

Human Factors and HMI for Future Air Domain

Jens Alfredson¹, Emilia Villani², Oscar Bjurling³, Jimmy Hammarbäck¹, Magnus Bång⁴, Andrew Gomes Sarmiento²,
Ivan de Souza Rehder², Jonas Lundberg⁴, Rego Granlund³, Cecilia Bergman¹, Björn Johansson⁴

¹Saab AB, Linköping, Sweden

E-mail: jens.alfredson@saabgroup.com, jimmy.hammarback@saabgroup.com, cecilia.bergman@saabgroup.com

²Aeronautics Institute of Technology (ITA), São José dos Campos, Brazil

E-mail: evillani@ita.br, andrewgps@ccm-ita.org.br, ivan.rehder@ccm-ita.org.br

³Research Institutes of Sweden (RISE), Linköping, Sweden

E-mail: oscar.bjurling@ri.se, rego.granlund@ri.se

⁴Linköping University, Linköping, Sweden

E-mail: magnus.bang@liu.se, jonas.lundberg@liu.se, bjorn.j.johansson@liu.se

Abstract

Future Air Domain will be defined by emerging technologies, such as the integration of autonomous systems and the application of artificial intelligence to support complex decision-making. A central concept in the Future Air Domain is the “system of systems” approach, in which multiple manned and unmanned platforms operate collaboratively. In this context, effective human-machine collaboration is critical, highlighting the need for investigating the design of human-machine interfaces (HMI) that facilitate interaction. This paper explores some of the challenges related to HMI design for Future Air Domain. It discusses the research currently under development within a joint Swedish–Brazilian collaboration that investigates how cognitive modelling and pilot state monitoring can contribute to HMI development, how adaptive interfaces can support varying levels of autonomy, and how human factors are influenced by the demands of communicating with and controlling multiple unmanned aerial vehicles (UAVs). To support this research, six different HMI concepts are currently being developed and will be tested in different simulation environments.

Keywords: Human Factors, HMI, Future Air Domain

1 Introduction

The future air domain is characterized by a set of challenges due to new and improved mission demands and technologies. Control of the skies directly influences the success of military operations across others domains, such as land, sea and space [1]. Beyond defense, the air domain is critically important from multiple perspectives, including economic, scientific, and humanitarian ones, as it provides speed and flexibility [2]. Air domain supports people mobility, contributes to global trade and commerce, and enables emergency response in case of disaster.

Future air domain refers to the combination of aerial operations, technologies, and strategic considerations that will shape how air power is projected and managed in the coming decades. It is characterized by novel challenges due to new and improved mission demands. Things that could not have been performed before will now be possible, including tasks supported by unmanned and potentially autonomous aircraft.

According to Panero and Russo [3], the core innovation in the operational concept behind next-generation aircraft lies in their integration with drones as part of a “system of systems.” These drones—either remotely piloted or autonomous—act as carriers for sensors and/or effectors, interconnected with the main aircraft through artificial intelligence (AI). AI enables real-time data collection and processing, providing critical decision-making and execution support to the pilot. Additionally, this future operational environment should not exclude collaboration with existing legacy platforms, which are expected to remain in service for years to come. Instead, it is necessary to assure the integration of next-generation systems with existing ones. The synergy between manned and unmanned systems through Manned-Unmanned Teaming (MUM-T) is a key success factor.

As a consequence, the role of humans engaged in future air missions will be different from the work performed today, extrapolating the traditional pilot—cockpit or ground station operator—control station interactions.

New and improved technologies will provide increased opportunities. Advanced decision support systems that explore the use of artificial intelligence (AI) is only one example, but one that will have large impact on human factors and human-machine interface/interaction (HMI), highlighting topics such as human-agent interaction and human-autonomy teaming. Working good together, man and machines, will be a key success factor. For this purpose, mixed initiatives between intelligent agents must be investigated from a human factors' perspective, so that work with human-in-the-loop, human-on-the-loop, human-out-of-the-loop, and shifts in between will be supported. Challenges include how to best use new technologies such as AI to support HMI, but also how HMI could support the use of AI, in, for instance, manned-unmanned teaming, including trust and explainability. Examples of applications and scenarios of concern are hand-over of unmanned aircraft, link loss situations, reconnaissance or search and rescue (SAR) scenarios.

This work investigates human factors and human-machine interface to support future design of aircraft and aeronautics systems. It discusses the main challenges and technologies trends, and summarizes on going and future work in context of Swedish Brazilian cooperation.

