Future Trends in UAS Avionics

Bálint Vanek

MTA SZTAKI, Hungary, vanek@sztaki.hu

Abstract: The emerging role of Unmanned Aerial Systems (UAS) for both military and civil operations depends on the ability to gain unrestricted access to national airspace. One of the key issues that must be resolved to open up the skies for UAS is to be able to coexist safely and effectively with current manned operations in the national and international airspace. This includes several functions all related to avionics. Future UAS systems will perform autonomous mission management, contingency management, collision avoidance, inteligent system health monitoring based on a reliable flight control system platform.

Keywords: UAS, avionics, navigation, guidance, control, fly-by-wire

1 Introduction

It is foreseen that the UAS industry will significantly increase in the next decade, if the UAVs can routinely access the national airspace. Historically, industry has often been guilty of being unrealistically optimistic in predicting the rapid emergence of a viable civil and commercial UAV market, but has also played an effective advocacy role in driving initiatives in the area. It is evident that the potential of the civilian market is considerably larger than the military sector, although there are presently major constraints on this market emerging. The lack of a central procurement authority, the absence of legislation and regulations for safe flight in integrated airspace, combined with a diffuse potential customer base has meant that initiatives in the use of UAVs in nonmilitary applications have been relatively un-coordinated and ad-hoc in nature. Work has began in earnest to kick-start a market through a number of initiatives, mainly coordinated by SC-203 in US and by WG-73 of EU.

There are several current and potential applications where unmanned vehicles can provide cost advantages and safety improvements and even fulfill jobs previously not possible for manned operations. To name a few future UAS platforms in military: agile UAVs (UCAV/URAV), solar powered stratospheric platforms for very long endurance, small UAV tactical transport (VTOL/STOL) to support frontline troops, replacing dull-dirty-dangerous jobs will emerge in the near future. Parallel with the military evolution civil applications are also waiting to emerge: low/medium altitude UAS for pipeline/power line surveillance, fishery/border patrol, environmental monitoring, traffic monitoring, agricultural use,etc. Solar powered stratospheric platforms for data relay, various monitoring tasks and single/zero pilot freighters are all potential fields.

A whole range of legislative and regulatory measures needs to be designed, mutually agreed, then drawn up and implemented before these UAS can enter the commercial airspace. These rules will in turn be founded upon certain essential technologies, the most notable being a reliable, light, low-power and cost-effective Sense and Avoid (S&A) system, which would eliminate the possibility of a mid-air collision between aircraft: manned or unmanned.

The benchmark, or goal towards which legislators and industry alike are striving is that UAVs should be able to operate at an Equivalent Level of Safety to manned aircraft. Meanwhile UAVs are required to fly either in segregated airspace or, if they need access to controlled airspace, they usually have to obtain an ad hoc ‘Exemption’ from their local Aviation Authority. At the moment, rules vary from one country to another, an incoherence which makes things more difficult for manufacturers and operators alike: hence the slow rate of progress towards a unified framework.

Many of the technical elements needed for such a system already exist. Autonomy and predictability are key attributes of sophisticated UAS’ avionics, enabled through redundancy and reliability within architecture. It is the integration of these components into a fully-functional and commercially viable device – within severe space and weight restrictions – that is the challenge. It is predicted that a solution will be ready by 2015.

2 Technical Gaps in UAS Avionics

A report by NASA [1] identified the key technological needs before the autonomous unmanned vehicles can enter the non-segregated airspace. They are as follows:

- Autonomous mission management
- Contingency management
- Collision avoidance
- Inteligent system health monitoring
- Reliable flight control systems

These goals can be solved with current technology but their cost would be prohibitive for widespread civilian use. Hence main technological enablers, redundant flight control systems, high performance navigation, advanced flight controls, sense-and-avoid systems has to be made affordable and integrated in a model based design framework aiming towards certification.

