Identification of the Psychophysiological State of Air Traffic Controllers Based on Eye-Tracking Monitoring Using Fuzzy Logic

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Abstract. Human performance monitoring has become a key component of next-generation aviation safety systems, as the human factor remains one of the leading causes of operational incidents. Among various physiological and behavioral indicators, eye-tracking data provide a direct and non-intrusive measure of cognitive workload, attention, and fatigue. This paper presents a fuzzy expert system for real-time identification of the psychophysiological state of air traffic controllers based on monitoring data obtained through the eye-tracking method. The developed expert system operates using four types of oculomotor metrics that characterize fixations, saccades, pupil variations, and blink dynamics.

The fuzzy rule base, which constitutes the core of the system's knowledge base, was constructed by generalizing expert knowledge and empirical observations obtained during the registration and statistical analysis of eye-tracking parameters of air traffic controllers. Based on the data, multifactor dependencies were identified that describe the dynamic relationship between oculomotor behavior and the operator's psycho-physiological state. This enabled the implementation of an adaptive fuzzy inference mechanism capable of accounting for individual variability and cognitive response dynamics in real time. The fuzzy logic approach with the Mamdani decision-making procedure effectively addresses uncertainty, individual differences, and the nonlinear nature of human physiological data, outperforming traditional threshold-based methods.

The developed system provides continuous and adaptive assessment of cognitive readiness without interfering with operator performance. Integration of the above-mentioned indicators with other psychophysiological parameters enhances the re-liability of decision-making. The proposed methodology represents a step toward human-centered intelligent aviation systems, combining fuzzy logic, psychophysiological sensing, and ma-chine learning techniques to improve safety and operational efficiency in complex human–machine environments.

Keywords: Air traffic controllers, Eye-tracking monitoring, Psychophysiological state, Fuzzy logic, Cognitive workload and fatigue

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1 Introduction

The modern flight safety assurance system is increasingly oriented toward monitoring the human factor. Despite the widespread implementation of automated and intelligent air traffic management tools, the psychophysiological state of air traffic controllers (ATCOs) remains a critical link in the safety chain [1, 2]. Increased cognitive workload, prolonged maintenance of attention, shift work, and high responsibility for the consequences of decisions lead to the development of fatigue, a decrease in vigilance, and a higher probability of errors [1, 3].

Traditional methods for assessing the psychophysiological state of ATCOs include subjective questionnaires, periodic medical examinations, and episodic use of physiological sensors (EEG, ECG, HRV, etc.) [4, 5]. In contrast to these methods, an approach based on oculomotor activity is non-invasive and therefore more appropriate for continuous monitoring. Eye-tracking technologies make it possible to record blink rate, saccade and fixation parameters, pupil diameter, and related integral indicators such as PERCLOS, which show a stable relationship with cognitive workload, fatigue, attention, and situational awareness [1, 6–8].

In parallel, methods of intelligent analysis of psychophysiological data are actively developing [9]. Fuzzy logic and hybrid models based on it are used to assess cognitive workload and drowsiness in operators, drivers, and pilots [10–12]. Fuzzy systems make it possible to describe hard-to-formalize states (for example, “moderate fatigue” or “high but controlled workload”) in linguistic terms and to form interpretable rules that are understandable to specialists in aviation medicine and safety.

The aim of this work is to develop the concept and structure of a fuzzy expert system for assessing the psychophysiological state of air traffic controllers based on eye-tracking indicators. To achieve this goal, the following tasks are formulated:

- To justify the choice of oculomotor metrics for assessing the cognitive workload and fatigue of ATCOs;
- To describe the hardware–software system for non-invasive monitoring of eye activity at the controller’s workplace;
- To develop the structure of the fuzzy model (input and output variables, membership functions, rule base, and inference method);
- To propose an experimental protocol for validating the model and integrating the system into aviation safety frameworks.

To enable continuous monitoring at the ATCO workstation, a compact hardware configuration is proposed (Fig. 1). It includes a monochrome infrared camera with a global shutter and a frame rate of at least 120 fps, which allows reliable detection of eye blinks, micro saccades, and pupil diameter variations. The system uses a lens without an IR-cut filter, making it suitable for infrared illumination and enabling the acquisition of high-contrast eye images. An 850 nm IR filter is employed to block the visible spectrum while transmitting infrared radiation, thereby improving robustness to changes in ambient lighting conditions. Uniform illumination of the controller’s face is provided by an 850 nm IR light source, which ensures visual comfort and complies with eye-safety standards.

