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Extended Reality Safety Nets for Attention Guidance in Airport Control Towers

Sara Bagassi[⋆] *and Marzia Corsi*[⋆†]
[⋆]*Department of Industrial Engineering, University of Bologna*
Via Fontanelle, 40 - 47121 Forlì (FC) - Italy
sara.bagassi@unibo.it · marzia.corsi2@unibo.it
[†]Corresponding author

Abstract

Extended Reality (XR) technology is transforming the way to interact with the surrounding world, and the aviation industry is no exception. In airport control towers, XR can be exploited to overlay all the auxiliary information needed with the real-world data supporting the controllers during their operations without forcing them to continuously scan data on head-down displays and switch between the primary head-up out-of-the-tower visual field and the auxiliary head-down equipment, with a benefit in terms of workload and situational awareness, and lowering the risk of not detecting unpredictable situations. With the same aim of improved situational awareness, synthetic Safety Nets can be integrated with the out-of-the-tower view to guide the controller's attention toward alerting situations. An operational concept for attention guidance through the usage of Extended Reality Safety Nets based on visual and auditory cues in airport control towers is developed for the simulated scenario of Bologna Airport in Italy. To assess whether and how the air traffic controllers' Human Performances benefit from the introduction of XR Safety Nets, a human-in-the-loop technical test involving experienced air traffic controllers is executed. The outcome of the simulation test proves how the proposed solution effectively reduces both the time the controllers need to notice and react to a safety event and the number of switches between the head-up and head-down positions. Moreover, the controllers report a positive impact on the potential for human error, a benefit for situational awareness, and enhanced team situational awareness.

1. Introduction

Safety is a crucial aspect for the aviation system and Air traffic control (ATC) is a key component requiring highly qualified operators collaborating in a huge and sophisticated human-machine system. As a matter of fact, air traffic controllers play an essential part in the ATC system, as they have to preserve safety, order, and effectiveness of the air traffic flow [1]. Over the years, several initiatives and developments have been taken to support control towers' operations and bolster safety. Specifically, the prevention of runway incursions stands as a significant safety objective in ATC. As defined by the International Civil Aviation Organization (ICAO) [2], a runway incursion is *"any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft"*.

Several measures have been taken in order to decrease the occurrence of runway incursions. These include identifying best practices for safe runway operations, conducting awareness campaigns that focus on key factors contributing to runway incursions (such as phraseology), and implementing measures to enhance situational awareness for involved actors. These measures entail providing clear signage for flight crew and vehicle drivers, as well as ensuring ATCOs have a comprehensive and accurate traffic overview through high-quality surveillance. Moreover, safety nets are being introduced to promptly detect any runway incursions, allowing for a timely resolution of the issue [3]. In addition to other safety precautions, one approach to tackling runway incursions is the utilization of automated systems that can identify incursions or potential incidents and alert air traffic controllers, pilots, and vehicle drivers about such situations [4]. Conventionally, these systems rely solely on surveillance data, continuously monitoring the positions and movements of mobiles on and around runways. If a hazardous situation arises, they promptly issue warnings to the controllers. Such systems are referred to as Runway Incursion Monitoring Systems (RIMS) or Advanced Surface Movement Guidance and Control System (A-SMGCS) level 2 alerting systems [5, 6, 7]. More recently, by leveraging late technological advancements, a number of research have been conducted to introduce supplementary safety barriers aimed at mitigating potential risks associated with runway incursions and excursions, and other incidents and accidents

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involving aircraft at airports [8, 9, 10, 11, 12].
This paper, in particular, describes the experimental campaign conducted at the University of Bologna's real-time Humans-in-the-Loop simulation and validation platform to assess the implementation of eXtended Reality Runway Safety Nets in conventional airport control towers.