2.1 Redundant Flight Control Systems

If you consider a fly-by-wire aircraft, like the Boeing 777 [3] it has triple redundant flight control system with enormous amount of complexity and million lines of software code to make sure all redundancy management is handled within the complex network. It is estimated that 30% of software code is related to control laws, 60% to redundancy management and 10% to contionuous built-in-tests. It is not straight forward how to simplify such a system which can serve all purposes of a UAS flight control system. A bottom-up approach would be more favorable to pursue, but currently there is almost a complete lack of experience in “low-cost” FBW system design. With the exeption of the Global Hawk and Predator airplanes the current UAV fleet employs single threaded architectures with no reconfiguration schemes in place. The few examples currently in operation, like the one on Figure 1 (Global Hawk) are expensive, but have the potential to be extended to lower cost platforms.

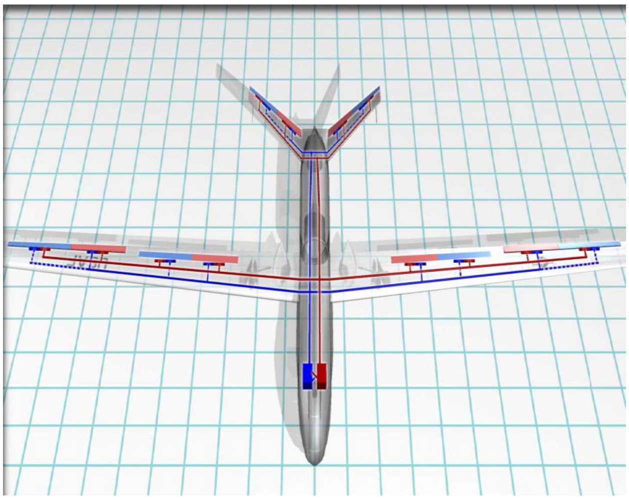

Figure 1
Global Hawk FBW architecture

The system employs 2 Flight Computers (IMMC) which are Frame Synchronized and have Cross Strapped Inputs. They are communicating via 2 Flight Critical Buses. The navigation units are also doubled with 2 Pitot Static Air Data Systems, 2 Air Data Management Systems, 2 Control Surfaces instead of the conventional aileron, elevator, rudder layout, with each flight control actuator being dual-redundant, both on the motor and on the electronics. Redundant electric brakes are also used. The navigation and control is based on 2 Primary IMU and 2 GPS aided INS systems plus 2 back-up GPS INS units in the payload. DGPS sources are also doubled, and even in the presence of all those landing is aided with 2 radio altimeters. 2 FADEC systems are controlling the engine. Since the whole architecture depends heavily on electricity 3 electrical generators (DC & 2X AC) and a Li Ion battery backup for engine out recovery are in place to provide uninterrupted service for the systems. The major consesnsus about future UAS avionics is that they will use Integrated Modular Avionics (IMA) architecture.

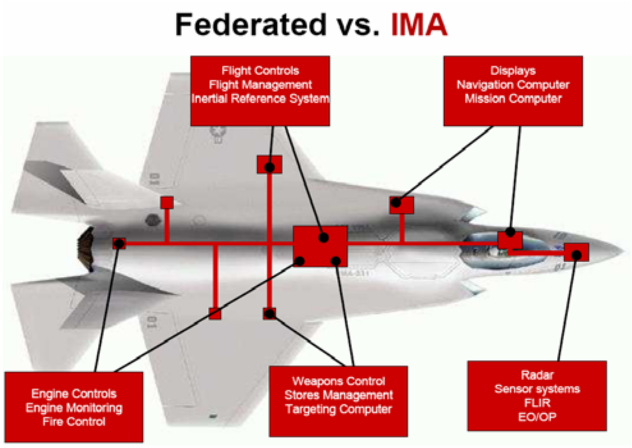

Figure 2
IMA architecture

Traditional aircraft computer systems are federated, with each system provided on a number of dedicated hardware units. Federated applications are physically separated from one another and analysis of the systems is undertaken individually. However, the aviation industry is moving towards the use of a common computing platform known as Integrated Modular Avionics (IMA). A full IMA system comprises of a number of computing modules communicating over a shared network. The basic platform supplies operating system services such as scheduling to applications running on the system. These applications may be spread across many modules and hence are not physically separated from one another. The IMA platform supplies mechanisms to ensure resources can be shared safely. The IMA concepts developed are based on the principles of modular systems, open systems and COTS. In an IMA architecture, the computing capacity is concentrated into a 'Core', which consists of interchangeable processing modules of a limited number of standardised types, particularly for data, signal and graphics processing. IMA systems provide a high level of technology transparency by being based on a set of open standardised interfaces, so facilitating the replacement of hardware components without affecting the application software. In addition, the use of open standardised interfaces directly supports the use of COTS components, which is of great benefit in combating the effects of component obsolescence. IMA systems also implement fault tolerance, so that when a module becomes defective, the system reconfigures and a spare module takes over the functionality of the failed module. A major advantage of IMA architecture for UAS is that changes in the onboard software require minimal recertification and different vendors can access the core with standard interfaces. Moreover, once an application is developed, it can be reused with minor modification on a different platform.

