Adaptive Automation and the Third Pilot: Managing Teamwork and Workload in an Airline Cockpit

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Abstract. The objective of this paper is to present a new adaptive automation concept which offers an innovative 'team' centred approach to solving human factors/workload management problems. The A-PiMod concept/approach is defined by the concept of partnership – specifically, the "Third Pilot" and the crew and automation are in charge together. We are proposing partnership as opposed to dynamic changes in control function where changes can be controlled autonomously by the system. In support of this, a new multimodal concept is proposed which supports improved assessment of crew state/workload (i.e. information inputs re crew activity/interactions provides a means to communicate with the crew in relation to crew state and decision support, and allows for flexible crew/cockpit interaction).

Keywords: Adaptive automation, Workload, Crew state monitoring, Pilot decision making, Stakeholder evaluation, Multimodal interaction and Cockpit displays

1 Introduction

1.2 Introduction to the Research Problem

Given automation advances over the last decade, Pilots share responsibility for different flight tasks with cockpit systems. Adaptable systems are systems which require human delegation of task and ‘function authority’ to automation during real-time operational performance (i.e. the task distribution is controlled by the user) [1]. Adaptive automation (AA) is defined as a ‘form of automation that allows for dynamic changes in control function allocations between a machine and human operator based on states of the collective human–machine system’ [2, 3]. As such, task distribution changes can be controlled autonomously by the system.

Today’s automation is indifferent to the emotional and cognitive state of the crew. Automation only supports the crew based on explicit and static task assignments, with no adaptive capabilities, even though it is capable of higher or lower levels of support if needed or when the capabilities of the crew are challenged.

The air accident and flight safety literature reports on the many still-open issues in relation to automation design. For example: Flight Air France 447 (2009) [4], Flight Spanair 5022 (2008) [5], Flight Helios Airways HCY 522 (2005) [6], Flight China Airlines 140 (1994) [7], and Flight Air Inter 148 (1992) [8]. Critically, several human factors problems have been documented. This includes: automation surprises, degraded situation awareness, unintentional blindness, workload concerns and issues pertaining to over-reliance on automation.

Human operators and automated systems have to act together, cooperatively, in a highly adaptive way. They have to adapt to each other and to the context in order to guarantee fluent and cooperative task achievement maintaining safety at all times. With increasing flight hours, fatigue and increased traffic growth, all crews can benefit from an “experience aid”. Ideally, the user and the “experience aid” (or assistance system) constitute a cooperative system - they share tasks and perform them as a team.

1.2 Introduction to the A-PiMod Project

The Applying Pilots' Model for Safer Aircraft (A-PiMod) project aims to address problems relating to crew/automation teamwork and workload management. The objective of the A-PiMod project is to demonstrate a new approach/concept (and associated technologies) for an adaptive automation and multimodal cockpit which will reduce human error. Specifically, the objective is to support adaptive distribution of tasks between the crew and automation, based on real-time analysis of the crew's cognitive state and behavior and on the risk associated with the mission. In relation to cognitive state, the focus is on situation awareness and workload and not emotional state. This research was funded by the European Commission and has been undertaken between September 2013 and September 2016.

2 Research Design

2.1 Overview

The high level Human Machine Interaction (HMI) design/evaluation methodology combines formal HMI design/evaluation activities (i.e. interviews and simulator evaluation), informal HMI design/evaluation approaches (i.e. participatory design activities), along with an integrated stakeholder approach to evaluation [9, 10, 11].

The A-PiMod safety case addresses the cockpit team concept (i.e. third pilot concept) and Human Multi-Modal Interaction (HMMI). Overall, the A-PiMod safety case has supported (1) the definition of user requirements and associated user interface design activities, and (2) the assessment of potential impact/benefits. This has involved twenty seven COP sessions and two phases of simulator evaluation. For more information about specific methodologies, please see [9, 10, 11].

The assessment of potential impact/benefits has been undertaken in relation to actual end user/operational scenarios. Scenarios have been developed as part of (1) formal evaluation activities (VC1 and VC2), and ongoing research with the A-PiMod COP.

2.2 Quantification of Safety Impact

The safety impact of the A-PiMod adaptive automation and multimodal cockpit concept was quantified by a systematic approach using the Total Aviation Risk model and structured feedback on change factors for base events in this risk model. The assessment of safety impact was undertaken for the A-PiMod concept, rather than for its particular implementation as achieved in the A-PiMod project (i.e. software/technology). For more information, please see [12].

