Report on Attention and HMI Tracking

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Abstract

This document describes the work done on attention and HMI tracking in the scope of the AWARE SESAR Project. The Attention and HMI Tracking play an important role in understanding the ATCOs intentions and Situational Awareness (SA).

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AWARE

Achieving Human-Machine Collaboration with Artificial Situational Awareness

AWARE

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1. Introduction

The AWARE project aims to advance human-machine collaboration in air traffic management by developing an Artificial Situational Awareness system. This system enhances the decision-making capabilities of Air Traffic Control Officers by providing timely, relevant support through artificial intelligence, allowing them to better manage complex air traffic scenarios.

The Artificial Situational Awareness integrates attention and HMI tracking technologies to enhance the situational awareness of ATCOs. This ASA system ensures that ATCOs can manage complex air traffic scenarios while maintaining a high level of performance and safety. The system achieves this through a combination of passive eye tracking, interaction monitoring, and correlation of gaze and input data with HMI elements.

2. HMI Components

In the context of ATC, the Human-Machine Interface (HMI) serves as the primary medium through which controllers interact with the system. Understanding attention in such high-stakes environments requires a thorough analysis of how controllers use and engage with these interfaces. In this project, we log specific HMI components, which are described below.

Each component was selected based on its critical role in operational workflows and its potential to reveal attentional focus and cognitive engagement. By capturing detailed logs of interaction, we establish a foundation for integrating these behavioural markers with eye tracking data to create a comprehensive model of operator attention.

The tracked components are described in detail below:

- Mouse movements (position & clicks)
- Interaction with track labels:
    - position of track label, when hovered over track label
    - clearances for heading/waypoints, flight level, speed
    - assumed & transferred status
    - flags (highlighting aircraft)
- Interaction with radar elements
    - separation tool
    - distance measurement tool
    - activation of filters
    - speed vectors
    - CPDLC usage
    - entry window
    - direction finder
- Route clearance interfaces

This information is gathered in the ATC system and sent over HTTP to the ASA system for analysis and integration to the Artificial Situational Awareness model.

By logging component positions on the HMI, this simplifies the process of synchronising eye-tracking data with specific HMI components. This approach addresses a common challenge when working with eye-tracking data, where such alignment is typically performed manually and can be a labor-intensive process.

3. Eye Tracking Components

To support real-time modelling of user attention, we incorporated eye tracking as a core input modality in our system. Visual attention offers a rich source of information about a controller's cognitive state, task focus, and interaction patterns, especially in high-demand environments [1]. By continuously monitoring where and how long a user looks at different interface elements, eye tracking helps characterise visual engagement and interaction dynamics [2]. When combined with contextual information from the HMI, this data contributes to inferring underlying intent and estimating mental workload [3]. This modality is particularly well-suited for applications involving multitasking and rapid decision-making, such as air traffic control, where understanding attention shifts can inform adaptive support strategies.

3.1 Eye tracking hardware

The Tobii Pro Fusion is a compact, screen-based eye tracker that employs a video-based pupil and corneal reflection method for gaze estimation, supporting both dark and bright pupil illumination. This technique involves the use of infrared illuminators and dual cameras to generate stereo images of both eyes. The captured images are processed to identify features such as the pupil centre and corneal reflections, which are then used in combination with a 3D eye model to compute the point of gaze on a display surface. In optimal conditions, it delivers a precision of approximately 0.04° RMS (applying Savitzky-Golay filtering) and around 0.2° RMS without filtering (raw signal). The accuracy is 0.3° in optimal conditions. The sampling rate is 120Hz. The tracker can be easily mounted on standalone or laptop screens up to 24" (16:9 aspect ratio) or installed on a tripod for use with larger displays or physical stimuli. It also allows for a generous head movement range: at 65 cm viewing distance, participants can move within a 40 × 25 cm area; at 80 cm, within a 45 × 30 cm area. The eye tracker connects via USB Type-A and is compatible with USB Type-C ports through an included adapter. Power can be drawn directly from a USB Type-C connection or through an external power adapter when using USB 2.0. [4].

