Towards a New Paradigm of UAV Safety

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Abstract—With the rising popularity of UAVs in the civilian world, we are currently witnessing a paradigm shift in terms of operational safety of flying vehicles. Safe and ubiquitous human-system interaction shall remain the core requirement but those prescribed in general aviation are not adapted for UAVs. Yet we believe it is possible to leverage the specific aspects of unmanned aviation to meet acceptable safety requirements. We start this paper with by discussing the new operational context of civilian UAVs. We investigate the meaning of safety in light of this new context, keeping in mind the operational and economical constraints. Next, we explore the different approaches to ensuring system safety from an avionics point of view. It mostly consists in lowering failure occurrences and managing/leveraging them. Formal verification, redundancy and fault tolerant control are discussed and weighted against the high cost of current methods used in commercial aviation. Subsets of operational requirements such as geofencing or mechanical systems for termination or impact limitation can easily be implemented. These are presented with the goal of limiting the collateral damages of a system failure. We then present some experimental results regarding two of the major problems with UAVs. With actual impacts, we demonstrate how dangerous uncontrolled crashes can be. Furthermore, with the large number of runaway drone experiences during civilian operations, the risk is even higher as they can travel a long way before crashing. We provide data on such a case where the software controller is working, keeping the UAV in the air, but the operator is unable to actually control the system. It should be terminated! Finally, after having analyzed the context and some actual solutions, based on a minimal set of requirement and our own experience, we are proposing a simple mechanical based safety system. It unequivocally terminates the flight in the most efficient way. Our Active Cutting System instantly removes parts of the propellers leaving a minimal lifting surface. It takes advantage of what controllability may remain but with a deterministic ending: a definite landing.

INTRODUCTION

In 2013, the number of fatal accidents in the US was down to 236 for roughly 64 million general aviation flights. Although one should be proud of such a safety achievement, the challenges that tomorrow will face should be addressed in a timely and appropriate manner. Among these challenges includes the rapid growth of the civilian UAV market, a market that has enabled anyone who can spare a few hundred dollars to gain full access to the general aviation airspace.

In general aviation, accidents have always had a high level of fatalities of the people on-board (steadily around 20% for the past 30 years [1]). Hence, the reason for rigorous design and certifications processes. However, this level of requirements costs a lot in terms of development time and vehicle cost. For UAVs, the paradigm changes completely. With unmanned vehicles, the only potential casualties become the people on the ground. Since human life is at stake, these systems now become safety critical systems that should be certified, although the same level of certification as for general aviation would make them impractically expensive. Hence, new strategies should be devised in order to enable proper safety while meeting budget and design costs.

In the current state, the lack of safety measures included in current civilian UAVs is alarming. To begin, most civilian UAVs are composed of “hobby-grade” components repackaged into a shiny fuselage. Even though some efforts have been done to implement safety features like geofencing, the state of the art UAV remains very far from reaching the safe-to-crash paradigm.

This paper will focus on evaluating this paradigm change that shifts attention from crash-free, as it is in the general aviation, to safe-to-crash design for UAVs. Furthermore, a thorough study of vehicle design and procedures that embrace this new approach is included. The paper is organized by first discussing this new paradigm of UAV safety in the light of the present and future operational context, while defining some high level safety requirements that fit this new paradigm. Then, Focus is shifted towards hardware and software-based approaches for meeting these safety requirements. Lastly, an innovative hardware based feature is disclosed that enables the UAV to crash safely in the event of the common “runaway” drone situation.

I. A NEW OPERATIONAL CONTEXT

The potential applications of UAVs in the civilian community are numerous. However, safe and reliable UAVs can only be introduced if the acquisition and operational cost is low enough to be economically viable in today’s economy. If performance is the only cost function, it is easy to use low cost consumer electronics and have very cheap products. However, the balance between performance and safety on the other hand can come at a steep price. For general aviation, the cost of software validation has been observed to be as high as half of the entire development cost. Hence, the question becomes: How can we reach an equivalent level of safety, but at a significantly lower cost? To answer this question we need to understand the context in which UAVs evolve in while mapping out the safety requirements which will enable civilian applications.

