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Cognitive pilot-aircraft interface for single-pilot operations

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ABSTRACT

Considering the foreseen expansion of the air transportation system within the next two decades and the opportunities offered by higher levels of automation, Single-Pilot Operations (SPO) are regarded as viable alternatives to conventional two-pilot operations for commercial transport aircraft. In comparison with current operations, SPO require higher cognitive efforts, which potentially result in increased human error rates. This article proposes a novel Cognitive Pilot-Aircraft Interface (CPAI) concept, which introduces adaptive knowledge-based system functionalities to assist single pilots in the accomplishment of mission-essential and safety-critical tasks in modern commercial transport aircraft. The proposed CPAI system implementation is based on real-time detection of the pilot's physiological and cognitive states, allowing the avoidance of pilot errors and supporting enhanced synergies between the human and the avionics systems. These synergies yield significant improvements in the overall performance and safety levels. A CPAI working process consisting of sensing, estimation and reconfiguration steps is developed to support the assessment of physiological and external conditions, a dynamic allocation of tasks and adaptive alerting. Suitable mathematical models are introduced to estimate the mental demand associated to each piloting task and to assess the pilot cognitive states. Suitably implemented decision logics allow a continuous and optimal adjustment of the automation levels as a function of the estimated cognitive states. Representative numerical simulation test cases provide a preliminary validation of the CPAI concept. In particular, the continuous adaptation of the flight deck's automation successfully maintains the pilot's task load within an optimal range, mitigating the onset of hazardous fatigue levels. It is anticipated that by including suitably designed Psychophysiological-Based Integrity Augmentation (PBIA) functionalities the CPAI system will allow to fulfil the evolving aircraft certification requirements and hence support the implementation of SPO in commercial transport aircraft.

1. Introduction

Due to the substantial growth in commercial air travel demand and the aggravating global shortage of qualified pilots [29], Single-Pilot Operations (SPO) are likely to be extended beyond military and general aviation operations in the next two decades [12,15]. Single-pilot airline transport aircraft are nonetheless associated with substantial challenges, as the individual pilot on board may suffer incapacitation, potentially resulting in fatal accidents. Additionally, compared to conventional two-pilot operations, SPO pose greater cognitive demands on the individual pilot. These demands, should they exceed the pilot's cognitive capacity, will adversely affect the pilot's ability to accomplish the task-at-hand. [20]. Pilots whose capabilities fall short of task requirements can make errors in safety-critical duties, leading to fatal accidents. Consequently, the transition to SPO require substantial increases in automation support both in the flight deck and on the ground as well as significant changes in the roles and responsibilities of pilots and Air Traffic Management (ATM) operators. In particular, the primary duties of pilots are progressively shifting towards supervisory roles, intervening only when necessary [33]. These new roles require a corresponding evolution in the Human-Machine Interfaces and Interactions (HMI^2). Current HMI^2 are static and do not take into consideration the dynamic variations in cognitive task loads [50]. Additionally, as part of the Technology Horizons project, the United States (US) Air Force identified that natural human capacities and advanced technologies become increasingly mismatched and humans will be the weakest component in the generalised processes and systems by 2030 (US [52]). Therefore, a dynamic sharing of tasks between human pilots and avionics systems through advanced HMI^2 will be required to achieve better overall performance.

Research in the past decade has examined the use of intelligent HMI^2 systems in dynamically reconfiguring cockpit displays according to the operator's task and actions [39], as well as reacting to external events [28]. Terveen [51] discusses three key issues

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concerning adaptive systems: how information is acquired, how the system represents and reasons the received information and how information is used. In the Taxonomy of Adaptations, Feigh et al. [21] describes four ways in which information can be used: modifying the task allocation between human and machine, the task scheduling based on priority, the machine's interaction with the user as well as the formats and functions. Developments in wearable and contactless sensing technologies have enabled new ways of acquisition, interpretation and exploitation of human physiological data in HMI[2], as in the case of activity recognition [38]. In our research, a Cognitive Pilot-Aircraft Interface (CPAI) is proposed to implement these new sensing technologies in an expert avionics decision support system. This novel system can dynamically assess the pilot's cognitive capacity through sensors that track his/her physiological measurables and complement it through system adaptation. In particular, CPAI modifies the task allocation between pilots and systems, generates suitable alerts and modifies the information presented to the pilot with adaptive interfaces. Thanks to these functionalities currently unavailable in the flight decks of commercial transport aircraft, CPAI can prevent human errors in the cognitive domain and optimise the interaction and task allocation between the human and aircraft systems. Consequently, commercial transport aircraft equipped with CPAI will potentially fulfil evolving certification standards for SPO.