2.2 Affordable, Reliable Navigation

Reduction in sensor cost also generally brings about a reduction in sensor accuracy and reliability. Coupled with the generally high mission dynamics that UAS vehicles undertake within civilian aerospace due to the restricted mission areas, ensures that the design and implementation of these sensors is an extremely challenging area.

More importantly, the implementation of low cost sensors which are used for the Guidance, Navigation and Control (GNC) of the aerial vehicle is where most interest lies although little research is done. When applying a low cost Inertial Measurement Unit (IMU) there are still a number of challenges which the designer has to face. The main restrictions are the stability of the Inertial Navigation System (INS) degraded by the inertial sensor drifts. The quality and integrity of aiding sensors is also the crucial factor for the integrated system.

The Global Positioning System (GPS) can provide long term stability with high accuracy. It also provides worldwide coverage in any weather condition. As a result lots of research have been done to optimally blend the GPS and INS [5].

Since the performance of the low cost GPS receiver can be easily degraded in high maneuvering environments, the quality and integrity of the GPS system becomes also a crucial factor. In case of GPS outage or fault conditions, the stand-alone

INS quality then becomes the dominate factor. If the cost is a prohibitive factor in developing or buying an IMU, then improvements in algorithms, and/or fusing the navigation data with other sensors is required.

When considering a flexible way for navigation solutions for multiple UAS platforms a common sensor fusion core algorithm is preferred: heterogeneous sources in a modular way can be included with different fidelity, different update rates. It is foreseen that sensors will be plug-and-play to increase accuracy.

Built in test and health monitoring (hardware and analytical redundancy) will be developed, based on parallel and dissimilar sources. With satelite augmentation systems like WAAS/EGNOS the integrity of the GNSS signal can be monitored and it can be used for safety related tasks.

One of the most promissing applications is multi antenna attitude determination, since attitude determination is cruical for both flight controls and for payload positioning. The main idea of the system can be seen on Figure 3. Two receivers detect the same GPS satellite, both of them tracking the phase of the signal. Phase differences can be used to determine the angle of the line defined by the 2 receivers. The only problem is the so-called integer ambiguity (the number of full cycles between the satellite and the receivers). When the integer ambiguity is resolved based on the known baseline between the two antennas, the angle relative to the satelite line-of-sight can be calculated. Attitude determination is, in a nutshell, a modification of very short baseline carrier-phase DGPS processing with geometric constraints on the relative positions of antennas.

A typical setup for GPS-based attitude determination includes 2, 3, or 4 independent GPS receivers connected to a set of antennas firmly affixed to a vehicle.

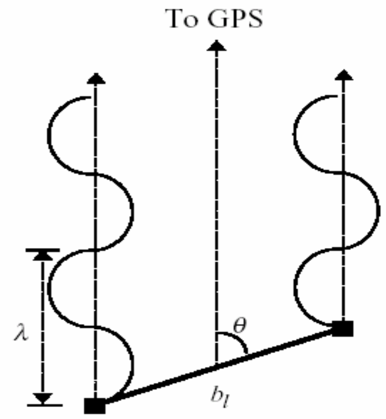

Figure 3
Carrier phase difference based attitude determination

Another approach getting wide acceptance is GPS/INS Tight integration.

Tight INS/GNSS architecture, as defined in [5], is illustrated in Figure 4. In this architecture, the INS and GNSS are reduced to their basic sensor functions. That is, pseudorange, pseudorange rate , accelerations, and gyro measurements are used to generate a single blended navigation solution.

