Fly-Crash-Recover: Safe Recovery of Faulty Unmanned Aerial Vehicles
(Technical Topic)

Viable Integration of Autonomous Aerial Systems: A Tightrope Act
(STS Topic)

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

The origins of unmanned aerial vehicles (UAVs) rest firmly in the history of military research with a focus on removing a vehicle's operator from danger. Despite those early years primarily concerned with large, military aircraft, the development of more powerful microcontrollers and cheap manufacturing methods have allowed UAVs to become available for commercial and recreational use. While the current state of the industry can be characterized by niche activities including photography, videography, surveying, and drone racing, large commercial UAV systems stand to be a formidable source of growth in coming years (Wolfe, 2017). Major companies such as Amazon, Fed-Ex, and UPS are developing their own systems to explore large commercial applications including drone-based delivery of small packages as a future alternative to traditional ground-based methods. Such systems could dramatically reduce both the time and cost associated with the final stage of package delivery. Because of this acute interest from commercial behemoths, the UAV market "is poised for entrepreneurial growth much like all of aviation was poised about 100 years ago" (Vance, Newburg & Patankar, 2014, p. 218). However, little to none of this economic and social value can be realized before the Federal Aviation Administration (FAA) can properly regulate and authorize these commercial systems. While these systems may bring many benefits to companies and consumers, the impact of a dramatic increase of UAVs in the national airspace will have far-reaching and uncertain effects on privacy and safety. Both the benefits and related concerns must be weighed and carefully evaluated by the FAA in order to develop socially and economically viable regulations.

In order to achieve overall viability for commercial UAV systems, these systems must include robust safety features within the physical vehicles while also adhering to well-developed regulations. This capstone project will attempt to develop on-board control schemes for UAVs to manage the recovery of a vehicle in the event of a failure in order to improve the system's safety. During a crash with another object or a hardware issue on the UAV, these control schemes would intervene with the goal of minimizing damage and danger to surrounding people and objects. Additionally, my STS research will attempt to analyze the multitude of viewpoints and pressures present in the process of integrating commercial UAVs into the national airspace. By investigating the benefits and drawbacks of commercial UAV systems for concerned parties and the general public, I will identify and contextualize the technical and societal concerns that must be addressed in FAA regulations to create a viable future for this technology.

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In the role of a commercial delivery UAV as envisaged by today's interested companies, a drone would generally be expected to fly from a home position to a destination with a package that it would deliver and then return home, all with little to no human involvement. While full UAV autonomy is still undergoing extensive research, many individual elements critical to the technical feasibility of autonomous flight are being developed independently. Some of these elements are flight path planning, path execution, and crash avoidance. Unfortunately, a critical element that is currently missing from nearly all UAV systems is a failure recovery mode that recognizes an event such as a crash or hardware failure of the drone and that attempts to safely recover the drone before complete catastrophe. Without such a control element, even the slowest of collisions or simplest of errors can cause immediate danger to nearby people and property.

Within the airspace surrounding a UAV's operation, many other objects such as trees, buildings, and other vehicles make the environment complex to navigate. Because of this complexity, the possibility of a UAV to crash into its surrounding environment can never be fully eliminated through path planning or crash-avoidance technology. Similarly, non-crash related issues such as mechanical or electrical failure of components from users over time can lead to the same danger to the vehicle's environment. Because of the possibility of these issues, the FAA has initiated widespread research with the goal of characterizing the risk posed to humans in the event of a collision with a faulty UAV. As a result, the Alliance for System Safety of UAS through Research Excellence (ASSURE) group has recently released one of the most extensive studies of UAV collision severity published to date. Through hundreds of collisions similar to the type shown in Figure 1 using various types of drones and experimental configurations, ASSURE has generated significant amounts of collision data and related recommendations towards minimizing crash severity.