2 Research Approach for HMI and Human Factors

In the context of Brazilian Swedish collaboration in Aeronautics, HMI and human factors was selected as a key area for the development of joint research projects [4]. This decision led to the development of the HMI-HUFLab Project, between 2019 and 2023, and its continuation as HMI-HUFLab Phase II Project, started in 2024, in parallel with the Air Domain Study, including the Virtual Demo.

The first HMI-HUFLab Project aimed at building up the knowledge regarding human machine interface for future military concepts, manned as well as unmanned. It investigated how new human-machine interface (HMI) solutions could contribute to improve performance and/or safety, the appropriate models and tools to measure the impact of HMI in different scenarios, and the extent to which flight simulators could be used to investigate the design of new pilot/aircraft interface [5].

From the Brazilian side, the scenario selected for investigation was the use of mixed reality in-flight for training purposes, where external elements that composes the simulation scenario, such as other aerial vehicles, were represented using mixed or augmented reality. From the Swedish side, the selected scenario was a future reconnaissance mission performed by a MUM-T with two use cases: Transfer of Control and Loss of Communication.

Modelling efforts explored during the project include knowledge elicitation by interviews of fighter pilots, and intent modelling. From the interview data, statements containing content of explicit and implicit intent were mapped to different level of cognitive control. Additionally, the project also investigated the use of neurophysiological

sensors and subjective questionnaires as tools for evaluating human performance and human-machine interaction. Finally, it also examined the differences between data collected during simulator-based experiments and those obtained in real flight conditions.

HMI-HUFLab Phase II is currently under development and is the main focus of this paper. The research questions approached in this work are:

- How can cognitive modelling and pilot state monitoring contribute to the development of adaptive HMI?
- How can physiological sensors and state-of-the-art analysis be used to monitor the pilot?
- How does the need to interact/communicate with multiple unmanned aircraft affect the pilot?
- What qualities of adaptive HMI for future fighter pilots are important?

Similar to the approach adopted in the first project, HMI-HUFLab Phase II is organized into three main work packages: Definition, Implementation, and Evaluation. The Definition work package involves proposing HMI concepts for specific contexts and defining the scenarios in which these HMIs will be assessed. The Implementation work package focuses on developing simulation prototypes based on the proposed HMI concepts. Finally, the Evaluation work package encompasses conducting experimental campaigns to investigate the research questions and assess the performance of the proposed interfaces.

The next section summarizes the HMI proposals approached by both Swedish and Brazilian teams. Current work includes human-in-the-loop simulations with implemented technologies as well as 'wizard of OZ' simulations for technologies and/or designs not yet implemented. It also approaches simulations of interaction with multiple unmanned aircraft, supported by future HMI concepts and pilot monitoring systems, AI-assisted HMI with different levels of autonomy, and the use of generative AI combined with traditional design methods to specify multi-modal interfaces.

3 HMI Concepts and Expected Contributions

In order to investigate the research questions discussed in the previous section, six HMI concepts are proposed and developed to be tested in simulation environments.

Following, each proposal is discussed in detail, as well as its contribution for future air domain.

3.1 HMI that will be tested in simulations of design based on pilot intent models

The first HMI to be tested in simulations is the design based on pilot intent models. The purpose of these studies is to explore bi-directional transparency and explainability in a hybrid human-technology teaming context, with the aim to identify interaction/communication strategies for comprehensible intent in Manned-Unmanned Teaming situations. In particular, the studies address core questions related to what and when as well as how and why intent

should be disclosed and clarified. Considering these core questions, the first study aims to identify communication strategies for making the intent of synthetic wingmen interpretable and understandable by fighter pilots in Manned-Unmanned Teaming situations. The second study aims to reverse the role, making fighter pilot intent interpretable and understandable by synthetic wingmen by disclosing and clarifying such comprehension back to the fighter pilot.

In this work, an overarching concept is designed that is generic to many different scenarios. It is then detailed for the scenario, to prepare it for testing, e.g. using specific area maps and events for that scenario. The main outcome is thus the HMI visual screen design and interaction design with a script for how it is to be used in the scenario. The concept concerns the core question of the project, how to explain the automation/AI to the pilot. It concerns content (what to present), timing (when to present it) and form (how to present it). It also concerns an adaptive part, the amount of pilot control that should be available for adjusting explanations, including the interface components for doing the adjustments. We assume that explanations will be most beneficial during training. However, some explanations can also be useful during operations, this will be assessed during testing, such as in unfamiliar or unexpected situations. In the design phase, operative experts will be involved, depending on their availability. The aim of the prototype is to be testable in a cockpit during a human-in-the-loop study. The implementation therefore focuses on information presentation and pilot interaction.

