Influence of Cultural, Organizational and Automation Factors on Human-Automation Trust: A Case Study of Auto-GCAS Engineers and Developmental History

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Abstract. This paper examines the influence of cultural, organizational and automation capability upon human trust in, and reliance on, automation in the context of an extended case study of the US Air Force Automatic Ground Collisions Avoidance System (Auto-GCAS). The paper focuses on the analyses of the system's developmental history and the perspectives of engineers involved in its development. Key findings indicate that the success of the system was a result of the innovative solutions developed; and a strong alignment between the engineering and experimental test pilot cultures. The findings suggest that the Auto-GCAS system was designed and tested in such a way as to promote effective trust calibration. A summary of the foundational lessons about how trust is influenced by cultural and organizational factors, implications of this research for adding to the body of knowledge on human-automation trust, and future research avenues, are also discussed.

Keywords: Trust, automation, reliance, F-16, military organization, engineer culture, extended case study methodology, automatic ground collision avoidance

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Introduction

Automation has been used in numerous applications to assist human decision making by automatically integrating and displaying information, and selecting and implementing decisions. While automation is an important asset for assisting operators, automation-related accidents and mishaps have shown that poor designs can cause the operators to mis-calibrate their trust and reliance on automation. Common examples of inappropriate reliance on automation include misuse and disuse [1]. Misuse refers to over-reliance on, or utilization of, automation in conditions, or for purposes, that the automation was not designed. Disuse refers to the under-reliance or rejection of automation in ways that undermine the potential strength and benefits of automation.

Lee and See [2] conducted a comprehensive review of the studies in the area of trust in automation, and used the review as the basis for an integrative view that links organizational, sociological, interpersonal, psychological, and neurological perspectives on inter-personal trust to the issue of human-automation trust. Specifically, they found that there is a general lack of data on, or research that examines, how cultural and organizational factors, and factors affecting automation capabilities, influence human-automation trust and reliance. Furthermore, while some studies have shown that these factors can influence human-automation interaction in unexpected ways, they have been mostly confined to experiments that examine the effects of a limited set of independent variables in a well-controlled environment. In actual operations, interactions between humans and automation usually take place in settings where there are many more variables of interest than data points available, and where the investigators do not have control over the events. Thus, to build on existing experimental data, and to lay the foundation for future research, it is essential to capture the richness of the phenomenon and the extensiveness of the real-life context in which human interacts with automation.

This paper addressed this need with a case study of an actual military automated system, identifying both practical lessons learned, and real-world perspectives on the appropriateness of reliance (i.e., where trust and use of automation matches system capabilities). Moreover, in addition to a standard approach examining how intrinsic properties of automation influence reliance, our emphasis on cultural and organizational factors allowed us to examine how human-automation reliance can be influenced in ways that are indirectly related to the characteristics of the automation. Specifically, the objectives of this case study are: 1) to reveal foundational lessons and best practices from real-world perspectives about the influence of cultural, organizational and automation capability on human trust and reliance on autonomous systems; and 2) to identify research issues critical to developing and designing more trustworthy automation.

To identify foundational lessons and best practices for appropriately calibrating reliance on automation, we conducted a case study of key Department of Defense (DOD) personnel with experience in operating and developing the Automatic Ground Collision Avoidance System (Auto-GCAS) [3]. In summary, Auto-GCAS avoids collisions by: 1) positioning the aircraft over Digital Terrain Map (DTM) with an inertial navigation system, 2) projecting the aircraft trajectory over the DTM, 3) generating a terrain profile from the local terrain map based on the aircraft's location and current maneuvering, 4) comparing the projected trajectory against the terrain profile to determine if an imminent threat exists, and 5), if the threat exists perform a last-second automatic recovery and return the control to the pilot as soon as the threat is avoided [4].

