2015

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Alez Kirlik

Kasey Ackerman

Ben Seefeldt

Enric Xargay

Donald Talleur

See next page for additional authors

Repository Citation

Kirlik, A., Ackerman, K., Seefeldt, B., Xargay, E., Talleur, D., Carbonari, R., Hovakimyan, N., Sha, L., Trujillo, A., & Gregory, I. (2015). Inverting the Human/Automation Equation to Support Situation Awareness and Prevent Loss of Control. *18th International Symposium on Aviation Psychology*, 482-487. https://corescholar.libraries.wright.edu/isap_2015/25

Authors

Alez Kirlik, Kasey Ackerman, Ben Seefeldt, Enric Xargay, Donald Talleur, Ronald Carbonari, Naira Hovakimyan, Lui Sha, Anna Trujillo, and Irene Gregory

INVERTING THE HUMAN/AUTOMATION EQUATION TO SUPPORT SITUATION AWARENESS AND PREVENT LOSS OF CONTROL

Alex Kirlik, Kasey Ackerman, Ben Seefeldt, Enric Xargay, Donald Talleur,
Ronald Carbonari, Naira Hovakimyan and Lui Sha
University of Illinois at Urbana-Champaign
Urbana, IL

Anna Trujillo and Irene Gregory
NASA Langley Research Center
Hampton, VA

Despite the contributions of automation to aviation safety and efficiency, the problems associated with technology-centered rather than human-centered automation are well known: decreased pilot situation awareness, deterioration of manual piloting skills, difficulties pilots experience when trying to jump into the loop when needed, and so forth. We present a prototype architecture for human-automation interaction that reverses their traditional roles: in our design, the automation "looks over the shoulder" of the pilot and jumps into the loop when needed rather than the other way around to prevent aircraft loss-of-control (LoC). The architecture exploits the LoC prevention algorithm proposed by Wilborn and Foster (2004). This quantitative definition uses a set of five two-dimensional envelopes relating to critical flight parameters that account for aircraft flight dynamics, aerodynamics, structural integrity, and flight control use. The LoC algorithm is used to both present the pilot with a graphical cockpit display depicting aircraft state in relation to these safety envelopes in passive mode (i.e., depicting behavior-shaping constraints), and also to compensate for ineffective pilot inputs that would cause aircraft LoC in active mode. The prototype system has been implemented in our flight simulation lab and the details underlying the design will be presented. We conclude by describing the design of an experiment we are using to evaluate this human-automation interaction design concept and its implementation.

Introduction

The presence of automated control systems in aircraft is ubiquitous. As demands for aircraft safety and efficiency have increased, so too have levels of complexity found in these systems. While this automation has resulted in significant safety benefits, increased incidents and accidents due to a lack of pilot engagement, variously described as the “out-of-the-loop” (OOTL) problem (Endsley & Kiris, 1995) or “out-of-the-loop unfamiliarity” (OOTLUF) problem (Wickens & Hollands, 2000), have prompted much recent research, including a recent study on automation-induced task-unrelated thoughts or “mind wandering” by pilots (Casner & Schooler, 2014). Ironically, the increased reliability of automation brings with it an increased level of safety coupled with the fact that in many cases, automation behavior becomes transparent only at the point of failure. When this occurs, pilots are thrown ‘back into the loop’ to attempt recovery. When pilots are required to reenter the control loop unexpectedly, their ability to do so effectively is often compromised, a phenomenon known as “automation surprise” (Billings & Woods, 1994) or the “return-to-manual-control deficit” problem (Hadley et al., 1999). Various attempts have been made to cope with related problems such as “mode confusion” and “mode error” (Sarter & Woods, 1995; Degani & Heymann, 2002) which result from pilots having an inadquate understanding of automation due at least in part to the fact that automation behavior is insufficiently revealed or presented in cockpit interfaces.

We believe that in large part, these difficulties can be attributed to the fact that there is a significant loss of situational awareness surrounding automation state. While a pilot may be fully aware of various flight variables (such as heading, altitude or airspeed), that appear on the primary flight display, they have few indications of automation state apart from an active/inactive marker. This setup disregards the fact that highly complex automation contains huge amounts of system information regarding not only current aircraft state, but also the control corrections necessary to maintain that state and potential future states. These automated systems can be seen as ‘silent co-pilots’, controlling the plane but offering no insights into their process. D. A. Norman’s (1990) paper on automation sets up a thought experiment where the reader is asked to compare flying with the aid of an automated system with a human flight crew. At the point of failure, Norman describes how the “informal chatter” in the human-only cockpit facilitates early detection of flight problems, while the automated system silently compensates until a more dramatic failure occurs. Overcoming problems of decreased awareness of automation then becomes a problem of reintroducing this informal chatter into the automated cockpit. Pilots should be given a steady stream of non-intrusive information to allow a continuous monitoring of automation's contribution to achieving safe flight.