In the scenario design phase, the aim is to include generic/typical situations of interactions with unmanned aircraft, that can be exemplified in one or several specific situations in a specific scenario, in a simulator, so that it becomes testable. These situations will be the setting of use of the explainer component that is designed and implemented. The scenario describes the main activity of the pilot and the AI agent. These agents can be one or more unmanned aircraft. There can be one or several unmanned aircraft in the scenario. Activities of surrounding agents such as other pilots or ground personnel can be included but are not the focus (it becomes context and secondary activities that can be used e.g. to tweak workload). The involvement of experts such as pilots and/or drone pilots is required to make the scenarios realistic and relevant.

The scenario is focusing on human factors for interaction between manned and unmanned aircraft. After drafting the scenario, it will be set up in a simulator, so that test flights can be made, and specific situations can be explored. The overarching scenario includes a set of important events in a plausible future in terms of agents, capabilities, artefacts, properties, and activities in a context.

After drafting the scenario, it will be set up in a simulator, so that test flights can be made, and specific situations can be explored.

The cockpit simulator that is used for the study consists of a large monitor with a view of the world and a representation of a head up display (HUD), a multi-touch large area display (LAD) as well as a hands-on throttle and stick (HOTAS). It is in the LAD the explainer component is implemented, and the user's main focus will be aimed here. The simulator uses the softwares TaCSi and XPlane, and the LAD is interacted with by touch. A test session in the simulator consists of several parts: first there is a briefing of study and HMI, after which the user gets a short training session, followed by two sessions of testing, as well as a survey at the end. The user will also have the possibility to ask questions before the testing begins.

3.2 HMI that will be tested in simulations of pilots interacting

The second HMI to be tested in simulations is that of pilots interacting, it will focus on human-collaboration aspects among humans and autonomous agents working on a shared mission. The overall research goal is to evaluate advanced interaction methods and user interfaces to control unmanned aircraft from the cockpit and to coordinate with the surrounding traffic and missions. Specifically, it requires being able to seamlessly transfer control between different actors (ground station, centralized autonomy, AI system on board, and pilot). Hence, it is partly about control [7][8], partly about the situational picture [6][9][10][11], partly about understanding the system's limitations and similar issues [7]. The final demonstration will show aspects of this.

The experimental implementation requires the integration of several technical components into a common technical environment. First, a plug-in user interface component for the XPlane simulator will be developed that enables pilots to control drones from a cockpit environment. Here, an ecological user interface design is envisioned, and the user is seen as a high-level supervisor of the surrounding drones. In such a design will only the high-level decisions reach the supervisor (i.e., a human-in-the-loop-AI approach). Additionally, an existing simulator – DroneSim – will be modified and drive the simulation scenarios and act as user interface to the ground station personnel.

We expect ground control to partly have a different operational picture, associated with a different role, than the pilot, especially regarding surrounding traffic and missions. Their event horizon of plans and expected developments may also differ. At times, they will collaborate sequentially by shifting command between them, and at times they may collaborate in working on specific situations requiring a coordinated effort and shifting command responsibilities. Challenges such as coordinating situation awareness for their different needs will be addressed.

The user evaluation of the approach will be done with pilots and ground station personnel acquainted with similar systems and task to jointly perform reconnaissance missions. Technically, the data collection will consist of eye tracking data from all human agents, screen capture as well as all audio communications among the personnel. Subsequently, having

the data, we will employ the Joint Control Framework (JCF), [7][8] for analysis of the decisions and actions taken by the different agents. JCF is an approach to analyse and temporally model an agent's cognitive control process including their functional role (e.g. determining plans, object statuses, objectives, in the current, past or future). It also regards aspects such as the coordination of intent, control and situational pictures in the temporal dimension.

3.3 HMI that will be tested in simulations of swarm interaction

The third HMI focuses on swarm interactions. Swarm technologies are being rapidly developed to enable single operators to control multiple autonomous UAVs simultaneously. While this promises scalable and flexible mission execution, it introduces significant human factors challenges. Human-Swarm Interaction (HSI) research has traditionally focused on algorithmic and interface performance, often in lab settings. However, there remains a gap in understanding how these technologies will operate in complex, real-world contexts. Recent work by Bjurling *et al.* [12] and Bjurling [13] emphasizes the need for nuanced interaction models and task-adaptive interfaces that can accommodate the dynamic demands of future swarm operations.

To support these operational needs, Bjurling *et al.* [12] introduces a multilevel interaction model for HSI that enables operators to traverse between different strata of control and attention. At Level 1, the operator manages the swarm as a single entity, issuing global commands and monitoring system-wide information. Level 2 involves interaction with functional subswarms—either emergent or user-defined—to execute geographically or task-specific objectives. At Level 3, control shifts to individual UAVs, enabling task-sensitive intervention such as object inspection or manual piloting. Finally, Level 4 focuses on engagement with sensors, diagnostics, and payload systems across the swarm. This model reflects real operational complexity, where operators must switch between broad oversight and fine-grained control depending on mission phase, urgency, and system state.

