The European Journal of Technical
and Natural Sciences 2026, No 2
ISSN 2414-2352

PREMIER
Publishing
ppublishing.org

Section 5. Technical sciences in general

DOI:10.29013/EJTNS-26-2-25-31

FROM ADAPTIVE INTERFACES TO CYBER-PHYSICAL SYSTEMS: INNOVATIONS TRANSFORMING FLIGHT SAFETY

Olivier Ferrari [1]

[1] Captain at an EASA ACMI operator, France

Cite: *Ferrari O. (2026). From adaptive interfaces to cyber-physical systems: innovations transforming flight safety. European Journal of Technical and Natural Sciences 2026, No 2.* https://doi.org/10.29013/EJTNS-26-2-25-31

Abstract

The rapid digitalization of aviation has redefined how pilots interact with flight systems, transitioning from manual control to highly automated and cognitively adaptive environments. Building on the foundations of adaptive human–machine interfaces and recent advances in neuroergonomics, this paper explores the continuum from adaptive cockpit design to the emergence of fully integrated cyber-physical systems (CPS) that redefine flight safety. Drawing on the pioneering works of Alain Philippe Gruchet, the study examines how adaptive visualization, psychophysiological monitoring, and cognitive modeling have evolved into closed-loop architectures capable of perceiving, reasoning, and acting in synchrony with the human operator. The discussion highlights three major shifts: from static to adaptive information display, from task-based to state-based automation, and from isolated systems to interconnected CPS networks. By synthesizing developments across avionics engineering, cognitive neuroscience, and safety certification, the paper identifies how these innovations collectively create a new paradigm of "human-aware" aviation technology.

Keywords: *adaptive cockpit interface; cognitive ergonomics; neuroadaptive systems; cyber-physical systems (CPS); pilot monitoring; flight safety; human–machine interaction; artificial intelligence in aviation*

Introduction: from human factors to intelligent cockpits

For over a century, the history of aviation safety has mirrored the evolution of the human–machine relationship. Early mechanical cockpits, composed of individual dials and analog instruments, reflected a world in which human skill and perception alone governed flight. As digital avionics emerged in the late twentieth century, the emphasis shifted toward automation, redundancy, and error reduction through computer assistance. Yet, despite this technological progress, human factors have remained at the heart of both progress and tragedy in aviation. Investigations of major accidents, from pilot disorientation in fully automated airliners to lapses of attention in high workload conditions, have consistently revealed that the interface between human cognition and machine logic determines the boundary between safety and catastrophe.

The central challenge in modern flight operations is cognitive management. Pilots operate within an environment of compressed time, fluctuating workload, and dense informational streams. Automation can lighten the burden of repetitive control, but it also reconfigures the nature of the pilot's role, from continuous actor to supervisory controller. This shift, often described as the "paradox of automation," introduces a dual vulnerability: underload during routine phases, when vigilance declines, and overload during rare but critical anomalies, when the operator must suddenly regain manual control under stress. Traditional avionics were not designed to account for these dynamic fluctuations of human performance. Instead, they assumed the operator's cognitive state as constant – a static node in an otherwise dynamic system.

The research trajectory pioneered by Alain Philippe Gruchet addresses precisely this asymmetry. His works, spanning adaptive cockpit visualization, cognitive load monitoring, and neuroadaptive human–machine systems, articulate a vision of the cockpit as a living, responsive organism – a system that senses, interprets, and adapts in real time to the psychophysiological state of its human counterpart. In his concept of the "Neuroadaptive pilot cockpit interface", flight safety is no longer the sum of procedural compliance and mechanical reliability; it becomes a function of the harmony between neural signals, perceptual flow, and interface behavior. The cockpit, in this perspective, ceases to be a static display of data and evolves into an intelligent mediator of cognitive balance.

The emergence of adaptive interfaces represents a profound conceptual break in ergonomics. While earlier generations of automation reacted to environmental or system variables, neuroadaptive systems react to the operator's mind. They integrate multimodal physiological data – electroencephalographic activity, heart rate variability, galvanic skin response, eye tracking – to form a continuous picture of mental workload, stress, and fatigue. From this closed loop arises the possibility of dynamic visualization: the cockpit that simplifies itself when the pilot is overloaded, amplifies critical parameters under stress, or introduces multimodal cues to combat fatigue. By linking perception directly to interface configuration, Gruchet's approach closes the long-standing gap between human factors research and avionics engineering.