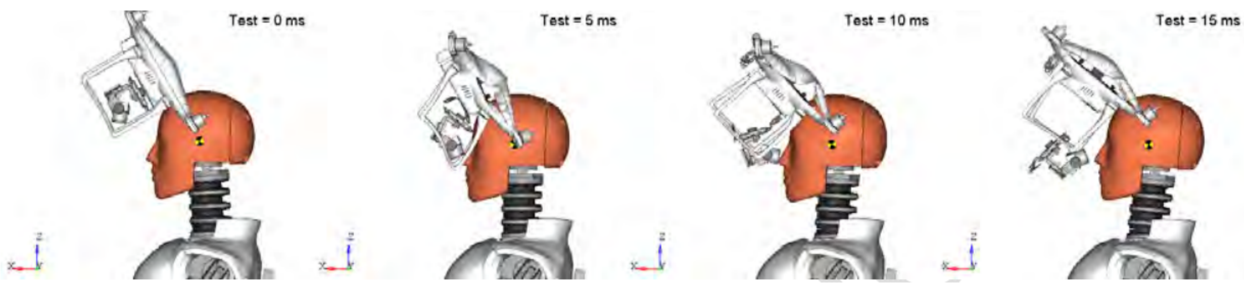

Figure 1: Four-frame visualization of a typical UAV-human collision performed in testing. Figure shows a common, lightweight recreational drone directly crashing into the head of a test dummy at a high angle to simulate a drone in free fall. Visualization is across a 15-millisecond time period (Arterburn et al., Annex B - E-17)

Of particular note, the study found that "Failure flight testing is essential for evaluating a vehicle's post-failure dynamic behavior to determine if the aircraft tumbles or stabilizes in a predictable orientation while falling" (Arterburn, Olivares, Bolte, Prabhu, & Duma, 2019, p. 18). This highlights the fact that a UAV's behavior in failure is one of the most important factors that determines the level of danger created by that vehicle. A more dangerous drone might behave erratically during its fall, potentially with its propellers oriented downwards, while a safer drone might fall upright and possibly attempt to slow its decent. The recovery controllers that my capstone project team will develop will first attempt to fully recover after a failure, and if subsequently necessary, to crash in the least destructive or dangerous manner possible.

One piece of research that the capstone team hopes to incorporate into the fundamental controller deliverable is the characterization of vehicle failure based on measurements from the vehicle's internal sensors. The first step that a drone must take in order to recover from a failure is to determine the type of failure and resulting dynamic behavior of the system. For example, during a crash with a rigid object, the direction that the UAV rotates upon impact will have a significant effect upon how the recovery controller must respond. While much of the wider research is applicable both to internal hardware failures and to a drone in a crash, our research will focus upon the vehicle's behavior during a crash. Using the work of Tomić & Haddadin (2014), which proved the feasibility of sensing a collision and the resulting wrenching torque on the body of the UAV, we will attempt to react and recover from the event. By gathering a wealth of data from on-board sensors at the exact moment of impact, we can allow the UAV to respond in a manner directly applicable to the type of collision that has occurred.

The other major piece of research that shows promise for our application is a control scheme that is capable of flying a quadrotor, a UAV with four main propellers, without using one or two of the four rotors. As long as two of the diagonal rotors can still provide thrust, the research explains methods to continue flying and maintain full positioning control (Mueller & D'andrea, 2014). Because of the exposed nature of the rotors on a quadrotor, at least one of the four rotors are likely to be damaged or completely broken during a crash. Our capstone team will explore the possibility of quickly switching from a normal flight mode to a recovery-mode which may incorporate flight with a reduced number of rotors in the event that a propeller or motor is damaged. Such a control scheme could then control an otherwise uncontrollable mechanical system.

Integration into the national airspace in a manner safe for other aerial objects and people on the ground must be at the forefront of expanded use of UAVs. Through continued development of work in the field of quadrotor control, commercial UAV systems can be made significantly more robust. This capstone group will attempt to develop control schemes to further prove the feasibility of sustaining flight after a mid-air failure or at a minimum, to crash-land in a controlled manner.