2. EXtended Reality Control Tower Concept: introduction of XR Safety Nets for attention capturing and guidance

In airport control towers, eXtended Reality can be exploited to overlay all the auxiliary information needed with the real-world data supporting the controllers during their operations without forcing them to continuously scan data on head-down displays and switch between the primary head-up out-of-the-tower visual field and the auxiliary head-down equipment [13], with a benefit in terms of workload and situational awareness [14], and lowering the risk of not detecting unpredictable situations [15, 16]. With the same aim of improved situational awareness, synthetic Safety Nets can be integrated with the out-of-the-tower view to guide the controller's attention toward alerting situations [17]. For instance, XR tools can be used to display alerts and warnings about potential safety risks superimposed onto the out-of-the-tower view, such as aircraft on collision courses or runway incursions, helping air traffic operators to quickly identify and respond to potential hazards, and take corrective actions in case of emergencies.
An operational concept for attention capturing and guidance through the usage of eXtended Reality Safety Nets based on visual and auditory cues in conventional airport control towers is developed for the simulated scenario of Bologna Airport in Italy.
In the proposed concept, the controllers are provided with head-mounted XR devices which enable the users to see all the necessary information, such as aircraft identification and tracking labels, weather information and aerodrome overlays, as superimposed to the primary out-of-the-tower window view. XR safety nets are then displayed through identification and tracking labels and directional alarms. Even if a first assessment of the developed solution is performed on a runway incursion triggered by an unauthorized runway inspection when the runway is already occupied by an aircraft, the same concept can be applied to several hazardous situation.

2.1 Simulation platform

Figure 1: University of Bologna simulation and validation platform at the Virtual and Simulation Laboratory in Forlì premises.

The campaign is conducted in the Cave Automatic Virtual Environment depicted in Figure 1, as a real-time human-in-the-loop simulation exploiting a simulation and validation platform encompassing all the components needed in order to integrate the following features.
Adaptive HMI and working positions: the exercise is conducted for two different working positions (i.e. Runway RWY and Ground GND Controllers). Two different points of view are tracked to customize the view for each one of the two controllers and therefore allowing the system to provide specific information based on working position, visibility conditions and flight status to the users;
Multimodal Interaction: the users can interact with the system by a combination of gesture and voice. Datalink

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messages (start-up, pushback, and departure clearances) can be issued by means of multimodal interaction [18];
Safety net: the V/AR overlays can be used to display safety warnings such as runway incursions and conflicting clearances.
The core of the platform is a 4D model of the reference scenario integrating all the data sources, able to manage events and respond to user inputs. This module communicates with five subsystems, namely, Out of the Tower View Generator (OOT), Ground Augmented Reality Overlay Application (GND App), Runway Augmented Reality Overlay Application (RWY App), Head Down Equipment (HDE) and Pseudo-pilot application (PP App). While the OOT provides the users with a consistent scenario of the out-of-the-tower view of Bologna airport, the GND and RWY Applications, tailored with respect to the user point of view and the specific information based on the working position, deploy the necessary AR overlays on two head-mounted Microsoft®HoloLens2 devices. The ATCOs can simultaneously see the out-of-the-tower view and the AR overlays (see Figure 2). The HDE is the same for the two controller working positions (CWP) and replicates in a simplified interface the actual HDE of the control towers. Lastly, through the PP App, the pseudo-pilot is able to update the state of the 4D model in accordance with the ATCOs instructions. Moreover, an additional interface (Datalink App) is present to allow the pseudo-pilot to reset the alarm after the controller acknowledges the safety event and takes the appropriate actions (Figure 3).

Figure 2: The ATCOs can contemporarily see both the out-of-the-tower view and the Augmented Reality Overlays through Hololens2. The personal view of the user during the XR Safety Net validation exercise is depicted in the green square.

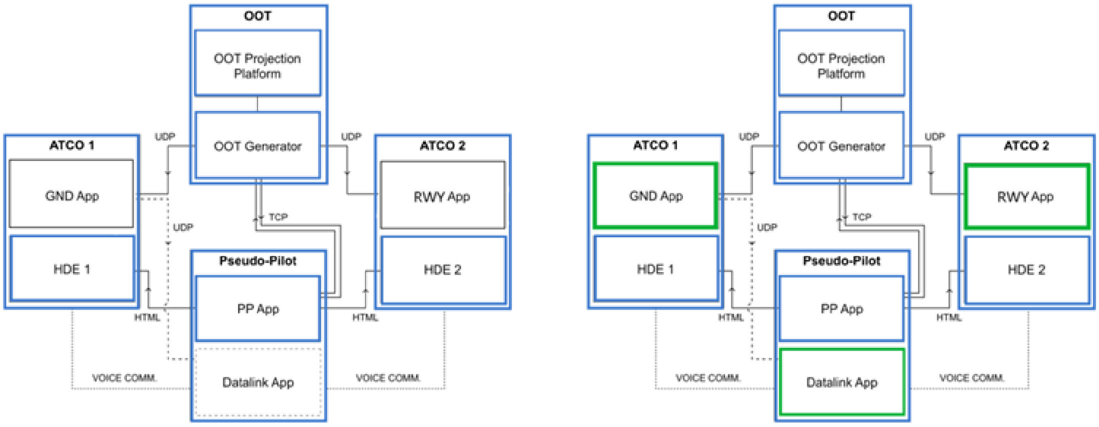

Figure 3: Validation platform architecture in reference scenario (left) and solution scenario with SN implementation for RWY controller (right).