We chose Auto-GCAS for the case study for several reasons. First, it illustrates critical issues with respect to how tasks and decisions are allocated between the user and automation, in particular the issue of a system that autonomously and aggressively takes control away from the user. Second, Auto-GCAS's development spans three decades, providing a rich history from which best practices, and lessons learned can be drawn. Third, the research team has working relationships with organizations (e.g. the US Air Force and NASA) who directly lead Auto-GCAS activities, as well as with the personnel involved.

This study employed a multi-case design in which cultural, organizational, and automation capability are studied through three interrelated cases: 1) Auto-GCAS experimental test pilots; 2) Auto-GCAS engineers; and 3) management who lead and oversee the Auto-GCAS program. This paper focuses primarily on the developmental history of Auto-GCAS and the case of Auto-GCAS engineers. A previous paper has addressed experimental test pilots [5] and future papers will address the managers and leaders as well as a cross case analysis among all three groups.

In the remainder of this paper we first discuss the methodology and methods. Then we present key findings from our analysis of the historical development of Auto-GCAS, and key lessons learned from the engineers about the influence of automation capability, cultural, and organizational factors on trust development. In the last section we present conclusions and implications of this research with respect to human automation trust.

Methods & Methodology

Extended Case Study

Figure 1 depicts the project's extended case study methodology, in which grounded theory approach sets the framework for the project's primary sources, while the traditional research methodology provides the project's secondary sources. Using grounded theory (an inductive hypothesis generating approach), the project aimed to answer and stimulate research questions by using questionnaires, surveys, interviews with participants, field notes, and participant observations. NVivo, an ethnographic research software package, was used to code this data. The team then used the coding to help identify trends and to establish a collective story out of the key events, people, and meetings that contribute to the development of trust in Auto-GCAS. Hypotheses are generated from observing patterns that emerge out of ethnographic data.

In contrast to grounded theory, traditional research tests theories in a deductive manner. In this project, the research team immersed itself in the current literature on human automation trust development, with an emphasis on automation capability, cultural, and organizational factors. This included doing extensive literature review on the cultures and organizations involved with the development and testing of Auto-GCAS, and using the results of this review to generate hypotheses to be tested after the synthesis of the literature review was completed.

Using both primary and secondary data, comments on existing theories about trust in automation can then be posed. Once theories and hypotheses were generated from both the traditional literature review, and from the grounded theory methods, they were compared to see if they converged or diverged from each other. For an extended discussion of our methodology, methods, and lessons learned from their implementation in this project, the reader is referred to [6].

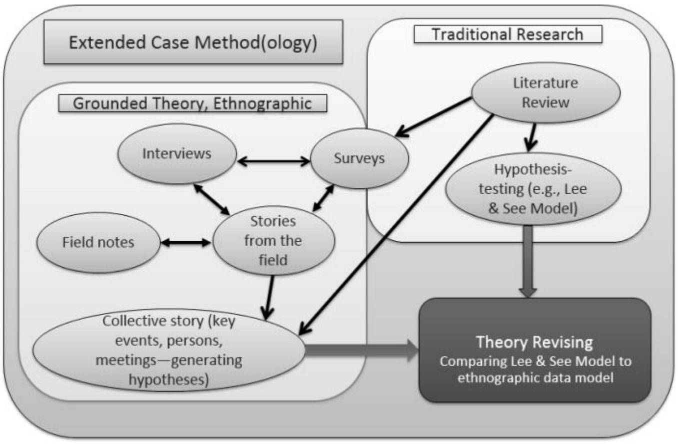

Fig. 1: Research Design Process and Strategy

Participants

15 Auto-GCAS engineers, with ages ranging between 26 and 59 (*M* = 38.64), completed surveys, and 12 completed follow up interviews. Of the 15 participants, only one was female; 13 were flight test engineers, whose involvement with Auto-GCAS ranges from one year to 20 years; one was responsible for all stages of the development; and one was responsible for developing the business case for Auto-GCAS.

