Towards a new paradigm of UAV safety

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***Abstract*—In 2013 in the US, the number of fatal accidents was only 236 for roughly 64 million flights. One can be proud of such an achievement, only if the challenges of tomorrow are addressed in a timely and appropriate manner. Among these challenges, the explosion of the civilian UAV market and the possibility for virtually anyone to access the sky poses safety problems never encountered before. The current airspace will have to adapt to this paradigm shift, where people do not operate from inside the vehicle but from the ground or some other location: safe and ubiquitous human-system interaction remains the core requirement. Although system safety requirements, as they are currently performed in aviation may appear to be overly strict for UAVs, we believe it is possible to leverage the specific aspects of unmanned aviation to meet such requirements. For example, the fact that human operators stand outside the vehicle completely redefining the requirements and operational constraints for UAVs.**

In this paper, we begin by analyzing the operational and safety issues arising from the growing usage of UAV in the civilian airspace. This then leads us to discussing the safety requirements arising from this new paradigm. By definition, safety is inherently an implicit property of any given system. Therefore, it becomes an important challenge to explicitly define what it means for a system to be safe, and to explore the entire range of safety-enhancing mechanisms. While self-destruction may not be an attractive concept for a traditional airplane, it may become a totally reasonable approach in the context of UAVs.

Next, we explore the new range of approaches to ensuring system safety from a vehicle-centric viewpoint. Considering hardware first, no real requirements or tests are currently conducted to assess the quality of the entire system and its parts. Hardware redundancy for safety-critical functions is largely lacking in commercial products , although it may be an important part of a safe unmanned solution. Dynamic sets of requirements (geographic flight restrictions and flight envelope protection for example) involve making decisions in real time. This decision process relies on the ability for the vehicle to determine its full state, or at least a critical part of it, including full knowledge of failed components. To achieve that goal, sensors play a fundamental role, especially since remote human presence make it more difficult for the pilot/operator to detect a failure on the vehicle using "seed of the pants". The question is then: which sensors should be mandatory? An interesting approach to determining vehicle state, including failure modes, is the development of analytic redundancy via online state estimation, as it allows to get information on the full vehicle state without full-state sensing. Such safety-enhancing features come at a cost in terms of needed accuracy and computational resources, and it will be interesting to quantitatively determine the trade-offs in terms of weight, cost, performances, computational load between direct sensing and state estimation for equivalent safety levels.

The foregoing leads this paper directly to software considerations. As safety requirements for UAVs differ from those applied to conventional aviation, they open the door to develop previously unexplored control algorithms and decision making strategies. For example, a vehicle crash is no longer necessarily catastrophic if its effects can be mitigated by good vehicle guidance and appropriate operational constraints. Such constraints may include enforcing operational altitude minima allowing a vehicle to glide out of trouble in case of engine failure, for example. Geofencing and damage-tolerant control are other examples of software-enabled, safety-enhancing features. The Verification and Validation (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. Changing a propeller should not void the safety certificate for the entire craft, as long as the concept of equivalent level of safety, currently in use by manned aviation, can be extended to unmanned aviation.

The outcome of this paper will be a detailed set of recommendations for the development of safe unmanned vehicles. These recommendations will be applied to a prototype unmanned system currently under development at Georgia Tech.

INTRODUCTION

Paradigm shift from fault-free to fault-tolerant design

Raise awareness on the fact that the state of UAV safety is catastrophic and solutions are within our reach.

Advertising for NASA crash project

Systems engineering approach

Outline of the article

I. A NEW OPERATIONAL CONTEXT

This new civilian UAV market is based on giving cheap and easy access to the sky to virtually anyone.

What it means for the hardware

Heterogeneity of the sky. How do we integrate UAV to general aviation. Maybe we merge?

What it means for the people (from pilots to operators).

At the moment it is mostly RPAS, but what about fully automated systems? Who becomes responsible? Manufacturer?

UAVs operate at a much smaller scale than general aviation (5th element the movie). We will have to build a new definition of airspace build around a complex an dynamic environment where people and infrastructure are the main safety issue.

Its not just about the UAVs but about the entire UAS built around the UAVs.

From autopilots following orders to fully aware systems capable of making decisions on the fly. Safer than humans?

II. Smart avionics

A. Preventing crash

1) Basic rules: Min alti (helicopter auto-rotation)

2) Geofencing: Safety nets.

Barrier functions.

3) Automated traffic management: Coexistence of general aviation and UAVs.

B. Managing failures

1) Electronics redundancy:

2) Online state estimation: Extracting information about the vehicle without relying on costly and sometimes heavy sensors.

Because pilots are not in the vehicle anymore, detecting problems and failures has to be done automatically, and that we can be smarter than loading the vehicle with sensor by doing some online fault detection through indirect sensing. And that we can then have a smart failure management system.

3) Alternative guidance laws: It is not about performance at this stage. Primal control capabilities could potentially make the difference between life and death.

Is auto-rotation relevant?

F18 without wing[22].

C. Software reliability and modularity

The Verification and Validation (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. Changing a propeller should not void the safety certificate for the entire craft, as long as the concept of equivalent level of safety, currently in use by manned aviation, can be extended to unmanned aviation.