Overall, this configuration minimally interferes with the ATCO's workflow, does not require the operator to wear any additional equipment, and can be easily integrated into existing workstations and training simulators.

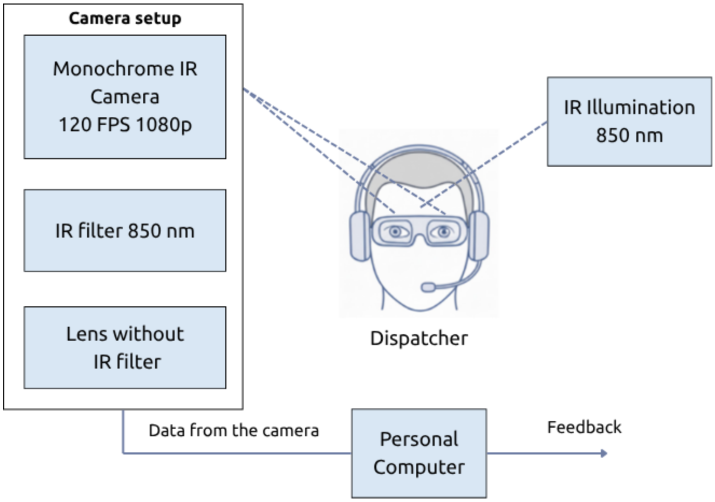

Fig. 1. Structural diagram of the air traffic controller's IR eye-tracking monitoring system

2 Algorithmic Foundations of a Fuzzy Expert System

Such a configuration minimally interferes with the ATCO's workflow, does not require the operator to wear additional devices, and can be integrated into existing workstations. Fig. 2 presents the structural and functional diagram of the fuzzy ex-pert system for determining the psychophysiological state of an air traffic controller. The input parameters characterizing the object are defined in the form of a vector

$$x = \{x_1, x_2, x_3, x_4, x_5\} \tag{1}$$

which is formed on the basis of data obtained by the eye-tracking method. Each component of this vector is associated with a linguistic variable with its own set of terms:

- x_1 (PupilDiam) – denotes the pupil diameter with terms: constricted, normal, and dilated.
- x_2 (SaccadeRate) – denotes the saccade rate (1/min) with terms: low, normal, and high.
- x_3 (FixMean) – denotes the mean fixation duration (ms) with terms: short, medium, and long.
- x_4 (BlinkRate) – denotes the blink rate (1/60 s) with terms: low, normal, elevated, and very high.
- x_5 (PERCLOS60) – denotes the PERCLOS value over 60 s (%) with terms: low, medium, high.

Each of these indicators is treated as a linguistic variable for which the corresponding membership functions are defined. The membership functions of the input variables are shown in Fig. 3 and are formed in the fuzzification block.

$$y = \{y_1, y_2, y_3\} \tag{2}$$

In an analogous manner, the output variables of the system are described and combined into the vector

- y_1 (LoadLevel) – representing the level of cognitive workload with terms: low, medium, high, and overload.
- y_2 (FatigueLevel) – representing the level of fatigue with terms: alert, moderate fatigue, high fatigue, and drowsy state.
- y_3 (PsychoPhysStateIndex) – representing the integral index of the psychophysiological state with terms: optimal, strained, borderline, and unacceptable.

The first two output parameters, y_1 and y_2, are predominantly local in nature, describing, respectively, the levels of cognitive workload and fatigue. The third output parameter y_3 is an integral indicator used for the final assessment of the air traffic controller's state during system operation.