Developmental History

In this section, we present a general timeline of Auto-GCAS development, and then discuss this developmental history in the context of the technical and human systems integration challenges. The information presented in this section is based on our review of the literature and analysis of surveys, interviews, and field observations with Auto-GCAS engineers.

Timeline of Auto-GCAS Development

The developmental history of Auto-GCAS spans 30 years. The initial research and development of Auto-GCAS began in 1984 [7] along with several other technologies on the Advanced Fighter Technology Integration (AFTI)/F-16 program. This first version of Auto-GCAS covered only a limited flight envelope and was based on a radar altimeter for determining terrain proximity instead of a DTM. From 1985-1997, development of Auto-GCAS continued solely on the AFTI/F-16 and only as a test support system, never being treated programmatically as a primary area of research. From 1990 to 1992, a number of variants of Auto-GCAS were developed bringing a slightly expanded envelope of capability and more importantly the use of a digital terrain map (DTM) for determining terrain proximity [7]. From 1992 to 1997 the Air Force Safety Center began to use the AFTI/F-16 team to support a number of F-16 mishap investigations where CFIT was suspected to be a contributing cause. In 1996, with USAF resources depleted for further Auto-GCAS development, the AFTI/F-16 team turned to foreign countries to solicit development interest. Sweden, just coming out of neutrality, joined the AFTI/F-16 team in further developing Auto-GCAS over the course of two test efforts. The first of these occurred in 1997 with a flight test effort to develop a nuisance criteria for the Auto-GCAS. This criteria was intended to form a core design requirement for Auto-GCAS so that there would be no adverse impacts from early recovery activations [7] (discussed later in the paper). In 1998, a full envelope system was developed and tested on the AFTI/F-16 in the first dedicated program for Auto-GCAS development. In 2000 and 2001 Auto-GCAS demonstration and evaluation tests took place with the Live Fire Test & Evaluation (LFT&E) office of OSD and Air Combat Command (ACC) [7]. A major turning point came in May 2003 with a Secretary of Defense Mishap reduction memo which set a requirement on all of the armed services to reduce mishaps by 50% [7, 8]. In 2005-06 the Defense Safety Oversight Council (DSOC) developed the Auto-GCAS fighter /attack business case [9]. This business case had two significant findings: 1) The CFIT mishap rate had remained unchanged despite the addition of numerous ground warning systems and 2) the mishap reduction goal could only be achieved in fighter aircraft by implementing Auto-GCAS. In 2006-07 the DSOC initiated the Automatic Collision Avoidance Technology/Fighter Risk Reduction Program (ACAT/FRRP) by investing $2.5 million dollars to start the program [8]. In 2008-2010, the ACAT/FRRP completed the research on Auto-GCAS and conducted an extensive test program to ready the system for production integration. This program was a collaborative effort between multiple organizations, led by the Air Force Research Laboratory (AFRL) at Wright Patterson AFB. The program not only included Auto-GCAS, but Automatic Air Collision Avoidance System (Auto-ACAS) and the Integrated Collision Avoidance System (ICAS) development. Significant advancements for DTM in terrain encoding were developed by NASA 2008-2011 for the purposes of enabling Auto-GCAS to be implemented on the F-22 platform [7]. From 2011-2014, the integration Auto-GCAS into the production USAF F-16 continued with a scheduled operational deployment in the summer of 2014.

