

AUGMENTED REALITY SAFETY NETS FOR INCREASED AIRPORT SAFETY

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Abstract

This paper presents the development and preliminary validation of an Augmented Reality (AR) interface for presenting Safety Nets (SN) in the airport control tower. Building on previous research conducted at the University of Bologna within the RETINA and DTT projects, the proposed solution transfers the concept from a simulated environment to a real-world platform based on a Microsoft HoloLens 2 device and a live ADS-B surveillance feed. A positional SN system has been developed to detect runway incursions and other conflicts using aircraft position data and airport geospatial information. The interface integrates visual and auditory attention-guidance mechanisms, including colour coding, directional arrows, spatial audio cues, and runway highlighting. The system has been technically validated by reproducing real traffic scenarios and subsequently deployed at Bologna Airport in shadow mode to assess its behaviour under operational conditions and to collect preliminary feedback from air traffic controllers. Preliminary results show that ADS-B data are sufficiently reliable for implementing a positional SN concept and that the proposed AR interface is considered useful and acceptable by controllers. The work represents a first step toward integrating advanced safety-net services into an operational AR platform for airport control towers.

Keywords: Augmented Reality, Safety Nets, Airport Capacity, ATM, Human Factors

1. Introduction

Over the past decade, research at the University of Bologna (UNIBO) has focused on the introduction of Augmented Reality (AR) in the airport control tower [1] for the benefit of the air traffic controllers and the general Air Traffic Management infrastructure, in terms of increased safety and performance, with a reduction of the controllers' workload and an increase of their situational awareness. Following the progress of an AR interface for aerodrome traffic management, the research continued to assess which surveillance concepts could be most effectively transferred from conventional head-down interfaces to the AR human-machine interface. This paper aims to describe the work performed at UNIBO on an AR interface for Safety Nets (SN), presenting the results obtained over the years, starting from two SESAR (Single European Sky ATM Research)-funded European projects and collateral work, till a recent validation campaign, which first assessed the concept in an operational environment.

1.1 Augmented Reality for the Airport Control Tower

In the current air traffic management system, the airport is often considered the "bottleneck" of the air traffic flow, particularly when ground movements are limited, as in low-visibility conditions. Since minimising the occupation of the runway means serving more aircraft with the least possible delay, solutions to safely reduce separation minima and, consequently, maximise runway throughput have been investigated over the years. However, in conditions such as low visibility, operations are highly limited by safety procedures. Meanwhile, expedited operations increase the controllers' workload while challenging their situational awareness [2], and an increasing number of surveillance tools worsen this trend, despite helping retain overall operational safety. Hence, research is constantly seeking solutions to support air traffic controllers and pilots in re-establishing a high level of situational awareness while reducing workload.

In this context, work at the University of Bologna focused on an Augmented Reality (AR) solution to help the controllers working mainly in a head-up position by means of a synthetic overlay that superimposes all surveillance information onto the airport tower's out-of-the-window (OTW) view, instead of forcing the operators to continuously shifting focus between their head-up OTW view and the head down Controllers Working Position where traditional HMI providing surveillance information are placed, a condition known to

have a high negative impact on both physical and cognitive workload, and thus on performance and at the end on the overall safety of operations [3]. This concept was mainly developed through the European SESAR-funded RETINA (exploratory research) and DTT (industrial research) projects – spanning approximately 2016 to 2022 –, which brought the solution to a technology readiness level 4 (TRL4). RETINA [4], coordinated by UNIBO, compared multiple AR technologies and developed a prototype to evaluate both Spatial Displays (SDs) and Head-Mounted Displays (HMDs). The AR HMI included rectangular, colour-coded labels that pinpointed each aircraft's position while displaying the relevant surveillance information for the corresponding flight. DTT followed RETINA with a larger consortium researching multiple solutions for airport digitalisation. Solution 97.1 [5] of the project focused on AR for the control tower, with an exercise run at UNIBO expanding on research in RETINA and focusing on multiple control positions, multimodal interaction, and seamless variation in weather conditions. Based on the RETINA outcomes, only the HMD was considered suitable for the proposed tasks, leading to the selection of a Microsoft HoloLens 2 device for DTT research development and further iterations.
These projects were carried out through fully controllable, human-in-the-loop (HITL) real-time simulations at the Virtual Reality and Simulation Lab of the University of Bologna, featuring a faithful view of Bologna Marconi Airport (ICAO code LIPE) from the control tower and a complete working reproduction of the controller's head-down interfaces at the CWP. Given the project's maturity, researchers are currently addressing the transfer of the developed concept into the real world [6] while maintaining a User-Centred Design (UCD) approach, thereby exploiting feedback on the AR interface's logical and graphical/semantic design to create a better real-world prototype.
As a shared ground for the development, the Bologna airport has been selected as a reference scenario due to the presence of primary and secondary surveillance radar, surface movement radar, low visibility procedures (often in place) that allow for managing more than one aircraft at the same time, ILS CAT IIIB, moderate complexity of the layout and moderate traffic (200/300 movements per day). Moreover, the proximity of the airport to the University of Bologna enables on-site testing campaigns required at the current stages of the research.

