Human Factors Analysis of Predator B Crash

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The 2006 crash of a Predator B in Arizona has prompted a great amount of scrutiny into Unmanned Arial System (UAS) operations. The direct cause of the Predator crash can be tied to an initial failure of the displays and a failed transfer of controls between operators. However, using the Human Factors Analysis and Classification System (HFACS), many latent errors that contributed to the accident were uncovered that were not addressed by the National Transportation Safety Board (NTSB) report. The HFACS approach for this accident examined all issues leading up to the crash and uncovered several organizational influences that were significant contributors to the Predator crash. Through augmenting NTSB efforts with the HFACS method, future UAS incidents can be prevented by addressing all causes, regardless of their distance from the pilot's seat.

Introduction

On April 25, 2006, an MQ-9 Predator B on a nighttime border patrol mission impacted the terrain northwest of Nogales, Arizona and destroyed the aircraft. Although no injuries occurred in the accident, the crash fueled concern about the safety of UASs. Extensive cases of aircraft incidents are available for study through years of NTSB reports and history; however, these data sets are almost exclusively manned systems. Increasing numbers of remotely piloted vehicles are proposed in applications for both military and civilian missions. With UAS mishap rates currently 30 to 300 times greater than general aviation, it is important to study these crashes to increase safety for future operations [1].

While aviation mishaps have steadily declined, the incidents attributed to mechanical failures have dropped much faster than those attributed to human errors [2]. To help address the non-mechanical mishaps, frameworks with varying degrees of acceptance have been developed to analyze the human factor issues and decrease incidents attributable to the human in the system. One commonly referenced framework is the HFACS [1], which was developed to specifically address the human and organizational role in military accident analysis. While it has been used to analyze many manned aircraft accidents, its use for UAS accident analysis is limited. Thus, this report provides background into the Unmanned Aerial Vehicle (UAV) and the Ground Control Station (GCS) configuration and functionality of the Nogales Predator B, and performs an HFACS. The NTSB report is then compared to the HFACS findings, and finally a set of recommendations are made for this case and similar UASs in operation today.

Predator B System Function and Configuration

The Nogales Predator B was flown by the Department of Homeland Security (DHS) for the purpose of border protection by the Customs and Border Patrol (CBP). The system consists of the UAV, a GCS, and the interfaces between the components. The GCS houses the pilot's and the sensor operator's work stations. These operators sit side by side at identical consoles, with the pilot normally in the left position (PPO-1) and the sensor operator on the right (PPO-2).

Figure 1: DHS Predator B (left) and inside view of GCS (right) [3]

Accident Events. The mishap flight terminated at 0350 Mountain Standard Time on April 26, 2005. This Predator B UAS was operated by General Atomics Aeronautical Systems, Inc. (GA-ASI), the Predator manufacturer. The GCS was located at Libby Army Airfield, and per standard procedure was operated by two people. The pilot was a GA-ASI employee and a CBP agent managed the camera controls. Two additional GA-ASI employees, an avionics technician and a sensor operator, were also in the GCS for the mission. After a short delay in takeoff due to an inability to establish a link between the Predator and PPO-1, the mission was launched successfully [3].

The mishap pilot took control after a normal change-over at 0300. Shortly after taking control, the lower monitor screen went blank on PPO-1. The pilot switched control over to PPO-2 without using the checklist process. Shortly after the console swap, the mishap pilot noticed the UAV was not maintaining altitude, so he shut down the ground data terminal, thinking this would initiate the lost-link procedure, climbing the UAV back into the LOS. The instructor pilot (IP), who was required to be with the non-qualified pilot and also a GA-ASI employee, was not in the GCS at the time. He returned to the GCS when the mishap pilot called him on his cell phone. Upon the IPs arrival, the mishap pilot explained the situation, and the IP looked at the controls and stated they were not positioned correctly. Attempts to restore communication to the UAV were unsuccessful [3].

For this flight, the pilot flew from the left seat, with the payload operator in the right seat. The PPO-1 and PPO-2 consoles are nearly identical with regards to physical layout, but have very different functionality depending on the mode of operation. When either console is configured for the pilot (PPO-1), the throttle quadrant provides UAV throttle function, including the condition lever, speed lever and flaps control. When this same console is configured for the payload operator (PPO-2), the controls operate tracking settings for the camera. Because of the similarity of PPO-1 and PPO-2, the GCS allows the operators to quickly transfer pilot and payload control from one console to the other.

