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Past, current and future trend for the usage of extend reality (XR) in aviation

Christophe Hurter, Mickael Causse and Maxime Cordeil

ENAC, french civil aviation university, ISAE-SUPAERO, The University of Queensland

1 Abstract

Extended, Virtual, Mixed and Augmented reality (XR, VR, MR, AR) devices, allow users to interact with computer-generated simulations that mimic or enhance the perception of the real world. AR overlays digital information onto the actual environment, while VR immerses users entirely in a virtual environment. MR combines elements of both to seamlessly blend the virtual and real worlds. XR technology provides immersive experiences, creating a sense of presence in the virtual realm. XR applications span various domains, such as training, education, medical, digital health, and aviation, benefiting pilots and air traffic controllers (ATCOs). In this chapter, we share our experiences using XR technology, detailing findings and the process of efficient implementation for end users like pilots and ATCOs. We present examples of improving the paper strip by projecting dynamic and updated information, ensuring smoother monitoring for controllers. Our remote tower project incorporates remote sensing with sound spatialization, enhancing situation awareness during airfield management. We also discuss developing an immersive analytic tool using XR devices for investigating recorded aircraft trajectories and its potential replication through dedicated APIs. We explore prospects for studying human behavior using VR devices under more immersive conditions, manipulating mental workload, prototyping and evaluating complex interfaces (e.g., cockpit design), and understanding conflict resolution algorithms through eXplainable AI (XAI). Finally, we address future challenges, such as improving interaction capabilities with tangibility in VR, and the opportunities XR technology could bring to aviation activities.

2 Introduction

Air Traffic Controllers (ATCOs) and pilots have to analyze large amounts of information in order to support efficient decision making in a constrained time frame. Information can be structured (e.g., aircraft data such as position, altitude, call sign) or unstructured and complex, and may include sources such as audio streams. While the goal of ATCOs is to maintain a safe distance between aircraft, it is nowadays almost as critical to optimize the traffic flow in terms of flight duration and fuel consumption. Research and development in this domain are active with the study of new systems and techniques and seek to improve

traffic management. ATCOs use today dedicated interactive visualizations to build a mental model with arranging *4-dimensional (space + time)* trajectories. While recent technological improvements in terms of visualization and interaction techniques arise, most existing systems display 2D representations of this 4-d data. New opportunities emerge with Head Mounted Display (HMD) and other types of immersive environments such as CAVE-style rooms to display and interact with 4-d data. Evolving with technology, visualizations have become more accurate with high-resolution displays, and now provide a sufficient amount of pixels to display fine-grained information. Immersive technology also provides support for more natural and *immersive interactions* (e.g. the use of head-mounted displays which embed head and gestures tracking).

Extended Reality (XR) technology provides immersive and engaging experiences, making users feel present in a virtual world. XR encompasses technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) devices. These tools enable users to interact with computer-generated simulations of real or hypothetical environments, enhancing and supplementing their perception of the world. In AR, digital information is overlaid onto the user's view of the actual world, offering an augmented experience. On the other hand, VR completely immerses users in a digital environment, isolating them from the real world. MR combines elements of AR and VR, seamlessly blending virtual and real-world components. XR finds applications in various domains, including training, education, medical and digital health, and aviation, such as for pilots and Air Traffic Controller (ATC). Moreover, XR plays a crucial role in research and development disciplines, allowing scientists and engineers to interact with and analyze complex data in innovative ways. For these reasons, this chapter focuses on recent investigations involving XR technology in the aviation domain, exploring its potential and benefits in this specific field.

In this chapter, we first provide a high-level description of how ATCOs work today to manage *the position of aircraft in the sky in real time*. We identify what is challenging with current used technology and provide an introduction to the *augmented paper strips*. We then introduce another aspect of the controller domain where immersive analytics can potentially play an important role: the new Remote Tower concept. We provide a detailed analysis of this activity through design requirements and scenario of usage.

In the following section we also present the problem of large data analysis (e.g., large quantity of aircraft trajectories) aspect involved in Air Traffic Management. We review the previous tools used for this application and we demonstrate a tool that shows how immersive Analytics, thanks to the use of HMDs, can be useful to perform collaborative air traffic data analysis. We then conclude this chapter with a discussion and the research agenda where all these efforts are in line with the future traffic evolution [of Growth 2013, 2013] where every model predicts continual traffic increase.

3 Air Traffic Control and novel technologies

ATCOs optimize traffic with the following considerations: reducing fuel consumption and noise, traffic management, preventing waiting loops, avoiding crowded areas, and coordinating aircraft between air spaces. While controllers monitor aircraft trajectory to prevent ground and air collisions, their activity also involves the cooperation with aeronautical practitioners. From a high perspective, traffic management can be carried out either in real-time or in a delayed time frame. With direct commands to aircraft, real-time traffic management is equivalent to actual aircraft management. Data analytic is preferably used in deferred time management to study traffic in order to enable long-term traffic optimization.