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3. Validation exercise

The attention capturing and guidance given by the introduction of safety nets and directional audio sources in the novel HMI developed for the Bologna Airport scenario is assessed through a technical test. The validation technique to perform the specific validation campaign is a Real-time Simulation (RTS) with Humans-in-the-loop (HITL). In this case, the HITL concerns two controllers, namely Tower Runway and Tower Ground Controllers, and pseudo-pilots. Bologna Airport is chosen as a reference simulation scenario for the validation; it has a moderately complex layout (one runway, several taxiways, and more than one apron) with medium traffic (between 200 and 300 movements per day). Bologna is a single Runway (12 and 30) airport with a main taxiway T and several taxiways and aircraft stand taxilane. The runway has orientation 12/30 with an asphalt strip of 2803x45 m. To validate the concept, a safety event, specifically a runway incursion, is simulated in two different scenarios, reference and solution. Thus, if performance is influenced in either a positive or negative way, this can be attributed to the solution offered.

The *reference scenario* is a replica of the out-of-the-tower view of Bologna aerodrome including a simplified head-down display interface comprising weather information, Flight Duty Period, Approach Radar and Ground Radar. In the reference scenario, ATCOs operate with this basic equipment and with a traffic comparable in configuration and volume to the one used in the scenario including the technical solution.

The *solution scenario* adds to the out-of-the-tower view and baseline head-down equipment overlays of digital data tailored according to user operative position, gaze orientation and phase of flight. The digital information shown is meteo information, airport layout overlays, tracking labels with aircraft identification and status. Tracking labels are linked to the aircraft with a bar and can present two different colours, cyan for departures, yellow for arrivals. The information reported on the tracking lables are of two types, permanent (Call Sign and Afc Type/WCAT) and adaptive (EOBT, CTOT, Push Back, Taxi, Hold position, Take off for departure label and Distance from touch down, Altitude and Speed for arrival label). Moreover, the controllers are supported by the symbology developed for attention capturing and guidance: when an hazardous situation occurs, the labels of the involved aircraft turn to red and a directional alarm sounds. Given the reduced augmented field-of-view of the HMD devices, the audio cue is present to drive the attention of the controller if he/she is not looking in the direction of the XR safety nets.

To trigger the alarming event, the pseudo-pilot starts an unauthorized runway inspection when the runway is occupied by one of the take-off aircraft or when an aircraft has already obtained permission to land and its distance is less than 4 miles from the runway.

3.1 Participants and test execution

During the validations, each batch of exercises is repeated five times by five different teams of RWY and GND ATCOs. The average years of experience of the RWY controllers is 18.4 years, with a minimum of 6 and a maximum of 33 years. Two RWY ATCOs are between 30 and 39 years old, one between 40 and 49 and two between 50 and 59. Moreover, two of them are working at LIPE Airport, whereas the other three are currently working at LIPK, LIPR and LIPY Airports. When considering the GND controllers instead, the average years of experience of the GND controllers is 18.4 years, with a minimum of 10 and a maximum of 25 years. One GND ATCO is between 30 and 39 years old, three between 40 and 49 and one between 50 and 59. Four of them are working at LIPE Airport, whereas the other one is currently working at LIMF Airport. To allow the users to make a good comparison between the reference and solution scenarios and to assess the introduction of XR safety nets, during the validation exercise there is no rotation of the ATCOs between the two working positions. Although one ATCO only occupies one position, the total of five ATCOs in each controller position ensures a comprehensive assessment of the proposed concept. Within the validation exercise, the first run is always performed on a reference scenario including nine movements (6 departures and 3 arrivals) for a total amount of 30 minutes and it is followed by 30 minutes solution run with the same number of movements and meteorological condition. Even if the simulation platform allows for the representation of different visibility conditions, this particular exercise considers only good visibility conditions.