Technical and Human-Systems Integration Context

Auto-GCAS was designed with a set of design principles meant to guide development and integration of the system. 1) Do no harm, which requires that Auto-GCAS not cause any harm to the pilot or the aircraft; 2) Do not impede, which requires the system to be nuisance free and thus does not interfere with the mission; and 3) Avoid Collision, which requires the system to avoid collision with terrain [3]. The principal goal of

Auto-GCAS is to mitigate the problem of Controlled Flight into Terrain (CFIT), the number one cause of the loss of life in aviation since the beginning of manned flight. One of the most effective technological measures to mitigate CFIT to date has been Terrain Awareness and Warning Systems (TAWS), which provide the pilot warnings and directions for avoiding terrain [9]. While the development of TAWS, and the mandate for its implementation, have played a critical role in significantly reducing CFIT accidents, they also have reached a point of diminishing return due to several limitations. The first is that current TAWS are prone to nuisance warnings (leading pilots to turn them off). The second is that, because these systems require the pilot to manually respond to a warning, they are not effective when the pilot is incapacitated or spatially disoriented. The third is that the pilot may not always correctly recognize a warning or correctly make the terrain collision evasion maneuver, especially in dynamic flight conditions. Thus, the human is the limiting factor in these situations.

To overcome these limitations, Auto-GCAS was developed with a number of innovative approaches and solutions. In order to address the nuisance problem, a nuisance threshold was determined, where a warning would not be considered too early by the pilot. This was accomplished by conducting a flight test program to define what would be the maximum acceptable time to initiate a recovery maneuver so that it would not be considered a nuisance by the pilot. Just considering this problem from a temporal perspective was novel where all previous efforts had looked at distance above the ground as a metric for nuisance. To determine the time in which a fly-up maneuver would not be a nuisance, pilots flew aircraft towards terrain at different conditions and then manually initiated a recover as they reached their comfort threshold. They then rated their anxiety level at recovery initiation to capture if whether they had accidentally initiated the recovery sooner or later than they had intended to. The time period after which a recovery initiation would be considered a nuisance and the point at which the aircraft's maximum performance recovery would just clear the ground is called a nuisance budget [10].

The nuisance criteria were found to be governed by two principles for an avoidance maneuver to be acceptable to a pilot. It must be both aggressive and timely. Aggressive in the sense that the avoidance is using a significant amount of the aircraft's available maneuvering authority. And timely in the sense that it does not begin the maneuver too early such that it is deemed a nuisance or too late in that the aircraft does not have sufficient maneuverability to avoid hitting the surrounding terrain. Available maneuvering authority is driven by the unique aerodynamics of an aircraft at a given fight condition. It is presumed that each pilot has a mental model of the aircraft's ability to maneuver. Using this mental model, the pilot assesses the approaching local terrain and determines a best escape path to avoid hitting what is ahead of the aircraft. To this, it was found that the pilot applies a safety buffer based on his uncertainty of the situation (rapidly changing aircraft attitude or conditions, high turbulence, poor visibility, etc.) to determine when the "aggressive" avoidance maneuver should be initiated. Because the "aggressive" portion of the criteria imbeds within it the aerodynamics unique to a vehicle, the "timely" portion of the criteria remains the same for all aircraft. It was also found that the “timely” criterion could be approximated by a single equation with the maximum acceptable time being 1.5 seconds prior to the point where the aggressive recovery will just miss the ground.

The design of the Auto-GCAS followed the same aggressive and timely criteria. First, the avoidance maneuver was chosen, designed and evaluated for acceptable aggressiveness in the F-16. Extensive use of flight evaluations and pilot comments were used to determine that the maneuvers were acceptable for the F-16. The maneuver chosen was an aggressive roll to wings-level, 5g pull. Next, just as with the pilot’s mental model, an algorithm was developed to model that aggressive recovery and assess the near terrain proximity to determine when a timely avoidance maneuver should be initiated. Uncertainties were also used to buffer the recovery initiation by capturing the inaccuracies in the recovery model, terrain model and those sensors which are used to position the aircraft over the terrain model and used to determine the recovery trajectory. The 1.5 seconds from the nuisance criteria formed the allowable error budget for the GCAS algorithm [10].

To address the human limitations and situations in which the pilot is incapacitated or disoriented, the recovery was automated. The automatic-recovery solution eliminates the human-limit problem (i.e., different pilots have different perceptions and capabilities) by taking these out of the equation. Instead, the system makes the decision to initiate the recovery at the last second so that the perception of nuisance is eliminated.