1.2 Augmented Reality Safety Nets

In light of global foresight for continually increasing air traffic volumes, research and industrial development for airports have consistently pushed toward greater runway capacity and minimised separation, leading to increased risk of collisions, incidents, and accidents across the airport ground and vicinity. As a mitigating solution, the SESAR – Single European Sky ATM Research – consortium developed the concept of Safety Nets (SN). These novel surveillance systems provide multiple supporting functions, such as conformance monitoring (e.g., adherence to airport procedures or to approved flight plans) and the detection of conflicting air traffic control clearances. While some of these functions are implemented within advanced surface movement guidance and control systems (A-SMGCS [7]), Safety Nets more generally rely on operational data from radar sensors, ADS-B, and aeronautical dynamic databases, which contain information such as flight plans and calculated take-off times. By continuously processing this information, Safety Nets help controllers identify hazardous situations in advance and support timely interventions.
One outcome of the RETINA validations campaign was the likely benefit of introducing an AR interface for visualising SN in a head-up position. The A-SMGCS HMI displays environmental and traffic information, including position and identification, via bird's-eye-view maps with labels. While this helps distinguish among aircraft, having visual guidance to the event in the OTW view may reduce reaction times without losing the mental picture of the traffic, both of which are fundamental during a critical event.
Thus, research at UNIBO started from the AR label design resulting from RETINA, aiming to develop the most beneficial design for presenting a SN-triggered event to the controller. A preliminary investigation evaluated the Services offered by A-SMGCS, focusing on Conflicting ATC Clearances (CATC), a predictive tool that assesses whether air traffic controllers issue multiple clearances within a line-up, crossing, landing, or take-off clearance, resulting in a hazard. While the preliminary study was conducted in a virtual static test environment (only providing a rendered picture of the interface under a specific operating condition) rather than with HITL simulations, it was intended as a first iteration of a User-Centred Design, with 40 controllers evaluating a single test case of line-up against take-off conflicting clearances. The simple case simulated the conflict without relying on a conformal SN system, focusing more on the interface design (colour coding for aircraft labels) and proposing two graphical solutions for information alerts (potential hazard) and alarm alerts (critical information that requires immediate action), as shown in Fig. 1. The results

highlighted several concerns in the design, especially regarding the selected colour coding. Still, the distinction between warnings and alarms was well received, as was the concept of presenting the SN in a head-up manner.



Figure 1. Test case presented to operators for an alarm trigger. Static interface representation in the Unity game engine editor.

Building on the potential of these results, the UNIBO DTT exercise [8] included a small validation of the SN, with 10 air traffic controllers evaluating a simple test case in which the Safety Car vehicle initiates a runway inspection without Air Traffic Control clearance, thus resulting in a runway incursion. This experiment was included in the UNIBO exercise's HITL validations, refining the SN design and incorporating the concept into the HMD AR interface under real-time simulation conditions. The laboratory tests showed that the V/AR prototype with Safety Nets improved operational performance and perceived safety. The primary measured metric was reaction time to the event, which was reduced by about 35% (from an average of 14.2 seconds to 9.2 seconds) compared to the same case in a reference scenario without the HMD AR interface. Such a reduction is highly beneficial for hazard prevention and resolution, as a runway conflict can result in an accident within a short, finite time [9]. Moreover, all ATCOs agreed that the Safety Nets reduced the potential for human error and supported the early detection of ATC critical situations. More than 75% of the participants considered the alerts effective and not intrusive. However, little information was collected on quantitative changes in situational awareness.

It is worth noting that a different exercise [10] within the DTT project, conducted by NLR in their NARSIM 360° simulator of Schiphol Airport, focused on capturing and guiding controllers' attention in response to critical events detected by the SN system integrated into the simulator. The experiment, which exploited an A-SMGCS fully conformant with the real one in use at Schiphol, was validated by two controllers.

Following DTT, the research on AR Safety Nets at UNIBO expanded, focusing on the Short-Term Conflict Alert service of A-SMGCS and evaluating a greater number of runway incursion cases than before – landing/take-off against landing/take-off and Safety Car incursion – triggered by vehicles moving without a controller's clearance. The application, based on the same platform used for DTT, implemented the previous feedback on the system design (especially correcting the runway and label colour changes during an SN event and the restoration of operational conditions once the event ends), and aimed to assess when to prefer warnings over alarms. The developed AR interface was subjected to a technical test involving one air traffic controller, whose feedback, despite suggesting some relevant changes, was favourable to further development of the concept (Fig. 2).