Complementing this multilevel model is a growing body of research on control input methods in HSI, which vary in precision, scalability, and cognitive demand. Direct control approaches (e.g., manual teleoperation or single-leader control) offer precision but scale poorly, as each additional UAV increases cognitive load [14][15]. Leader-follower configurations, where only one UAV is explicitly controlled while others follow, simplify input but can impair situation awareness [13].

In contrast, indirect control methods reduce input frequency by influencing swarm behaviour through system-level or environmental cues. Examples include stigmergic mechanisms, such as digital pheromones, and virtual beacons that guide UAV responses [16][17]. Other techniques involve modifying shared swarm parameters or setting task-weighted zones to shape collective behaviour. While these approaches support scalability and reduce operator workload, they often

limit the precision of control and can obscure intent, especially in time-critical contexts [18].

A third paradigm, supervisory control, positions the operator as a mission-level coordinator who assigns objectives and monitors execution. This supports high-level decision making with limited intervention but depends heavily on robust feedback and interface clarity to preserve operator trust and situational awareness [13]. The literature increasingly points to hybrid frameworks as a promising path forward—designs that allow dynamic switching between direct, indirect, and supervisory modes based on task demands and system status [13][18].

We designed and developed a drone swarm simulation environment building on these insights. Our HSI interface enables multilevel swarm interaction and integrates both direct and indirect control paradigms. The system supports high-level mission assignment, visual swarm abstraction, and drill-down inspection of individual agents. It also incorporates task-based grouping, timeline coordination, and contextual overlays to assist operator attention management. Planned simulations and experiments will assess how the HIS supports system level interaction traversal, control fluidity, and cognitive workload regulation under realistic mission conditions. In particular, the platform enables investigations into the resilience of both the swarm system itself and the broader human-swarm collaboration. These studies will examine how anticipation, (self-)monitoring, learning, and other resilience functions [19][20] contribute to swarm-level robustness, as well as how operators respond to and recover from disruptions within a joint cognitive system.

UAVs.

3.4 HMI that explores the use of predictive control techniques to compensate for time delay in the communication with UAVs

The fourth HMI to be tested in simulation environment aims at compensating for time-delay in the communication with UAVs.

The time delay in the communication between an UAV and its ground station, due to the use of satellite link, may become a critical factor when, in emergency situations, the pilot cannot rely on onboard autopilot and has to manually control the UAV. It can increase the operator's workload, affect the mission performance and jeopardize the aircraft.

To mitigate these effects, the proposed HMI offers a visual interface that projects the predicted current state of the UAV, despite the time delay in the communication. Its purpose is to minimize the impact of the time delay on the pilot's workload. As reported by Pestana [21] about the task of landing at bases other than those originally planned, "*pilots practiced landings in a simulator with satellite signal latency, and described it as - learning to land a few seconds into the future.*" The use of predictive systems provides the pilot with a forecast of the aircraft's actual position and attitude, compensating for the communication delay. The proposed

HMI is an evolution of a previously designed interface and explores the use of a HUD display. The improvements are based on suggestions from different users.

The simulation environment developed to evaluate the predictive HMI has an additional purpose of providing a testbed to evaluate the use of different physiological sensors to monitor the pilot state.

The scenario considered for the evaluation of the predictive HMI investigates the pilots' ability to control the UAV in the presence of communication time delay. It considers the situation in which the UAV needs to switch from an autonomous operation mode to a directly piloted operation mode, given the occurrence of an emergency that results in the need to land in a base other than those originally planned.

The task to be performed by the pilot consists of defining an approach and landing route where the pilot must maintain the trajectory within pre-defined limits. The experiment associated with this scenario investigates the increase in the pilot's workload as the communication delay increases and the corresponding degradation in his/her performance. The compensatory effect obtained by the introduction of a predictive system is also investigated.

The current version of the predictive interface is illustrated in Figure 1 and adopts a more interactive visual approach than the previous versions. It features indicators on the left and right that display roll and pitch angles, respectively. Each indicator uses a color-coded system to communicate the status of these angles to the pilot: green indicates an ideal condition, yellow signals the need for attention, and red warns of dangerous situations requiring immediate action. At the centre, a fixed reticule and a movable reticule create a dynamic visual cue where the movable reticule, always pink, predicts the aircraft's trajectory, while the fixed reticule changes colour to indicate whether the predicted manoeuvre is safe or not. These and other interface elements aim at creating an intuitive control environment, aiding the pilot in managing the aircraft during complex flight situations.