Working procedures for controllers are continuously improved while preserving and sustaining safety considerations. Every modification must be evaluated and validated, which slows down but secures the process. By offering new methods to capitalize on ATCOs' operations, Visual analytic suggests valuable potential. Particularly, 360-degree immersive displays surround people to address the constraints of conventional screens. The user can select to view the required information by turning their head. Mixed reality, as offered by the Microsoft HoloLens, is a new and developing technology that offers additional interesting capabilities. Holograms are shown and anchored in the space as if they were a natural part of the user's surroundings, but the user is not entirely submerged in a virtual reality. With the metaphor of a very big transparent display (360 degrees of field of vision), this new technology offers tangible opportunities for ACTOs. In this sense, Willett et al. [Willett et al., 2017] discussed opportunities to embed data representation in immersive or mixed reality environments and also provides possible research agenda in this area.

VR is also booming in the field of piloting, enabling for example to train to new procedures or checklists, or to learn piloting without relying on complex and expensive flight simulators. For research purpose, it provides an easy way to reproduce complex piloting environments and simulated scenarios [Labedan et al., 2021, Peysakhovich et al., 2020]. Oberhauser [Oberhauser et al., 2018] conducted a study to examine the functional accuracy of a VR flight simulator when compared to a traditional flight simulator. The study aimed to assess various aspects of flight performance, such as heading, altitude, flight path deviations, and delays in control operations. Their results showed that the deviations in flight performance were significantly larger in VR than in the conventional flight simulation. As such, VR remains an environment where interactions can be more challenging than in the reality.

4 The augmented paper strip

A paper strip is a physical strip used by air traffic controllers to record flight information. It contains details about an aircraft's call sign, altitude, speed, heading, etc. Controllers use it to track and coordinate aircraft movements for

safe and efficient air traffic flow. Several earlier works have examined Air Traffic Management (ATM) and Control (ATC) from various angles [Hurter et al., 2014b]. While Mackay et al. specifically investigated the usages of paper strips to learn more about ATC activity [MacKay, 1999], Letondal et al. explored mental models for ATCOs with tangibility support [Letondal et al., 2013], and Hurter et al. looked into augmented paper strips [Hurter et al., 2010]. Numerous real-time control interfaces, interactions, analytical tools, and techniques have been developed as a result of research in this application space. In this section, we go into further depth on the idea of *augmented paper strips* to help decision-making.

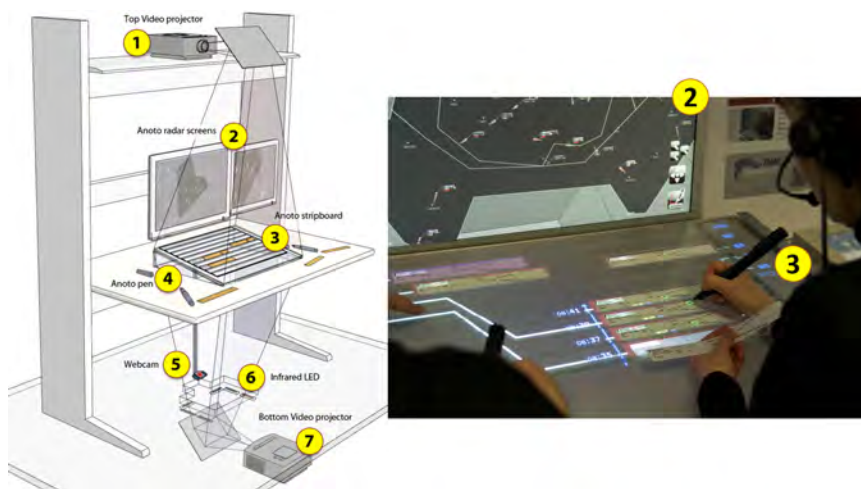


Fig. 1. Strip'TIC (Stripping Tangible Interface for Controllers) is an augmented and tangible environment for control. This prototype is composed of seven parts: a top projector (1), a bottom projector (7), a radar screen (2), a strip-board (3), digital pens (4), a webcam (5), and an infrared lighting system (6).

4.1 Strip'TIC system description

Once printed, the paper strip cannot be updated, nor can the information reported on the strip be used as input into the system. This strong limitation hinders the development of more responsive systems with more accurate future aircraft locations, complex conflict detection and resolutions. Taking into account this limitation, Strip'TIC (Stripping Tangible Interface for Controllers) has been developed [Hurter et al., 2012b].