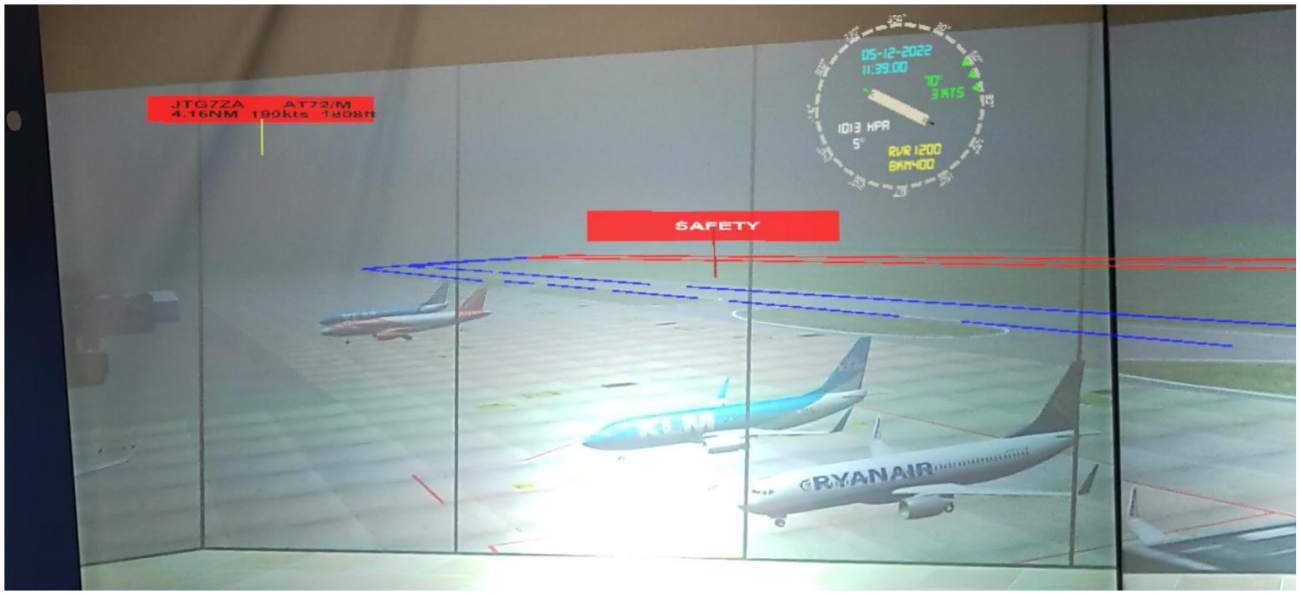


Figure 2. Safety car incursion while arrival traffic near the runway. Implementation in the full-scale simulator with HoloLens 2 providing the AR overlay.

Following these results, a broader validation, including a larger number of controllers, should be performed, since the previous study considered a minimal number of controllers or very simple test cases. Meanwhile, as a real-world prototype of the AR platform is being developed, the AR SN concept will be transferred to this domain, addressing the challenges and requirements of using real-world data and necessitating a novel definition of the system logic.

1.3 Validation of the concept in an operational environment

Exploiting the technology already adopted for the real-world AR prototype platform, the SN could be based on Automatic Dependent Surveillance – Broadcast (ADS-B), a cost-effective surveillance sensor suitable for research, as it allows the receipt of precise telemetry data directly from the aircraft without accessing the closed ATM data network. While ADS-B data alone are less accurate and reliable than an A-SMGCS system and don't include flight data such as clearances, over the past few years, multiple FAA and SESAR solutions have addressed the use of ADS-B with other sensors for the SN [11, 12]. In Europe, the SESAR Enhanced Ground Controller Situation Awareness in all Weather Conditions [13] project's solutions are already deployed at multiple airports, and ADS-B is becoming increasingly relevant in the ATM surveillance infrastructure.

While clearance monitoring would not be available in this scenario, an ADS-B SN prototype can be designed to focus on runway incursion and non-conformal behaviour detection, integrating known airport procedures such as taxi routes, separation minima, line-up sequence, taxiing speed limits, etc. This would include some SN events not considered in previous research at UNIBO, while testing the attention guidance and alert mechanisms with real-world data and preparing the interface for a possible future feed of A-SMGCS-derived data.

1.4 Research questions

In developing an ADS-B-based SN system, several questions arise regarding the interface design, the real-world data feed, and the technical feasibility of the concept. Hence, the proposed research question concerns, first, the conformance of the developed system with the expected behaviour, and the integration and execution of technical tests for all the considered hazards. A second research question concerns the acceptance, perceived usefulness and usability of the proposed AR Safety Net interface among operational air traffic controllers. In particular, the study investigates whether the proposed interaction techniques effectively support situational awareness and are considered suitable for operational use under real environmental conditions, by means of video recordings and questionnaires submitted to controllers. Finally, a question aims to investigate whether the ADS-B alone is a suitable surveillance sensor for feeding the SN system, and, more broadly, how the interface behaves with a real-world live data feed, including physiological disturbances in the signal.

2. Experiment design

2.1 The real-world platform

The AR application prototype for the real world runs on a HoloLens 2 device and receives real-time aircraft surveillance data from an external ADS-B receiver through a UDP connection. The messages received are decoded and stored in a local database that contains the most up-to-date information for each detected aircraft. A calibration procedure aligns the device reference frame with global coordinates, enabling aircraft positions to be correctly registered in the physical environment. Aircraft geodetic coordinates are converted to a local East-North-Up frame and then transformed into the headset's virtual reference frame. For each tracked aircraft, the application renders a holographic label anchored to its estimated real-world position. The label consists of a small sphere pinpointing the aircraft's position, connected to a canvas above that displays surveillance information, including callsign, altitude, speed, and heading/reference runway. Labels are rendered at a constant focal distance from the user to improve readability and reduce visual discomfort. Colour coding is adopted to distinguish arriving and departing traffic. The holograms are updated continuously at the device's rendering frequency and whenever new surveillance information is received, ensuring that aircraft information and positions remain synchronised as the user moves within the environment. The solution had already been tested twice at the Marconi airport [14], collecting precious feedback for design refinement (Fig. 3).