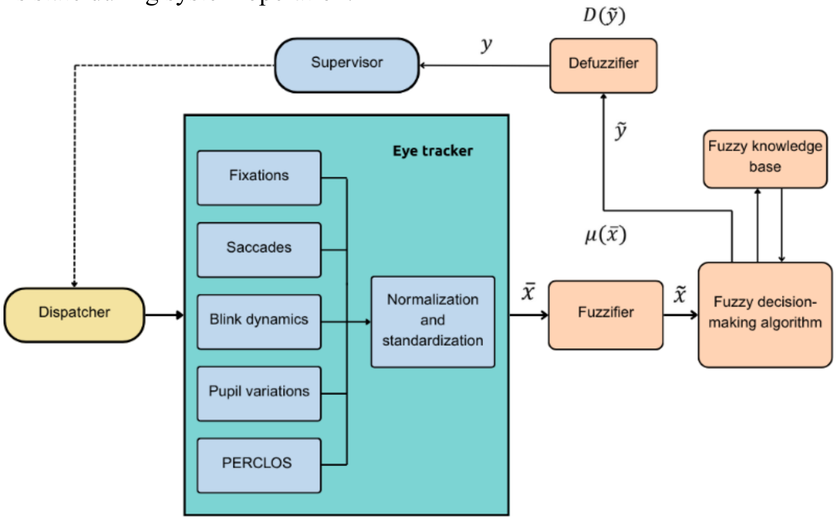

Fig. 2. Structural and functional diagram of the system for determining the psychophysiological state of an air traffic controller based on eye-tracking technology with the use of fuzzy logic.

For each input and output variable, sets of linguistic terms and the corresponding membership functions are defined. The core of the fuzzy expert system is the decision-making block, which implements the fuzzy inference algorithm according to the Mamdani method.