This prototype (see figure 1) combines augmented paper and digital pens on a multi-touch glass strip-board, using vision-based tracking and augmented rear and front projections. The paper strips, the strip-board and the radar screen are all covered with Anoto Digital Pen patterns (DP-patterns), i.e. small patterns

used by the pen's infrared digital camera to compute the location of the pen on the dotted surface. The controllers' actions with the digital pen are sent in real-time to the software. They can annotate paper strips, and the resulting strokes are both physical (pen ink) and digital (projected ink). Controllers can use the pen to point at symbols on the radar display or names on the paper strips. The strip-board, which helps to structure the set of strips, is semi-opaque. This enables both a bottom projection on the strip-board and strip tracking thanks to Augmented Reality patterns printed on the back of the strips. A second projector located above the device displays graphics on top of the strip-board and the strips (i.e. projected ink, aircraft labels. . .). The user can manipulate the paper strips as tangible objects and use gestures to fulfill air traffic management [Savery et al., 2013].

In the following scenario, we describe how controllers handle time and organize sequences of actions with paper strips for aircraft landings. When approaching an airport with dense traffic or bad weather, controllers can delay aircraft landings and place them in standby holding stacks. The stacks are organized vertically by flight altitude, and each aircraft entering the stack is placed at the highest altitude, flying in a hippodrome at this level. The controller gradually asks the aircraft to descend to the next available altitude. When a plane leaves the stack, a fixed time elapses until it lands on the runway. For example, when planes land east on runway 06 at Paris Orly airport, the time to reach the track is 9 minutes from the stack located at the stack ODRAN and 17 minutes from the stack located at the stack MOLEK. In this case, the Air Controller must mentally calculate when each aircraft has to leave the stack, sequencing the planes from the two stacks and maintaining a separation of 90 seconds between each landing. Figure 1 shows the arrangement of strips on the strip board, helping Controllers build a mental image of each aircraft in the stack. The strips represent the aircraft in the ODRAN and MOLEK stacks, as well as the planes allowed to leave the stacks in a given landing sequence.

Thanks to an immersive environment with augmented items (paper strips) and multi-modalities (pen, touch, tangible objects), Strip'TIC demonstrate how to support ATC operations [Hurter et al., 2012b, Letondal et al., 2013] .

5 Immersive environment for Remote Towers

ATC service providers never stop to innovate with new methods and facilities in order to maintain or increase the safety level and efficiency. One of the most recent inventions is called the Remote Tower (RT) concept [N., 2016]. Aeronautical services can be performed using Remote Tower from a place other than the original control tower ². To do this, an airfield mast with numerous sensors (cameras, radio antennas, etc.) is installed. Thanks to network connection systems, the video streams and additional data are sent to a remote location. Many nations have begun to work on establishing remote towers to support aviation services in aerodromes with little traffic or challenging access and to reduce development expenses compared to actual towers.



Fig. 2. Typical Remote Tower room (left). The immersive environment for the Remote Tower concept (right).

In the following, we present scenarios where they have shown to be effective in terms of supporting decision-making and safety level [Aricò et al., 2019, Reynal et al., 2019].

Sound location: At 2 p.m, the airspace is busy with various small (VFR) and large (IFR) aircraft. A new aircraft enters and contacts the tower, but the controller can't establish visual contact due to other aircraft in the same direction. One potential solution is a sound location system with a surround setup in the remote tower. It accurately reproduces airport sounds at their actual locations. For instance, if an aircraft is on the left of the controller, its sound will come from the left, helping the controller locate it. The system also alters the speech of pilots from further distances, indicating their distance from the airport. This technology enables controllers to identify the aircraft's position and establish visual contact more efficiently. It provides additional information, enhancing working speed. Even in good weather, spotting aircraft from the tower can be challenging, but the surround system helps identify them faster and with greater precision.

Haptic feedback: At 5 p.m, the airport experiences high traffic density with numerous ground movements, particularly at taxiway crossings. Currently, two aircraft are taxiing towards one of these crossing points. The controller receives an alarm indicating the situation, but it takes time to pinpoint the exact location due to the high volume of ground movements. One potential solution is to use a Haptic seat with SpeechCon and graphic prediction. The ground controller receives feedback via vibrating lines in the backrest, indicating the possible danger's location. The vibration's tempo correlates with the distance between the involved aircraft. The controller also hears an alarm saying "Crossing! Crossing!" through the SpeechCon system. Additionally, a visual prediction of the path is displayed on the ground radar. These indicators draw the controller's attention to the dangerous situation, enabling quick resolution. The SpeechCon system allows customized messages for specific situations, aiding faster problem identification. The haptic seat helps emphasize the situation's significance.