It allows better tracking, higher accuracy and propagate position solution even with less than 4 satellites. The error characteristics of an INS and GNSS are complementary. When the information from INS and GNSS are fused, the high-fidelity GNSS position and velocity estimates are used to calibrate the INS sensor errors. The INS, in turn, provides the high bandwidth attitude, position, and velocity estimates needed for vehicle guidance and control. The INS estimates also allow coasting through momentary drop-outs of the GNSS solution, which can result from signal blockage caused by obstructions between the GNSS antennas and the satellites. Yet another way the INS information can be used is to help increase the robustness of GNSS receivers to jamming or radio frequency interference (RFI). This involves using INS information to aid the signal processing algorithms inside a GNSS receiver.

In summary, note that the key feature of loose integration is that both the INS and GNSS receiver are independent navigators. The information from the two navigator s is blended to form a third navigation solution.

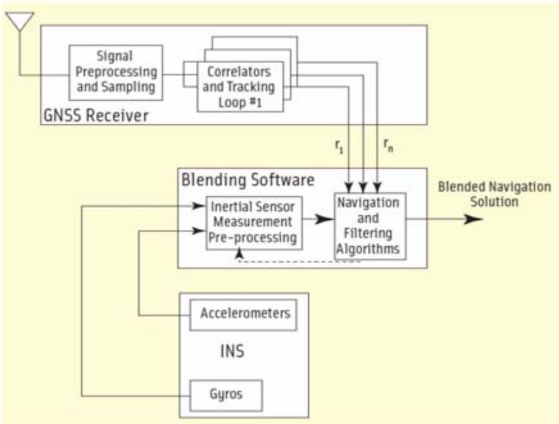

Figure 4
GPS INS Tight integration

2.3 Advanced, Certifiable Flight Controls

It is easy to see that future UAS will need more autonomy then current systems, since increased flight safety, simpler operation, lower operating costs are required. All flight phases, including take-off, landing, in-flight emergency procedures have to be handled by the flight control system. For this purpose robust, model based flight control laws with high SW reuse will be developed. This will shorter their development cycle and provide a uniform framework, which needs minimum customization to the various platforms. Nonlinear and adaptive methods are getting wider acceptance, like on the Boeing X-45 UCAV, where the control gains are adaptively tuned to achieve better handling qualities without extensive tuning and simulation analysis.

The state-of-art in flight control law certification is to grid the flight envelope and apply linear gain/phase robustness analysis. The continuous time design, is implemented discretized on an 8-bit FPGA. Extensive Monte-Carlo simulations are used to ensure the linear results match the nonlinear response. The shortfalls are: these methods are not suitable to cope with hybrid and adaptive systems, they are very hard to extend to more complex systems. It becomes more pressing when an UAV flies without a pilot onboard in the common airspace. The control design requires good understanding of the A/C model, configurations failure modes, flight conditions, hence a model based systematic procedure to cover all possibilities is required.

Reconfigurable control is another emerging area, which coupled with fault detection and isolation can provide the high reliability figures required by the aviation authorities. The advantages of fault tolerant control become evident if you consider the UAV flight control system problem. Triple redundancy probably too heavy for a small UAV, while double redundancy in its pure form is not safe enough. Hardware redundancy can be reduced by using software redundancy based on Vehicle Health Monitoring (VHM) and model based Fault Detection and Isolation (FDI) approach to provide background for reconfigurable control ideas. Controller reconfiguration can be used to improve system reliability without additional physical redundancy. Control law has to accommodate a failed control surface and redistribute the control effort among the remaining working surfaces to retain satisfactory stability and performance.

Consider the example of a UAV with four surfaces driven by servos with a MTBF of 7000 hours.

Approach 1: Use *dual* servos on each surface with *no* control reconfiguration. The reliability of a single surface (i.e. a *pair of servos*) assuming a coverage factor of 0.99 (optimistic) is ~1.4e-6 failures/hour. With no controller reconfiguration, all four surfaces are required for flight. Reliability is ~5.8e-6 failures/hour.

Approach 2: Use *single* servos on each surface with control *reconfiguration.* The reliability of a *single surface* is 1/7000hrs~1.4e-4 failures/hour. Assume the controller can be reconfigured to fly with only three of the four surfaces. Reliability doubles to 1.2e-7 failures/hour.