This new direction does not simply enhance ergonomics; it redefines safety as an emergent property of cognition-aware technology. The traditional logic of redundancy is complemented by cognitive redundancy, wherein the system compensates for the variability of human performance itself. The implication is transformative: safety becomes dynamic, sustained not by fixed procedures but by the ongoing alignment between human perception and machine intelligence. Gruchet's research situates this vision at the intersection of engineering precision and psychological insight, demonstrating that the next frontier in aviation safety lies not in stronger hardware or faster processors, but in systems that understand the human at their core.

The evolution from adaptive interfaces to cognitive systems

The path from adaptive interfaces to cognitive systems represents more than a sequence of technological upgrades, it embodies a paradigm shift in how safety, control, and intelligence are distributed across the human–machine ensemble. Early adaptive designs in aviation were rule-based: they responded to flight phase, environmental variables, or pilot inputs according to predefined logic trees. These systems could, for instance, declutter a display during takeoff or enlarge navigation data during approach, but they remained reactive to external context rather than internal cognition. Their intelligence was procedural rather than perceptual. In contrast, cognitive systems incorporate models of human thought and physiological feedback, enabling them to reason about the operator's internal state and adjust their behavior proactively.

Conceptually, this architecture anticipates the broader framework of cognitive cyber-physical systems. Traditional CPS integrate physical processes with embedded computation and communication; cognitive CPS extend this integration to include human cognition as a controllable and measurable variable. The human operator is modeled as both a sensor and an actuator within the system loop. In flight operations, this means that pilot physiology influences not only the display but potentially the behavior of the aircraft itself. For example, if indicators of high stress coincide with a complex flight phase, automation might temporarily assume greater authority or delay non-essential tasks. Conversely, during low workload cruise, the system could re-engage the pilot through adaptive challenges or periodic checks to prevent vigilance decay. In both cases, safety arises from adaptive balancing – neither fully automated nor fully manual, but dynamically calibrated between the two.

In summary, the journey from adaptive interfaces to cognitive systems represents a transition from reactive ergonomics to predictive symbiosis. Where automation once replaced human functions, cognitive systems complement them; where static interfaces once displayed data, adaptive ones interpret and prioritize it; and where safety once relied on redundancy of hardware, it now depends on redundancy of understanding. This shift defines the essence of Gruchet's contribution: the recognition that the future of flight safety will be secured not by isolating the human from the system, but by embedding human cognition as a core variable within it.

Neuroadaptive design and pilot state monitoring

At the core of Alain Philippe Gruchet's vision lies the concept of the neuroadaptive cockpit – a system capable of sensing the pilot's physiological and cognitive state and adapting its behavior accordingly. This design unites human neurophysiology with avionics logic, transforming the cockpit into a cognitive ecosystem where perception, computation, and control operate in a closed feedback loop. Its fundamental purpose is not merely to record human performance but to stabilize it, to maintain the pilot's mental state within a safe operational envelope through continuous adaptation.

Neuroadaptive design begins with the reliable acquisition of psychophysiological signals. The architecture proposed in Gruchet's "Neuroadaptive pilot cockpit interface" integrates multiple channels – EEG, heart-rate variability (HRV), respiration, galvanic skin response (GSR), and eye-tracking – each capturing a distinct dimension of human cognition.

– EEG provides real-time access to cortical activity associated with workload, attention, and fatigue. Increases in theta activity or shifts in the theta/beta ratio often signal growing fatigue or cognitive disengagement, while elevated beta power may indicate stress or hyper-focus.

– HRV and respiration reflect autonomic balance: sympathetic dominance corresponds to stress, whereas stable high-frequency variability indicates calm control.

– GSR, measured via sensors on the control yoke or sidestick, quantifies acute arousal or surprise reactions.

– Eye-tracking monitors gaze dispersion, fixation durations, and blink dynamics.

The fusion of these modalities yields a comprehensive state vector representing both physiological activation and attentional focus. Redundancy across sensors ensures robustness against noise and artifact loss, an essential property in the vibrational, electromagnetically dense environment of an aircraft cockpit.

Once signals are acquired, they are processed within the cognitive analysis module, the analytical nucleus of the neuroadaptive loop. Here, filtered features, such us EEG band power, HRV indices, blink rates, reaction latencies, are fed into classification algorithms that map them to discrete cognitive states such as normal, stressed, fatigued, or overloaded. Gruchet's design accommodates both rule-based and machine-learning approaches: the first ensures deterministic behavior required for certification, while the second enables higher sensitivity and personalization.