Figure 3. AR interface for real-world operations. Colour coding is adopted for departures (cyan) and arrivals (yellow).

2.2 Safety Nets operational concept and interface design

The developed ADS-B-based SN is built on the aforementioned real-world application and primarily relies on positional data. The airport map is integrated into the system by identifying all airport sectors (runways, aprons, taxiways, and gates) and holding points using geodetic coordinates. Using GNSS coordinates obtained from ADS-B, each aircraft's position within the airport sectors can be identified, and by analysing aircraft movement, it is possible to determine when an aircraft enters a sector and its route through different sectors. Comparing data from different aircraft and from the same aircraft in subsequent instants, it is possible to identify when a hazard may occur, for example, when an aircraft crosses the “runway ahead” holding point while another is landing and is already too close to the runway. Separation rules are considered to identify non-conforming behaviours. All cases of a runway incursion have been considered (including all possible combinations of take-off, line-up, and landing conflicts). This “positional” SN don’t consider the controller’s provision of clearance, thus having limited capabilities with respect to a full A-SMGCS implementation. However, this choice is coherent with the availability of data from ADS-B or radar systems, which is the case at the Bologna airport, as well as in most mid-sized airports, where digitalisation of the controllers' clearances (through an electronic flight strip system) is not available, and clearances are mainly provided through voice communications. With respect to the full set of SN still possible to implement based on ADS-B data, only those related to any conflict occurring within the active runway have been

considered. This is because the main focus of the study presented in this paper is on the feasibility of ADS-B as a source of surveillance data alone and on the initial evaluation of the proposed AR HMI design and behaviour before extending and thoroughly testing a more complex set of triggering conditions, which could be better addressed in a simulated environment. The developed prototype, therefore, focuses on the behaviour of the safety nets and their interaction modalities, with the objective of assessing whether the proposed design can effectively support controllers in their activities and identifying possible improvements or modifications. Furthermore, to facilitate interface evaluation, conservative triggering conditions were adopted, leading some safety nets to activate in situations that would not necessarily constitute an operational hazard. Since hazardous runway events are fortunately rare during normal airport operations, these conservative triggering thresholds were intentionally adopted to ensure that warning and alarm conditions could be observed repeatedly during the experimental campaign. This allowed the complete interaction sequence of the proposed interface to be evaluated, including visual highlighting, directional guidance, acknowledgement mechanisms, and audio feedback, providing representative material for both the on-site direct user evaluation and the subsequent video-based questionnaire administered to additional controllers.

As for the design of the data presentation (Fig. 4), feedback from previous experiments conducted at UNIBO has been integrated to build the real-world platform. For both warning and alarm conditions, the labels of all aircraft involved in the conflict are highlighted using specific colour coding: orange for warnings and red for alarms. In addition, two directional arrows are displayed to guide the controller's attention towards the area where the conflicting traffic is located whenever it falls outside the current field of view. In the alarm condition, a spatial audio warning is generated from the direction of the hazard to provide an additional cue and facilitate the identification of the conflict source. The audio alert is automatically deactivated after 10s or immediately after the operator acknowledges the event by selecting one of the labels associated with the conflict directly in the AR interface. The same interaction also removes the directional arrows while preserving the visual highlighting of the traffic's labels involved. Once the conflict condition no longer exists, all visual and auditory cues are automatically removed, and the labels return to their original colour coding. In addition, the same colour coding is applied to an overlay which highlights the runway boundary. This overlay is normally turned on only in low-visibility conditions but automatically appears during an SN event, providing clear information about the current situation. When the SN event ends, the runway turns off its nominal colour (white if free, yellow if in use for landing, and cyan if in use for take-off), or disappears, depending on its current status.

The interaction techniques described above constitute the complete set of interface elements evaluated during the User-Centred validation presented in Section 3, where both direct interaction with the prototype and video-based assessments were employed.



Figure 4. Safety Net alarm event for aircraft entering the runway while it is already occupied. The involved labels are red, as is the runway, and an arrow guides the controller toward any out-of-sight aircraft. The picture is a reconstructed view of the user's view, captured by the HoloLens 2's built-in camera.

3. Methods

3.1 Conformance monitoring of the interface behaviour in a virtual environment

For the technical test, a data simulator has been developed that reproduces real ADS-B traffic feeds from Bologna airport, preserving the original data flow. Using some Matlab scripts, the ADS-B data for different aircraft are separated, appropriately processed, time-shifted, and joined, creating ad-hoc traffic scenarios that can be reproduced while preserving each aircraft's original message time flow, triggering warnings and alarms in the AR interface for preliminary tests. The recreated scenarios include all the considered SN events and can be run directly in the Unity engine Editor, where the HoloLens 2 application is developed (Fig. 5). The testing involves all the features of the HMI: runway overlay activation, colour coding, acoustic alarm, out-of-sight arrow cues, automatic return to nominal conditions, and the use of gestures [15] to deactivate arrows and the acoustic alarm.