III. Fault tolerant UAV design

As of now, we have only talked about software based approaches for making UAVs safer. As we said earlier, as the avionics becomes more and more involved the cost of developing and maintaining overly complex software might become prohibitive. And even if we were capable of efficiently developing arbitrarily complex avionics, it is ludicrous to think that we could achieve an absolute zero crash state. All our efforts in terms of V&V could only allow us to asymptotically converge to this ideal state but the remaining epsilon has to be handled with intelligent system design of the vehicle itself. In the end, it may be more efficient to have simpler software combined with efficient safety features 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 this section, we will discuss several hardware solutions that could be used for civilian UAVs, mainly of the multi-rotors type as they seems to be the most popular platform currently used.

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 [15]. Therefore, reducing the projectile (in this case the falling UAV) impact energy is the most natural thing to do. The french regulation for example limits this impact energy to 69J[13].

1) Parachutes: The most common device actually used for UAVs is the parachute. Since its popularization during the first world war, the parachute technology has had time to mature and is now a relatively reliable solution for slowing down objects. However, in order for the 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 flight its UAV in order to assure the proper functioning of its 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 flight over populated areas. These rules will have to 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 the parachute is deployed, the more uncertain the landing spot becomes[20]. This is even more true of an engine happens to get jammed at full throttle. Therefore, deploying the parachute as soon as possible may not be the best strategy. And even if the parachute is deployed at the right time, there is still a significant number of ways the canopy and the lines can malfunction. Many skydivers die each years because of such malfunctions, usually because of improper folding of the canopy. Note that parachutes needs to be inspected and refolded regularly opening one more door for errors, especially if not done by professionals. Finally, if everything works as planed and the parachute allows the UAV to slow fall to the ground, there is still a lot of safety issues arising from the shock itself that we will discuss later in this article.

In the end, parachutes, if use correctly, can be efficient devices. However, because there is so much room for errors, imposing regulations on the technology itself seems necessary, as is the usage of complementary technologies to reduce the impact trauma on humans.

2) Lifting control surfaces: As we discussed previously, one of the drawbacks for parachutes is the passive nature of the fall. Controllable parafoils (or ram-air) can be used but with the same drawback as for parachutes. Therefore, it is natural to think about using dedicated fully rigid control surfaces as an integrant part of the structure. In the end, what really matter is that UAVs don't hit anyone, so trading off lower impact energy for better control has to be considered. This concept already exists[21] and it wouldn't take much space and weight to implement on classical multi-rotors.

In complement to control surfaces, a lifting component could be added to better slow down the fall, and possibly stabilize a vehicle that would have entered an uncontrolled spinning state for example. Similar concept have already been tested (e.g. Virgin Galactic SpaceShipTwo) and even purely passive designs could be effective enough to slow down the fall to acceptable speeds.

In the end, the need for hybrid vehicles that combine wings and stationary flight capabilities is already there, and it is just a matter of time before purely vertical flight vehicles become replaced. Not only will this have a significant impact on UAVs performances, but it will also contribute to making these machines safer by having fundamentally redundant flying capabilities.

3) Controlled disintegration: The two previous solutions were mainly aiming at lowering terminal velocity, but one could also try and reduce the terminal kinematic energy by playing with the other term of the equation i.e. mass. 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 [6] 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[8, 7]. 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 though of to intelligently reduce the vehicle into smaller pieces, possibly through a chain reaction as is done in building demolition[9] or rocket stage separation[10]. Despite they intimidating nature, pyrotechnics are now a well mastered technology that the general public is subjected to on a daily basis[12] (e.g. airbags and seat belts). It 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 [5], 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: If we look at the automotive industry, the introduction of airbags in the mid-1970s has had a very positive impact on the reduction of accident casualties[16]. It is a very efficient mechanism to absorb energy during a shock and reduce the impact force. It is therefore not as surprise to see this technology 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 product for UAV applications[2]. It is interesting to note that at the moment, airbags are only used to prevent damage to the vehicle! But what about people? If asking everybody to wear a personal airbag seems a bit out of proportion, even though it is not completely unimaginable[11], requiring that all UAVs carry an airbag system that would activated in case of emergency would make a lot of sense. Used in conjunction with energy reducing features, airbags could be prove to be very efficient at minimizing human injuries, especially because of their very fast speed of deployment[17]. Note that the deployment trigger can obviously not be the impact itself like in cars, and that a preventive triggering strategy needs to be put in place. Because of the deployment speed of such systems, the minimum altitude requirement is much better than for parachutes for example.

2) Propellers brake or jettison: As seen earlier in [5], propellers present an important danger for humans. Their sharp profile and fast rotating speed makes them dangerous even though the vehicle is not moving. To address this specific threat, several passive solutions can be implemented like ducted fans or protection shells [18]. Furthermore, active solution can also implemented in the vain of section 3.1.3 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. Finally, motor brakes could be implemented on the same model as for [19] 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).

3) Energy absorbing structures: Learning again 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 also 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.

Acknowledgment

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