At the end of each run and of each exercise, the feedback from the ATCOs is collected to assess the validation objectives in specific key performance areas (KPA), in particular Human Performance and safety, and to determine if the solution success criteria have been fulfilled.

4. Results and discussion

To assess the introduction of XR Safety Nets in the HMI, different data are collected anonymously in the form of objective quantitative measurements derived by the platform (Head-up and Head-down time, number of switches head up/head down and time to react to the safety events) and subjective qualitative assessment such as workload, acceptability, trust, usability, human error, and user comfort obtained through questionnaires and/or interviews. Even if the

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aforementioned data are collected for both CWPs, this paper reports and analyses only the ones related to the RWY ATCO who is responsible for the provision of aerodrome control service in the Aerodrome Traffic Zone and on the runway where the hazardous events under investigation (runway incursion) take place. Table 1 shows the quantitative data collected during the validation exercise, the data are reported as average values of the five participants (with standard deviations in brackets). The first column reports the total time spent performing the exercise run, whilst the second and third columns report the time spent in head-up and head-down positions respectively. The fourth column shows the number of switches between the head-up and head-down positions and the last column indicates the time it took to the RWY ATCOs to react to the safety event. For the sake of clarity, the share of time spent head-down/head-up by the RWY ATCO in Reference and Solution scenarios is visualized in Figure 4, the number of switches between head-up and head-down position in Figure 5 and the time to react to the safety event in Figure 6.
The subjective qualitative measurements, namely Workload, Physical workload, Situation Awareness and acceptance level assessed, respectively, through Bedford Scale, 7 points Likert scale, China Lake and CARS scale questionnaires are presented in Table 2 and reported in Figures 7-9 with the relative threshold level.

Table 1: RWY ATCO: objective quantitative measurements. Average values of the five Reference and Solution exercise runs along with standard deviation (in brackets).

	Total time [s] (SD)	**Head-up time [s] (SD)**	**Head-down time [s] (SD)**	**N. of switches (SD)**	**Time to react [s] (SD)**
Reference	1694 (17)	809.2 (176)	884.8 (189)	338 (60)	14 (1.5)
Solution	1721 (32)	1269.4 (273)	451.6 (271)	238.8 (85)	9 (2.1)

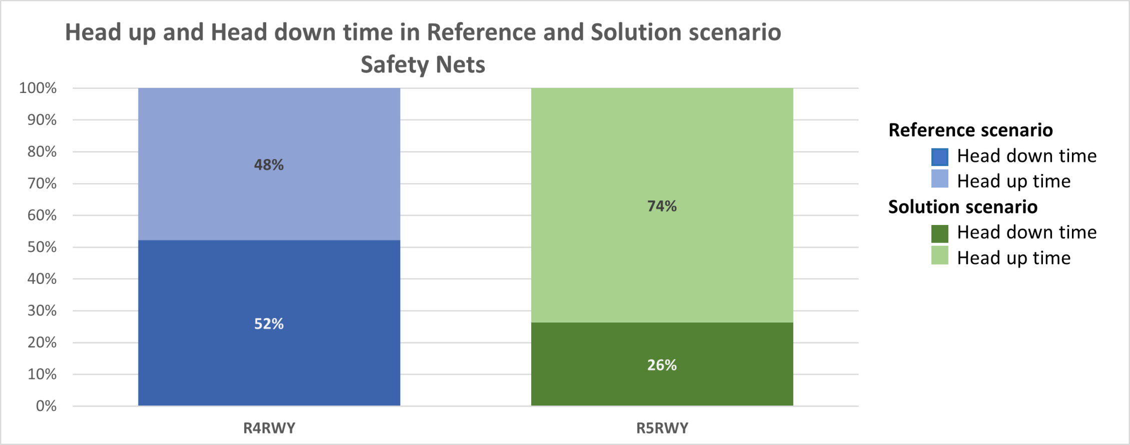

Figure 4: Share of time spent head-down/head-up by the RWY ATCO in Reference and Solution scenario. Average values.