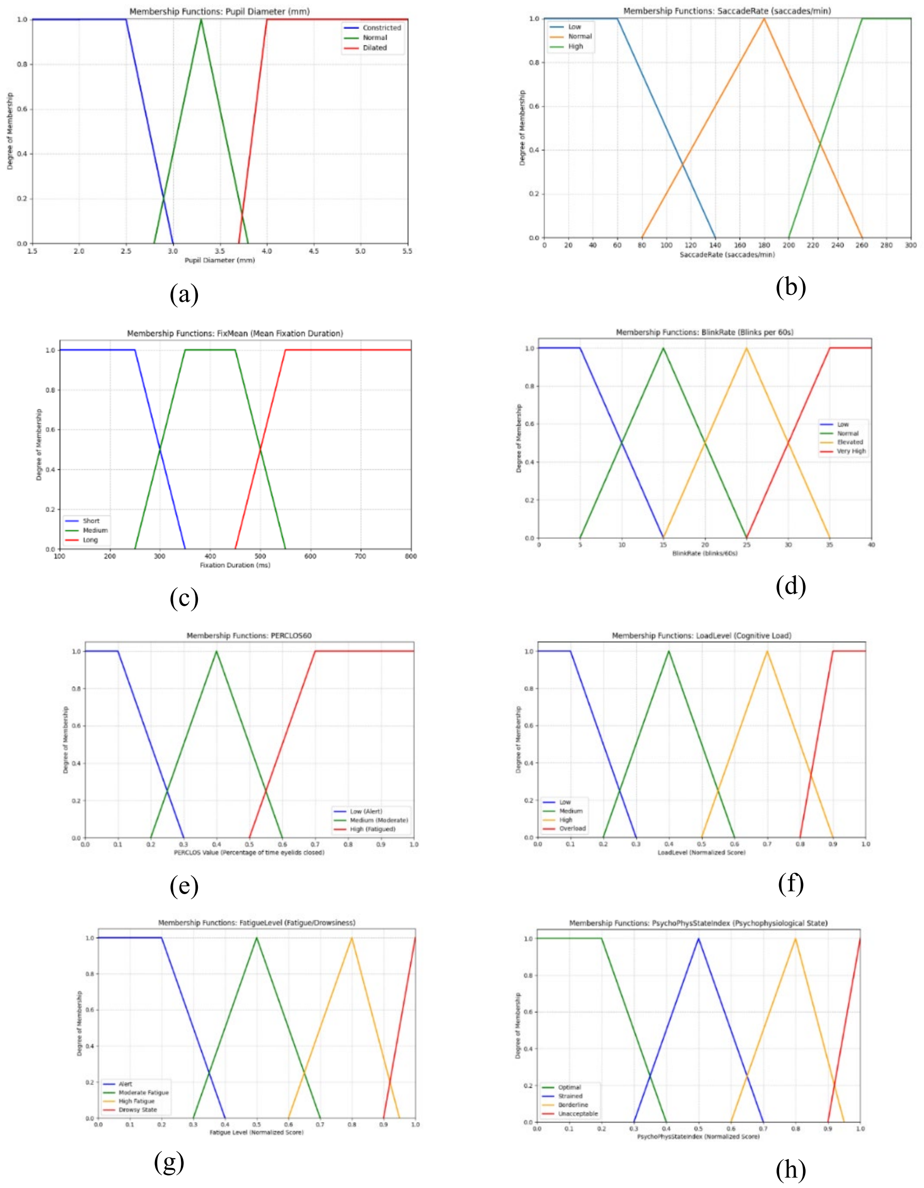

Fig. 3. Membership functions of the input and output variables: (a) x_1 - pupil diameter, (b) x_2 - saccade rate, (c) x_3 - mean fixation duration, (d) x_4 - blink rate, (e) x_5 - PERCLOS60, (f) y_1 - cognitive workload level, (g) y_2 - fatigue level, (h) y_3 - integral psychophysiological state index

The knowledge used in the fuzzy inference algorithm is formed based on expert assessments in the given domain and the results of statistical analysis of experimental data. The knowledge base stores information in the form of a set of fuzzy production rules that define the relationships between the input oculomotor metrics and the output indicators of the air traffic controller's psychophysiological state.

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1. IF x_1 = normal AND x_2 = low AND x_3 = medium AND x_4 = normal AND x_5 = medium, THEN y_1 = low, y_2 = alert, y_3 = optimal.
2. IF x_1 = elevated AND x_2 = moderate AND x_3 = short AND x_4 = high, THEN y_1 = medium, y_2 = moderate fatigue, y_3 = strained.
3. IF x_1 = low AND x_2 = high AND x_3 = long, THEN y_1 = medium, y_2 = high fatigue, y_3 = strained.
4. IF x_1 = elevated AND x_2 = high AND x_4 = high AND x_5 = dilated, THEN y_1 = high, y_2 = high fatigue, y_3 = borderline.
5. IF x_1 = low AND x_2 = high AND x_3 = long AND x_5 = constricted, THEN y_1 = high, y_2 = drowsy state, y_3 = borderline.

To perform logical inference in the system, the classical Mamdani approach is used, which enables an expert-oriented decision-making scheme based on a set of "if–then" rules. The Mamdani method provides a natural interpretation of the inter-actions between the input oculomotor indicators and makes it possible to obtain defuzzified assessments of the controller's state that are consistent with expert logic and experimentally observed regularities.

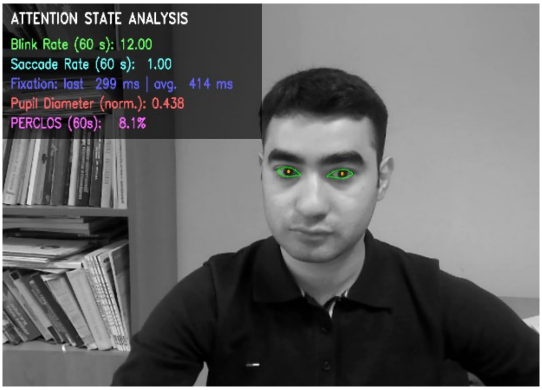

Fig. 4. Example of oculomotor metrics visualization during the analysis of the operator's attentional state

3 Results and Conclusion

In the course of the study, a method for identifying the psychophysiological state of air traffic controllers was developed and validated, based on a set of oculomotor activity indicators and the apparatus of fuzzy logic. The proposed model makes it possible to integrate heterogeneous biometric parameters—blink rate, fixation duration, saccade rate, pupil diameter, and the PERCLOS index—into an interpretable integral state index that reflects the levels of cognitive workload, fatigue, and functional readiness of the operator.

For identification, three scenarios were considered: a baseline mode with moderate traffic intensity and standard operating conditions, a high workload mode with an increased number of aircraft, conflict situations, and the need for multichannel radio communication, and a fatigue mode involving prolonged task performance with a gradual increase in complexity.

During the experiment, the following data were recorded: eye-tracking data.

The developed Mamdani-type fuzzy expert system demonstrates robustness to variability in physiological data and makes it possible to formalize expert knowledge about regularities in changes of visual behavior under the influence of workload and fatigue. Experimental verification on a sample of 20 participants performing standard air traffic control scenarios in a simulator environment confirmed the model's ability to detect transitions between the "optimal", "strained", "borderline", and "un-acceptable" states with a high degree of agreement with subjective and expert evaluations.