6 Immersive environment for pilots

Numerous aspects related to aircraft piloting can be addressed through XR. The development of virtual flight simulators [Valentino et al., 2017] enables the creation of realistic situations in which individuals can train for piloting or understand the functioning of flight instruments. The space and financial gains are substantial, and it becomes feasible to easily design new systems and assess their usability during virtual in-flight condition. Additionally, it is possible to create immersive environments simulating piloting scenarios with the aim of challenging pilots or operators, and evaluating, for instance, their capacity to manage high mental workload. A study by Gozzi et al. [Gozzi et al., 2022] aimed to develop a virtual version of the well-known MATB-II task [Comstock Jr and Arnegard, 1992]. The purpose of this study was to assess the potential benefits offered by an immersive version of the MATB-II. Indeed, this task is widely used in the field of piloting to evaluate, for example, the ability to manage multiple tasks simultaneously under high workload. However, the original version implemented on a simple 2D computer screen provides limited immersion. Furthermore, it does not account for the spatial distribution of the different cockpit tasks simulated by MATB-II. For instance, the tracking task of the MATB-II replicates the control of the aircraft's attitude, and this instrument is located in front of the pilots, whereas the occurrence of visual alerts, simulated by the system monitoring task, may occur at distant locations within the cockpit.

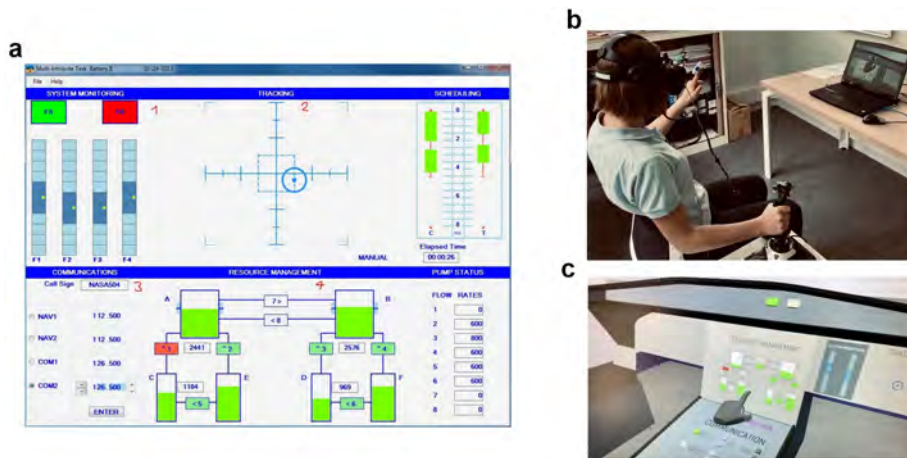


Fig. 3. a: the classical MATB-II task developed by NASA. b: a participant performing the MATB-II VR task. c: the MATB-II VR task as seen by the participant. The different task of the classical MATB-II are now located on different areas of the virtual cockpit (e.g., tracking task, resource managements task...). Image adapted from [Gozzi et al., 2022]

The result obtained with 31 participants that were submitted to the "MATB-II VR" showed that mental and physical effort was higher in the virtual version vs the classical 2D MATB-II. Heart rate, measured throughout the task, was also higher in the VR version. These findings confirmed that immersive environments can be more challenging than aeronautical tasks performed on a classical 2D computer screen. However, the authors highlighted that interaction within virtual environments must be improved before complex operational tasks, such as piloting, can be effectively performed.

7 XR usages for aeronautical Data Analytics

Controllers and pilots deal with 4D real-time information: managing and controlling aircraft positions in the sky over time. However, most aeronautical interfaces rely on 2D radar screens, leading to inherent perceptual challenges with 3D+time data and constantly burdening Controllers' mental load. Researchers in the domain have explored solutions using immersive technology like stereo displays, CAVEs, and HMDs. Mazzucchelli and Montelone introduced the AD4 project [Mazzucchelli and Monteleone,], which utilizes immersive technology (auto-stereoscopic monitors) and 3D visualizations of air traffic data. However, they did not study users' performance with this setup and assume that immersive technology might not necessarily reduce the mental load but could offer new decision-making opportunities for controllers. Lange et al. [Lange et al., 2003] proposed a multi-modal immersive control system using 3D stereo screens and voice commands. They assumed that replacing voice commands for object selection could reduce the need for gestures and hand-based interactions. However, navigation, flight selection, and way-point manipulation still rely on a 'virtual reality wand' (i.e., a 6DOF tracked pointer). The visualization system integrates 3D aircraft representations, flight paths, way-points, weather, and high-fidelity geography. The authors outlined a plan for evaluating the system, but no actual evaluation was provided. Little work has been done to assess Virtual Reality environments' effectiveness in supporting controller work.

7.1 Immersive Analysis of air traffic data

Air Traffic Analysts study vast records of air traffic data. For instance, a single day's recorded traffic over France contains around 500,000 multidimensional data points. Understanding how traffic is reconfigured in non-nominal situations is crucial for ensuring fluidity and security. Air Traffic Analysis involves various tools for extracting knowledge from real-time or recorded aircraft trajectory data. These tools offer different metrics and interaction techniques to understand traffic structure and evolution [Hurter et al., 2014c]. One approach is analyzing traffic from a flow perspective, enabling users to compare trajectories and examine temporal changes [Scheepens et al., 2016]. Simplification techniques like Edge Bundling aid in visually exploring flow patterns [Hurter et al., 2012a]. Dynamics of flows can be analyzed using dynamic network and schematizing techniques [Hurter et al., 2014d, Hurter et al., 2010]. Visual analytic tools also help

extract flow dynamics [Andrienko et al., 2013], sometimes revealing unexpected information such as meteorological parameters [Hurter et al., 2014a]. Interacting with large aircraft trajectory datasets is challenging, but Pixel Based Techniques like [Hurter, 2015] offer solutions. Previous research in this field enhances our understanding of air traffic data management and its unique characteristics.