This paper presents the conceptual design, development and numerical verification activities of CPAI. Model verification activities are performed by means of representative simulation case studies to preliminarily validate the technical feasibility of CPAI. Six layers of variables including operational conditions, environmental conditions, physiological measurables, cognitive indicators, system and interface variables are identified for the mathematical model development. The mental workload is determined by means of two distinct methods. Physiological data including heart, respiratory and blink rates are used to infer the current cognitive states using suitably defined empirical models. Furthermore, environmental and operational conditions are analysed to generate future mental workload demand estimates.

The CPAI presented in this paper is an expert decision support system, which exploits the input information on monitored and predicted cognitive states to enhance operational safety and efficiency. In particular, system adaptation, driven by expert decision logics, is implemented based on the key variables and mathematical relationships. The opportunity of dynamically adapting the decision logics based on the characteristics of the monitored individual and on the particular flight phase is highlighted and further developments in this direction are outlined.

1.1. Single pilot operations

Current commercial transport aircraft adopt two-pilot flight crews, comprising of a Pilot Flying (PF) and a Pilot Non-Flying (PNF). Both of them are on board and the primary responsibility shared between them consists in controlling the aircraft while it is flying or moving on the ground. Four fundamental duties are shared between the PF and the PNF: *aviate, navigate, communicate, manage*. SPO are defined such as these tasks are conducted by only one pilot in the Flight Deck (FD) (CASR 1998-REG 61.010). Compared to conventional two-pilot operations, the primary duty of the single on board pilot (PF) is still controlling the aircraft. However, ground-based human operators located in the Airline Operations Centre (AOC) are able to support the airborne PF in SPO [32]. AOC operators monitor the aircraft mission and assist the PF in the role of dispatchers. In case of emergency, AOC operators upgrade their roles to ground-based first officers, who assist the on board pilot by real-time voice coordination with the FD and control of the aircraft through the HMI[2] in the ground workstation [13]. Fig. 1 presents a comparison between the interactions involved in two-pilot, single-pilot and Remotely Piloted Aircraft Systems (RPAS) operations, including Air Traffic Controllers (ATCo).

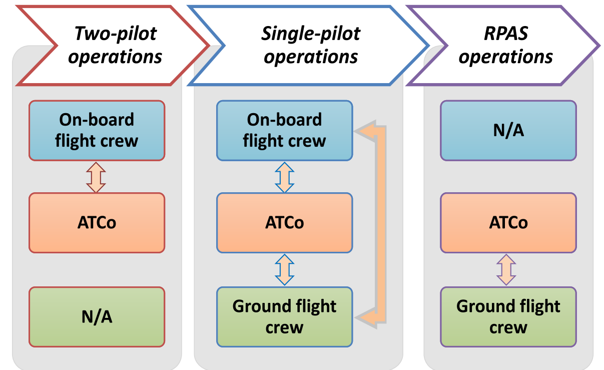

Fig. 1. Human operator interactions in different operational settings.

As mentioned above, the primary responsibilities of PF in SPO include a variety of mission-essential and safety-critical tasks [1,19]:

Aviate

- Monitor aircraft flight, traffic and weather statuses;
- Manually fly the aircraft by controlling stick, pedal and throttle;
- Detect and resolve potential in-flight conflicts and hazards;
- Setup autopilot to assist/supplement in attaining the desired flight profile.

Navigate

- Monitor the aircraft position and course;
- Select and configure applicable navigation modes;
- Configure the cleared flight plan or 2/3/4-dimensional trajectory in the Flight Management System (FMS).

Communicate and coordinate

- Communicate and coordinate with ATCo and AOC operators;
- Dispatch declarations of urgency and emergency.

Manage

- Monitor the status of aircraft systems;
- Monitor compliance with the Required Communication, Navigation and Surveillance Performances (RCP, RNP, RSP);
- Supplement or supersede the system as required.

The primary responsibilities of the AOC operators include [12,32]:

- Monitor SPO aircraft throughout the flight;
- Support the PF in decision making as a co-pilot would;
- Assist the PF in following the Reference Business Trajectory (RBT) en route to maximise the PF's attention on other tasks;
- Share the PF workload in unexpected and challenging conditions (e.g. system failures, adverse weather);
- Assist in the critical approach and landing phases;
- Take over the PF's responsibility in the event of incapacitation;
- Communicate and coordinate with PF and ATCo.

The ATCo also plays a significant role in SPO in adverse conditions such as system failures and severe weather conditions.