In this paper, we present both a concept for coupling pilots and control automation and display designs that integrate information from an automated system into the traditional flight display. Additionally, we provide a novel display placed to the right of the primary flight display dedicated solely to surfacing automation information. Our work centers around a dynamic Flight Envelope Protection (FEP) system augmented with logic for loss-of-control (LoC) prediction and prevention. Previous work addressing technological solutions to LoC prevention, especially in off-nominal conditions, appears in Belcastro & Jacobson (2010), Belcastro (2011) and Belcastro (2012), using both visual and aural methods for notification and cueing, and adjustable autonomy (Kaber, 2012) in the way authority is partitioned between pilots and automation. Relatedly, Connor et al. (2012) present an approach to cockpit display design using perceptual cueing to indicate corrective control actions that should be taken to avoid aircraft LOC.

Our own approach toward reducting LoC events is part of a larger set of efforts to develop technologies to prevent incidents and accidents based on a combination of the AIRSAFE concept described in Belcastro's research (op. cit.), technologies for fault-tolerant flight control (Hovakimyan & Cao, 2010; Hovakimyan et al, 2011), fault detection and isolation (Lee et al., 2014), safe flight envelope estimation and detection (Tekles et al., 2014) and LoC prediction and prevention (Chongsvisal et al., 2015). The ovararching concept is to reduce LoC through the novel use of a set of safety envelopes defined by a set of flight parameters. This vocabulary of envelopes and safety limits is extended to our display enhancements, and to a logic by which flight envelope protection automation selectively engages to compensate for combinations of pilot commands and environmental disturbances to maintain stability to prevent LoC events when detected. We believe that this form of joint, compensatory architecture for coupling humans and automation is much in the spirit of the "horse and rider" or "H-Metaphor" guideline for vehicle automation and interaction (Flemisch et al., 2003). Additionally, we present our experimental design for a series of pilot-in-the-loop flight tests intended to gauge the efficacy of our system in scenarios requiring pilots and automation to maintain control in the presence of significant wind shear. We predict that the increased situational awareness provided by our augmented displays, coupled with an ability for automation to adaptively augment pilot inputs will result in improved overall performance, seen primarily through a decrease in the number of LoC events, the number of envelope exceedences and in the time needed to recover safe aircraft state.

Loss of Control Envelopes

The system described in this paper is based on a quantitative definition of loss of control as described in Wilbourn and Foster (2014). For a more comprehensive description of the system, refer to Chongsvisal et. al. (2014). The displays described in future sections utilize information taken from the FEP system. This system takes advantage of five predefined safety-envelopes. These envelopes describe overall loss-of-control (LoC) as a relationship between dynamic flight parameters. Flight protection then, becomes a task of ensuring these flight parameters remain within the defined safety envelopes. Each envelope defines two boundaries, 'soft' LoC limits which are more restrictive but less critical, and 'hard' limits that are maintained by the protection scheme. The protection scheme computes these dynamic envelopes and determines an ideal control solution.

Display Design

In this section we present an overview of our display design. The material in this section is adapted from Ackerman et. al. (2015), which contains a more detailed account of automation and display design. The primary flight display (PFD), shown in Figure 1, is based on the standard flight display design, with the addition of three non-standard displays (Angle of Attack, Angle of Sideslip, and Load-factor).

Primary Flight Display

The elements of this modified PFD are further enhanced by the addition of FEP derived limits. As discussed in the previous section, the framework for LoC used by our system uses sets of hard and soft limits to define envelopes around critical flight features. A set of indicators (airspeed, pitch/roll, AoA, AoS, and load-factor) are modified to display not only current status, but current envelope position. By providing salient cues concerning boundaries used by automation, pilots will become more aware of the reasons for automation engagement.

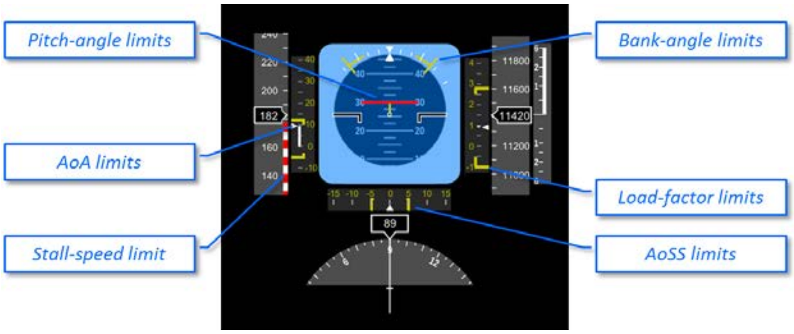

Figure 1. Primary flight display with FEP limit augmentations.