To enable real-time eye-tracking data collection, we use the Tobii Pro SDK [5] via the official "tobii_research" Python package. This SDK provides access to the full functionality of the Tobii Pro Fusion device, including streaming of gaze data (gaze point coordinates, gaze origin, and pupil diameter), execution of calibration routines, and real-time monitoring of tracking status (e.g. mouse pointer position, gaze position). The screen is recorded concurrently, providing a visual reference for overlaying the tracked gaze. This integrated setup allows us to assess the ATCOs' intent by correlating gaze behavior with on-screen elements and operational context in real time.

It is important to note that the Tobii Pro Fusion does not support wireless communication for data access. All API functions, including calibration and data streaming, require a direct USB-C connection between the eye tracker and the host computer. This limitation necessitated the use of a tethered setup, which may constrain physical placement of the system but ensures low-latency and high-throughput data transmission. At the same time, it offers a security advantage, as the eye tracking data is inaccessible from external sources.

3.2 Pre-processing of Gaze Data

The gaze data cleaning process begins after constructing the dataset by associating the recorded time series data with the correct controller task labels. First, gaze and mouse features are extracted, and blinks are identified. We detect blinks by identifying periods in the gaze data where no valid gaze points are recorded for a duration consistent with a typical blink, usually between 100 and 400 milliseconds. To ensure consistency across samples, the data is resampled either to a fixed number of data points or using a fixed timesteps, typically through linear interpolation.

Next, missing values (NaNs) in the gaze data are addressed through interpolation methods, specifically using forward-fill or backward-fill techniques, ensuring no gaps remain in the time series. Padding is applied where necessary to align data lengths across samples.

Once the time series is cleaned and complete, relevant scalar features are extracted. These include the number of gaze coordinates, saccades, average fixation duration, and average speed of eye movement, among others. This results in a final cleaned time series dataset along with a set of derived scalar features, ready to be used for model training and subsequent analyses.

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4. HMI and Eye Tracking Components Mapping

The integration of HMI and eye tracking data provides a multidimensional view of air traffic controller behaviour (see Figure 1). At the controller's working position, we capture and synchronise three main input streams:

1. Eye Tracking Data: An eye tracker, positioned below the screen, records the controller's gaze vectors over time, providing detailed information about visual focus - where the controller is looking, for how long, and in what sequence (fixations, saccades, scanpaths).
2. HMI Data: The HMI logs the exact screen coordinates of all interface elements and events, including aircraft positions, interactions with track labels, tool activations, and system messages. These dynamic interface elements define the spatial context of controller interactions.
3. Mouse Input Events: Mouse clicks are captured with precise screen coordinates and timestamps, reflecting active manual interactions with the interface.