Because no human being is on-board these systems, only people and infrastructures on the ground are endangered by flying UAVs. Therefore, the safety paradigm isn’t about avoiding crashes, but about avoiding crashing into civilians.
on the ground. This high level requirement then translates into rules concerning the vehicles and the rules concerning the operations. This two points are fundamentally coupled, and requirements on the vehicles cannot be decided independently of the mission flown.

In this section one can distinguish two general scenarios: 1) UAVs operating over civilians and infrastructures, or 2) UAVs flying in un-populated areas. In the current state of regulations, civilian UAVs are prohibited from flying over civilians and controlled airspace. Hence, leaving room for softer requirements for the vehicles in terms of quality and safety features. One could argue that it is a trust based scenario where one must trust a human pilot to follow the rules. Since strict training is not required to fly a UAV, human error often becomes the main cause for UAV disasters. Furthermore, due to the lack of presence of pilots on the UAV, it becomes more difficult to detect and react to failures. Therefore, it is believed that mandatory efforts should be made to embedded decision making features into avionics in order to ensure the enforcement of the rules at all times.

Since the safety requirements are strictly mission specific in UAV applications, it is important to understand the operational context each UAV will be subjected to in order to design a vehicle with the appropriate safety features. Having wings to glide to a safe area could for example be mandatory if flying over a crowd, whereas a kill switch, instead of wings, could be required when flying over un-populated fields to prevent the UAV from drifting into a nearby schoolyard in the event of a communication failure. In the end, a lot of safety enhancing features can be incorporated intelligently into UAV to reduce the risks and minimize the damage in the event of a failure.

As society continues to strive forward, the level of autonomy in UAVs will increase proportionally. Eventually, one can imagine reaching a state where operation becomes so complex and fast paced that we would reach the limits of humans capacity. Hence, a sole reliance on automated control algorithms. In order for this scenario to reach full maturity, a level of “automated safety” must evolve. In that futuristic but not fairy context, human-system interfaces will play an increasingly important role as pilots operate UAVs at higher levels of abstractions. Eventually, the range of the scale at which UAVs operate will be expanded, from advertising inside a mall to long range cargo transport. Therefore, the entire notion of airspace will require once again a revision in order to take these different scenarios into account where the dynamic nature of the interaction between UAVs, people and the environment become important. In the end, it is about this entire infrastructure that must be built around the emerging UAV market, and making this transition to a fully automated airspace will only be possible if safety is at the core of this revolution.

II. Safe-to-crash UAV design: An Avionics Perspective

A. Enforcing flight safety

As discussed in the introduction, automation can ensure the safe operation of a UAV. In practice, this means making sure it only flies in specific areas defined by the legislation or by the operator. In this context, the concept of geofencing becomes important. Similar to safety guards on interstates that prevent a car from deviating into the in-coming traffic, a geofence defines the operational “safe” regions of space. Although geofencing is commonly used by defining a safe-to-fly space using GPS coordinates, one can further define a safe sets on the entire state space of the vehicle as well as its flight envelope.

To address this problem, different ideas have been explored. A lot of them fall into the path-planning category. The idea is to compute a path in a known environment that gets the UAV to a desired position. This can be done by solving optimization problems [23] or using randomized algorithms [24], and if we now have the computational power to do that in real time, it is still difficult to get formal guarantees of safety [23]. But what happens when it is a human controlling the system as it is the case for most UAVs today? In that context, path planning algorithms fail to provide an operational solution. This is where an second kind of “obstacle avoidance” algorithm enter into play. The idea is to operate directly inside the control loops of the systems and enforce safety through real-time feedback. That way, the safety is assured independently of where the input comes from (human pilot or high level controller). Several methods can be used to realize this approach [25] and we are currently working on an optimization based solution to this problem [26, 30].

B. Managing failures

Detecting and managing faults on a UAV is a task that must be performed by the autopilot. Therefore, fault detection becomes an essential part of this type of safety-critical system. For years, several methods have been proposed for detecting possible issues in dynamic systems to anticipate the loss of functionality. Although most of these methods are more suitable for off-line fault detection tests [43, 31], the rapid evolution of digital computers and micro controllers over the past decade has enabled the implementation of online-fault-detection algorithms either through physical redundancies or software based algorithms [32, 33, 34].