This approach allows the use of actual data previously recorded with the same antenna and downlink pipeline later used in on-site testing. This guarantees that the data are representative of real-world conditions that may influence SN triggering. In particular, missed ADS-B messages due to antenna limitations or message jamming in the airport area, degraded messages, and other performance reductions in the telemetry system may affect SN triggering, and using real, possibly degraded telemetry helps test for conformal behaviour under real operating conditions.

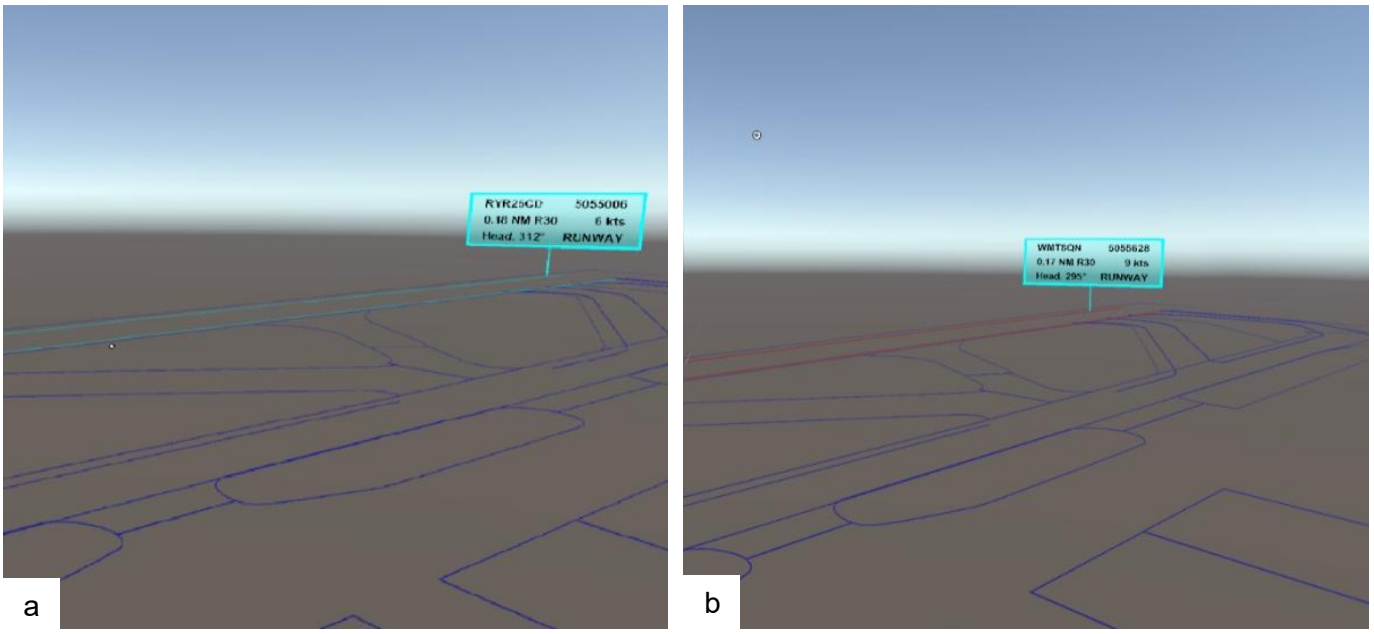


Figure 5. Test of Safety Nets in the development environment using recorded real data inside the Unity engine's editor. (a) Normal conditions during a take-off run. (b) Safety Nets (red runway overlay) are activated when a conflict is detected.

3.2 UCD evaluation of the proposed interface

A User-Centred approach is needed to evaluate the system through an HITL validation involving controllers, and to use debriefings and questionnaires to assess the interface design. Since SN triggers are luckily rare in the real world, two validation methods have been evaluated. The first one was to reproduce the ADS-B SN behaviour in the simulator used for RETINA and DTT, and perform a validation campaign with a large number of controllers. This would require minor adaptations to the previously tested interface, implementing SN trigger scenarios in accordance with those implemented in the real world using ADS-B data (positional SN). In addition, the airport digital scenario in the simulator has recently been updated to reflect the latest work on the physical airport.

However, this approach doesn't provide a full understanding of the controller's behaviour under real environmental conditions, including lighting and environmental noise. It was preferred to initially focus on a validation campaign conducted in shadow mode in the real world to assess the reliability of the ADS-B feed and to obtain the controller's feedback on the proposed interface under realistic operational conditions, including lighting, visibility, and traffic scenarios. In this way, the usability and efficacy of the proposed

interface could be assessed under more realistic conditions before a large validation campaign. As a drawback, since SN events are fortunately extremely rare under operational conditions, generating them required considering airport procedures with increased minima to trigger them under normal traffic conditions. With respect to the normal behaviour of the interface, it was thus chosen to trigger an information warning whenever arrival traffic was detected below 8NM for the runway threshold, with other traffic on the runway or approaching the runway beyond the *runway ahead* holding point. In the same way, an alarm was planned to trigger when the landing traffic was within 5NM of the threshold, if the runway was already in use. As an additional condition, an alarm was triggered whenever an aircraft crossed the *runway ahead* holding point with the runway occupied by another aircraft. For onsite validation and video recording, the interface was deployed on a HoloLens 2 in Bologna's airport control tower.