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Because of the massive benefits to both consumers and participating companies, future commercial UAV delivery systems have the potential to drastically disrupt the logistics sector and associated industries. Most importantly, these systems are a revolutionary solution to the last-mile delivery problem. The last-mile of a delivery is the portion between the final hub of a network, such as a distribution center, and the delivery destination. Despite being a geographically small portion of a package's journey, it remains the most expensive and risky portion of a delivery. Because of their relatively low cost and automation, commercial UAV systems are a strong candidate to solve this problem. These benefits, as well as applications in other industries, have been recognized by the US government with the passing of the *FAA Modernization and Reform Act of 2012.* This legislation cemented government support for commercial UAVs and tasked the FAA with developing the necessary regulations and oversight, leading Jeff Bezos and Amazon to quickly pitch the novel idea of delivery by drone to the wider public (Olsen, 2017, p. 621). Despite delays in the regulation needed to achieve Amazon's vision, companies interested in the technology have continued to push the development of this technology, while also continuing to prepare the public for a future filled with drones. As demonstrated by UPS and their recently acquired approval to conduct human-operated, smallscale UAV deliveries, the work of these companies to slowly integrate UAV technology into everyday society has begun to pay off (Josephs, 2019). With support from the government's legislation and incentivization from significant business benefits, interested companies have been motivated to continue pushing this technology forward into society.

Despite many of the future benefits of commercial UAV systems, the relatively small sector of recreational UAVs has already displayed several problems that will become even more relevant for large numbers of commercial systems. Even with the large majority of growth occurring in this recreational sector, the US government recognizes that "Unmanned aircraft system (UAS) operations are growing at an exponential rate" (United States, 2018, p. 6). Unfortunately, such growth has come with serious issues such as small UAVs endangering commercial airlines and other vehicles. Several near misses of recreational drones with commercial flights, as well as an incident where a helicopter may have crashed while avoiding a drone, have exemplified initial issues with integration of this technology. Additionally, cases of intentional invasion of privacy by drone operators have demonstrated a need for legal reform and national statutes that are designed for citizens' privacy (Scharf, 2019). Similarly, the dangerous potential for UAV-operating companies to also collect significant data on citizens will present a significant regulatory challenge for the US government. Because of the risk of collision with other aerial vehicles, danger to people and property on the ground, and potential for violations of privacy rights, the process of integrating commercial UAVs into the national airspace will be fraught with complications and obstacles that the government and responsible companies must overcome.

Since the original suggestions for UAV delivery systems by Amazon and others, news and discussion within public media has taken on a feeling of technological determinism about the future of commercial drones. I argue that the content and delivery of these news stories are less about true technological determinism and more about companies that are determined to implement these systems. This is evident in that the narrative of these stories generally fail to discuss the important process of acceptance by society, regardless of whether they are discussing the benefits or the difficulties of such systems. In actuality, society as a whole must evaluate both the benefits and drawbacks that come with new technology in order to best integrate it into the future. These points were captured best by Emmanuel Mesthene when saying that the negative effects of technology that we criticize "are traceable less to some mystical autonomy presumed to lie in technology and much more to the autonomy that our economic and political institutions grant to individual decision making" (Mesthene, 1970, p. 40). In the case of this system, decision makers must include corporations, since the involved companies are also critical stakeholders. Only through the process of striking a balance between corporate stakeholders and the interests of the public can the FAA develop regulations that create a useful and robust system.

By analyzing the FAA's history of UAV regulation and their path towards national integration, I hope to discover and articulate the need for an effective and viable UAV system in the near future. Additionally, I will explore how companies will adequately prove the reliability, safety, and utility of their UAV services in order to have society accept such technology. My STS research paper will attempt to characterize the current and future directions of UAV integration and the trickle-down effects to the general public.

Conclusion

As UAV hardware, control theory, and the relevant public policy continue to evolve, both the delivery industry and the entire country may soon see dramatic changes coming to the national airspace. The technical portion of my thesis will build upon work from other research groups to advance the control of drones and improve safety and reliability by creating a robust recovery controller. For my STS research, I will develop a snapshot of evolving commercial drone systems and regulations and then investigate the steps that must be taken to realize socially acceptable UAV systems of the future. The completion and implementation of the failure-recovery control scheme into UAVs could directly reduce the number of injuries and the severity of damages resulting from a drone crash. By incorporating this technology, companies operating drones may drastically increase the safety of their fleets and much more easily meet safety regulations. As a result of this STS research, I hope to demystify much of the world that surrounds drone technology and help lawmakers and the public gain a useful understanding of the issues surrounding UAV integration into the national airspace.

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