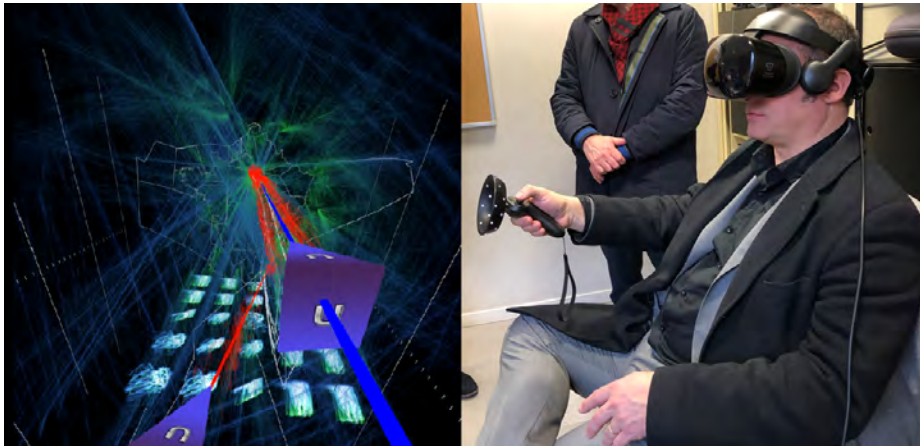


Fig. 4. Exploration of aircraft trajectories with Virtual Reality headset.

FiberClay [Hurter et al., 2019] is a tool that employs a bi-manual interaction metaphor, simulating the manipulation of clay to carve out content and create data queries from dense 3D dataset. The tool facilitates analyst’s tasks of filtering and selecting interesting 3D curve patterns by directly interacting with the 3D content using hand controllers. For trajectory analysis (Figure 6), users can select and filter subsets of trajectories through Boolean operations (e.g., selections, intersections, exclusions) similar to a selection brush tool in photo editing software. This design aims to reduce cognitive load and task difficulty when dealing with complex 3D scenes, which can be challenging in traditional 2D desktop setups. Initial evaluations with domain experts show promising results, with users finding the tool easy to use and helpful in discovering and analyzing curve patterns.

7.2 XR usage for Collaborative Trajectories Visualisation

The previous section calls for collaborative and immersive aircraft trajectory visualization to facilitate common understanding, shared expertise, and reporting from distant locations. Currently, this is achieved using 2D visualization tools displaying 3D aircraft trajectories, along with video conferencing systems for sharing insights. However, this setup is not optimal for viewers when presenters navigate the visualization (e.g., pan and zoom operations) and describe 3D data

using 2D visualizations. Affordable immersive display and input technology, like the Oculus Rift head-mounted display and Leapmotion hand tracking device, enables the creation of efficient tools for remote collaboration in trajectory analysis. We developed a platform that facilitates collaborative aircraft trajectory visualization, allowing multiple users to analyze large datasets together using affordable head-mounted displays and hand tracking devices.