2.3 Community of Practice & Stakeholder Participation

The concept of a Community of Practice (COP) proposed by Wenger underpins the stakeholder evaluation approach [13]. Stakeholder participation involves consultative interaction along with engagement in technical research tasks [14]. Overall, twenty seven COP sessions and two phases of simulator evaluation have been undertaken. The first phase of simulator evaluation involved eight participants, while the second phase involved twelve participants.

The COP panel comprised fifteen participants (see figure 1 below). The Radar Diagram below (see Figure 1) shows the two overlaying levels of expertise both from the internal and external stakeholders. The composition of the internal stakeholders is represented in blue, while the composition of the external stakeholder is represented in amaranth. The red dotted line corresponds to the 2-level expertise.

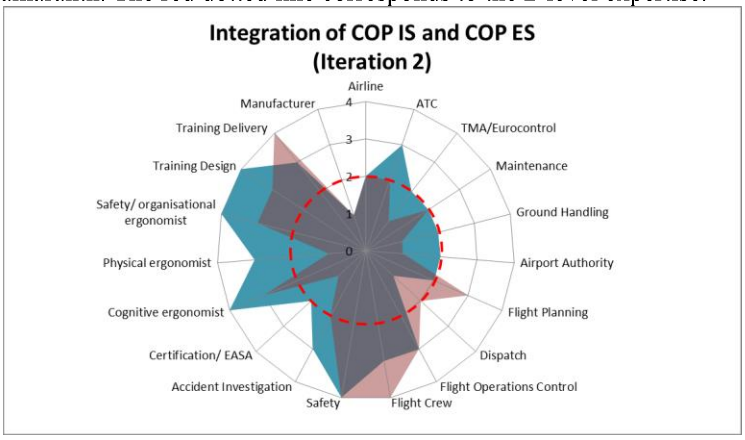

Fig. 1. – Current state of stakeholder competency knowledge in A-PiMod

3 Adaptive Automation & Multimodal Concept

3.1 Objectives & Overall Concept

The goal is to support crew in situations when they may need help irrespective of experience, and/or in situations when the crew has less experience, and/or in situations where the crew is experiencing high workload, under pressure and potentially fatigued. Automation is conceptualized as a third crew member, providing support to crew in both high and low workload situations, to optimize flight safety and ensure the mission level goal is achieved.

The A-PiMod concept/approach is defined by the concept of partnership – specifically, the “Third Pilot” and the crew and automation are in charge together. The team comprises the pilot flying (PF), the pilot monitoring (PM) and automation. Automation is a virtual team-member. The team co-operates in relation to mission level decisions. Critically, this partnership concept is underscored by a core notion of Pilot authority. The system continuously monitors the operational situation and the allied crew/automation/aircraft state, to determine the tasks the team has to perform together, and how to best distribute them between the crew and automation. A-PiMod flags potential risks - providing operational guidance in relation to managing those risks. The crew forms their own judgement/ideas as to risk status of situation and the appropriate course of action. The crew is not mandated to follow the decision support provided by A-PiMod (this is an aid, not a requirement). Overall, the crew can over-ride system proposals/decisions, except in certain critical situations (i.e. incapacitation). As such, the crew have final control (i.e. make the final decisions), but are responsible and accountable for their decisions/actions.

A-PiMod adopts a team centred approach as opposed to a crew centred approach. We are focusing on the outcome; considering what is best for the safe and efficient completion of the mission/flight, and not particularly trying to adapt to human needs. If the Pilot Flying/Pilot Monitoring is overloaded and this threatens the completion of the mission, the task distribution is adapted at the agent level. Automation is adapted to the crew states and capabilities, so that at all times the cockpit-level tasks that have to be performed for safe and efficient mission completion are achieved.

The emerging Third pilot concept can be conceptualized on several levels - (a) automated task distribution, (b), crew workload monitor, (c) crew task performance monitor, (d) scanning cycles monitoring, and (4) a risk assessment/ decision support aid, enabling briefing and situation awareness.

The Third Pilot concept is underpinned by the A-PiMod multimodal cockpit – which (1) enables monitoring of crew interactions with cockpit systems (i.e. provides inputs to crew state inference module), (2) facilitates crew interaction with automation (MCM Display) and (3), allows for flexible and natural interactions (i.e. touch and voice) with cockpit displays.