Results

In this section, we report the findings of our case study on the Auto-GCAS engineers. References and comparison will be made to our case on the pilots, which is reported in another paper [5]. We then present the lessons learned and best practices.

Auto-GCAS engineers

As part of the survey, engineers were asked to rate the highest level of Auto-GCAS automation that they would be comfortable with. The Sheridan and Verplank [11, 12, 13] taxonomy on 10 automation levels were used, where level 1 is lowest level (Human does the whole job up to the point of turning it over to the computer to implement) and level 10 is the highest level (Computer does the whole job if it decides it should be done, and if so, tells human, if it decides that the human should be told). The majority (80%) of the engineers selected level 7 (computer does whole job and necessarily tells human what it did). Additionally, engineers were asked to speculate how they believe pilots would respond to the same question. In this context, their response should show greater variation. However, the largest portion (46%) selected level 7. By way of comparison, when pilots were asked the same question the majority (65%) also selected level 7 [5]. The agreement between the engineers and pilots on Auto-GCAS automation level shows that the designer/engineers understand the needs of the users/pilots, and reinforces the decision, described in the previous section, to use an automatically executing Auto-GCAS recovery maneuver.

Further analyses included an investigation into the working relationship between engineers and their pilot and manager colleagues. The majority of the engineers reported in the surveys that they either agreed or strongly agreed that the engineers, pilots, and managers with whom they worked were competent and professional. This mutual positive regard could be a key factor contributing to the ability of the engineers to correctly predict the pilot preference of the Auto-GCAS automation levels (discussed above) and the pilot trust evolution (discussed below).

Investigations into Auto-GCAS engineers' culture yielded valuable information that illuminates the impact that engineers' trust of a system has on end-users' acceptance and trust of that system. First and foremost, engineers commented that engineers' professional duty holds them responsible for the safety and wellbeing of the operator. At the system conception and design stages, this manifests in the analysis and design of a system that meets safety requirements before conducting flight tests to refine and validating the design. At the testing and validation stages, engineers report feeling a strong sense of responsibility for protecting the lives of the test pilots, whose task is to fly and test the system at its limits. As such, the engineers indicated that they had a drive to make up for their limited first-hand experience with the system (because they do not fly), by being particularly meticulous in their data collection, analyses and reporting. This culture and interaction with test pilots has led the engineers to adopt a "healthy skepticism" attitude towards new systems, a notion reflected in the test pilot culture reported in our previous paper [5]. In this context, healthy skepticism can be described as an initial withholding of trust in the system, but one that is warranted due to their profession. It would be professionally unhealthy to immediately trust a system without vetting it first. Engineers stated that their "distrust" of the system begins to calibrate towards appropriate trust as the automation continues to work successfully and as the engineers began to ingest data to verify that the system was working as intended.

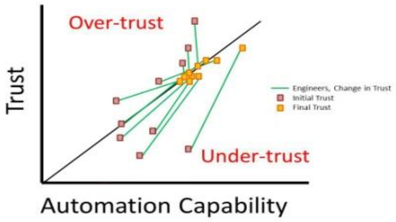

Fig. 2. Engineer Trust Evolution

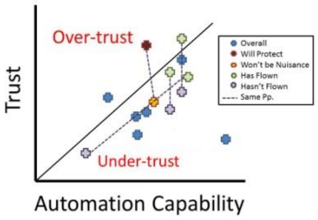

Fig. 3. Engineers' Impression of Pilots' Trust

When asked to indicate how meaningful it was to them to be involved in the Auto-GCAS development, most engineers commented that Auto-GCAS and other projects were equally meaningful. However, some of the engineers who had been highly involved in the development of the system reported feeling more strongly about Auto-GCAS, and a resultant enhanced devotion to being accurate and equitable in how they report their findings. Overall, all engineers commented that their professional culture is evidence-based, believing in what the data support, and that their trust in the system is a function of verified conclusions, rather than the degree to which they believe in the importance or value of that system. Thus, their trust that Auto-GCAS would function as it was designed only developed after having tested it thoroughly. Synonymously, they indicated that their initial perception of the system had little effect on their final trust in the system, which is based on tests that showing that it will prevent collision for 98% of all cases.