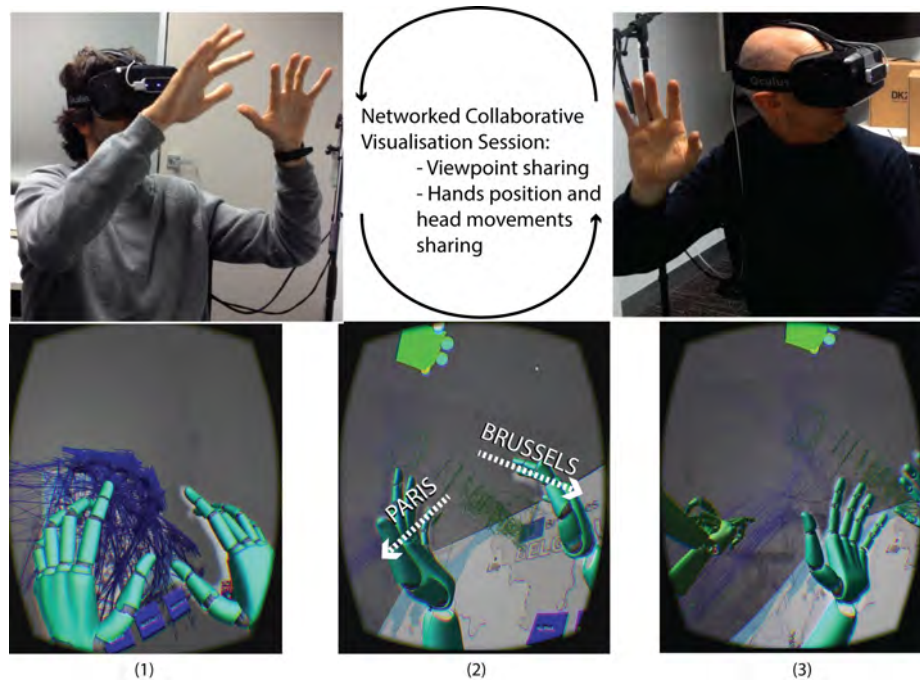


Fig. 5. Top: Remote users in the collaborative visualization platform wearing Oculus Rift DK2 head-mounted displays with Leapmotion for hand tracking. Bottom: Visual representation of the remote collaborative session in the Unity client. The session begins with an overview of the dataset (1), showcasing a day of air traffic data over France. An expert sends a rendezvous position to the other viewer and explains how the stack was formed and handled (2). Both participants share the same virtual space, communicate orally through VOIP, and can directly describe and display specific spatial arrangements of trajectories using their hands (green and blue hands) (3).

As a collaborative platform for immersive big data visualization, we have identified the following system needs: immersive visualization, navigation, landmark, user gaze visualization, data filtering. Cordeil et al. [Cordeil et al., 2016] created a networked Unity application that connects two users from remote sites using Oculus Rift headsets for immersive visualization (Figure 5, top). Users' hands and fingers are tracked with Leapmotion, providing high fidelity feedback within the Oculus Rift. Navigation is achieved through head-tracking, leaning,

and rotating the head, along with gaze direction and a game pad. Rendezvous interaction allows users to send location cues in the virtual environment, while basic filtering operations enable traffic replay and opacity adjustments for trajectory visualization. Communication is supported with VOIP clients like Skype or Zoom. This platform is an initial step to enhance communication between remote experts.

7.3 Explainable AI (XAI) opportunities

In Air Transportation Management, the Decision Making Process is already integrated with AI, aiming to assist controllers in their daily tasks. However, AI systems still face challenges regarding acceptability. Recent surveys, such as the one by Degas [Degas et al., 2022], highlight the current use of XAI (Explainable AI) and its potential application in future aeronautical systems. Currently, AI/Machine Learning automation systems lack transparency as they only provide results without additional information to support explanations. The goal is to transform the Decision Making Process into a "White Box," delivering understandable outcomes through transparent processes. The ARTIMATION project (<https://www.artimation.eu/>) focuses on achieving this by using data visualization, data-driven storytelling, and immersive analytics to create a transparent and explainable AI model [Hurter et al., 2022]. This project leverages human perceptual capabilities to enhance understanding of AI algorithms through appropriate data visualization, facilitating Explainable AI (XAI). Immersive analytics is also explored as a means to present information effectively.

A Virtual Reality proof of concept was developed by adapting the existing tool FiberClay [Hurter et al., 2019]. This prototype explores trajectory optimization possibilities, utilizing the third dimension to differentiate between candidate solutions (Figure 6). The virtual reality environment aids in explaining traffic optimization behavior and offers various dataset presentations and filtering options. This interface proves beneficial to developers for analyzing and certifying behaviors, especially in post-operations.

8 Conclusion and Future work

Aeronautical activities are cautious about technical evolution due to safety concerns. ATCOs and pilots working methods and technological environment can't change rapidly; modifications must be carefully assessed for safety. While immersive environments are readily available, widespread adoption will take time. However, as a long-term plan, they offer valuable opportunities for integration with aeronautical practitioners. Deferred data analysis using immersive environments supports effective decision-making. Immersive Analytics has remarkable data visualization and interaction capabilities but faces challenges with emerging technology. Long-term effects on users' physiology are not well understood. Introducing this technology may affect ATCOs and pilots' work duration and lead to different types of fatigue. New media or devices must undergo validation for

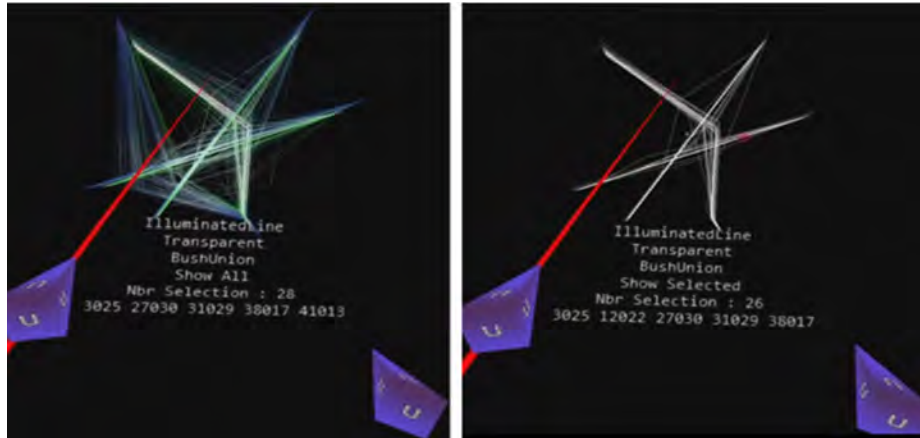


Fig. 6. This displays a typical traffic situation with stacked trajectories showcasing potential optimized traffic flow.