3.2 Architecture Concept

The adaptive automation system integrates three key components: (1) model-based evaluation of flight crew state, (2) real-time automated risk assessment, and (3) adaptation of the Human Machine Interface. These components are currently missing in cockpit systems and are essential for safe crew-automation interaction.

The A-PiMod architecture allows adapting the organization of the cockpit (task distribution between the crew and automation) and the circulation of information between the crew and the cockpit systems (including automation) to the current - and forthcoming - situation(s).

As detailed in Figure 1, the whole A-PiMod architecture is based on a 3-layers hierarchy of tasks. The highest level is the mission level. The middle one is the cockpit level. The lowest level is the agent level, where tasks are executed by the agents in the cockpit: the crew and automation.

Tasks at a given level are translated - or instantiated - into the tasks of the level below based on the context of their execution. For the mission level for example, the context of execution is the context in which the A/C is flying (e.g., weather, ATC, traffic) and the A/C state. At the cockpit level, the cockpit context is mostly defined by the state of the cockpit agents (crew & automation) and of the cockpit equipment (e.g., displays).

This contextual adaptation of tasks into the tasks of the level below is one of the main mechanisms by which adaptiveness is provided by the A-PiMod architecture each level providing additional degrees of freedom to perfectly tune the execution of the mission to current circumstances (at each level).

We are proposing partnership as opposed to dynamic changes in control function (where changes can be controlled autonomously by the system). A main aspect of the concept is the A-PiMod architecture, which describes at a high level the means for the adaptive distribution of tasks between the crew and automation, such as the real-time analyses of the crew's state (situation awareness and workload), and the mission risks. The new, improved automation system will permanently assess what the crew is - or is not - doing, as well as what they should be doing at the current time (i.e. recover from a stall, avoid ground obstacles etc). How automation is adapted is through task distribution. Task distribution is the end result of the situation management process where the crew and other automated processes cooperate to assess the situation, its risks, what has to be done (cockpit level tasks), their risks, and produce an appropriate task distribution.

The cockpit is viewed as a 'cooperative system of human and machine agents that adapts its task distribution at all time in order to perform a mission, safely and efficiently'. Automation is adapted to the crew states and capabilities, so that at all times the cockpit-level tasks that have to be performed for safe and efficient mission completion are achieved.

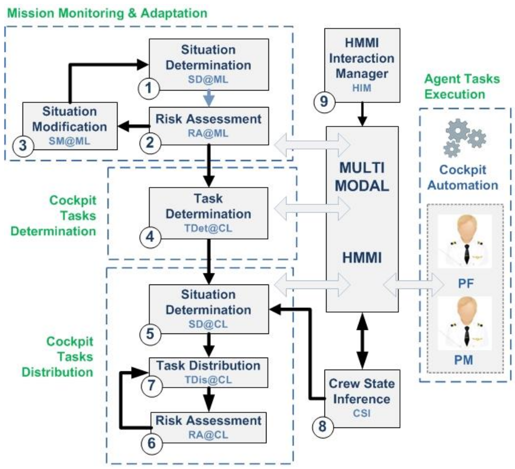

Fig. 2. – Architecture Concept

3.3 Pilot Interaction in the Cockpit & User Interface Design

Pilot interaction in the cockpit can be characterized in relation to the following points:

- User friendly and flexible information/decision support
- The crew interact using voice/touch and traditional controls
- This interaction is tracked by the system (i.e. what tasks performing, level of fatigue, involvement in activity): this is referred to as ‘crew state monitoring’
- The crew obtain feedback via a new cockpit user interface (Mission and Cockpit Level Management Display - MCMD) as to:
  - The risk status of the operational situation (this includes an assessment of the status of joint crew/automation system)
  - What to do – including the provision of best options/alternatives based on different ‘technical’ contributing factors (i.e. fuel remaining, status of alternates etc)
- The proposed MCMD features two related sub-displays – the mission and cockpit level displays
- The crew can over-ride system proposals/decisions – except in certain critical situations (i.e. incapacitation)

The A-PiMod MC-M Display (i.e. the Mission & Cockpit Management Display) is the A-PiMod interface between the user and the proposed A-PiMod adaptive automation technologies. The MC-M Display supports all crew activities related to Mission management, as well as to Cockpit management. The Cockpit is seen as a team made of the crew itself and a series of dedicated A-PiMod modules that provides adaptive automation.

The MC-M Display has been implemented on a tablet /Microsoft Surface. The tablet/Microsoft Surface is a touch display, and it can be operated via touch by the crew.