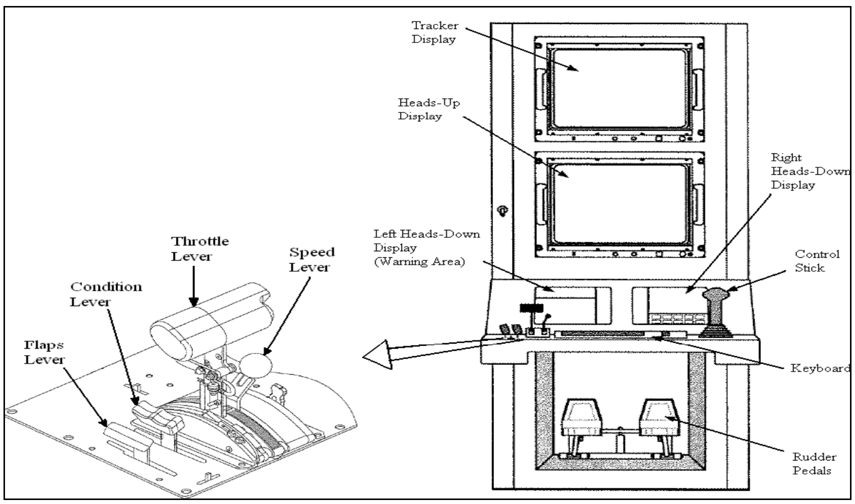

Figure 3: PPO-1 Setup with Condition Lever [3]

The condition lever shown in Figure 3 played a significant role in this mishap. In pilot mode, the condition lever controls the engine. The condition lever in the forward position allows fuel flow to the engine, the middle position closes or stops fuel flow (shutting the engine down), and the aft position feathers the propeller blades to reduce drag. In payload operator mode, the condition lever changes the camera's iris setting. Moving the lever forward opens the iris, placing it in the middle position locks the iris in its current setting, and moving it back narrows the iris. The condition lever functions are summarized in Table 1. If control is transferred from one console to the other, the checklist dictates that the condition lever position on the payload operator console must be matched to the current positioning on the pilot console before the switch is executed.

Table 1: Condition Lever settings [3]

Condition Lever Control Position	PPO-1 (pilot) Result	PPO-2 (sensor operator) Result
Forward	Opens fuel valve to engine	Increases camera iris opening
Middle	Closes fuel valve to engine (and shuts down engine)	Locks camera iris setting
Aft	Feathers prop	Decreases camera iris opening

Control of the Predator B from the GCS relies on line-of-sight (LOS) communications. If the aircraft descends below the GCS's field of view, the GCS is unable to directly communicate with the UAV. When the GCS loses communication with the UAV, the Predator is designed to autonomously follow a pre-programmed lost-link profile consisting of waypoints at various altitudes, forming a loop [3]. The UAV autonomously follows the lost-link profile until it reestablishes contact with the GCS or runs out of fuel and crashes. The lost-link profile is often changed during a mission for two reasons: 1) To ensure the profile will not take the UAV out of its approved airspace, because the minimum allowable altitude increases after the aircraft gets far enough away from the landing strip, 2) To allow more time to reestablish contact because the higher the aircraft is, the longer it takes to descend below the LOS if the engine dies.

The Predator B also has a backup communications system which uses Iridium® satellites to control the UAV beyond LOS [3]. The Iridium® system provides limited control through the use of autopilot hold modes. Direct pilot control of the aircraft is not currently possible when using the Iridium® satellite system. During normal operations, the Predator receives both a LOS signal and an Iridium® signal. The LOS signal takes precedence when it is available. If the aircraft loses power due to an engine failure, the Iridium® communications equipment is automatically deactivated to conserve battery power. The UAV's engine auto-ignition system requires the Iridium® signal and will not function unless the aircraft is in contact with the satellite. As will be discussed, this design had a significant effect in this Predator B mishap.

HFACS Analysis

While many frameworks have been proposed to analyze human factors causality issues, Reason's "Swiss Cheese" model has earned wide acceptance, particularly in the military aviation community [2]. The "Swiss Cheese" model identifies four levels of failure that contribute to accidents: Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts. In Reason's model, accidents happen when anomalies (i.e., holes in the cheese) align between the four levels. HFACS builds on Reason's four levels of failure by defining causal categories for each level [2].