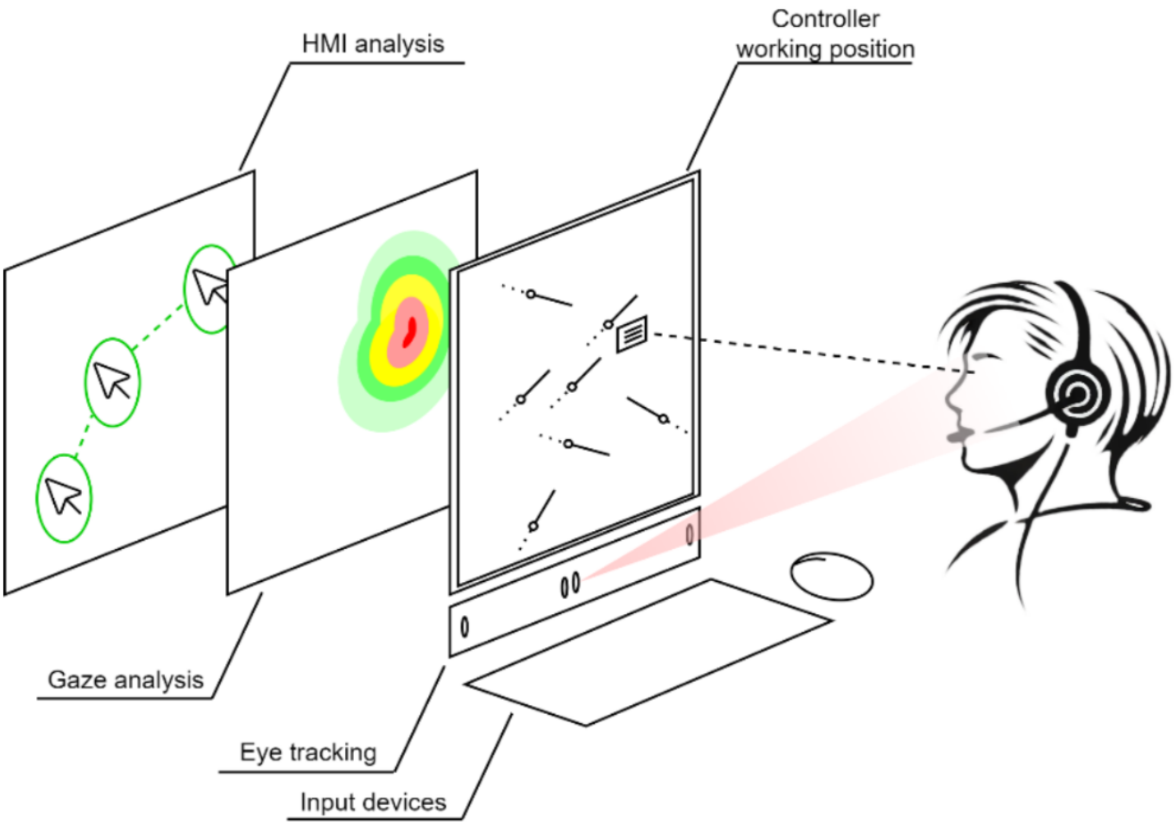

Figure 1. Attention and HMI tracking technologies used in the ASA system

All data streams are time-synchronised and merged via a central Knowledge Graph, which provides input to the intent recognition algorithm. This synchronisation enables precise correlation between gaze behaviour, manual inputs, and the dynamic state of the HMI at any given moment. Since both gaze data and HMI element coordinates are recorded in screen space, they can be aligned within a common coordinate system, and mouse events integrate natively.

This unified dataset enables several layers of analysis:

- Attention Allocation Analysis: We can determine whether an ATCO visually attended to a component before or during interaction, assess how long their attention lingered, and identify patterns of attention distribution across tasks.
- Behavioural and Task Assessment: By comparing intended system use (mouse clicks and tool activations) with visual verification (gaze), we can validate task performance, detect attention lapses or inefficiencies, and evaluate workflows.
- Advanced Visualisation: Heatmaps can be generated to visualise attention density across interface areas, revealing which regions attract the most or least focus.
- Intent and Task Inference: A key advantage of integrating aircraft coordinates from the HMI is the ability to infer controller intent. For instance, repeated gaze shifts between two aircraft may signal conflict detection or resolution activity. Combining visual attention patterns with interaction data enables the system to assess which task the controller is engaged in at any moment.

Overall, this integrated approach supports behavioural analysis and also paves the way for adaptive systems that understand and respond to the controller's intentions in real time. It offers actionable insights for improving interface design, training interventions, and ultimately, operational safety and efficiency.

4.1 HMI Component Mapping to Eye Tracking Use Case

Table 1 provides an overview of the tracked HMI components and the description of why this component is important to assess ATCO attention.

Component Name	Details	Eye tracking use case
Mouse	Position	Mouse movement closely correlates with visual attention, especially when eye tracking fails (e.g., due to blinks or occlusions). Comparing gaze and mouse trajectories helps validate intention and attention allocation.
	Clicks (on a component level)	Clicks indicate definitive action. Mapping gaze to click targets allows us to determine whether visual confirmation occurred before decisions, supporting workload and error potential assessments.
Track Label	Position	Track labels often represent aircraft data, which is used by ATCOs to collect aircraft information. Logging their position lets us match fixations to