High level features of the MC-M Display include:

- The device was shared for use by both the PF and PM
- The screen had a portrait orientation to include both the ML (Mission Level, top half) and CL (Cockpit Level, bottom half) interfaces.

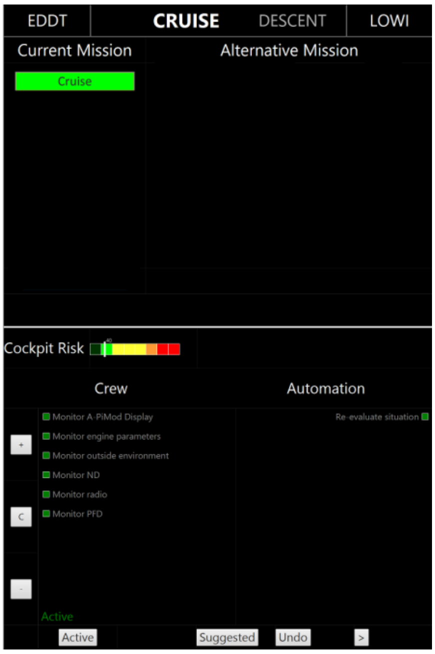

Fig. 3. – MCMM Display (Prototype)

3.3 Systems to Monitor Observed Behavior

Several systems (i.e. eye tracking, gesture recognition and head pose) are linked to the A-PiMod components (i.e. crew state estimation/task determination), to infer possible errors, missed events and missed piece of information. Specifically, visual analysis of pilots' behavior is recorded to infer human operator's (pilot's) mental state, stress level, and general workload. For more information, please see Appendix 1.

3.4 Benefits & Impact

This research indicates that the 'Third Crew Member' will provide many operational and safety benefits. This includes:

- Improving teamwork between crew and automation
- Providing task support in safety critical situations (i.e. operational risk assessment/decision support)
- Providing task support in high workload situations (i.e. operational risk assessment/decision support)
- Supporting workload management
- Improving team situation awareness

- Augmenting Pilot monitoring performance (i.e. avoid monitoring errors, link to error chain)
- Providing support in relation to error detection and management

Overall, this new concept/approach will significantly improve the safety of flight, especially in abnormal situations and during situations of crisis management. Critically, A-PiMod will not eliminate human error. Rather, it will reduce it. That is, it will reduce the accident rate, given improvements in error detection and error management. As validated in field research, the A-PiMod concept/approach will allow for an improved partnership between crew and automation (the "team players" idea), which will reduce human error and make substantial progress in relation to the EU aim of reducing the accident rate by 80%.

3.5 Quantification of Safety Impact

Overall it is assessed that the A-PiMod concept facilitates a reduction in the probability of fatal accidents by 43% from 4.0E-7 to 2.2E-7 fatal accidents per flight. This is about half of the FP7 Area 7.1.3 objective to reduce the accident rate by 80%. For more information, please see [12].

A cockpit that is designed with the A-PiMod approach in mind will extend automation capabilities in an adaptive way, to the extent necessary to support a safer flight. Potentially, such an adaptive automation approach might prevent many accidents. For more information, please see [11, 12].

4 Discussion

4.1 Innovation

The Third Pilot/A-PiMod system (1) reflects a mix of the logic associated with adaptable systems and adaptive automation, and (2) provides something new (i.e. multimodal cockpit concept).

In relation to (1), we are

- Going beyond notions of assistance (adaptable systems), where the crew are fully in charge (i.e. in all situations/all of the time)
- Adopting certain aspects of adaptive automation – that is, supporting the pilots based on an understanding of crew state (situation awareness and workload)
- Proposing partnership as opposed to dynamic changes in control function where changes can be controlled autonomously by the system

In our concept, the crew is in charge together with automation (team concept)

- In principle, the pilot remains in charge/in command
- However, there are certain special situations when automation can take charge (i.e. fully adaptive)

In relation to (2), we have developed new multimodal concepts which supports improved assessment of crew state/workload (i.e. information inputs re crew activity/interactions), provides a means to communicate with the crew re crew state and decision support (i.e. MCM Display – enabling assistance), and allows for flexible crew/cockpit interaction.

The third pilot has different modes of operation. This includes (1) passive monitoring, (2) active monitoring and (3) over-ride. In relation to A-PiMod, we expect that (1) and (2) will be the standard/typical modes - operating as an adaptive automation supporting the pilots, based on understanding of crew state/workload. In extreme cases (3) will occur. Here A-PiMod/third pilot will take charge of the aircraft control (i.e. fully adaptive). We are calling (1) + (2) + (3) a third pilot or partnership concept. If automation would progress, aspect (3) might become more normal and (1) and (2) less typical. Of course major development and certification would need to be taken, especially for (3).