The general design for a limit indicator shows both hard and soft limits. For any given measurement, a yellow line is drawn parallel with the indicator movement. This line represents the range of values that are between the soft and hard limits. Moving into this region is an exceedance of the soft limits, and proper care should be taken that hard limits are not reached. The hard limit is marked at the end of the soft limit by a perpendicular yellow line. In the case of a soft limit excursion, this hard limit line turns red, drawing the pilot's attention. In Figure 1, we see that the pilot is within the safety envelope defined for bank, but has pitched upward at too extreme an angle. The soft limit has been crossed, and the hard limit line indicates this change.

This general design is replicated across other PFD parameters. However, the altimeter and heading indicator, which display aircraft position, and not aircraft movement are not augmented, as they have no limits defined in the FEP system. Additionally, the lower limit for airspeed does not show the traditional limit indicator, but rather is marked by a red and white bar that displays stall speed. This is in keeping with current design practices.

Envelope Protection Display

The primary flight display described above is primarily concerned with indicating current status and the presence of limits in relation to these measurements. It is necessary to distinguish between a purely descriptive interface, and one which provides feedback in relation to control input. The additional envelope indicators in the PFD do not provide the pilot with directly actionable information. When the FEP system is active, it directly limits pilot control input in response to potential envelope excursions. To communicate saftey envelopes in direct relation to pilot control inputs, we add the Envelope Protection Display (EPD) to the right of the PFD.

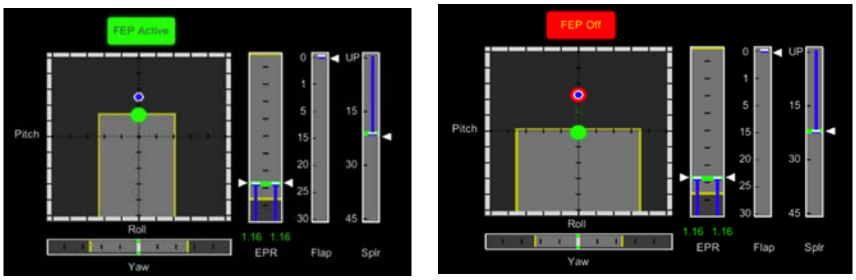

Figure 2a/b. The EPD in FEP On mode and Active state (left) and in FEP Off mode (right).

There are two main elements to the Pilot Input Display (PID): a square pitch/roll command box and a horizontal yaw command bar below the box. The box and the bar are marked by axis marks at regular intervals. The pitch/roll box and yaw bar depict the entire range of movement of the control yoke and rudder pedals respectively.

Within both display areas is a light gray rectangle bordered by yellow showing safe control inputs. Constraining control input to these rectangles guarantees hard FEP derived limits are not exceeded. These rectangles move in response to changing flight status. Any area beyond the yellow boarder is considered 'unsafe' operation. Both displays are marked by two control input indicators. The first, a blue circle or bar outlined in white, represents the directed pilot input. This always corresponds to the position of the yoke or rudder pedals. The second, a larger green indicator, represents the ideal FEP derived control position. This marker will always remain inside the light gray box. As seen in Figure 2a, the green marker tracks the blue one indicating the safe position that is closest to the directed pilot input. When the pilot is directing input that is inside the light gray box, the two markers will overlap. At the top of the PID is an annunciator indicating the status of the FEP system. The behavior of this annunciator is dependent on the specifics of mode operation as described below.

Display Operations

FEP On. One motivation for our design was the observation that during previous FEP flight trials, pilots were unaware of the impact FEP automation was having on aircraft control. When control input was modified during a difficult flight scenario, they perceived these modifications as a loss of (their) control. Despite the fact that the control system was actually maintaining aircraft stability effectively, pilots felt hindered by the system. The design described above aims to provide pilots with a window into the automation, the so called “informal chatter” mentioned earlier. This allows pilots to construct a more veridical model of overall system state, and easily accounts for situations where pilot control input requires active compensation from FEP-based automation.

While the FEP system is in the “On” mode, there are two states that are reflected on the FEP state annunciator. When the pilot is current maintaining aircraft state and the directed input is within safety envelopes, the system is “Armed”. This is noted by the FEP state annunciator being colored yellow and containing the text “FEP Armed”. While in this mode, both blue and green indicator marks are overlapped, showing that the pilot is in complete control of the aircraft. The second possible state is “Active”. This state occurs when the pilot directs a control position that is outside the displayed envelopes of safety. At this point, the FEP modifies pilot input, directing the aircraft using a control position that is inside the safety envelopes. When the excursion takes place, the state annunciator changes from yellow to green, and displays the text “FEP Active”. Additionally, the blue indicator will move beyond the yellow boarder, while the green indicator remains within the envelope. In this situation, the pilot is no longer in direct control of the aircraft, rather the input displayed by the green indicator is being used.