The obtained results indicate the feasibility of integrating the proposed system into automated ATC workstations and adaptive automation systems for early detection of unfavorable psychophysiological states. This may enhance situational awareness, reduce the risk of operator errors, and improve overall flight safety.

References

1. Hu, Y., Shen, H., Pan, H., Wei, W.: Fatigue Detection of Air Traffic Controllers Through Their Eye Movements. Aerospace **11**, 981 (2024). https://doi.org/10.3390/aerospace11120981
2. Aricò, P., Borghini, G., Di Flumeri, G., Bonelli, S., Golfetti, A., Graziani, I., Pozzi, S., Imbert, J.-P., Granger, G., Benhacene, R., Schaefer, D., Babiloni, F.: Human Factors and Neurophysiological Metrics in Air Traffic Control: A Critical Review. *IEEE Reviews in Biomedical Engineering* **10**, 250–263 (2017). https://doi.org/10.1109/RBME.2017.2694142
3. Borghini, G., Aricò, P., Di Flumeri, G., Cartocci, G., Colosimo, A., Bonelli, S., Golfetti, A., Imbert, J.-P., Granger, G., Benhacene, R., Pozzi, S., Babiloni, F.: EEG-Based Cognitive Control Behaviour Assessment: an Ecological Study with Professional Air Traffic Controllers. *Scientific Reports* **7**, 547 (2017). https://doi.org/10.1038/s41598-017-00633-7
4. John, A.R., Singh, A.K., Do, T.-T.N., Eidels, A., Nalivaiko, E., Gavgani, A.M., Brown, S., Bennett, M., Lal, S., Simpson, A.M., Gustin, S.M., Double, K., Walker, F.R., Kleitman, S., Morley, J., Lin, C.-T.: Unraveling the Physiological Correlates of Mental Workload Variations in Tracking and Collision Prediction Tasks. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **30**, 770–781 (2022). https://doi.org/10.1109/TNSRE.2022.3157446
5. Das Chakladar, D., Roy, P.P.: Cognitive Workload Estimation Using Physiological Measures: a Review. *Cognitive Neurodynamics* **18**, 1445–1465 (2024). https://doi.org/10.1007/s11571-023-10051-3

6. Hu, X., Lodewijks, G.: Detecting Fatigue in Car Drivers and Aircraft Pilots by Using Non-Invasive Measures: The Value of Differentiation of Sleepiness and Mental Fatigue. *Journal of Safety Research* **72**, 173–187 (2020). https://doi.org/10.1016/j.jsr.2019.12.015
7. Marchitto, M., Benedetto, S., Baccino, T., Cañas, J.J.: Air Traffic Control: Ocular Metrics Reflect Cognitive Complexity. *International Journal of Industrial Ergonomics* **54**, 120–130 (2016). https://doi.org/10.1016/j.ergon.2016.05.010
8. Babu, M.D., JeevithaShree, D.V., Prabhakar, G., Saluja, K.P.S., Pashilkar, A., Biswas, P.: Estimating Pilots' Cognitive Load from Ocular Parameters Through Simulation and In-Flight Studies. *Journal of Eye Movement Research* **12**, (2019). https://doi.org/10.16910/jemr.12.3.3
9. Allakhverdiev, A.R., Dadashov, F.G., Huseynov, N.E., Dadasheva, K.G., Asadov, E.Z.: Model for Predicting Learning Effectiveness in an Intelligent Trainer Based on Psychophysiological and Scenario Factors. *International Journal of Advanced Fundamentals Research*, 5–9 (2025). https://doi.org/10.17513/mjpfi.13751
10. Testa, A., Simeone, A., Zecca, M., Paoli, A., Settineri, L.: Fuzzy-Based Sensor Fusion for Cognitive Load Assessment in Inclusive Manufacturing Strategies. *Sensors* **25**, 3356 (2025). https://doi.org/10.3390/s25113356
11. Celecia, A., Figueiredo, K., Vellasco, M., González, R.: A Portable Fuzzy Driver Drowsiness Estimation System. *Sensors* **20**, 4093 (2020). https://doi.org/10.3390/s20154093
12. Arava, M., Sundaram, D.M.: Multi-Fatigue Feature Selection and Fuzzy Logic-Based Intelligent Driver Drowsiness Detection. *IET Image Processing* **19**, e70052 (2025). https://doi.org/10.1049/ipr2.70052