The HFACS analysis starts with the most direct causes, and then each causal factor of the accident is grouped into one of the four levels of failure [1]. Although the unsafe acts of operators are typically the most direct causes of the accident, they are often the result of many latent errors built into the system or organization. The HFACS systems approach allows the accident to be analyzed as a whole, and recommendations for improvement can be offered for a diverse set of causal factors.

As with most aircraft accidents, the Nogales Predator accident cause stems from a convergence of factors rather than a single event. The first potential source of trouble arose shortly after takeoff when the pilot failed to increase the altitude setting of the lost-link profile. The GA-ASI pilot appeared to be unaware that the current profile was set for a flight pattern below the approved altitude, and that it needed to be updated for this flight [3]. This act reveals a precondition for unsafe acts, as the pilot did not fully understand the lost-link profile. If the altitude setting had been changed, the UAV may not have descended as quickly, providing more time to reestablish communications.

The next precondition for an unsafe act came with a lockup of the telemetry data, which forced the pilot to operate without current information on the state of the aircraft [3]. The lockup was a known recurring problem of the system, but was not seen as high a priority because of the built-in lost link flight plan for the UAV. After the lockup, the pilot toggled a control switch to change the piloting controls to the sensor operator station, a typical response for this situation [3]. Whenever this procedure is performed, a checklist must be followed to ensure a safe switch of control. This checklist stresses the importance of having the command controls in the same position at each station.

An unsafe act occurred when the CBP payload operator moved out of the GCS during the switch. As stated in the checklist, both operators must remain in their seats during control transfer in case it becomes necessary to revert controls. In addition, during a switch, the avionics technician is to assume the duties of a co-pilot to help perform the checklist items, which did not happen [3]. The pilot's not matching the controls, the payload operator's leaving the GCS, and the technician's failure to help are all examples of unsafe acts by the operators.

This failure to follow the checklist became one of the major factors leading to the crash. When flight control was switched from PPO-1 to PPO-2, the two condition levers were not matched. The mishap pilot was unaware of the mismatched control situation which led to mode confusion [4]. Mode confusion occurs when the state of a system is overlooked, and a technical system behaves differently from the user's expectation [5]. Initially, the pilot console lever was set to allow fuel flow (forward position) and the payload operator console lever was set to lock the iris (center position) [3]. After the transfer, the iris setting became the new engine setting, causing the engine to shut down. If the pilot had followed the checklist, this error may have been noticed or prevented.

A further precondition for an unsafe act came from the design of the backup communication mode. As previously mentioned, the LOS and Iridium® systems could both be used to control the UAV, but the Iridium® system is limited to the hold modes that must be set first [3]. These were set during the flight, but LOS communication takes priority when it is available. After the engine was inadvertently turned off, the UAV began shedding electrical systems to save power. One of the first functions shed was the Iridium® connection [3]. The UAV was also equipped with an auto-ignition system in case the engine quits. However, this system only works if the Iridium® system is operable. These two features, although intended to make the system more robust, were poorly designed because they gave the operators a false sense of security. This single-point failure was a latent error in the system and not discovered until it was too late, causing a failure in the system. As the UAV descended towards the ground, the operators believed the UAV was correctly following a lost-link plan: holding altitude and circling [3].

The next issue addresses personnel readiness for the flight, which both impacts the precondition for unsafe acts and unsafe supervision classifications. The accident pilot had most of his UAV experience flying the Predator A, which is not as advanced as the Predator B variant, but has a similar control setup. A significant difference is that the Predator A's condition lever does not need to be matched between PPOs when switching between control consoles. The pilot was also missing some of the mandated modules of training. In fact, 5 of the 32 required training events for pilot conversion were not accomplished, according to the Pilot Conversion Form [3].

Inadequate supervision also occurred within the pilot certification process. Final pilot approval was the responsibility of a Defense Contract Management Agency (DCMA) Government Flight Representative (GFR), who examined the training records after a pilot completed all elements of the Predator training syllabus [3]. If approval was given by the GFR, GA-ASI would then seek the approval of CBP for the pilot in question. However, at the time of the accident, CBP did not have a fully trained GFR on staff, which limited the organization's ability to properly supervise the pilot certification process. The relationship between the DCMA GFR and CBP GFR was also unclear, causing confusion in who could certify a pilot to fly.