The A-PiMod architecture has been developed to support the transition towards more automation while staying in the same framework (something that is impossible in the assistive paradigm). This is possible because each component in the architecture is a small cooperative system made of the crew + a module. When there is no crew (full automation), there is just the module. When there is no automation (manual flight), there is just the crew (or a single pilot). A single pilot during manual flight superposes all the components.

4.2 Cockpit Centred .v. Task Centred Approach

A-PiMod adopts a team centred approach as opposed to a crew centred approach. We are focusing on the outcome; considering what is best for the safe and efficient completion of the mission/flight, and not particularly trying to adapt to human needs. As indicated in the architecture concept [15,16], if the pilot flying/pilot monitoring is overloaded and this threatens the completion of the mission, the task distribution is adapted at the agent level.

Underpinning the A-PiMod concept is the idea that automation operates with a better understanding of the Pilots/crew state. In this way, automation is a 'true' member of the team. That said, we are trying to see what is best for the safe and efficient completion of the flight, and not particularly trying to adapt to human needs (that's a means more than an end). As such, automation delivers on mission/cockpit requirements (i.e. what is best for the safe and efficient completion of the flight). If we see that the human is overloaded and this threatens the completion of the mission at the mission level we will adapt the task distribution, at the agent level. This is not necessarily at odds with human centred automation insofar as it considers the Pilot position (i.e. situation awareness and workload status) and the Pilot provides feedback as to whether he/she accepts the suggestions of the automation system (i.e. decision support and task functions undertaken by automation).

4.3 Partnership Concept

A-PiMod is intended as an ‘experience aid’, a ‘Smart Pilot Assistance’. This does not mean that A-PiMod will supplant Pilot experience; rather, it is intended to complement existing experience, and compensate for when someone might not be at his or her best. As such, A-PiMod needs to be seen as, and behave as a team-player. Anything that could be interpreted as undermining the authority or command held by the Captain will undermine A-PiMod’s effectiveness in strengthening the team. A-PiMod should be a support, and not thought of as behaving like a tell-tale child constantly running to the teacher. Thus, it is important that changes are implemented at the ‘right’ pace, to enable to address safety issues properly.

4.4 Crew State Monitoring

The real gain in A-PiMod relates to crew state monitoring – that is focusing the pilot’s attention on their state (i.e. crew state) along with that of their crew member - and on the current and future state of the aircraft. If over-loaded and/or under pressure, pilots may forget or not consider all the safe options. However the 3rd crew member (automation) will not, so a quick check will refresh the possible options, to allow a safe decision to be made. In this context, a key challenge is how to get the two human crew members to share their ‘current state’ with the 3rd crew member such that it is mean-influx, informative but not self-incriminating in any post hoc analysis. Normal human interactions can easily accommodate this in simple pre-flight social interactions. Formalizing it such that the 3rd crew member can make useful sense of it may be more problematic.

The assessment of crew state is not just about workload, it’s about the crew experience, flight hours, familiarity with route, when last flown there and training background. If the Pilots are not familiar with the route, then the crew state might be assessed as less optimal. From a Pilots perspective, the starting point for crew state monitoring is the crew briefing/flight planning. This might occur a week before the flight. Or at least, at the time of the pre-flight, flight planning and briefing task. For crew state monitoring to work, we need to establish a picture/sense of the crew state from the very beginning of the flight. The A-PiMod system needs to know what the join crew status is and any threats associated with this. Potentially, we will need the crew to provide feedback about their state in advance of the flight. Further, it takes into account real-time crew behavior. This involves monitoring the crew state via the assessment of (1) crew activity (gesture), and (2) crew interaction with cockpit systems including new multi-modal input (i.e. touch, voice and gesture) and traditional controls.

4.5 Airline SOP

The introduction of the A-PiMod concept might drastically change airline SOP. Existing SOPs are premised on enabling different crew members with different levels of experience, knowledge or skill find 'common ground' to conduct consistent and safe operations. One significant factor to be considered in that respect would be how to handle introducing the A-PiMod concept on a mixed fleet basis, given that it would inevitably be introduced over a considerable period of time and pilots would have to operate on mixed aircraft (with and without the system). Given the nature of the system, this could prove quite challenging. Further, final authority to override the A-PiMod systems' actions should reside with the operating crew. As a specific exception to that principle, the occasions on which A-PiMod could take action that could not be overridden by the crew would need very careful and very detailed SOP specification.