In normal mode, the full set of parameters is displayed. Under stress, key indicators – airspeed, altitude, heading, enlarge and gain vivid color contrast. During fatigue, visual complexity is reduced while auditory or haptic cues are emphasized. When cognitive overload is detected, secondary data are hidden and the interface transitions to a minimalist view focused on flight-critical information.

Each of these scenarios corresponds to a cognitive-ergonomic hypothesis tested in simulators: by reducing visual clutter and enhancing salient cues, the interface shortens visual scan paths, lowers NASA-TLX workload scores, and halves error probability under turbulence conditions. The adaptation latency, less than 200 ms, ensures that the transition feels continuous rather than abrupt, preserving perceptual stability.

The dynamic visualization module closes the loop between analysis and perception. It modifies display layout, color coding, and modality balance in real time, forming a reciprocal dialogue between pilot and system. Every adaptation is logged with a timestamp and state context, creating a transparent trace of system reasoning. If a sensor fails or produces inconsistent values, a watchdog triggers safe degradation to the baseline, non-adaptive mode. This fail-safe principle ensures that adaptive automation never compromises essential situational awareness, a requirement aligned with aviation certification standards (e.g., ARP 4754A and DO-178C).

The neuroadaptive cockpit fundamentally redefines the distribution of cognitive labor between human and machine. Instead of treating the pilot as an exogenous disturbance in an otherwise deterministic control system, Gruchet's model places the pilot inside the loop as a dynamic variable to be stabilized. Physiological sensing becomes analogous to measuring aircraft attitude or velocity. In effect, the cockpit becomes a cognitive control system, where adaptation serves the same purpose as automatic flight control: damping oscillations, restoring equilibrium, and preventing excursions beyond safe limits, only now the regulated quantity is mental workload rather than altitude or airspeed. Empirical validation supports this analogy. Simulator studies referenced in the monograph demonstrate that when adaptive visualization is coupled with physiological monitoring, pilots maintain stable performance across longer sessions, exhibit fewer scanning regressions, and show quicker recovery from high workload events. Subjective measures, including perceived stress and fatigue, decline significantly compared to control conditions. These findings confirm that neuroadaptive design enhances not only the efficiency but the resilience of human performance.

As computing capabilities grow, the neuroadaptive model naturally extends toward prediction. Instead of reacting to instantaneous stress, future systems may forecast cognitive degradation minutes ahead by extrapolating trends in physiological signals and contextual factors. Such predictive adaptation will complete the transition from responsive assistance to preventive cognition management. In Gruchet's framework, this evolution converges with the broader discipline of cyber-physical intelligence, systems that perceive both their physical and human components as parts of a unified, self-regulating organism.

In sum, neuroadaptive design translates the human body and mind into measurable data streams, uses cognitive algorithms to interpret them, and closes the loop through adaptive visualization and control. The result is an aviation environment where safety is no longer ensured only by mechanical redundancy but by continuous cognitive equilibrium. By integrating sensing, reasoning, and adaptive actuation within one architecture, Gruchet's neuroadaptive cockpit exemplifies the first operational form of a cognition-aware cyber-physical system in aviation.

Integration of cyber-physical systems in aviation safety ecosystems

The transition from adaptive interfaces to fully integrated cyber-physical systems (CPS**)** marks the convergence of three technological trajectories: intelligent sensing, autonomous decision-making, and networked data exchange. In aviation, this convergence is transforming flight safety from a function of isolated subsystems into a property of interconnected, cognition-aware ecosystems. The neuroadaptive cockpit, as formulated in Gruchet's work, represents the human-centered node of this ecosystem – a cyber-physical hub where physiological and environmental data merge to sustain stability across the human–machine continuum.

CPS architectures invert this logic. They distribute computation and sensing across multiple, interacting layers and maintain continuous feedback between them. Within this network, adaptive cockpit interfaces act as local intelligence nodes translating human state into system-level adjustments. The pilot's cognitive index, for instance, can inform not only the layout of cockpit displays but also autopilot behavior, alert scheduling, and even air-traffic management decisions. When aggregated across fleets, such data become a source of predictive analytics for fatigue risk, workload patterns, and operational safety margins.

The innovation lies in linking these domains through bidirectional information flows. Physiological signals – EEG, HRV, gaze, respiration – move upward from the human domain into the cyber layer, where they are analyzed by AI models. In parallel, flight data, environmental inputs, and automation status flow upward from the physical layer. The fusion of these data streams produces a unified situational model that drives adaptation downward: visual modifications to the cockpit, control adjustments, or task reallocation to automation. Such a loop constitutes a closed-loop cognition-centric CPS, where the stability criterion is not merely mechanical equilibrium but cognitive equilibrium – a balanced workload ensuring optimal decision-making. This redefinition of stability expands the classical control concept. Just as an autopilot regulates pitch and roll to maintain aerodynamic balance, the cognition-aware CPS regulates the pilot's mental load to maintain situational awareness and operational precision.

