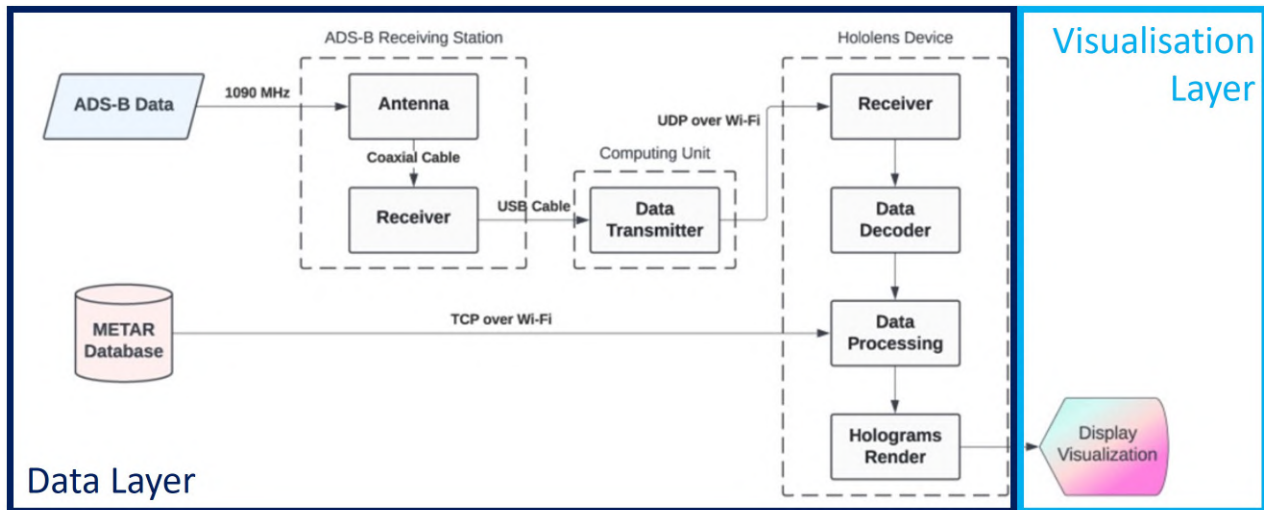


Figure 6 – Augmented Reality Airport Control Tower Platform.

Figure 7 shows the sequence of an aircraft (cyan tracking label) from the parking slot to the take-off with the weather interface and a landing aircraft (yellow tracking label) on the runways displayed to the user through the AR HMI. The preliminary assessment demonstrated the feasibility and reliability of the solution. Feedback from tower controllers was collected to guide the future development of the platform [16].

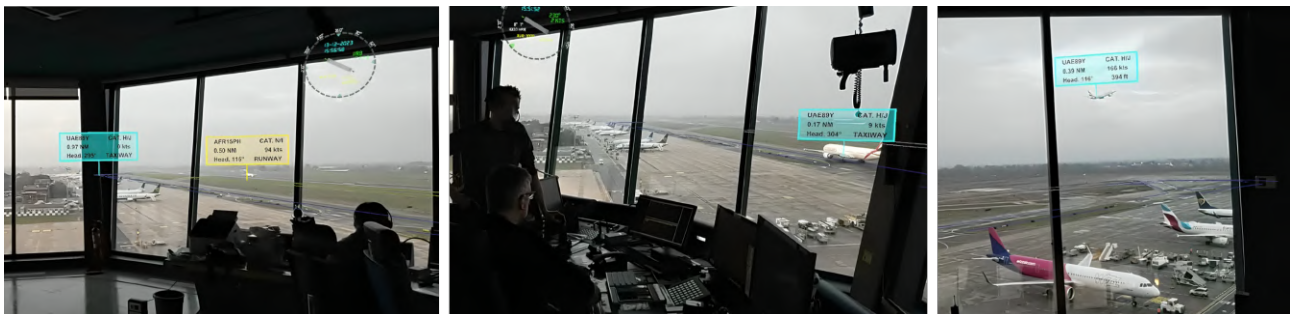


Figure 7 – Sequence of an aircraft (cyan TL) from the parking slot to the take-off as captured by the AR platform together with the runway layout overlay, the weather interface and a landing aircraft (yellow TL) on the runway.

The platform design proved to be robust, all the information was displayed correctly, and the ATCOs provided helpful feedback to improve the application further. However, despite the success of the technical test, challenges emerged. Information cluttering on AR HMI, already observed in laboratory simulations, became a focal concern. The introduction of additional overlays raised questions about the cognitive load on controllers and the potential negative impact on their workflow. These challenges emphasise the need for a nuanced approach to data presentation in XR applications, ensuring that the benefits of enhanced situational awareness and reduced mental workload are not compromised by information overload. Furthermore, the improved version of the real-world live platform should encompass additional features that have already proved to smooth the ATC operations: multimodal interaction and attention guidance.