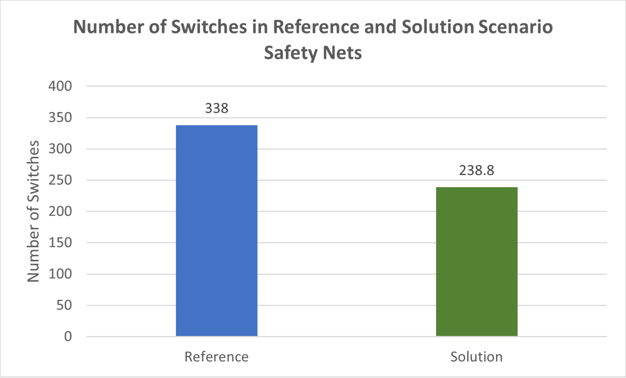

Figure 5: Number of switches between head-up and head-down position in Reference and Solution scenario. Average values.

The results of the laboratory test showed how the proposed prototype of an innovative Human-Machine interface for airport control towers encompassing XR safety nets is technically feasible. Moreover, assessing the results of

Figure 6: Time to react to a safety event in Reference and Solution scenario. Average values.

Table 2: RWY ATCO: subjective qualitative measurements. Average values of the five Reference and Solution exercise runs along with standard deviation (in brackets).

	Reference	**Solution**
CARS scale:Avg. acceptance level		7.8
Bedford Scale: Avg. Workload (SD)	2.5 (0.67)	2.3 (0.64)
Avg. Physical Workload (SD)	1.8 (0.75)	3.3 (1.49)
China Lake: Avg. Situation Awareness (SD)	8.7 (1.00)	8.6 (1.11)

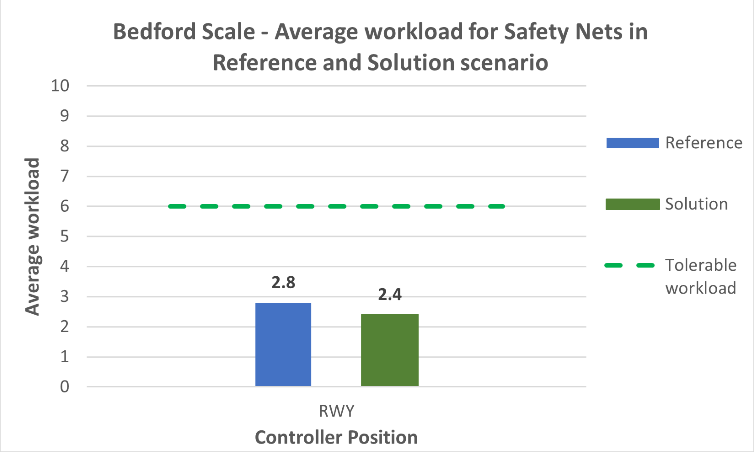

Figure 7: Bedford scale - Average workload in Reference and Solution scenario.

objective quantitative and subjective qualitative data, the solution proves to have an overall positive effect on human performance and efficiency of the controllers. Compared to the reference scenario, the technical solution provides a substantial increment of the time spent in head-up position looking at the out-of-the-tower environment rather than at the HDE. The data concerning head-down and head-up time are strictly related to the number of switches between the two positions. As can be observed in Table 1, with the introduction of the head-mounted device, the number of switches is significantly reduced. This reduction is particularly relevant since the continuous change of perspective on the same out-of-the-tower environment would lead to a decrease in situational awareness [19] and the possibility of not detecting unpredictable events.
The introduction of safety nets proves to be very helpful in reducing the time needed by the RWY ATCO to react to a safety event which was reduced by almost 65% in the solution scenario with respect to the reference one (See Figure 6). It worth noting that the time needed to react not always reflects the one to notice the event. As a matter of fact, in some cases even if the time to take actions was almost the same in reference and solution scenarios, the time to notice the runway incursion was drastically reduced in the solution scenario.

The results of the qualitative assessment of the simulation related to the Attention Capturing and Guidance feature demonstrate how the proposed concept solution is highly appreciated. Although the results of the CARS scale

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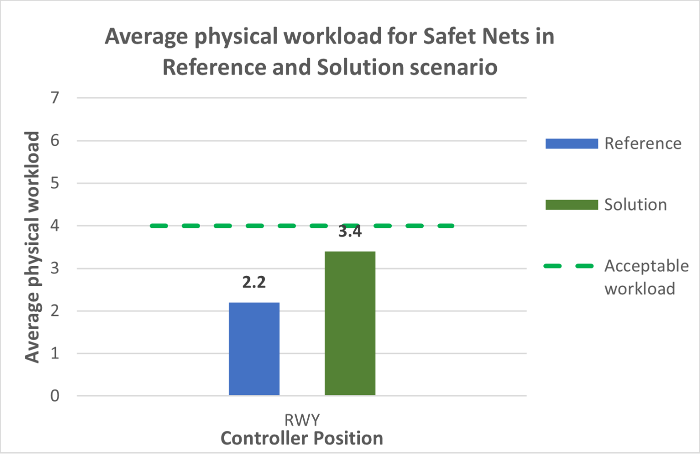

Figure 8: Average physical workload in Reference and Solution scenario.