FEP Off. While the primary configuration is intended to inform pilots of system state by making salient the impact of automation, it is possible to fly the aircraft without the use of the FEP system. Turning the FEP off allows the pilot to be in direct control of the aircraft, even in situations where the plane is in a potential loss of control event. In this mode, the FEP continues to compute safety envelopes and ideal control positions without modifying pilot input while continuing to display these envelopes. However, when the pilot directs the plane outside an envelope of safety, when the blue dot exceeds the yellow border, it is surrounded by a red halo, highlighting the excursion. Additionally, the state annunciator turns red, communicating to the pilot that an envelope has been breeched. The green marker remains inside the envelope of safety, marking an ideal position. This can be seen in Figure 2b, where the pilot has pitched up higher than is safely allowed. A 5-minute explanatory video depicting our design prototype in operation is available at: https://www.youtube.com/watch?v=gLZpFfXwGVQ#t=282.

Experimental Evaluation

As part of our continuing research, we are beginning experimental trials evaluating our design. We will be performing pilot-in-the-loop testing at the flight simulator at the Illinois Simulator Laboratory. Our simulator is a Frasca 142 cockpit, with the primary flight display panel replaced with a digital display panel. Surrounding the cockpit, are three projectors providing a 140° view of the outside world generated by X-Plane, while our physics model and FEP system are implemented in Matlab/Simulink. Our study participants are drawn from the Parkland College Institute of Aviation at UIUC. We are recruiting both students and instructors, with the minimum requirement for participation being Private Pilot certification.

We will be conducting a within-subject design comparing three aircraft configurations. Our control condition is the basic aircraft with no additional modifications or enhancements. Pilots will fly using the standard PFD with no envelope display. FEP will be disengaged entirely and the pilots will be in full control of the aircraft. The two additional experimental conditions are intended to provide a general ‘stepping-up’ of support in terms of display and automation aid. In both of these conditions, we will provide the pilot with the full extent of display modification. Pilots will fly this configuration both in “FEP Off” and “FEP On” modes.

In all configurations, pilots will complete ten separate scenarios designed to emulate challenging wind shear. Each scenario will be approximately two minutes long and consist of an initial level flight period, followed by a unique wind shear profile, in which the pilot will be instructed to regain control of the aircraft and return to initial flight conditions. These scenarios are designed to prompt the excursion of at least one safety envelope. For each of the three conditions, these ten scenarios will be run in a unique order, but the order will remain the same for all participants completing the given condition. To eliminate ordering effects, we counterbalance condition ordering.

Each participant will be evaluated on four separate days. The first of these will be exclusively used for participant training. On each subsequent day, the participant will fly the set of ten scenarios under different configurations. There will be a short training period for pilots to become familiar with the interface design before evaluation begins. Between scenarios the pilots will be prompted to complete an evaluation using a modified Cooper-Harper scoring system to determine a performance score. We will also evaluate pilot performance by recording live flight variables, specifically those related to envelope exceedance and ideal flight path deviation. In order to assess the impact of our novel interface panel we will also be gathering eye tracking data to determine the manner in which the various experimenal conditions affect participants' visual attention allocation patterns.

We anticipate testing will reveal the benefit of additional display information regarding automation state. The increase in situational awareness should allow pilots to apply expertise to the scenarios in a more accurate way. Rather than relying on secondary information regarding automation (that is, 'testing' the automation response to certain control movements), pilots will be able to directly observe the impact of automation. Even without automation control directly affecting flight, understanding flight dynamics in terms of safety envelopes and observing the impact certain control movements have on their parameters should increase performance, thereby reducing the number of times pilots either lose control of the aircraft or exceed LOC safety envelope barriers. We expect best perforrmance in the final condition when automation selectively provides active control compensation.

Conclusions

Our work aims to surface information provided by advanced automation systems to pilots in salient ways that promote overall situational awareness. We believe certain failures are caused not by a failure in automation, nor by a lack of pilot training or skill, but rather by insufficient communication between the two. We believe the insights gathered in this work apply not only to the domain of aircraft automation and control, but to a variety of domains which necessitate automation systems and human operators working in conjunction. In particular, the language of safety envelopes seems particularly effective for a subset of these problems. Future work will be informed by the results of our initial simulator study and focus on developing generalizable methods for use in other disciplines.

Acknowledgements

This research was supported by the National Aeronautics and Space Administration and by the National Science Foundation.

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