1) Redundancies: Fault management through physical redundancies allow autopilot technology the reliability necessary to safely carry out sensitive flight missions by incorporating multiple autopilots into one device. An n-th redundant arrangement is comprised of n similar software and hardware systems. If any one of the n systems fails, the remaining n – 1 continue the operation. Note that an additional “voter” mechanism is also included to oversee
these systems. Although redundant autopilots are not new and well established within the aviation industry, military aircraft such as the RAF’s Trident fleet used a triple redundant autoland systems in the early 1960’s, and ten years later, the Aérospatiale-BAC Concorde took advantage of 3X technology in its flight control system, redundant autopilots are a relatively new addition to UAVs. MicroPilot®, one of the leading professional grade UAV autopilot manufacturers, set the benchmark for triple redundancy UAV autopilots when it launched the MP2128-3x at the end of 2010. Figure 1 illustrates this device. Since the autopilots do not have an individual casing, the overall weight and real estate added is kept to a minimum. However, the one major drawback in this case belongs to the financial set, since each one of these units retails for over $6,000 USD.

Figure 1. The MP2128-3X contains three MP2128-HELI2 autopilots [45]

Fortunately, high-end “hobby-grade” flight control boards are emerging with implemented redundancy features at significantly lower costs. For example, the Pixhawk [46] flight control board manufactured by 3D Robotics®, features advanced processor and sensor technology from ST Microelectronics® and a NuttX real-time operating system which delivers incredible performance, flexibility, and reliability for controlling any autonomous vehicle at a cost of $200 USD. It uses advanced algorithms in order to perform “sanity checks,” which compare data from different sensors and ignore figures that seem inaccurate. It contains a dual IMU system where an InvenSense MPU 6000 supplements ST Micro LSM303D accelerometer to provide redundancy and improve noise immunity of the power supplies. Furthermore, it is triple-redundant on the power supply if three power sources are supplied and will automatically switch in the event of failure.

2) Software Based Fault Management: As we have seen in the previous section, professional grade autopilots are often outside of a typical budget. Furthermore, depending on their size, they could have a significant effect on the performance of the vehicle and could decrease the payload the UAV can carry. One of the benefits of online software-based fault management is that it can be carried out at very little added computational cost without affecting the controlling algorithms. Software based fault detection and management provides analytical redundancies for monitoring the operation of the system, analyzing input-output data and comparing the result with the nominal behavior of the system. Some of these methods often go as far as isolating faults or even estimating their degree of severity [32, 33, 34]. Among various model-based fault detection methods, observer-based methods have been studied more than the others. They have been implemented in industry in the past for the monitoring safety-critical systems [35, 36]. Furthermore, a survey on those methods is included in [37]. One particularly simple software based fault management algorithm is the Unknown Input Observer (UIO). UIOs provide two important functional properties related to UAV safety: detecting and isolating faults. Arguably, the greatest benefit from this type of software-based fault detection and isolation algorithms is that it operates in open loop mode. Hence, it does not intrude nor affect the vehicle’s control law since it only uses the system’s inputs and outputs to perform its duties. Figure 2 illustrates that the system model required in model-based fault detection and isolation is the open-loop system model although we consider that the system is in the control loop. This is because the input and output information required in model-based fault detection and isolation is related to the open-loop system. Hence, it is not necessary to consider the controller in the design of a fault diagnosis scheme.

Figure 2. Open loop structure of a full-order unknown input observer [33]

C. Software Reliability and Validation

The operational requirements for UAVs require the adoption of advanced and intelligent control algorithms. In order to meet safety and operational demands, significant progress has been made towards the development of control and health management algorithms with features like dynamic programming, online learning and adaptation, self-tuning and reconfiguration. However, the use of these advance control algorithms is limited due to the fact that flight-certification of these systems requires that they undergo thorough Verification and Validation V&V to achieve high confidence in their safety. Unfortunately, the certification of these algorithms has proven to be sometimes impossible with the current state of the art V&V practices, not to mention the immense costs associated with such task. In the current state of V&V, certification is highly dependent on exhaustive testing from Monte-Carlo simulations to ensure proper functionality across the flight envelope. However, with the increase complexity of these algorithms, these methodologies for V&V become prohibitively costly and in some cases impossible at achieving a proper level of safety confidence. There are efforts underway to improve the practical applicability of design-time V&V.
approaches based on formal methods like theorem proving, model checking, to provide mathematical proof of the safe execution of highly complex advanced systems. The V&V of all these algorithms and their implementation could be similar to today's industry standards, but the associated costs should be measured against the overall UAV market value for the industry to remain competitive. Minimizing the cost of system certification via extensive process automation and component-based system safety evaluation are definitely two of the main challenges in this area. For example, changing a propeller should not void the safety certificate of the UAV.