Figure 1. HUD with the predictive display.

3.5 AI-assisted HMI with different levels of autonomy for UAV

The fifth HMI explores the employment of different levels of autonomy when controlling multiple UAVs. The purpose is to investigate how different levels of autonomy could help to alleviate pilot workload when dealing with abnormal conditions.

Today, methods to operate a UAV are effective for widely known missions, but while operating a pre-degraded or degraded aircraft, detection and action to save it is still done through manual checks and decisions taken in training. To exemplify, some UAVs have problems with the increase in engine temperature above a certain altitude; if, after the alert, the pilot does not take direct and safe action, the propulsion system shuts down. This problem is aggravated when the operator is responsible for operating more than one aircraft; in addition to the high mental demand for being in an abnormal condition, there is still a division of attention with other UAVs. This scenario increases the difficulty in the case of operation when several aircraft are used simultaneously.

To tackle this challenge, the HMI under development includes a Procedure Following Evaluation (PFE) algorithm to alert the operator of UAV failures, help it to cope with the situation and/or interfere in the UAVs management and control. The PFE uses Artificial intelligence (AI) techniques to process data from the UAVs' onboard systems and detect failures and/or dangerous situations.

The HMI is also used to evaluate the viability of operator monitoring systems based on physiological data and subjective questionnaires to estimate his/her mental workload and distribution of attention. The purpose is to improve the operator's capacity in emergencies with one or more aircraft simultaneously.

Three different approaches will be tested to reconfigure the trajectories of a set of UAVs performing a given mission in the case of failure or emergency situation, as illustrated in Figure 2. Each approach corresponds to a different level of autonomy:

- Human operated: corresponds to a low level of autonomy. The pilot has to reconfigure the UAVs trajectories manually.
- Human delegated: AI algorithm defines a set of options for the mission reconfiguration. The pilot decides whether to choose one of them, modify one of the them or define a new one.
- Human supervised: AI algorithm determines the best option and informs it to the pilot. If he/she wants, he/she can change it, otherwise the system automatically adopts it.

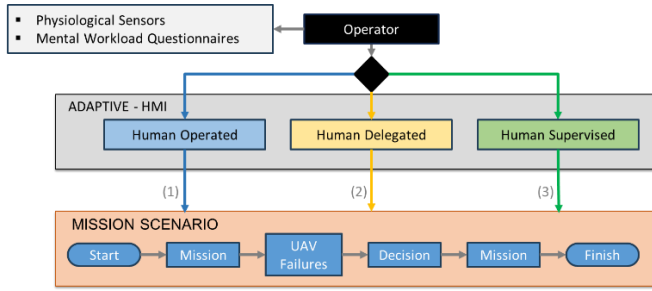


Figure 2. AI assisted HMI with different levels of autonomy.

3.6 Design of multi-modal interface based on generative AI

The sixth HMI explores the development of a framework for designing multimodal interfaces, leveraging the capabilities of generative AI, particularly Large Language Models (LLMs). The objective is to define a framework that induces innovation by using LLMs either as a design tool or a catalyst for creative ideas [26], [27], [28].

Multimodal interfaces allow users to interact with systems using multiple communication modes - such as speech, touch, gestures, eye movement, and physiological signals - either simultaneously or interchangeably. The purpose is to enhance interaction flexibility, efficiency, and robustness by adapting to user needs and environmental conditions.

The research begins with a comparative analysis of three established design methods - Delphi, Function-Behaviour-Structure (FBS), and Ecological Interface Design (EID) - and how to integrate the use of LLMs with these methods.

As example, Figure 3 illustrates the Delphi method, a structured, iterative process used to gather and refine expert opinions on a specific topic or problem. It requires multiple rounds of questionnaires for gathering experts' opinions. When combining the Delphi method with the use of LLMs, the AI is initially used to elaborate a system description using UML diagrams. This description is used by both specialists and the AI engine to generate set of requirements that are then used to develop the HMI.

Figure 3. Delphi method.

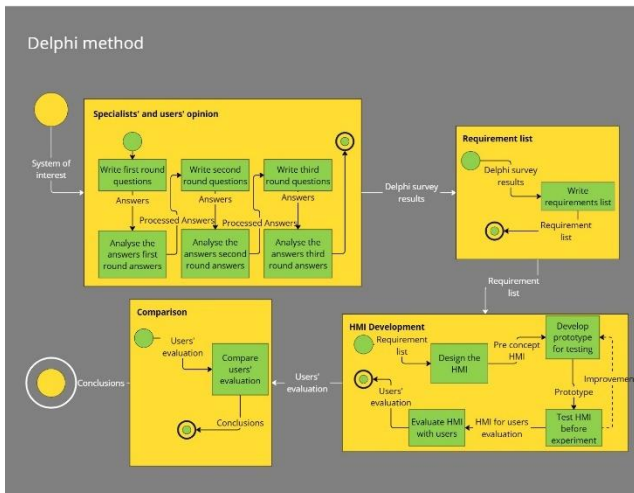
After the investigation of how to individually combine each method with LLMs, the next step is the proposal of a single framework that extracts the best of the above methods and combines them in a single approach.