Prior to the accident, GA-ASI contacted the GFR trainee and requested that the accident pilot be added to the list of approved pilots, knowing that he had not completed his training modules. Because the pilot in question was still not fully certified, the GFR trainee gave GA-ASI a verbal approval for the pilot to fly the Predator B, as long as there was an IP present in the GCS [3]. Such verbal approvals were not standard practice at CBP, classifying this act as a supervisory violation. Allowing a pilot who had not yet completed the full training regimen to operate the UAS significantly increased the probability of errors during operations, errors which a fully-trained pilot might not have committed.

Additional factors at the organizational level contributed to the crash, starting with failed organizational training oversight. For the pilots of the Predator B, no simulation training was available [3]. This lack of training meant that pilots could not practice emergency scenarios. If pilots never experience systemic failures, they may develop an incorrect mental model of the actual limits of the UAV. This lack of training corresponded directly with a lack of personal readiness for the pilots.

Furthermore, complacency in vehicle readiness was prevalent. One example was the lockup problem, which was a common occurrence. According to a log book kept in the GCS, 16 lockups occurred between the two stations in the previous five months, and CBP had no immediate plan for rectification. In addition, there was also a lack of spare parts available, so problems often existed for long periods of time before addressed [3]. These examples suggest CBP failed in its organizational oversight of their maintenance program.

HFACS Conclusions & Recommendations

The crash of the Nogales Predator B stems from many causal factors (see Table 2 for a summary of the errors and their respective HFACS levels of classification), but these can be condensed into three general problem areas can be seen, not just for the Predator, but for all UASs.

The first is the need to address basic human factors considerations when designing a UAS. The most immediate cause can be traced to the mode confusion seen in the condition lever of the operating station, which was amplified by a lack of training and poor oversight by GA-ASI and CBP. These shortcomings were exacerbated by the latent error of a poorly designed backup system. Mode confusion is a well-known and well-researched phenomenon in manned aviation. This could have been prevented with additional automation that would provide a warning and lockout if a transfer is attempted when the controls are not matched. While some would advocate for more training to address this problem, humans are imperfect systems, and it is important to design for an operator that may make mistakes [8].

Additionally, UAS's should not rely on operator memory to execute critical steps such as the need to constantly update the altitude setting of the lost-link profile. Electronic checklists have been very successful in commercial aviation to prevent such memory lapses, and including this kind of supervisory automation is beneficial for these tedious tasks that can often be forgotten in periods of high (and low) workload. The lost-link profile is already highly automated, so one would expect that adding an automatic change of an altitude setting based on distance from the landing strip would be rather straightforward. This application of automation could reduce the pilots' workload, allow them to concentrate on other tasks which require human input, and provide a more fault-tolerant system robust to human error.

The second problem area is the need for more careful and principled system reliability analyses for UASs, which are just as critical for unmanned systems as they are for manned systems. The single-point failure of the auto ignition system due to a loss of engine power, which led to a loss of communications, is a failure that could have been anticipated in advance. There are a number of analytical models that could have been used [6], and while no analytical model is perfect, more rigorous and principled reliability analyses will have to be performed on any UAS that hopes to fly in the National Airspace System (NAS.)

Lastly, there were organizational influences seen in this accident, on the part of the CBP, GA-ASI, and the Air Force. CBP supervision was lacking in terms of maintenance and personnel supervision. From a maintenance perspective, spare parts should be available for an aircraft that is expected to fly on a regular basis. Moreover, a lack of organizational oversight and the failure to ensure the presence of the required IP shows the indifferent attitude taken towards UAV operations While the IP was a GA-ASI employee, ultimately the CBP bears responsibility for not ensuring the IP was present at all time, thus they violated the Air Force GFRs directive.

There was also evidence of institutionalized complacency on the part of GA-ASI, particularly in the aspect of training. Responsible for pilot training, GA-ASI requested that a pilot be certified that had not finished all required training modules, and as noted, the IP was not present despite the GFR directive. Again, while CBP was ultimately responsible for oversight of personnel conducting CBP missions with CBP aircraft, it appears that there is a culture of complacency within the training and qualification programs for GA-ASI pilots.

Lastly, the DCMA also bears some responsibility with the confusing system put in place to approve and monitor pilots. Allowing a partially-trained GFR the authority to grant pilot waivers to fly without full completion of training is an issue that must be addressed, as there should be clear oversight for pilot authorization.