1) Credible Autocoding: Simulations and real world practical tests on system are necessary. However, we can never test all possibilities for input signals and fault scenarios. In addition, the software might work slightly differently from what we expect in theory and based on original design specifications, due to the computational errors. To detect hidden bugs and errors we need to perform many tests. Still, the direct link between software operation and the original mathematical proofs is missing. This issue is more crucial for fault detection in safety-critical systems like UA Vs. In the light of evolving software certification requirements, it becomes important to formally specify the correctness of these algorithms.

One way of developing reliable software for safety-critical systems is by using formal methods, which are mathematically based languages, techniques, and tools for specifying and verifying such systems [38]. Static software analysis methods include “model checking”, “theorem proving” and “abstract interpretation”, where the latter can be sometimes interpreted as one instance of deductive software verification [39]. Credible autocoding becomes a complement to these methods as it focuses on software design and the ability to insert software semantics at design and coding time as opposed to a-posteriori semantics extraction. The semantics included in the code look very much like those found in deductive sequential software verification (See [39], Ch. 7).

A credible autocoding tool-chain prototype based on theorem proving approach had been built to automatically generate annotated control software and then verifying them [40, 41]. In [40, 41] the aim is to verify the stability of the controller and closed-loop system controlled by software. For that purpose, annotations are generated along with the control software so that the control software can be automatically analyzed by theorem proving tools. Invariant sets are chosen for system states based on Lyapunov theory. A theorem prover can check the validity of those invariant sets automatically provided that it is equipped with the necessary mathematical theories and strategies. If the sets are proved to be invariant by such theorem prover, the software is verified. Figure 3 illustrates the credible autocoding chain.

However, it is uncertain whether these methods will address all of the difficulties associated with achieving the necessary confidence in the use of these algorithms in safety-critical systems. In particular, algorithms that are adaptive, reconfigurable or non-deterministic in nature present the greatest challenge to design-time verification approaches. While there are also current and ongoing efforts to develop analytical proofs and stability/convergence guarantees for some of these algorithms, often the assurance results are deemed relatively weak and insufficient in meeting the stringent criteria for safety-critical purposes.

2) Run Time Assurance for Complex Autonomy: Since there exists a growing realization that no single V&V approach will be sufficient to address all of the challenges associated with providing safety guarantees for these advanced or complex systems, it is speculated among the community that run-time monitoring or run-time verification methods can play a complementary and enabling role [42]. The basic premise makes use of “monitors” to observe the execution of an uncertified algorithm in question to insure that resulting system behavior remains constrained within acceptable bounds of stability. A schematic of the run-time assurance methodology is illustrated through Figure 4.

In a run-time assurance framework, the primary advanced algorithm is responsible for achieving all performance objectives. These algorithms can be non-deterministic, adaptive, and enabled at all times under nominal conditions even though it is difficult to fully certify at design time. However, the backup system (Fail-Safe) hides in the background and is composed of a simplified control system with emphasis on safety rather than performance. It does not posses advanced features that are difficult and expensive to certify. Hence, this control law is certified at design time using state of the art traditional methods. The RTA monitor and transition
control continually monitors the overall state of the system, including critical parameters such as safety and operational limits, as it compares against validated representation of safe operating envelope. If a violation occurs, the transition controller disables the advance system and transfers control back to the backup system.

D. Security

One important issue with UAVs is that, not only should the systems be safe and reliable and the operators trained and respectful of the laws, regulations and common sense, but should also be protected against virtual “attacks”. It should be noted that these are also counter-measures that are being explored by the different security authorities around the globe as a way to control the threat that UAVs can represent.