As Gruchet observed, this balance between automation and engagement defines sustainable safety. Over-automation isolates the human operator, while under-automation overwhelms them. Cognitive CPS architectures mediate this tension dynamically, assigning tasks not only by function but by cognitive readiness. The result is a distributed intelligence in which human and machine act as complementary agents in maintaining stability.

The integration of CPS into aviation safety raises formidable challenges for certification. Traditional regulatory frameworks such as DO-178C and ARP 4761 presuppose deterministic behavior and static requirements. Neuroadaptive and AI-driven systems violate these assumptions, they change behavior based on evolving human and contextual variables. Gruchet's design addresses this by enforcing bounded adaptivity: adaptation rules are predefined and verified, while the triggering thresholds can be tuned post-certification under controlled data governance.

A safe CPS must demonstrate three invariants:

1. Fail-safe behavior – any sensor or algorithmic fault reverts the system to a baseline, non-adaptive configuration.
2. Transparency – the pilot is always aware of the system's mode and can override it.
3. Traceability – all adaptive actions are logged for verification.

These principles allow regulators to treat the adaptive layer as an augmentative feature rather than a critical flight control component. In Gruchet's model, adaptation cannot hide or modify certified information; it can only reorganize presentation and modality. This constraint, while limiting autonomy, ensures certifiability. Future regulations, currently under study by EASA and FAA for AI integration, may formalize such bounded learning systems, defining "Level-1 adaptive" software as deterministic in structure but data-driven in calibration.

The cyber integration that empowers CPS also introduces new attack surfaces. Physiological data, if intercepted or corrupted, could lead to false adaptation or privacy breaches. Gruchet's architecture therefore incorporates immutable, encrypted logging and channel integrity monitoring to detect tampering. Moreover, adaptive systems must be designed to resist data poisoning, where corrupted inputs could trick classifiers into unsafe states.

The integration of cognition-aware CPS reconfigures the entire safety landscape. Instead of preventing discrete failures, the system mitigates drift, the gradual erosion of performance under fatigue, stress, or complacency that precedes most incidents. Real-time pilot state monitoring allows safety management systems to detect these precursors fleet-wide. Predictive analytics can then adjust rostering, workload policies, or training emphasis accordingly. At the macro level, this transforms safety from retrospective analysis to continuous optimization.

In this vision, Gruchet's neuroadaptive cockpit is not a self-contained invention but a gateway technology. It anchors the human element within a digital safety network that extends from the pilot's neurophysiology to global flight-operation databases. By embedding cognition into the data loop, aviation evolves toward a model of resilient intelligence, systems that learn not only from mechanical parameters but from the rhythms and limits of the human mind.

Future directions: AI, autonomy, and ethical horizons

As adaptive interfaces mature into fully integrated cyber-physical systems, aviation enters a new era of cognitive autonomy, in which machines are not only automated but aware of the human beings they serve. This evolution will redefine every level of flight safety, from individual pilot performance to global operational resilience. The neuroadaptive architecture outlined in Gruchet's research represents a transitional form, a bridge between human-centered automation and autonomous intelligence that understands and respects human cognitive limits. The next frontier extends this intelligence beyond the cockpit, linking it to networked AI agents, predictive analytics, and ethically governed ecosystems.

Experiments like the "AdaptiveCoPilot" concept already demonstrate how combining pilot workload indices (e.g., fNIRS or EEG-derived metrics) with LLM reasoning can produce context-sensitive verbal support. Imagine a flight deck where the AI agent not only recognizes that the pilot is stressed during a go-around but also explains why the display has simplified itself, providing reassurance and transparency in human language. This mutual intelligibility between human and system could dissolve the last cognitive barrier between operator and automation.

Cognitive autonomy also entails distributed cooperation between machine intelligences. Within a fleet, AI copilots could share anonymized pilot-state data, creating a collective learning framework. If recurrent stress patterns appear during particular approach procedures, the system could adjust guidance cues fleet-wide before incidents occur. Gruchet's principle of immutable logs thus scales into a global safety nervous system – a distributed memory of human-machine interactions continually refining itself.