data presentation quality, security, and resilience. While immersive environments have a long history, Immersive Analytics' recent interest lacks scientific work on its support for aeronautical activities. Investigation and potential applications in future developments are promising.

References

- [Andrienko et al., 2013] Andrienko, G., Andrienko, N., Hurter, C., Rinzivillo, S., and Wrobel, S. (2013). Scalable analysis of movement data for extracting and exploring significant places. *IEEE Transactions on Visualization and Computer Graphics*, 19(7):1078–1094.
- [Aricò et al., 2019] Aricò, P., Reynal, M., Di Flumeri, G., Borghini, G., Sciaraffa, N., Imbert, J.-P., Hurter, C., Terenzi, M., Ferreira, A., Pozzi, S., Betti, V., Marucci, M., Telea, A. C., and Babiloni, F. (2019). How neurophysiological measures can be used to enhance the evaluation of remote tower solutions. *Frontiers in Human Neuroscience*, 13.
- [Comstock Jr and Arnegard, 1992] Comstock Jr, J. R. and Arnegard, R. J. (1992). The multi-attribute task battery for human operator workload and strategic behavior research. Technical report.
- [Cordeil et al., 2016] Cordeil, M., Dwyer, T., and Hurter, C. (2016). Immersive solutions for future air traffic control and management. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces*, ISS Companion '16, pages 25–31, New York, NY, USA. ACM.
- [Degas et al., 2022] Degas, A., Islam, M. R., Hurter, C., Barua, S., Rahman, H., Poudel, M., Ruscio, D., Ahmed, M. U., Begum, S., Rahman, M. A., Bonelli, S., Cartocci, G., Di Flumeri, G., Borghini, G., Babiloni, F., and Aricò, P. (2022). A survey on artificial intelligence (ai) and explainable ai in air traffic

- management: Current trends and development with future research trajectory. *Applied Sciences*, 12(3).
- [Gozzi et al., 2022] Gozzi, Z., Peysakhovich, V., Cantu, A., and Causse, M. (2022). Behavioral and physiological assessment of a virtual reality version of the matb-ii task. In *HUCAPP 2022*, pages 77–87.
- [Hurter, 2015] Hurter, C. (2015). *Image-Based Visualization: Interactive Multi-dimensional Data Exploration*. Morgan & Claypool Publishers.
- [Hurter et al., 2014a] Hurter, C., Alligier, R., Gianazza, D., Puechmorel, S., Andrienko, G., and Andrienko, N. (2014a). Wind parameters extraction from aircraft trajectories. *Computers, Environment and Urban Systems*, 47:28 – 43. Progress in Movement Analysis – Experiences with Real Data.
- [Hurter et al., 2014b] Hurter, C., Conversy, S., Gianazza, D., and Telea, A. (2014b). Interactive image-based information visualization for aircraft trajectory analysis. *Transportation Research Part C: Emerging Technologies*, 47:207–227. Special Issue: Emerging Technologies Special Issue of ICTIS 2013 – Guest Editors: Liping Fu and Ming Zhong and Special Issue: Visualization Visual Analytics in Transportation – Guest Editors: Patricia S. Hu and Michael L. Pack.
- [Hurter et al., 2014c] Hurter, C., Conversy, S., Gianazza, D., and Telea, A. (2014c). Interactive image-based information visualization for aircraft trajectory analysis. *Transportation Research Part C: Emerging Technologies*, 47, Part 2:207 – 227.
- [Hurter et al., 2022] Hurter, C., Degas, A., Guibert, A., Durand, N., Ferreira, A., Cavagnetto, N., Islam, M. R., Barua, S., Ahmed, M. U., Begum, S., Bonelli, S., Cartocci, G., Flumeri, G. D., Borghini, G., Babiloni, F., and Aricó, P. (2022). Usage of more transparent and explainable conflict resolution algorithm: air traffic controller feedback. *Transportation Research Procedia*, 66:270–278. 34th Conference of the European Association for Aviation Psychology.
- [Hurter et al., 2014d] Hurter, C., Ersoy, O., Fabrikant, S. I., Klein, T. R., and Telea, A. C. (2014d). Bundled visualization of dynamicgraph and trail data. *IEEE Transactions on Visualization and Computer Graphics*, 20(8):1141–1157.
- [Hurter et al., 2012a] Hurter, C., Ersoy, O., and Telea, A. (2012a). Graph bundling by kernel density estimation. *Comput. Graph. Forum*, 31(3pt1):865–874.
- [Hurter et al., 2012b] Hurter, C., Lesbordes, R., Letondal, C., Vinot, J.-L., and Conversy, S. (2012b). Strip’tic: Exploring augmented paper strips for air traffic controllers. In *Proceedings of the International Working Conference on Advanced Visual Interfaces, AVI ’12*, pages 225–232, New York, NY, USA. ACM.
- [Hurter et al., 2019] Hurter, C., Riche, N. H., Drucker, S. M., Cordeil, M., Alligier, R., and Vuillemot, R. (2019). Fiberclay: Sculpting three dimensional trajectories to reveal structural insights. *IEEE Transactions on Visualization and Computer Graphics*, 25(1):704–714.