4. Adaptive Layer-based XR Airport Control Tower Platform

In response to the identified issues for a real-world augmented reality airport control tower platform, the proposed solution is to integrate a logic system that is able to analyse and select the received data to be displayed by the HMI. Initially, finite state machines (FSMs) can serve as the logic system capable of filtering data and triggering the visualisation of specific overlays. However, as technology progresses, the role of FSMs will transform with advancements in fields like artificial intelligence (AI)

and machine learning (ML). This evolution will see FSMs being integrated with AI and ML algorithms, creating more intelligent and adaptive systems. Through this integration, FSMs will gain the ability to learn and dynamically adjust their states, transitions, and actions based on real-time data and complex patterns, resulting in more sophisticated and context-aware decision-making. These advanced systems, which can dynamically select and prioritise displayed information, offer a viable solution to mitigate the risks of information overload in extended reality (XR) applications for airport control towers. By incorporating FSM and AI and utilising a refined layer-based approach, there is a significant potential to enhance the efficiency and effectiveness of XR technologies in air traffic control, especially when integrating features like multimodal interaction and attention guidance. In particular, when coupled with AI technology, the latter could lead to the transition from reactive (act when a problem appears) to predictive (anticipating a problem, enabling preventive actions) ATC operations, increasing airport safety. The proposed layer-based approach foresees three different layer components: data, logic and visualisation and interaction (Figure 8).

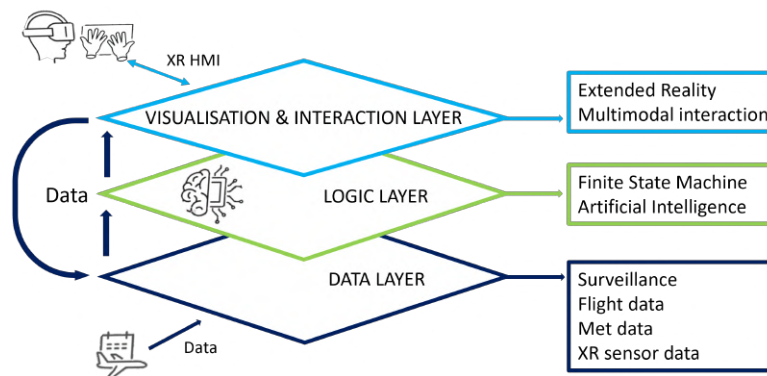


Figure 8 – Layer-based approach for an XR HMI in Airport Control Tower.

Data Layer

The Data Layer component supplies essential data to the Logic Layer, enabling it to determine the appropriate overlays for display in the Visualization and Interaction Layer. This layer collects and organises data to ensure its usability by other layers. Specifically, it integrates surveillance, meteorological, flight, and airport layout data. The Display Logic component will utilise this data source to determine what information to display and how much detail is necessary to effectively support operators in their tasks. Designing the data structures in a clear and standardised manner is crucial to ensuring they can be seamlessly used by various display logic services. Acting as the single source of truth for the entire operation, the Data Layer supports the Adaptive Display Logic in making decisions about data display for specific devices or interfaces. Additionally, the Data Layer could incorporate inputs from an automatic speech recognition system to automatically suggest virtual elements that could serve as attention-capturing elements in the XR device. Feedback from the XR device, such as gaze direction or other human performance metrics, is also processed through this interface.

Logic Layer

The Adaptive Display Logic component pulls data from the Data Layer and determines which elements should be used to enhance the controller's outside view, sending this data to the XR device interface. To achieve this, events must be prioritised to ensure the optimal presentation of information in various situations. A significant part of this task involves defining the necessary data to decide on the type of virtual elements to display and how to display them.

Visualization and Interaction Layer

This layer adapts the visual and/or aural synthetic overlays presentation to the current situation according to the input coming from the Logic Layer and enables the natural interaction between operators and the XR overlays enabled by multimodal interaction.