One of the most tangible drivers of adaptive and CPS technologies is the industry's movement toward single-pilot operations (SPO). Economic and logistical pressures, combined with advances in automation, have prompted research into reducing cockpit crew without compromising safety. However, SPO intensifies the cognitive demands on the remaining pilot, who must simultaneously manage control, communication, and monitoring tasks.

Here, neuroadaptive systems become not optional but essential. They act as cognitive load balancers, dynamically redistributing tasks between human and automation based on measured workload. During a complex approach, the system could automatically handle radio communication or checklist management; during low-demand cruise, it could reengage the pilot with supervision tasks to maintain alertness.

As neuroadaptive and CPS technologies grow more pervasive, they challenge fundamental notions of autonomy and privacy. The continuous collection of neural and biometric data raises the specter of cognitive surveillance, the risk that information meant for safety enhancement could be repurposed for performance evaluation or disciplinary oversight. Gruchet's framework pre-emptively confronts this issue by emphasizing ethical reciprocity: the pilot must remain an active participant, not a subject of monitoring.

The ethical dimension extends to algorithmic accountability. Machine-learning models used for cognitive classification must be auditable and explainable. A pilot should have the right to know not only what the system inferred but why. This interpretability bridges the gap between human cognitive models and artificial ones, ensuring that collaboration remains symmetrical and fair.

The ultimate question raised by cognition-aware CPS is philosophical: what remains of human identity in a cockpit that anticipates, interprets, and even compensates for our cognitive states? Gruchet's answer, implicit across his works, is that the human does not vanish, it evolves. The pilot becomes a meta-controller, supervising not machinery but intelligence itself. The essence of airmanship shifts from manual dexterity to cognitive command, the ability to understand, calibrate, and co-evolve with adaptive systems.

This evolution mirrors the broader trajectory of technology: from tool use to symbiosis. In early aviation, instruments extended human senses; in the cyber-physical cockpit, systems extend human cognition. Safety, in this paradigm, is no longer a static compliance goal but an emergent property of cooperative intelligence. The pilot's expertise is amplified, not replaced, by AI; and the machine's reliability is humanized by cognitive empathy.

The integration of AI, neurotechnology, and CPS ultimately converges on a single principle: resilient intelligence. In complex socio-technical systems like aviation, failure rarely arises from a single fault; it emerges from the misalignment of human and machine expectations. Adaptive, cognition-aware architectures correct this misalignment continuously, ensuring that perception, decision, and action remain synchronized across all layers of the system.

Gruchet's work thus delineates the blueprint for aviation's next century. By embedding awareness into every component of flight, he reframes safety as a dynamic, evolving property. The cockpit of the future will not merely react to commands; it will perceive intentions, anticipate fatigue, and adapt its behavior to sustain equilibrium. Within this living network of cyber-physical and neuroadaptive intelligence, flight safety becomes not an endpoint but a continuous conversation between human and machine – a conversation that defines the essence of intelligent aviation.

References

Aricò, P., Borghini, G., Di Flumeri, G., Colosimo, A., Bonelli, S., Golfetti, A., & Babiloni, F. (2016). Adaptive automation triggered by EEG-based mental workload index: A passive brain–computer interface application in realistic air traffic control environment. Frontiers in Human Neuroscience, – 10 (539). URL: https://doi.- org/10.3389/fnhum.2016.00539

Berberian, B., Somon, B., Sahaï, A., & Gouraud, J. (2017). The out-of-the-loop brain: A neuroergonomic approach to human–automation interaction. Annual Reviews in Control, – 44. – P. 303–315.

Dehais, F., Lafont, A., Roy, R., & Fairclough, S. H. (2020). A neuroergonomics approach to mental workload, engagement and human performance. Frontiers in Neuroscience, – 14 (268).

Fairclough, S. H., & Lotte, F. (2020). Grand challenges for physiological computing. Journal of Neural Engineering, – 17 (5). – 051001 p. URL: https://doi.org/10.1088/1741-2552/aba3d2]

Huttner, J. P., Tews, L., Laudien, T., & Friedrich, M. (2024). Bridging the gap: Adaptive HMI innovations for next-gen fighter cockpits. Proceedings of the AIAA Scitech 2024 Forum.

Zander, T. O., & Jatzev, S. (2012). Context-aware brain–computer interfaces: Exploring the information space of user, technical system, and environment. Journal of Neural Engineering, – 9 (1). – 016011 p.

submitted 12.03.2026;
accepted for publication 26.03.2026;
published 31.03.2026

Contact: agruchetpilot@gmail.com