The resulting framework will be applied to the design of a multimodal interface for manned-unmanned teaming (MUM-T) and evaluated in a border surveillance and reconnaissance mission performed by manned-unmanned aircraft teaming. Three different scenarios are considered in the evaluation: a) *No Comm*: there is no direct communication between the pilot and the UAVs and intermittent information is provided by the UAVs ground station; b) *Unilateral Comm*: the UAVs provide the manned aircraft with real-time data, but the pilot cannot send any command to the UAVs, any interference should be made through the ground station; c) *Bilateral Comm*: the manned aircraft can receive data and send commands to the UAVs.

Resultant HMIs will be used to evaluate critical human factors such as mental workload, situation awareness, and trust. The findings will offer valuable insights into the potential of AI-augmented design processes and their impact on the effectiveness and reliability of multimodal interfaces in the aircraft industry.

The integration of Unmanned Aerial Vehicles (UAVs) with manned systems in military and aerospace operations necessitates advanced autonomy and refined pilot-vehicle interfaces to enhance Manned-Unmanned Teaming (MUM-T) efficiency, as explored in studies on controlling multiple UAVs from manned platforms [22], [23], [24]. As highlighted by Endsley [25] the transition towards increased autonomy in aerospace systems brings forth challenges in ensuring that human operators remain effectively in the loop. Other researches underscore the critical need for interfaces that optimize human-machine interaction through visual, auditory, and tactile feedback, and manage the complex task distribution in single-seat fighter operations managing UAVs [29]. Together, these advancements in autonomy, interface design, and situational awareness frameworks are pivotal for redefining collaboration in complex operational fields, enhancing the decision-making process, and ensuring the operational effectiveness of both manned and unmanned components in future aerospace missions.

The adoption of multi-modal interfaces in Manned-Unmanned Teaming (MUM-T) operations significantly enhances both operational efficiency and situational awareness. Levulis *et al.* [30] demonstrates the superiority of touch and multi-modal methods over traditional voice commands, evidencing marked performance improvements, reduced cognitive burden, and increased situational awareness. These findings advocate for the critical role of multi-modal interface design in streamlining cognitive load and boosting operational efficiency, underscoring the need



for systems that adapt to varied operational demands and user preferences. Further investigations, as presented in Margienė e Ramanauskaitė [31] alongside Hansberger *et al.* [32] and Karpov e Yusupov [33], affirm the value of these interfaces in creating more intuitive, human-centric computing environments.

Moreover, Cohen *et al.* [34] provides critical insights into how the anthropomorphic features of multi-modal interfaces can influence trust levels within MUM-T operations. This research highlights the significance of designing interfaces that not only facilitate operational objectives but also foster a deeper trust and understanding between human operators and autonomous systems, thereby enhancing team cohesion and decision-making efficiency in complex scenarios. Such interfaces, capable of processing and synthesizing multimodal inputs, are essential in scenarios that necessitate quick and complex decision-making, signifying a significant shift towards designs that resonate more closely with human cognitive processes and modes of communication.

4 Conclusions

A key concept for Future Air Domain is the “system of systems” approach, where multiple interconnected platforms - manned and unmanned - operate collaboratively. Another important feature is the integration of emerging technologies, such as autonomous systems and artificial intelligence (AI), to support complex decision-making processes.

In this context, effective human-machine collaboration becomes essential, as well as the design of human-machine interfaces (HMI) that support it.

This paper discussed the challenges of HMI design for Future Air Domain and presents six HMI concepts that are current under development as part of a joint Swedish and Brazilian research project. The project investigates how cognitive modelling and pilot state monitoring can contribute to HMI design, how concepts of adaptive interface can be explored to support different levels of autonomy, and how pilot human factors are affected by need of communicating and interacting with multiple UAVs.

As next step, the six HMI will be tested in different simulation environment in order to improve current knowledge of HMI design for future air domain.

Acknowledgment

The Brazilian authors acknowledge the financial support of Brazilian funding agencies FINEP and CNPq. The Swedish authors acknowledge the financial support of Swedish Defence Material Administration and NFFP (National Aviation Research Programme), which is funded by VINNOVA (Swedish Governmental Agency for Innovation Systems, 2024-01946), the Swedish Armed Forces, and the Swedish Defence Material Administration.