- [Hurter et al., 2010] Hurter, C., Serrurier, M., Alonso, R., Tabart, G., and Vinot, J.-L. (2010). An automatic generation of schematic maps to display flight routes for air traffic controllers: Structure and color optimization. In *Proceedings of the International Conference on Advanced Visual Interfaces, AVI '10*, pages 233–240, New York, NY, USA. ACM.
- [Labedan et al., 2021] Labedan, P., Darodes-de Tailly, N., Dehais, F., and Peysakhovich, V. (2021). Virtual reality for pilot training: Study of cardiac activity. In *VISIGRAPP (2: HUCAPP)*, pages 81–88.
- [Lange et al., 2003] Lange, M., Hjalmarsson, J., Cooper, M., Ynnerman, A., and Duong, V. (2003). 3d visualization and 3d and voice interaction in air traffic management. In *The Annual SIGRAD Conference. Special Theme-Real-Time Simulations. Conference Proceedings from SIGRAD2003*, number 010, pages 17–22. Linköping University Electronic Press.
- [Letondal et al., 2013] Letondal, C., Hurter, C., Lesbordes, R., Vinot, J.-L., and Conversy, S. (2013). Flights in my hands: Coherence concerns in designing strip'tic, a tangible space for air traffic controllers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '13*, pages 2175–2184, New York, NY, USA. ACM.
- [MacKay, 1999] MacKay, W. E. (1999). Is paper safer? the role of paper flight strips in air traffic control. *ACM Trans. Comput.-Hum. Interact.*, 6(4):311–340.
- [Mazzucchelli and Monteleone,] Mazzucchelli, L. and Monteleone, A. A 4d immersive virtual reality system for air traffic control.
- [N., 2016] N., F. (2016). *Virtual and Remote Control Tower. Research, Design, Development and Validation*. Springer, Research Topics in Aerospace.
- [Oberhauser et al., 2018] Oberhauser, M., Dreyer, D., Braunstingl, R., and Koglbauer, I. (2018). What's real about virtual reality flight simulation? *Aviation Psychology and Applied Human Factors*.
- [of Growth 2013, 2013] of Growth 2013, C. (2013). <http://www.eurocontrol.int/articles/challenges-growth>.
- [Peysakhovich et al., 2020] Peysakhovich, V., Monnier, L., Gornet, M., and Juaneda, S. (2020). Virtual reality vs. real-life training to learn checklists for light aircraft. In *Eye-Tracking in Aviation. Proceedings of the 1st International Workshop (ETAVI 2020)*, pages 47–53. ISAE-SUPAERO, Université de Toulouse; Institute of Cartography and . . .
- [Reynal et al., 2019] Reynal, M., Imbert, J.-P., Aricò, P., Toupillier, J., Borghini, G., and Hurter, C. (2019). Audio focus: Interactive spatial sound coupled with haptics to improve sound source location in poor visibility. *International Journal of Human-Computer Studies*, 129:116–128.
- [Savery et al., 2013] Savery, C., Hurter, C., Lesbordes, R., Cordeil, M., and Graham, T. C. N. (2013). *When Paper Meets Multi-touch: A Study of Multi-modal Interactions in Air Traffic Control*, pages 196–213. Springer Berlin Heidelberg, Berlin, Heidelberg.
- [Scheepens et al., 2016] Scheepens, R., Hurter, C., Wetering, H. V. D., and Wijk, J. J. V. (2016). Visualization, selection, and analysis of traffic flows. *IEEE*

- Transactions on Visualization and Computer Graphics*, 22(1):379–388.
- [Valentino et al., 2017] Valentino, K., Christian, K., and Joelianto, E. (2017). Virtual reality flight simulator. *Internetworking Indonesia Journal*, 9(1):21–25.
- [Willett et al., 2017] Willett, W., Jansen, Y., and Dragicevic, P. (2017). Embedded data representations. *IEEE Transactions on Visualization and Computer Graphics*, 23(1):461–470.