3.3 Usability evaluation with recorded videos and structured questionnaires

Given the User-Centred Design approach adopted throughout the project, the proposed interface was evaluated through both qualitative observations and a structured questionnaire completed by operational air traffic controllers, in addition to the technical conformance testing conducted directly by the researchers. Direct experimentation with the prototype by many controllers was not feasible because the validation campaign was conducted in shadow mode within an operational control tower, where only a limited number of personnel could interact directly with the HoloLens 2 device without interfering with airport operations. To allow a broader evaluation while preserving operational safety, the experimental sessions were recorded directly from the HoloLens 2 point of view. The recorded videos reproduced the complete behaviour of the interface during different Safety Net events, including warning and alarm conditions, activation and acknowledgement mechanisms, colour coding, directional arrows, runway highlighting and spatial audio cues. The videos were then shown to additional operational controllers, who evaluated the proposed interface using a structured questionnaire on a five-point Likert scale and complemented their responses with qualitative observations collected during the debriefing sessions.

3.4 Quantitative metrics for usability evaluation

A sample of six operational air traffic controllers (N=6) participated in this phase. This sample size is consistent with standard methodologies for formative usability evaluations involving highly specialised domain experts, where small groups are mathematically proven to uncover the majority of core UI flaws and layout mismatches [16].

To robustly analyse 5-point Likert-scale questionnaire data without relying on large-sample assumptions, descriptive statistics were extended using advanced small-sample inferential methods [17]. For each questionnaire item, the arithmetic mean

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

was calculated to estimate the overall appreciation of the proposed solution. The variability of the responses was evaluated through the sample standard deviation

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

while the degree of agreement among participants was quantified through the coefficient of variation

$$CV = \frac{SD}{\bar{x}}$$

which expresses the dispersion relative to the average score. Following the recommendations for usability metrics, coefficients of variation below approximately 15% were considered indicative of high consensus among participants [18].

Finally, because the number of respondents was lower than thirty, confidence intervals were computed using Student's *t*-distribution. The confidence interval was calculated as

$$CI = \bar{x} \pm t_{0.975,n-1}\frac{SD}{\sqrt{n}}$$

for an α value of 0.05, allowing robust estimates of the observed average values despite the limited sample size. In particular, the 95% Student's t lower bound

$$CI_{low} = \bar{x} - t_{0.975,n-1}\frac{SD}{\sqrt{n}}$$

was isolated and utilised during the analysis as a conservative, worst-case estimate of user acceptance. This combination of quantitative metrics and qualitative observations was adopted to provide a comprehensive assessment of the proposed interface before conducting a larger-scale Human-in-the-Loop validation campaign.

4. Results

4.1 Technical conformance of the SN trigger mechanism

The prototype application, including all the runway incursion cases, has already been validated for technical conformance, demonstrating reliable behaviour in triggering the updated SN graphical presentation and releasing it when the conflict is resolved. The application has been tested against existing procedures for line-up, take-off, and landing separation. In doing so, the conformance of the data feed application has also been validated. The application's behaviour confirmed the feasibility of a real (non-ideal) ADS-B data feed for reliably triggering the SN system.

Similarly to the simulator-based experiments, the interface proved reliable in the real-world environment, and the safety nets always behaved as expected, without missed activations or false alarms. In particular, the experimental campaign at the Bologna airport verified the airport geodetic coordinates used to define runways, taxiways, aprons, and holding points, confirming the correct alignment between the virtual overlays and the real airport environment. User interactions based on HoloLens 2 gestures also performed reliably, and all interface elements, including the spatial audio cues, operated as intended, both when tested by researchers and by air traffic controllers.

The most frequently observed alarm condition during the tests was a line-up on an occupied runway after a landing. This situation occurs relatively often in operational practice, as a conditional line-up without take-off clearance is common, and take-off clearance is usually issued as soon as the runway becomes available. This scenario allowed repeated observation of the alarm condition when the holding point was crossed while the runway was still occupied. Warning conditions were more commonly generated when a departing aircraft had not yet vacated the runway, and an arriving aircraft approached within the predefined threshold distance from the runway (Fig. 6).



Figure 6. Warning SN event, triggered with runway occupied and inbound traffic between 8 and 5 NM.

4.2 On-site feedback from the air traffic controllers

Once the application's functional conformance had been verified, the interface was evaluated by a few controllers who were not actively providing air traffic services at the time. The collected informal feedback was generally positive and confirmed the perceived usefulness of the proposed interface. The main concerns regarded visibility conditions and the possibility of increased visual clutter, issues that had already emerged during previous experimental campaigns conducted in the control tower.

One controller, in particular, conducted an extended evaluation of the application and found the interface particularly useful for presenting safety-net alerts. The controller also noted that the proposed warning mechanism is consistent with existing operational practices, in which runway occupancy during safety-car inspections is already communicated through head-up visual and acoustic cues. Interestingly, multiple controllers suggested further increasing the salience of both the audio warning and the visual indicators to ensure prompt detection and response to hazardous situations. This result was somewhat unexpected, as controllers often report concerns about the intrusiveness of highly salient alerting interfaces.