References

- [1] M. J. Forsty, Command of the air? Military Review - The Professional Journal of the U.S. Army, Army University Press, 9p., 2024. ISSN 0026-4148.
- [2] H. Foster. The air domain and the challenges of modern air war-fare. In: 2018 Index of U.S. Military Strength, pp. 59–73, Washington DC, The Heritage Foundation, 2018.
- [3] E. Panero, A. Russo. The future of the Air Domain at the advent of the Sixth Generation. Technical Report. Ce.S.I. Centro Studi Internazionali, 29p., 2024.
- [4] High Level Group (HLG). Long-Term Strategic Plan for the Brazilian-Swedish Cooperation in Aeronautics. HLG Meeting Minutes - Annex 2. pp 1-10, 2017.
- [5] E. Villani, J. Alfredson, M. Bång, B. Johansson, U. Anderini, D. Arjoni. HMI-HUFLAB – A Brazilian - Swedish initiative in human factors for Aeronautics. The 33rd Congress of the International Council of the Aeronautical Sciences (ICAS 2022), Stockholm (Sweden), September 2022.
- [6] J. Lundberg. Situation awareness systems, states and processes: a holistic framework. *Theoretical Issues in Ergonomics Science*, vol 16, nr. 5, pp. 447-473, 2015.
- [7] J. Lundberg, M. Nylin, G. Praetorius *et al.* Modelling operator control work across traffic management domains: implications for interaction design. *Cognition, Technology & Work*, vol. 26, pp. 281–299, 2024. <https://doi.org/10.1007/s10111-024-00754-w>
- [8] J. Hammarbäck, J. Alfredson, B. J. E. Johansson, J. Lundberg. My synthetic wingman must understand me: modelling intent for future manned–unmanned teaming. *Cognition, Technology & Work*, vol. 26, pp. 107-126, 2024 <https://doi.org/10.1007/s10111-023-00745-3>
- [9] K. L. Palmerius, A. Ugglä, G. Fylkner, J. Lundberg. End-to-end drone route planning in flexible airspace design. *Transportation Research Interdisciplinary Perspectives*, vol 27, 101219, 2024. <https://doi.org/10.1016/j.trip.2024.101219>
- [10] M. R. Endsley. Supporting Human-AI Teams: Transparency, explainability, and situation awareness. *Computers in Human Behavior*, vol. 140, 107574, 2023 <https://doi.org/10.1016/j.chb.2022.107574>
- [11] M. R. Endsley. Situation Awareness Misconceptions and Misunderstandings. *Journal of Cognitive Engineering and Decision Making*, vol. 9, nr. 1, pp. 4-32, 2015. <https://doi.org/10.1177/1555343415572631>
- [12] O. Bjurling, R. Granlund, J. Alfredson, M. Arvola, T. Ziemke. “Drone Swarms in Forest Firefighting: A Local Development Case Study of Multi-Level Human-Swarm Interaction,”. In: Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society, Tallinn Estonia: ACM, pp. 1–7, 2020. <https://doi.org/10.1145/3419249.3421239>.
- [13] O. Bjurling, “Designing Human-Swarm Interaction Systems,” Doctoral dissertation, Linköping University, Linköping, SE, 2025. <https://doi.org/10.3384/9789180759595>
- [14] M. L. Cummings. “Operator Interaction with Centralized Versus Decentralized UAV Architectures,” in Handbook of Unmanned Aerial Vehicles, K. P. Valavanis and G. J. Vachtsevanos, Eds., Dordrecht, NL: Springer, pp. 977–992, 2015. https://doi.org/10.1007/978-90-481-9707-1_117