Since they work on unlicensed bands and standard technologies it is quite easy to physically disrupt the communication channels used for controlling the drone or for its telemetry. This can lead to some sort of simple denial of services which will eventually cause the UAV to enter a safe mode (Return to Home, Hover, Land, Safe Crash...). Now someone can purposely cut the communications of a UAV. Depending on its fail-safe program, he could therefore be taking down the system, which would hover and eventually land, to grab its payload, or simply steal the expensive UAV. In our crowded “airwave” space, it would not require much to achieve such results. The RC world mitigates the “noise” issue with things like frequency/channel hopping or diversity, which copes with the natural growth of the number of objects flying at the same time and emitting simultaneously. The notion of coexistence as it was studied between WiFi and Bluetooth is a challenge if you extend the number of competing and incompatible technologies and users.

Of course, the use of Return to Home mode needs a working GPS. With the advances in cheap electronic (COTS), GPS scrambler units (even though they are illegal in some countries, we are not here considering people that abide the law) or Software Defined Radio, it is feasible to make the RTH difficult or impossible: the issue is eventually a crash or un-managed landing. The same goes with the use of cellular (3G/4G etc.) modems which could also be scrambled even thought their operating frequencies are licensed.

But with the use of general RC communication technologies or more domestic wireless ones such as Bluetooth or WiFi, or analog video, one could conduct more advances cyber attacks such as trying to gain access to the telemetry or the video feeds, getting data and even taking the control of part of the remote systems.

Examples of hijacking drones have been studied and published[21]. Even without having access to the embedded software, remote activation and destabilization could be the result of well thought fuzzing for example. The implementations of all the protocols used in these systems should be tested against such attacks.

It will eventually be necessary to protect the code running in the Ground Stations and in the UAVs. Since most of the Ground Stations are installed on more general systems (PCs, SmartPhones), they could be used as Trojans and leave backdoor to access the data and controls of the drone. When updating the firmware by downloading new ones from the internet, the same type of attacks could be performed. In the same principle as the one used to ensure that the controller of the UAV behave correctly, supervision could be used to monitor the software behavior of the controller, i.e for example the standard succession of system calls [27].

Recently, proof of concepts of very advanced attacks such as GPS spoofing have made the headlines [28, 29]. Using this, a UAV path could be diverted to any other location the attacker would want to. Regarding security and safety in general, the last important point is to develop forensic for the recovered drones and ground stations so that information such as proofs of wrongdoing and identification of the wrongdoers can be collected.

III. Safe-to-crash UAV design: A Mechanical Design Perspective

Up to this point, with the exception of redundant control boards, software-based approaches for making UAVs safer has been the focus of this article. As the avionics become increasingly involved, the cost of developing and maintaining overly complex software may reach its limit and become prohibitive. Furthermore, every effort related to V&V can only allow us to asymptotically converge to an ideal safety state, but the remaining tolerance has to be handled with intelligent system design of the vehicle itself. Hence, in some cases it may be more efficient to have simpler software combined with efficient safety features that are implemented at the hardware level. This approach is coherent with the current regulation mindset that tolerates crashes as long as they are safe for people on the ground. In what follows, several hardware solutions will be discussed that could be used for civilian UAVs, with special emphasis on the growing multi-rotors scene as they seem to be the most popular platform employed for commercial applications.

A. Reducing impact energy

As discussed earlier, the main safety requirement is about humans. Therefore, most safety specifications are based on potential injuries to the human body. As the head is naturally exposed to vehicles falling from the sky, blunt head trauma is one of the most likely injury that can have devastating short and long term effects [14]. Therefore, reducing the projectile impact energy, in this case the falling UAV, is the aim of this topic. The French regulatory agency, for example, limits the allowable impact energy to 69 Joules[12].

1) Parachutes: The most common device actually used for UAVs is the parachute. Since its popularization during WWI, this technology has matured and is now a relatively reliable
solution for slowing down objects. However, in order for a parachute to have time and open, a minimum flight altitude is required. If maximum altitudes are explicitly defined by most regulations, it is down to the operator to fly its UAV in order to assure the proper functioning of the device in order to limit impact energy. This is because most regulations prevent UAVs flights over populated area, but as we move forward, rules similar to general aviation will have to be put in place regarding flying over populated areas. These rules should integrate the recovery systems capabilities of current UAVs and maybe impose what type of technology to use. Predefined take-off and landing site may also be part of the solution to safely get to the minimum altitude.