The directional audio cue and the use of directional arrows were generally appreciated, as was the option to dismiss these cues after acknowledging the event, a preference that had already emerged in previous full-scale simulator experiments. However, some aspects of the interface were identified as requiring further improvement. In particular, the mechanism used to display the directional arrows when the labels are outside the user's field of view was found to be occasionally cumbersome and imprecise, causing the arrows to remain visible for longer than necessary or to become excessively large and overlap with labels and other interface elements, thereby increasing visual clutter. Furthermore, the current projection mechanism, which causes the arrows to move along orbital planes around the user, could be refined to provide smoother, more precise guidance.

4.3 Questionnaires results

The quantitative analysis of the questionnaires, regarding video recordings of the operator's view under different operational conditions involving safety nets, confirmed a remarkably high level of acceptance and consensus across the majority of the evaluated design dimensions, verifying that the positional Safety Nets (SN) framework behaves intuitively under real-world data constraints (see Tab. 1).

For situational awareness and visual clarity, the system achieved near-perfect evaluation scores. The item assessing the overall clarity of the interface operations (including labels, colour-coding, and telemetry) returned a Mean ($\bar{X}$) of 4.83 with a Standard Deviation (SD) of 0.41, translating to an exceptionally low Coefficient of Variation ($CV = 8.4\%$). This falls well below the 15% consensus threshold [18], proving that the information architecture is highly unambiguous. Similarly, the colour-coding strategy for warning (Orange: $\bar{X} = 4.67, SD = 0.52, CV = 11.1\%$) and alarm conditions (Red: $\bar{X} = 4.83, SD = 0.41, CV = 8.4$) was unanimously validated. The 95% Student's t lower bound for general clarity sits securely at $CI_{low} = 4.40$.

Attention-guidance features were highly praised. Both the synchronous colour-shift of conflicting aircraft labels and the off-screen tracking arrows achieved an identical score of $\bar{X} = 4.83, SD = 0.41, CV = 8.4\%, \mathrm{CI} = [4.40\text{-}5.00]$. This indicates that the AR overlay effectively resolves the physical bounds of the control tower window and the controllers' view, optimising their overall awareness. The 3D spatialized audio cue was also recognised as highly useful ($\bar{X} = 4.67, SD = 0.82$), though it exhibited slightly higher dispersion ($CV = 17.5\%$), pointing out that while the spatial sound concept is approved, the specific auditory timbre requires localised tuning.

As for the technology acceptance, the perceived operational utility of the safety nets was strongly validated ($\bar{X} = 4.67, SD = 0.52, CV = 11.1\%$), confirming that the tool is recognised as a genuine barrier against airport risks. At the same time, good results were observed for system desirability (*'Overall, would you like to have the AR interface available for safety nets?')*. This item yielded a very good score ($\bar{X} = 4.5, SD = 0.55, CV = 12.2\%$)**,** indicating strong practitioner enthusiasm for adopting the tool.

However, notable exceptions to user consensus emerged in two specific items where the CV exceeded 30%. A critical review of the dataset isolates two items tied for the lowest score ($\bar{X} = 3.67$), exposing a lack of full consensus on ergonomic and interaction behaviours. First, the item assessing whether *'the overall design of the label (position, colour, shape) is satisfying'* yielded an SD of 0.82 and a lower confidence bound of 2.81, suggesting that the precise graphical layout requires further iterative tuning. Second, the statement *'I would prefer that, once I acknowledge the safety net, the labels return to their nominal colour immediately'* triggered severe statistical polarisation ($SD = 1.21, CV = 33.0\%, \mathrm{CI} =$ [2.40 - 4.94]). This high

variance proves there is no uniform agreement on the alert lifecycle: some controllers prioritise an immediate visual cleanup to minimise screen clutter, while others mandate that alert colours persist as long as the conflict is active.

Table 1. Interface usability questionnaire results

Questionnaire Statement	Mean ($\bar{X}$)	SD	CV	95% Confidence Interval (CI)
The overall design of the label (position, colour, shape) is satisfying.	3.67	0.82	0.222680886	[2.81 - 4.52]
The activation and release mechanism for Alarm (red) labels is clear.	4.33	0.52	0.119168718	[3.79 - 4.88]
The activation and release mechanism for Warning (orange) labels is clear.	4.33	0.52	0.119168718	[3.79 - 4.88]
The interface clearly indicates when a Warning or Alarm is triggered.	4.5	0.84	0.18592445	[3.62 - 5.00]
The colour used for the Alarms labels (red) is appropriate.	4.83	0.41	0.084465164	[4.40 - 5.00]
The colour used for the Warnings labels (orange) is appropriate.	4.67	0.52	0.110656667	[4.12 - 5.00]
I find it useful that a sound signal guides me to the source of the danger in case of an immediate threat.	4.67	0.82	0.174963553	[3.81 - 5.00]
The sound used for Alarms is appropriate.	4.17	0.98	0.235966099	[3.13 - 5.00]
I find it useful that the labels of all aircraft involved change colour to signal danger.	4.83	0.41	0.084465164	[4.40 - 5.00]
I find it useful that the directional arrows indicate the positions of the aircraft involved in the safety nets.	4.83	0.41	0.084465164	[4.40 - 5.00]
I find it useful that, upon resolution of the danger condition, the labels automatically return to their nominal colour.	4.67	0.52	0.110656667	[4.12 - 5.00]
I find it useful to be able to acknowledge the hazard, disabling the sound signal and label status.	4.67	0.52	0.110656667	[4.12 - 5.00]
I would prefer that, once I acknowledge the safety net, the labels return to their nominal colour immediately.	3.67	1.21	0.33028913	[2.40 - 4.94]
I think the interface for presenting safety nets is useful.	4.67	0.52	0.110656667	[4.12 - 5.00]
I think the design (colour, shape, position) of the safety nets is adequate.	4.33	0.52	0.188422288	[3.48 - 5.00]
Overall, would you like to have the AR interface available for safety nets?	4.5	0.55	0.121716124	[3.93 - 5.00]
Overall, do you think the safety net interface would be useful for your work?	4.33	0.52	0.119168718	[3.79 - 4.88]