- [15] A. Hocraffer, C. S. Nam. "A meta-analysis of human-system interfaces in unmanned aerial vehicle (UAV) swarm management," *Applied Ergonomics*, vol. 58, pp. 66–80, 2017, <https://doi.org/10.1016/j.apergo.2016.05.011>.
- [16] E. Bonebeau, M. Dorigo, G. Théraulaz. *Swarm Intelligence: From Natural to Artificial Systems*. New York, NY: Oxford University Press, 1999.
- [17] A. Kolling, K. Sycara, S. Nunnally, M. Lewis. "Human Swarm Interaction: An Experimental Study of Two Types of Interaction with Foraging Swarms," *Journal of Human-Robot Interaction*, vol. 2, no. 2, pp. 103–128, 2013, <https://doi.org/10.5898/JHRI.2.2.Kolling>.
- [18] A. Kolling, P. Walker, N. Chakraborty, K. Sycara, M. Lewis. "Human Interaction with Robot Swarms: A Survey," *IEEE Trans. Human-Mach. Syst.*, vol. 46, no. 1, pp. 9–26, 2016. <https://doi.org/10.1109/THMS.2015.2480801>.
- [19] J. Lundberg, B. J. E. Johansson "Systemic resilience model," *Reliability Engineering & System Safety*, vol. 141, pp. 22–32, 2015. <https://doi.org/10.1016/j.ress.2015.03.013>.
- [20] B. J. Johansson, J. Lundberg. No robot is an island-what properties should an autonomous system have in order to be resilient? *Theoretical Issues in Ergonomics Science*, vol. 26, n. 2, pp. 197–216, 2025.
- [21] M. Pestana. Flying unmanned aircraft: A pilot's perspective. In: *Infotech@ Aerospace 2011*. pp. 1490, 2011.
- [22] A. Das, P. Kol, C. Lundberg, K. Doelling, H. E. Sevil, F. Lewis. A rapid situational awareness development framework for heterogeneous manned-unmanned teams. In: *IEEE. NAECON 2018-IEEE National Aerospace and Electronics Conference*. pp. 417–424, 2018.
- [23] Y. Lim, A. Gardi, R. Sabatini, S. Ramasamy, T. Kistan, N. Ezer, J. Vince, R. Bolia. Avionics human-machine interfaces and interactions for manned and unmanned aircraft. *Progress in Aerospace Sciences*, Elsevier, v. 102, pp. 1–46, 2018.
- [24] G. S. Taylor, T. J. Alicia, T. Turpin, A. Surana. Controlling multiple unmanned aircraft from a manned helicopter: The need for advanced autonomy and refined pilot-vehicle interface. In: *SAGE Publications, Los Angeles (CA). Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. v. 61, n. 1, pp. 78–82, 2017.
- [25] M. R. Endsley. From here to autonomy: lessons learned from human-automation research. *Human factors*, Sage Publications Sage CA: Los Angeles, CA, v. 59, n. 1, pp. 5–27, 2017.
- [26] V. Kumar, A. Pandey, R. Singh. Can artificial intelligence be a critical success factor of construction projects? practitioner perspectives. *Technology Innovation Management Review*, v. 11, n. 11-12, 2021.
- [27] G. H. Steinke, M. S. Al-Deen, R. C. Labrie. Innovating information system development methodologies with design thinking. *Proceedings of the 5th Conference in Innovations in IT*, vol. 5, nr. 1, pp. 51-55, 2018.
- [28] J-C. Cong, C-H. Chen, P. Zheng, X. Li, Z. Wang. A holistic relook at engineering design methodologies for smart product-service systems development. *Journal of Cleaner Production*, Elsevier, v. 272, p. 122737, 2020.
- [29] S. Gangl, B. Lettl, A. Schulte. Management of multiple unmanned combat aerial vehicles from a single-seat fighter cockpit in manned-unmanned fighter missions. In: *AIAA Infotech@ Aerospace (I@ A) Conference*. p. 4899, 2013. <https://doi.org/10.2514/6.2013-4899>.
- [30] S. J. Levulis, P. R. Delucia, S. Y. Kim. Effects of touch, voice, and multimodal input, and task load on multiple-uav monitoring performance during simulated manned-unmanned teaming in a military helicopter. *Human factors*, SAGE Publications Sage CA: Los Angeles, CA, v. 60, n. 8, p. 1117–1129, 2018.
- [31] A. Margienè, S. Ramanauskaitė. Trends and challenges of multimodal user interfaces. In: *IEEE. 2019 Open Conference of Electrical, Electronic and Information Sciences (eStream)*, p. 1–5, 2019.
- [32] J. T. Hansberger, C. Peng, V. Blakely, S. Meacham, L. Cao, N. Diliberti. A multimodal interface for virtual information environments. In: *SPRINGER. Virtual, Augmented and Mixed Reality. Multimodal Interaction: 11th International Conference, VAMR 2019, Held as Part of the 21st HCI International Conference, HCII 2019, Orlando, FL, USA, July 26–31, 2019, Proceedings, Part I* 21. p. 59–70, 2019.
- [33] A. Karpov, R. Yusupov. Multimodal interfaces of human-computer interaction. *Herald of the Russian Academy of Sciences*, Springer, v. 88, p. 67–74, 2018.
- [34] M. C. Cohen, M. Demir, E. K. Chiou, N. J. Cooke. The dynamics of trust and verbal anthropomorphism in human-autonomy teaming. In: *IEEE. 2021 IEEE 2nd International Conference on Human-Machine Systems (ICHMS)*. p. 1–6, 2021.