Figure 2 shows the engineers' trust evolution (in Auto-GCAS) from when they were first exposed to the system to after having tested it. The graph is a notional framework between trust and automation capability. The horizontal axis is a measure of automation capability (trustworthiness), the vertical axis is a measure of trust in the automation, and the 45-degree angle on the graph represents a line of appropriately calibrated trust, which is a 1:1 ratio between trust of a system and that system's automation capability (trustworthiness). Markings on the calibrated line would indicate that their trust in the automation appropriately reflects the automation capability. If a person marked themselves below the line, they would be indicating "distrust" and if they marked above the line, they would be indicating "over trust.' Participants were given the above graph with the diagonal line (blank of other responses) and asked to mark where they were on the graph when they first heard about Auto-GCAS to where they are now. They were also asked to indicate where they thought pilots and managers would fall on the graph. While the engineers' trust levels move toward the calibrated line, on average, they end up on the under-trust side of the line. This result is consistent with the engineer's reported sense of "healthy skeptism", and their sense of responsibility for the lives of the pilots.

In addition, the engineers were asked to predict where the pilots might place themselves on the same graph. The results are shown in Figure 3. Instead of giving a direct response, many engineers chose to dissect their prediction. As is shown in the figure, some engineers decided to place points on the graph for where the pilots might place themselves for two different situations: before and after flying with Auto-GCAS. One engineer also placed two points, but one for the pilot's trust in the system for saving the aircraft, and another point for the pilot's trust that the system does not interfere with the mission. Despite the diversity in the responses, the engineers' prediction of pilots' trust calibration is consistent with pilots' own calibration as reported in previous papers [5].

Lessons Learned

Collection, analysis, and interpretation of both the developmental history of Auto-GCAS and the data from the Auto-GCAS engineers have revealed the following valuable lessons and best practices:

- The three design principles of Auto-GCAS (1. Do No Harm, 2. Do Not Impede, and 3. Avoid Collisions) provided the framework for its success in being a trustworthy system. Most notable is the fact the "Avoid Collision" requirement is ranked lower than the other two requirements, indicating the importance of avoiding interference with the pilot. Auto-GCAS took the end-user's needs into high consideration which should help in facilitating appropriate trust on the system from the pilot community. These three principles can be considered as best practices which developers of future automated safety systems can consider.