2.4 Sense and Avoid System

Mid-air collision avoidance can be divided into two parts. The first part is involved with ensuring appropriate separation of aircraft, which is achieved via procedural rules and ATC instruction as shown in **Error! Reference source not found.**, but does not apply to all aircraft and airspace classes. The second part is involved with actually avoiding a collision in the case of inadequate separation. This entails systems like the TCAS-II and ADS-B as well as the FAR-mandated ‘‘see and avoid’’ requirement. Collision avoidance in manned aviation is achieved through various mechanisms that build additional layers of security to minimize the probability of collision. The first layer, cooperative collision avoidance, is currently realized through the ADS-B system. This system operates by broadcasting the current location and vector of the aircraft to other aircraft in the area. Although this system offers superior deconfliction, it may fail even if one aircraft in the area is not equipped with it. Since it is currently in the very early stages of adoption, its effectiveness is greatly reduced. Significant modifications would be required to successfully use the system in UAS due to the differences in aircraft characteristics and the nature of possible collisions. Based on current regulations, it can be expected that for the foreseeable future UAS collision avoidance cannot depend exclusively on either the ADS-B or the TCAS. This is because there will be airspace users that will not be equipped with any of these systems. A change in current regulation is also unlikely, since UAS integration in the NAS should be possible with current ATM systems and not incur any cost to current airspace users. Furthermore, these systems are not capable of terrain and other obstacle, like birds and powerline, avoidance. Thus, the requirement for sense and avoid capabilities becomes apparent.

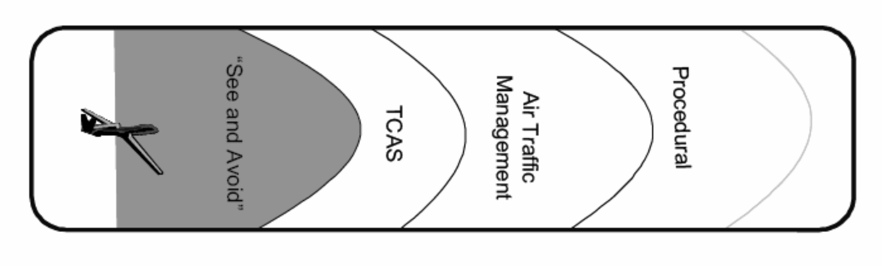

Figure 5
Layers of safety in the airspace

SAA capability is currently required from all aircraft operating in the NAS. A SAA system installed on a UAS should be capable of operating under various weather conditions and situations and, as autonomy increases, with limited operator involvement. This entails information fusion from multiple sensors. SAA sensor research has investigated electro-optical, acoustic and microwave sensors. When combined, these sensors offer unique characteristics that enable a UAS to detect and in some cases track one or more targets in difficult conditions like fog, glare or darkness. In technology demonstrations SAA systems were able to surpass human pilots in detecting approaching aircraft from greater distances. Although successful demonstrations of various SAA systems have been made, extensive simulations and field testing are required to evaluate their performance under various conditions and collision scenarios, before they can be used in civilian applications.