5 Conclusions

The A-PiMod concept/approach is defined by the concept of partnership – specifically, the "Third Pilot" and the crew and automation are in charge together. A-PiMod adopts a team centred approach as opposed to a crew centred approach. We are proposing partnership as opposed to dynamic changes in control function where changes can be controlled autonomously by the system.

A main aspect of the concept is the A-PiMod architecture, which describes at a high level the means for the adaptive distribution of tasks between the crew and automation, such as the real-time analyses of the crew's mental state and the mission risks. Automation is a virtual team-member (third pilot) and the team co-operates in relation to mission level decisions. Task distribution is the end result of the situation management process where the crew and other automated processes cooperate to assess the situation, its risks, what has to be done (cockpit level tasks), their risks, and produce an appropriate task distribution.

An advanced A-PiMod system cannot supplant experience. However, it is ready to provide extra information in relation to risks/ hazards and potential courses of action – if required by crew. In this way, an advanced A-PiMod system features different "levels" of response, similar to the way a Captain would have with different co-pilots of varying experience. Ideally, the A-PiMod system would provide an airline with the most experienced and capable crew possible in any situation, where skill level is constant, across all weather/routes/airports/time zones. A-Pimod helps avoid dramas – everything is routine (i.e. the crew is briefed about all possibilities).

The third pilot/cockpit team concept and HMMI has been demonstration at two levels – namely (1) at a conceptual level and (2) at a level of software demonstration. The assessment of safety impact mostly relates to what has been advanced at a conceptual level (i.e. A-PiMod concept), rather than for its particular implementation as achieved in the A-PiMod project.

In the course of the A-PiMod project a particular implementation of the concept was achieved by development of a set of tools, and these tools were used in validation experiments in a flight simulator context (i.e. validation sessions 1 and 2). This set of tools can be viewed as a first technical instantiation of the A-PiMod system, and the sophistication, scope and integration of the tools can be improved in future research and development.

Acknowledgments. The research leading to these results/preliminary outcomes has received funding from the European Commission's Seventh Framework Programme (FP7/2007-2013) under grant agreement N. 605141 - Applying Pilot Models for Safety Aircraft (A-PiMod) Project. We would like to thank member of the A-PiMod Project Team and our COP members – particularly, Paul Cullen, William Butler, Martin Duffy and Stephen Duffy.

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6 Appendices

6.1 Systems to Monitor Observed Behavior

Eye tracking

In both sets of simulator evaluation sessions, SMI Eye Tracking Glasses 2 were used to measure the gaze positions. Please note that his was demonstrated – but not implemented in real time. SMI Eye Tracking Glasses is a binocular tracking device which operates with 60 Hz. It is connected with a Laptop via USB on which videos of the eyes and the scene camera are recorded and the gaze position is calculated. The system is combined with an A.R.T Optical Head Tracking system. Retro reflective targets are attached to the glasses which are recorded by infrared cameras installed in the simulator. This system allows us to calculate the head position and orientation. With both systems combined, it is possible to calculate a 3D gaze vector for each eye.

Gesture recognition

The Gesture recognition is meant to recognize the upper body parts of a human operator – aeronautic pilot – in order to detect "implicit gestures". Implicit gestures refer to movements of the upper body parts, which are normal actions taken by the crew (e.g. controlling different parts of the cockpit, or interaction among the crew).

Head pose recognition

The head pose estimation functionality serves to provide information about where the pilot is looking within the cockpit (which instruments, screens, control elements, etc.). The technology is designed to be completely passive and non-intrusive in the sense that the pilot does not wear (or otherwise consciously interact with) any additional pieces of equipment, such as eye-tracking glasses. Also, the head pose estimation device does not emit any infrared light, which would be the case for contemporary remote eye trackers or depth cameras (based on structured light projection or infrared time-of-flight sensors). In A-PiMod, the first application of the said technology in the cockpit is detecting "missed events" – when the pilot is provided with a piece of information by the cockpit, but she misses it by not looking at the appropriate display for a time period. The cockpit display (MC-M Display) provides a notification of the missed event. Depending on the Pilots response, the saliency of such message is increased. The second application is contribution to the estimation of the pilot's state of mind and workload level from the patterns of the head motion.