- The primary lesson learned from the nuisance criteria was that with substantial data from previous work showing that at least 2 seconds of reaction time is required for a situationally-awared pilot to consistently begin a proper recovery, warning a pilot 2 seconds before a recovery is needed will always fail the 1.5-second nuisance criteria. Therefore, it is not possible to design a nuisance-free warning system. Thus, the designer must automate the recovery and take out the reaction time to have a nuisance free system.
- Taking the control away from the pilot (however momentarily as is in the case of Auto-GCAS), especially from a fighter pilot, appears to be a viable strategy for high pressure situations such as avoiding a collision threat. While the pilot culture [5] may shun this strategy because the pilot wants to be in control, it can be done with proper considerations of human factors. In the Auto-GCAS case, the automatic recovery can be seen as an extension of what a pilot would do in a temporally-demanding situation of a terrain threat. Successful fielding of Auto-GCAS will further reinforce the notion that this strategy is applicable for other systems and platforms.
- Healthy skepticism is an essential attitude for both designers and users to have in order to facilitate appropriate trust development. The Auto-GCAS engineers embraced this attitude because of their data-driven, and interestingly, the experimental test pilots also embraced the same attitude as reported in our sister paper [5].
- The engineers' and pilots' common preference for the automation level that Auto-GCAS should have, and engineers' accuracy in predicting the pilots' preference suggest that there is a strong potential for Auto-GCAS to be ultimately accepted by the operational pilots. However, both the engineers and the test pilots had extensive experience with the system, so pilots who are unfamiliar with the system may still be resistant to the system taking control of the aircraft. The mutual professional respect that the engineers and pilots have of each other played a key role in facilitating the common understanding and preferences.
- The Auto-GCAS engineering culture is primarily defined by meticulousness in attention to technical details and thoroughness in considering the data before making conclusions. This data-driven culture is strongly influenced by their responsibility for the safety of, respect for, appreciation of the pilots. This finding suggests that pilots who understand the motivations of the engineers might be more readily to accept automated safety systems. Additionally, the common presence of a "healthy skepticism" in the professional cultures of both the pilots and engineers again indicates further alignment of the two cultures. The data suggest that engineers' understanding of pilot culture helps them to design and test system that will be more readily accepted by pilots. It also further suggests that pilots will be more likely to accept systems if they have a better understanding of the nature of engineering culture as well as the similarities that this culture has to their own. Thus, the development of future systems can greatly benefit from the utility of user feedback and cultural variables to design trustable automation.

Conclusions and Future Research Avenues

The findings in this study showed: a) that there is a strong alignment between the engineering and experimental test pilot cultures, and b) that the innovative technical solutions and unique strategy adopted for Auto-GCAS development were effective. These findings indicate strong potential for appropriate trust development in operational pilots. This conclusion corroborates with the conclusion of our case study on Auto-GCAS experimental test pilots. However, these findings are based on pre-deployment data, and because trust calibration is a dynamic process, spanning from the time when the system is first conceived until it goes into operation and retirement, it would be beneficial to conduct a field study of the deployment of Auto-GCAS with operational pilots in order to collect data to validate the hypotheses and to examine the various research issues raised (e.g., potential Auto-GCAS misuse/disuse due to pilot occupational culture and/or operational circumstances, trust evolution from beginning of deployment to stages when opinions are stabilized). Such a field study would generate data and results that could influence and improve the design of the class of systems that take away control from the operator while eliminating nuisance activations and preventing interference with the mission.

The present study offers rich data related to the development of a complex form of automation that has the potential to save lives. The development, testing, and perspectives of engineers, in this case, are closely aligned to the literature on trust in automation as it relates to fostering trust. Specially, Lee and See [2] suggest that trust can be enhanced by: showing past performance of the system, showing the process (i.e., how the system works), making the technology and its algorithms understandable, communicating or visualizing the intent of the system, and using training to assess and verify the system's reliability. The auto-GCAS system exemplifies many of these recommendations, for instance: 1) it has demonstrated high reliability through extensive operational testing and this data has shaped the trust of engineers whose value system strongly emphasizes data, 2) the fly-up maneuver is consistent with a pilot's preferred behavior (e.g., wings level and 5g pull up) which helps the pilot to be familiar with the system and understand its behavior, 3) the intent of the system is to protect the pilot but also avoid interfering with the pilot by circumventing violations of the nuisance budget, this is both a unique aspect of this particular in relation to prior systems and represents an excellent factor to communicate to the pilots in order for them to understand the system's intent, and 4) the system has undergone extensive testing with test pilots receiving considerable training on the system which has supported more calibrated trust overtime. Experience with the Auto-GCAS system has moved engineers and test pilots (see [5]) toward more optimal trust strategies. It will be imperative for the trust-relevant tenants of the system to be shared with the operational pilots who will be interacting with this system for the first time. While the system was designed in such a way as to promote effective trust strategies, and past data suggests that both the engineer and test pilot communities have adopted these optimal strategies, it will be the acceptance or rejection of this system from the operational community that will determine the overall success or demise of the system.

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