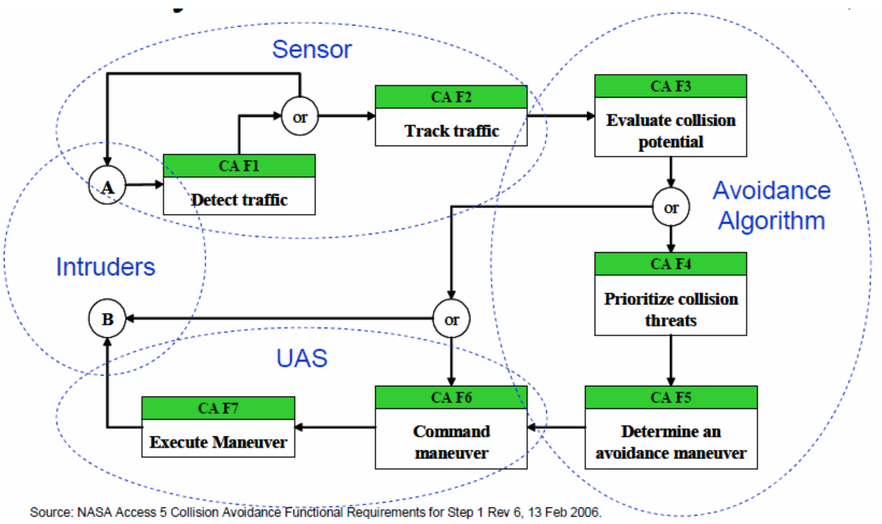

Figure 6
SAA System Functions

Non-cooperative collision avoidance technologies are independent of target aircraft equipage, they are self-contained systems, which are also more analogous to human "seeing". But their accuracy/integrity is still in question. They also have physical limitations to detecting targets/obstacles. One key attribute is the false/missed detection rate is critical to effectiveness. Since one single sensor is not likely to provide all the required information, a suite of technologies (i.e., sensors) is likely to be needed. There are currently no solutions or standards available for the non-cooperative SAA problem, since legislation is waiting for an industrial solution which can serve as a baseline for the certification procedure, but the industry is reluctant to develop a system without clear certification and performance objectives. For this reason weight, power and cost of aggregate solution is unknown, but it is likely that the first SAA solutions will appear on Medium Altitude Long Endurance (MALE) and High Altitude Long Endurance (HALE) UAS, like Predator and Global Hawk, and later migrate to tactical, mini and micro vehicles.

The consecutive SAA system tasks, show in Figure 6

SAA System Functionscan be divided into three different groups: detection and tracking is related to sensor technology where a clear trade-off between sensor types and detection range and accuracy can be seen. The most probable candidate sensor types suitable for UAS SAA all have weaknesses. Range cannot be directly sensed with optical and thermal sensors, Laser/LIDAR and acoustic sensors have limited range, while radars are heavy, expensive and have low update rate – they can be used only on large UAS where multifunctional radar provides weather, surveillance and collision avoidance at the same time. Sensor information from different sources has to be fused to estimate the trajectory of the encountering traffic. It is a non-trivial task since the intent of the other vehicles is unknown and only estimates can be given with certain probabilities about their future path. Techniques like unknown input observers can predict future intent of the encountering traffic, while novel sensor processing algorithms have to extract information about potential encountering airplanes.

The second step in Figure 6

SAA System Functions addresses the collision avoidance algorithm. It is composed of decision making about the collision potential, based on the traffic estimates and the predicted path of the vehicle. Then in case of multiple threats they are prioritized based on the consequences and risks associated with each of them. The avoidance maneuver is determined based on multiple objectives. The avoidance maneuver has to provide maximum safety while it is desirable to keep the interruption of all flight routes to minimal while complying with the constraints of air traffic rules. Different approaches, like pursuit evasion games, have been proposed to provide optimal conflict resolution.

The last part of SAA system functions is the execution of the commanded maneuver. The onboard guidance, navigation and control system has to be able to follow the proposed trajectory with sufficient precision, unless the avoidance maneuver would not satisfy the calculated separation figures. It is often the case, that the guidance and control system is coupled with the surveillance (or SAA) system to provide persistent coverage of the target.

Conclusions

As described in this article, there are several hurdles before UAS can enter the national airspace. The most striking are Sense and Avoid capability and reliable flight control systems, which can be solved efficiently only with automated model based tools, depending heavily on reusable software and hardware components. A few building blocks to make a complete system operational and certifiable are described to point the attention to emerging engineering areas.

Acknowledgement

The author would like to thank George Papageorgiou, Petr Kanovsky and Peter Seiler for the discussions on the topics mentioned above.

References

[1] NASA: A report overview of the civil UAV capability Assessment (Draft)

[2] Frost and Sullivan: STUDY ANALYSING THE CURRENT ACTIVITIES IN THE FIELD OF UAV

[3] Yeh, Y.C. Triple-triple redundant 777 primary flight computer, Aerospace Applications Conference, 1996

[4] Spitzer, C.R., The Avionics Handbook, CRC Press, 2001

[5] R.L. Greenspan. GPS and Inertial Navigation. In American Institute of Aeronautics and Astronautics, 1996

[6] Weibel, R.E. Safety Considerations for Operation of Different Classes of UAVs in the NAS, AIAA, 2004

[7] Chen, W.Z. Sense and Avoid (SAA) Technologies for Unmanned Aircraft (UA), National Cheng Kung University, 2008