Another critical component to parachute operation is its passive nature when it comes to wind. The highest it is deployed, the more uncertain the landing spot becomes[19]. This is true in the event of an engine jam at full throttle on a run-away UAV. Therefore, deploying the parachute as soon as possible may not be the best strategy. Furthermore, even if the parachute is deployed in the proper conditions and timing, there exists a significant number of ways in which the canopy and/or the lines can malfunction or get stuck on a fly-away drone whose attitude is not necessarily compatible with parachute deployment. Note that parachutes need to be inspected and re-folded regularly generating room for error, especially if this task is not performed by a professional. In the end, parachutes, if use correctly, can be efficient devices. However, due to the low tolerance for failure, imposing regulations on the technology itself seems necessary, as is the usage of complementary technologies to reduce the impact trauma on the surrounding civilians.

2) Lifting control surfaces: As we discussed previously, a major drawbacks for parachutes is the passive, often uncontrolled, nature of the fall. Controllable para-foils (or ram-air) can be used in exchange, but with the same other drawback of a parachutes. Therefore, the use of failure-dedicated control surfaces as an integrated part of the system becomes worthy of discussion. Such a device could allow a failed system to navigate away from a crowd and is likely to reduce the impact energy. A thorough investigation revealed that similar concepts have been developed in recent years[20]. Furthermore, it was noted that the real-state impact and weight associated could be kept at minimum on a classical multi-rotor.

In complement to control surfaces, a lifting component could be added to better slow down the fall. A similar concept made the dynamic stability of the Virgin Galactic SpaceShipTwo system possible. To conclude, the need for hybrid vehicles that combine wings and stationary flight capabilities is already present, and it is simply a matter of time before purely vertical flight UAVs such as the classical multi-rotors become a thing of the past.

3) Controlled disintegration: Parachutes and lifting surfaces mainly aim at lowering impact velocity, but it has been discussed that another way to minimize impact energy would be to reduce the UAVs mass through a controlled disintegration. Strategically destroying the vehicle is definitely not appropriate for general aviation where the safety of the people on board is the priority, but with UAVs it becomes a interesting and viable option. This option has been discussed in the distant but not antithetical context of asteroid deflection [5] where transforming a big mass into a cloud of smaller debris allows for a better dissipation of energy into the atmosphere.

If the explosion is quite dramatic for asteroid deflection (nuclear explosion!), it can be applied in a much more controlled and safe way for UAV. Polymer-bonded explosives (PBX for example, exhibit good strength and machining capabilities[7, 6]. This material could therefore be used for making specific parts of the vehicle to provide controlled destruction capabilities of the UAV. Sequential destruction strategies could then be thought of to intelligently reduce the vehicle into smaller pieces, possibly through a chain reaction as is done in building demolition[8] or rocket stage separation[9]. Despite they intimidating nature, pyrotechnics are now a well mastered technology that the general public is subjected to on a daily basis[11] and could very well play a major role in the UAVs of tomorrow.

B. Reducing impact force

Restricted kinematic energy at impact is necessary to minimize the risk of blunt trauma, but one must realize that it is definitely not enough to ensure the physical integrity of people on the ground. It doesn’t take much energy to create irreversible trauma in the case of impact of the human skull against a hard surface. As we can see in [4], it doesn’t take much either to perforate human flesh with a small UAV parts. The overall geometry of the vehicle is therefore fundamental in preventing fractures and penetrating trauma. Ducted fans and smooth structures (i.e. without protruding parts or with shells) could for example greatly reduce the likelihood of such injuries. Note that a real full scale UAV collision with a human dummy will be performed at Georgia Tech this summer to study the technical and legal repercussions of such an incident. Following this idea, we will discuss 3 solutions to reduce impact stress of crashing UAVs.

1) Airbags for UAVs: The automotive industry introduced airbags in the mid-1970s which has had a very positive impact on the reduction of accident casualties[15]. It is very efficient to absorb energy during a shock and reduce the impact force. Unsurprisingly, this technology is used to soften UAV landing when done via a parachute like for the Elbit Systems - Skylark II. Research has been done for this specific use of airbags[3] and companies are even developing dedicated products for UAV applications[2]. It is interesting to note that at the moment, airbags are only used to prevent damage to the vehicle, but could be a key player in protecting civilians as well. If asking everybody
to wear a personal airbag seems a bit out of proportion, even though it is not completely unimaginable[10], requiring that all UAVs carry an airbag system activated in case of emergency would make sense. Used in conjunction with energy reducing features, airbags may prove very efficient at minimizing human injuries, especially because of their very fast speed of deployment[16]. Note that the deployment trigger can obviously not be the impact itself like in cars, and that a preventive strategy is needed. Because of the deployment speed of such systems, the minimum altitude requirement is not as constrained as with the parachute.