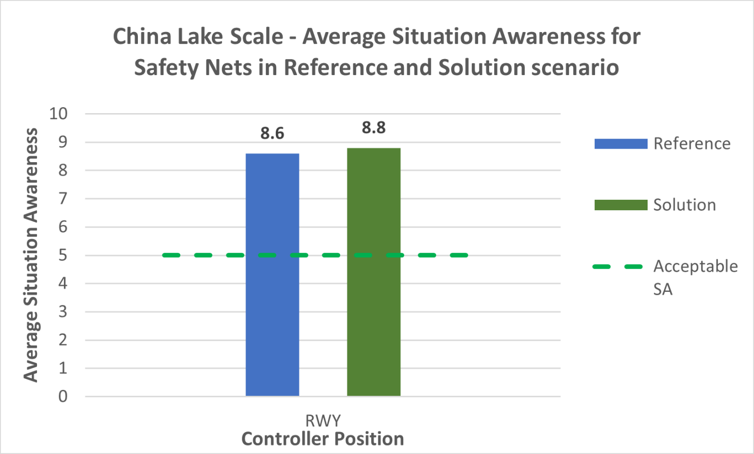

Figure 9: China Lake Scale - Average situation awareness in Reference and Solution scenario.

demonstrate that the concept is highly acceptable (7.8 out of 10), its implementation still needs to be further improved to be fully acceptable. Nevertheless, some ATCOs mentioned that the level of acceptance might depend on the age and experience of the ATCO.

Looking at Figure 7, it is possible to see how the introduction of XR Safety Net positively influenced subjective workload which is reduced with respect to the one experienced in the reference scenario and is well below the threshold level.

The physical workload, instead, despite being within the acceptable level, is increased in the solution scenario (Figure 8). According to the controllers, the negative impact of the solution on the physical workload is due to the usability and ergonomics of the specific XR head-mounted device.

Lastly, the safety net tool was said to benefit Situational Awareness, since it helped the ATCOs to immediately recognise a hazard as can be seen in Figure 9.

On the overall, the ATCOs were very positive about the attention capturing and guidance tool, indeed all the five RWY ATCOs agreed that the proposed Safety Nets should be persevered given the benefit in terms of perceived Human error and level of safety. Almost all ATCOs agreed that the system helped them in the early detection of critical situations and the acoustic cues guide their attention. Moreover, because both ATCOs (ground and runway) receive the notification, there is no need to communicate it and the team Situational Awareness is enhanced.

5. Conclusions

This paper introduces the concept of an innovative Human-Machine interface for conventional airport control towers and describes the exercises conducted to validate the developed technical solution to demonstrate how eXtended Reality, along with Tracking Labels and Safety Nets, enables a more natural and effective interaction in control tower

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improving on one hand the performance and on the other hand the situational awareness of the Air Traffic Control Operators.
As expected, the results show that the prototype concept developed is feasible from both an operational and technical perspective. The proposed solution proves to support the ATCO in working in a head-up position more than in a head-down and to lower the time to react to critical or alerting situations.
Overall, the implemented HMI has a positive impact on the human performances of the users; feedback from the ATCOs showed that the prototype supports controllers in maintaining an acceptable level of workload, (team) situation awareness, potential for human error, trust, acceptance, job satisfaction, and perceived safety. Nevertheless, in the future, a further improvement of these factors could be achieved by increasing the synthetic field of view, currently limited to the one of the XR device, and enhancing the label design and positioning following the suggestion of the air traffic controllers collected during the validation campaign.
Coming to the XR Safty Nets, additional test should be performed analysing different situations (e.g. Conflicting ATC Clearances) in different visibility conditions, and differentiating between warnings, to be used to inform the controller of a potential hazardous situation, and alarms to inform the controller of critical situation that requires immediate action. Lastly, to evaluate the actual benefit of the proposed solution, the exploited technology should be evaluated against a reference scenario encompassing safety nets already available in the head-down equipment of some airports.

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