4.1 Adaptivity of the Layer-based XR Airport Control Tower Platform

The proposed concept builds on the Milgram and Kishino reality-virtuality continuum [17], where the transition from fully real to fully virtual environments is considered a seamless continuum with no specific dividing points between adjacent technologies. This includes all possible variations that blend real and virtual objects, providing the user with an extended reality experience. Unlike the previous investigations, this approach is based on a seamless transition between reality and virtuality. The synthetic overlay presentation, driven by the logic layer, dynamically adapts to the current situation. Previous activities performed within *RETINA* and *DTT Solution 97.1-EXE002* proved the potential of an adaptive AR HMI to show different overlays to conventional tower ATCOs depending solely on the visibility conditions. For instance, Figure 9 illustrates an adaptivity of the HMI capable of displaying synthetic overlays of the runway and taxiway contours as soon as the visibility at the airport decreases, triggered by the Runway Visual Range (RVR). The aerodrome layout overlay was activated only under reduced visibility, ensuring consistent visual conditions across all weather operations. This approach complements the ATCO's out-of-tower view by adding overlays of objects that might not be visible under specific conditions.

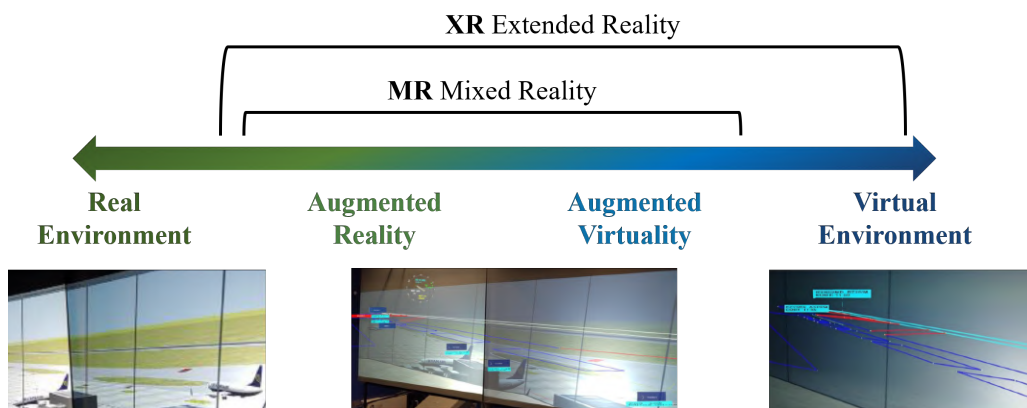


Figure 9 – Reality-virtuality continuum: Adaptive logic of displayed overlays with respect to RVR.

The adaptivity of the layer-based XR platform guarantees that the optimal blend between real out-of-the-tower view elements and synthetic overlays is achieved in every condition for each operator, ensuring the potential to overcome any adverse effects on airport capacity due to either meteorological or non-nominal conditions while maintaining current safety levels. This contributes to the medium-term ambitions of reduced departure delays and reduced capacity degradation. For instance, in low visibility conditions, exploiting such a platform can potentially eliminate some of the low visibility procedures currently in place, thereby minimising capacity loss. Furthermore, providing controllers with a head-up view of the traffic under any visibility condition, as already demonstrated in a simulated environment, showed several advantages for the ATCOs' human performance and airports' overall safety and resilience in situations of low visibility. The adaptivity of the platform is expected to lead to enhanced resilience at airports in the event of unforeseen circumstances, whether predictable, like adverse weather, or unpredictable, as long as the logic layer can trigger the appropriate response based on the available data.

5. Conclusions

This paper presents the study conducted to explore the feasibility and potential benefits of integrating eXtended Reality technologies, into airport control tower operations. By focusing on the challenges of maintaining situational awareness and reducing controller workload, an XR-based Human-Machine Interface (HMI) that overlays crucial information directly onto the controllers' out-the-window view was developed and validated. The investigation was carried out on multiple projects, including *RETINA* and *Digital Technologies for Towers (DTT)*, and progressed from simulated laboratory environments to real-world applications. Key findings from the research indicate that AR can significantly enhance

controllers' situational awareness, particularly in low-visibility conditions, by providing a head-up conformal view of essential information. The AR systems, particularly See-Through Head-Mounted Displays (ST-HMDs), effectively reduced controllers' time in a head-down position and improved reaction times in critical situations. The validation campaigns, both in simulated and real-world environments, confirmed the technical and operational feasibility of the proposed solution and feedback from air traffic controllers underscored the system's potential to improve operational efficiency and safety. However, several challenges were identified, particularly related to information clutter and the limited field of view of current AR devices. These issues highlight the need for a more refined approach to data presentation and interaction within the AR HMI. Artificial Intelligence, with its ability to dynamically select and prioritise displayed information, emerges as a solution to mitigate risks associated with information overload in XR applications for airport control towers. The integration of AI, coupled with a refined adaptive layer-based approach, offers a promising way to enhance the efficiency and effectiveness of XR technologies in air traffic control.

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