2) Engine neutralization: As seen earlier in [4], propellers present with their sharp profile and fast rotating speed are an important danger for humans, even when the vehicle is not moving. To address this specific threat, several passive solutions can be implemented like ducted fans or protection shells [17]. Furthermore, active solution can also implemented in the same vain as controlled disintegration, were propellers could be jettisoned in case of emergency. This is particularly relevant in case of motor controller lockup. Through proper design, the jettisoned propellers could use their own shape to slow down their descent like maple keys falling from the trees. This way, the rotational energy of the propellers is reduced (because not attached to the rotor anymore) and they become much less harmful to people on the ground. One obvious problem with this approach is the fact that now you have a UAV free falling out of control. Also, motor brakes could be implemented on the same model as for [18] but specifically designed for electric motors. Again, such technology is relatively straight-forward and could potentially prevent severe injuries in the future (ocular trauma for example). Finally, intelligently cutting the propellers could be a great solution to maintain control of the vehicle while assuring it doesn’t have power to continue flying, hence get back to the ground in a controller descent... as we will see in subsection IV-C

3) Energy absorbing structures: Borrowing concepts from the automotive industry, energy absorbing structures is a key technology for minimizing trauma in case of collision. This is achieved through proper geometrical design and material choice, usually utilizing the various FEA analysis tools currently available. These tools allow engineers to precisely control the way structures will fail without relying on costly destructive testing, and for example chose the failure points to maximize plastic deformation and energy absorption during crash. Thanks to the recent rise of additive manufacturing technologies, intricate polymer or metallic structures can now be build with a single mouse click. Resistant and highly optimized structural elements can therefore be incorporated into UAVs like porous or composite parts (ref needed), that way providing good strength and energy absorption at the same time. Because these features are fundamentally passive and an integrant part of the vehicles structures, no complex electronic mechanism is required hence making them very reliable and relatively inexpensive compare to additional device like airbags of parachutes.

IV. CASE STUDY

A. Impact

As UAVs get more and more capable, their weights and sizes increase proportionally. The duality of these two factors not only represents the likelihood of a drone impacting with a human is increasing[13], but also the damage associated with such collision also increases. In the state of current regulations, UAV’s weights can legally range between 0.5 and 55 lbs. Any object within this mass range falling at proper velocity can cause serious injury to a human. Furthermore, as the head is naturally exposed to vehicles falling from the sky, blunt head trauma is one of the most likely types of injuries. According to Knight [44], a human skull can be fractured with forces as little as 73 Newtons, and with very high probabilities at forces exceeding 510 Newtons.

In the evaluation of crash data from one of Georgia Tech’s fast descent-recovery experiments, it was observed that crashes of a midsize recreational quad-copter with a mass of 2.5 kg (5.5 lbs) can involve accelerations exceeding 10 g’s, implying an impact force around 250 Newtons. Figure 5 illustrates the accelerometer data of an event in which a vehicle was not able to recover from a fast descent, ultimately crashing into the ground below.

![Fig. 5. Filtered IMU data from the Pixhawk control board](image)

It is noted that this is enough force to cause fractures to the skull approximately 50% of the time. Components such as plastic, fiberglass spars, and landing gear pieces were shown to contain enough energy to cause penetrating wounds when broken and can further increase that chances of a fatal impact.
Hence, it was concluded that an impact of this type can cause a variety of life threatening injuries to the human body. A concussion can be caused by accelerations of the head at 8.5 m/s². Evaluations of crash data show accelerations of upwards of 100 m/s² are very possible and a concussion from a drone strike like this is almost certain. Figure 6 illustrates the crash scene corresponding to the data shown in Figure 5. A video of this even can be found by clicking here.

![Forensics of a UAV crash](image)

The ability for UAVs to cause harm is not an argument against UAVs, but rather a reason and a framework for looking critically at UAV safety. By understanding the potential and magnitude for bodily harm UAVs can cause, the industry can work to reduce the likelihood of causing injury.