		specific aircraft, identifying focus points and attention distribution over traffic.
	Hover	Hovering over a label without clicking may reflect information sampling or hesitation. Correlating with gaze duration helps to assess the depth of information processing.
	Route interaction/waypoint clearance	This interaction reflects task execution. Eye tracking confirms whether visual attention was allocated to the correct track before task completion.
	HDG clearance	
	FL clearance	
	SPD clearance	
	Flight assumed	Status shows if the aircraft is in the area of responsibility. It is used to confirm that the ATCO visually assessed the aircraft before taking/releasing responsibility, indicating task readiness/closure and anticipatory attention.
	Flight transferred	
	Flags (marking AC that need attention later)	Flags are used to determine whether the ATCO prioritised or intended to monitor a specific flight more closely, indicating elevated attention or perceived relevance.
Separation tool	Activate/deactivate	Activation/deactivation of tools suggests need for additional info or action. Gaze before and after the event clarifies whether usage is proactive (anticipatory) or reactive (problem-solving).
	Minimum distance	To assess whether the ATCO visually monitored potential conflicts in time, by linking gaze behaviour to predicted separation issues and identifying whether attention was directed toward high-priority aircraft during critical time windows.
	Time to minimum distance	
	Aircraft being checked by the tool	
Distance measurement tool	Activate/deactivate	Activation/deactivation of tools suggests need for additional info or action. Gaze before and after the event clarifies whether usage is proactive (anticipatory) or reactive (problem-solving).
	Actual distance	To verify whether the ATCO used visual attention to assess spatial relationships between aircraft, confirming alignment between gaze behaviour and the use of the tool for situational awareness and conflict evaluation.
	AC on specific levels	

Activation of filters	Inbound flights	Usage of filters suggests need for additional info or information filtering. Gaze before and after filtering clarifies whether usage is proactive (anticipatory) or reactive (problem-solving).
	Outbound flights	
Speed vectors	Activation/Deactivation	Activation/deactivation of tools suggests need for additional info or action. Gaze before and after the event clarifies whether usage is proactive (anticipatory) or reactive (problem-solving).
	Scrolling in and out (expansion of speed vectors)	To determine whether the ATCO visually assessed aircraft trajectories and anticipated movement, with speed vector expansion indicating intentional analysis of future positions supported by gaze fixation on relevant targets.
CPDLC	When used/clicked	To assess whether the ATCO visually engaged with digital communication content, linking gaze to message reading or composing behaviour and evaluating attention allocation during non-verbal coordination tasks.
	Message sent to AC	
Entry window	Hover	ATCOs use the entry window to monitor and prepare for incoming aircraft entering their sector to ensure smooth integration into the existing traffic flow and anticipate necessary control actions. Eye tracking can confirm whether the ATCO actively attended to the entry window, indicating proactive monitoring of inbound traffic and supporting assessments of anticipatory attention and situational awareness.
	Click	
Direction finder	Activation	Activation of tools suggests a need for additional information or action. Gaze before and after the event clarifies whether usage is proactive (anticipatory) or reactive (problem-solving).
Other	airspace position (coordinates of the ESM23 sector)	

Table 1 Mapping of HMI Components and Eye Tracking reasoning

5. Conclusion

The integration of attention and HMI tracking within the AWARE project represents a significant step toward the ability of the ASA system to be aware of the ATCOs intentions and situational awareness. By combining high-resolution eye tracking with detailed HMI interaction logs, the system enables a comprehensive understanding of ATCOs attention, decision-making patterns, and cognitive workload in real-time.

This approach not only supports the validation of user actions against visual engagement but also offers valuable insights for adaptive interface design and user tailored support strategies. The ability to detect attentional lapses, predict workload peaks, and assess interaction efficacy enables the development of more intuitive and responsive ATM systems. Ultimately, these advancements contribute to safer, more efficient airspace operations and provide a foundation for future research in human-machine teaming in complex environments.

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7. List of acronyms

Acronym	Description
API	Application Programming Interface
ASA	Artificial Situational Awareness
ATCO	Air Traffic Control Officer
CPDLC	Controller-Pilot Data Link Communications
HMI	Human-Machine Interface
RMS	Root Mean Square
USB-C	Universal Serial Bus Type-C

Table 2 List of acronyms