Table 2: Errors grouped by category

Category	Responsible Organization	Issue
Organizational Influences	CBP	Complacency in maintenance supervision
		No simulation training available
		Lack of pilot authorization & training oversight
	DCMA	Unclear relationship and responsibilities between DCMA GFR and CBP GFR
	GA-ASI	Complacency in training certifications
		Lack of sufficient reliability analyses
Unsafe Supervision	CBP	Did not ensure IP was present in GCS
	GA-ASI	IP did not supervise pilot as directed by GFR
Preconditions for Unsafe Acts	GA-ASI	Lost-link profile not updated prior to flight
		Condition lever design
		Auto-ignition single point of failure
		Lock-up of displays
Unsafe Acts	GA-ASI	Technician did not assume the duties of a co-pilot in the control change
		Pilot switched controls from PPO-1 to PPO-2 without operator in second seat
		Pilot switched controls from PPO-1 to PPO-2 without following checklist procedures
	CBP	Sensor operator left GCS during control switch

NTSB Conclusions and Recommendations

As noted previously, the NTSB conducted an investigation of this accident, and asserted the direct causes of the crash were the pilot's failure to follow the proper checklist procedures during the switch between the operating consoles, and that an IP was not present in the GCS [3]. The former directly caused the Predator to lose power, and the latter was a violation of the conditions of the approval granted to CBP to allow the accident pilot to operate the UAS. In classifying the IP's absence as causal, the NTSB appears to assume that had he been present, he would have prevented the lever position error from occurring or would have been able to diagnose the problem quickly enough to save the aircraft. This assumption is reasonable, as the instructor almost immediately identified the incorrect control input when he examined the consoles upon arriving in the GCS post-crash.

The NTSB's report also identified several other factors associated with the crash but not considered causal to it. One contributing factor was the frequent lockups of the console screen, and the fact that no action had been taken at the time of the mishap to resolve them. The maintenance procedures performed on the Predator B by GA-ASI were deemed to be incomplete and therefore also a contributing factor, as was CBP's oversight of their UAS program. Based on these findings, the NTSB made a series of safety recommendations to the FAA and CBP [3].

Comparison

The NTSB investigation points to many of the same causes as the HFACS process, but there are some major differences. Both point to the faulty design of the control lever, as well as the absence of the IP during flight. They also each point out that the faulty design of the Iridium® control system and lock-up of controls were major factors in the crash. However, the NTSB focuses more on the immediate causes, and points to "human errors" committed by the operators of the system, which seems to be the Board's official conclusion in many aircraft accidents [7]. HFACS, instead, sees these errors as the likely byproducts of faulty design and improper management.

With factors involving human control, HFACS helps to diagnose why the error occurred, and points to solutions for future operations. The HFACS recommendations point out the need for system reliability analysis and complacency across a number of organizations. Neither of these were direct outputs of the NTSB report. Highlighted in gray, Table 2 shows the organizational influences that led to this accident that were not mentioned by the NTSB. This shows that many of the high-level organizational influences that may have been missed by other analyses were discovered using HFACS, which draws the connection between the organization and the accident. Although the NTSB recommendations will certainly help prevent similar incidents, the HFACS solutions cover a much wider range of problems that need to be addressed. The HFACS process provides insight as to *why* problems occur, which suggests *how* they can be mitigated. Moreover, HFACS outcomes suggest not just specific redesigns or additional training, but also address more systemic, cultural problems. By focusing on the human factors causes, future accidents can be prevented by designing systems that are flexible enough to be used by operators of all skill levels.

Conclusion

As the number of unmanned vehicles continues to increase, it is important to keep the same standard of safety for the flying environment. When analyzing a crash, it is important to look not only at the direct causes within the system, but also to trace those causes to their roots. Using the HFACS process for accident investigation addresses the causes using a human factors viewpoint. This often helps to shift blame from pilot error to organizational and latent errors, which are problems that exist in the system unknown to the user. In the crash of the Nogales Predator B, it can be seen that the latent errors in the system were overwhelming, and it was only a matter of time until the holes in the cheese would align, causing a complete breakdown of control. The use of HFACS helps to assign responsibility to these latent errors, addressing these problems for future flights. The HFACS approach for accident analysis looks at all issues leading up to the crash, and in this case with the Predator B, helped to uncover some of the organizational influences that may have otherwise been missed. Through this method, future incidents can be prevented by addressing all causes, regardless of their distance from the pilot's seat.

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