5. Discussion

Overall, based on our observations, ADS-B data demonstrated to be a feasible sensor candidate for a positional SN system. Throughout the evaluation scenarios, all safety nets were activated precisely when and only when required, verifying the logical accuracy of the triggering mechanisms. This consistent behaviour, combined with an observed positional error of less than one meter and highly precise boundary mapping, suggests that ADS-B precision is adequate to trigger safety net events reliably under the tested conditions.

Concurrently, the controllers' preliminary feedback was generally positive toward the design of the AR

interface for SN, confirming its potential benefits in an operational environment and highlighting some corrections that are natural at this stage of design. Rather than representing an absolute consensus, individual remarks from the different respondents provided targeted operational insights across the questionnaire. For instance, specific comments noted that arriving aircraft tracking should be extended earlier than short final, while another suggested exploring alternative acoustic designs for alarm states to optimise sensory differentiation. Furthermore, individual feedback emphasised the need to expand future use cases to include opposite runway configurations, with dedicated warning thresholds and explicit visual blocks preventing runway use once a landing clearance has been issued. These diverse expert viewpoints validate the system's core architecture while establishing a practical, user-driven roadmap for its next iteration.

6. Future work

The work presented in this paper constitutes an initial step toward implementing AR-based Safety Nets in operational environments. Future developments will first focus on refining the interface based on feedback collected during the real-world campaign, particularly regarding the behaviour and presentation of the directional arrows and the overall salience of the warning mechanisms.

From an operational perspective, additional triggering conditions and Safety Net services will be integrated into the current prototype, extending the system beyond the runway-incursion cases considered in this study. Furthermore, trajectory prediction algorithms currently under development at UNIBO will be investigated to anticipate hazardous situations earlier and provide more predictive support to controllers.

A large-scale Human-in-the-Loop validation campaign is also planned. To this end, the ADS-B-based Safety Nets developed for the real-world prototype will be transferred to the full-scale simulator previously used in the RETINA and DTT projects, allowing the reproduction of a significant number of hazardous scenarios under controlled conditions and involving a larger population of air traffic controllers. Such a campaign will enable quantitative assessment of the impact of the proposed interface on reaction times, workload, and situational awareness, while collecting additional feedback to support the iterative User-Centred Design process.

Finally, the developed interface may serve as a basis for future integration with more advanced surveillance infrastructures, such as A-SMGCS systems and digital tower environments, where additional information, including controller clearances and flight intentions, could enable the implementation of more sophisticated, predictive Safety Net services, such as STCA (Short Term Conflict Alert) and CMAC (Conformance Monitoring Alerts for Controllers), exploiting the validated interface design for data presentation.

7. Conclusions

This paper presented the development and preliminary validation of an Augmented Reality interface for Safety Nets in the airport control tower, based on a real-world platform fed by live ADS-B surveillance data. Building upon previous studies conducted in simulated environments, the work demonstrated the feasibility of transferring the concept to operational conditions while preserving the expected behaviour of both the interface and the triggering logic.

The technical validation confirmed the reliability of the developed positional Safety Nets and showed that real ADS-B data, despite their limitations relative to a complete A-SMGCS infrastructure, can serve as a suitable source of surveillance information for implementing runway-incursion-related services. The real-world experimental campaign also confirmed the correct behaviour of the AR interface and its ability to present alerts and guidance cues in line with operational needs.

Preliminary assessment from air traffic controllers, based on both informal qualitative feedback and quantitative questionnaires, was positive and confirmed the potential benefits of presenting Safety Nets in a head-up AR environment. In particular, the proposed visual and auditory cues were considered useful for promptly attracting attention to hazardous situations without requiring controllers to divert their gaze from the out-of-the-window view. At the same time, the campaign highlighted several aspects of the interface that still require refinement, confirming the importance of maintaining an iterative User-Centred Design approach.

Overall, the results support the feasibility and potential usefulness of an AR-based Safety Net interface and represent an important step toward more comprehensive validations involving a larger number of controllers and more advanced surveillance and prediction capabilities.

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