### B. Runaway

As the UAV industry continues its rapid growth, it struggles to overcome a major problem known among the enthusiastic community as “fly-away.” Fly-aways is a term used to describe a UAV that has gone wild and flown off from its user. They are one of several safety risks that the drone industry and aviation officials are aiming to solve. This problem has been around for many years now, dating back to a military-drone operation in 2010 who struggled with a 3K lb. unmanned helicopter as it glided autonomously for 30 minutes after a software glitch severed its connection to its U.S. Navy pilots. Furthermore, in October of 2015, U.S. Army pilots lost control of a hand-held drone over Columbus, Ga., telling air-traffic controllers the device was headed southwest and would run out of fuel in 40 minutes.

Technology has made UAVs cheaper and easier to fly, giving anyone who can spare a few hundred dollars access to small aircraft that can climb thousands of feet. UAVs can zoom off or drift away with the wind for a variety of reasons, including software glitches, bad GPS or compass data, connection errors between receivers and transmitters, or simple human error. Human error can occur due to either pilot inexperience or failure to properly calibrate the compass or configure its fail-safe functions.

Many incidents end with the devices barreling into homes, buildings, trees, bodies of water, and in some cases civilians. Ultimately, preventing fly-away drones either requires a fix in the core technology, or the introduction of innovative concepts. GPS and on-board compasses, used to help orient and stabilize the devices, can set drones adrift if tall buildings, cellphone towers or even solar flares interfere with their accuracy. Furthermore, electromagnetic interference, which many electrical systems emit, can also potentially disrupt the compass and the link between a drone and its controller. Therefore, a solution devised by this team of researchers will now be discussed in the following chapter.

### C. The Optimal Active Breaking Braking System: an innovative safety solution for UAVs

After having written in former paragraphs how we believe safety in the UAV should be considered and handled, we’ve tried ourselves to apply the minimum set that we deem
necessary. This led to the following requirements for a simple yet efficient solution to a safe termination of a flight, applied here to a multi-rotor:

1) It should react quickly  
2) This solution shouldn’t allow for an on flight or quick recovery: when it’s been activated, we can’t come back to a normal operation with a flip of a switch  
3) The system should give a chance to control the speed and the path of the descent, in order to limit the kinetic energy on impact, possibly keep it in a given attitude (no high speed spinning, flipping) and ideally to steer it away from people, animals or important objects

![Fig. 8. Propeller breaking tool, before and after actuation](image)

We came up with the Optimal Active Breaking Braking System. It is being prototyped and tested at the time of this writing, but a proof of concept has been developed. Each arm of a quadcopter is equipped with a servomotor that (very quickly) pushes a blade in the paths of the rotating propellers.

![Fig. 9. The OABBS system](image)

Its purpose is, when activated, to cleanly cut them to an optimized length that lowers the lift to a controlled descending speed, even at full throttle. This leaves enough propeller surface to still be able to guide the UAV in its landing, thus allowing to avoid people or structures on the ground if enough control is left of the system. Finally, the operator can’t just go back to work with this UAV, he has to change at least the propellers. A video of this system in action is provided by clicking here.

![Fig. 10. Clean cuts on different types of blade](image)

This could also work in cooperation with a smart parachute[22]: what’s left of maneuverability can ensure it’s deployed with an optimal attitude.

**Conclusion**

This paper discusses the safety paradigm differences separating commercial UAVs and General Aviation, placing strict emphasis in the fact that a UAV should be crash-safe by design. Suggestions on how to manage safety demands associated with regulatory agencies such as software Validation and Verification as well as security related issues are addressed from an avionics and mechanical design perspective. This perspective includes suggestions on how to make commercial UAVs a reality while maintaining software validation and verification costs in mind, which have the potential to cripple the entire UAV revolution. Furthermore, a mechanical design perspective explores several solutions on how one can reduce the danger associated with failed devices from a design perspective, with special emphasis on reducing impact energy. Lastly, a case study, using real crash data from the Afman Aeromechanics Laboratory at Georgia Tech, evaluates the energy of an impact and suggests a novel mechanical solution that is introduced in this paper for the first time. This novel device aims at tackling the single biggest issue encountered by UAV pilots to date, safely landing a run away UAV.

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