The Smart Phone as UAV flight management system

1. Abstract

The internet connected smart phone is one of the marquis technologies of the 21st century, transforming the way daily life is conducted. Another likely marquis technology is the unmanned aerial vehicle (UAV). The potential for UAVs is enormous, but before that potential can be reached UAV flight management systems (FMS) must achieve smart-phone-like cost and sophistication. For smaller UAVs the smart phone has almost all of the components needed to be the flight management system. In this paper I explore what it would take to use a smart phone as a UAV flight management system.

2. What is flight management for a UAV?

Unmanned aerial vehicles (UAVs) have made their presence felt on the battlefields of the 21st century in a big way. Providing reconnaissance, search and rescue, attack, and even cargo delivery to dangerous locales; the UAV has transformed the modern battlefield airspace. Less obvious but no less inevitable is the coming use of UAVs in domestic airspace. A wide range of missions await the public and political acceptance of UAVs for domestic uses. These include power and pipeline survey, property and agricultural survey, search and rescue, law enforcement, disaster relief, forestry, wildlife management, etc.

Whatever the application or size of the vehicle every UAV requires a flight management system (FMS). The FMS is responsible for the core flight control of the vehicle, management of failure scenarios, mission management, payload management, and communications. The FMS is arguably the most complex component of a UAV, representing a fusion of many different hardware components and man-years of software. There are multiple commercially available FMSs, both proprietary and open source. They run the gamut from relatively simple systems to systems sophisticated enough to fly large wheeled vehicles from runways with autonomous landing and takeoff capability. As UAVs make the transition from strictly military platforms the FMS will transition as well, becoming much less expensive and more capable. For smaller UAVs the modern smart phone has the potential to be an inexpensive but sophisticated FMS.

3. Components of an FMS

Flight management systems come in every shape, size, and cost; but they all share a similar list of components.

3.1. Hardware components of an FMS

3.1.1. Global Positioning System

At the top of the list is the Global Positioning System (GPS) receiver. The modern UAV owes its capability to GPS more than any other technology. Without precision position and velocity measurements autonomous navigation of a UAV would be prohibitively complex and most systems would be limited to human-in-the-loop operational paradigms. There is a great deal of variety in the cost and quality of GPS receivers, but even the crudest is capable of providing once per second position updates accurate to within a few meters. While this may be a far cry from the survey grade systems that allow autonomous landing on moving ships, it is nevertheless good enough for most small UAVs, particularly those that land vertically on non-moving platforms.

3.1.2. Inertial Measurement Unit

Sensing rate of rotation and specific force in three dimensions is the job of the inertial measurement unit (IMU). These six numbers are typically used directly in flight control, and also indirectly to provide an estimate of the vehicle orientation in space, and its position and velocity at rates faster than the GPS provides. As with GPS there is an enormous variety in the cost and quality of IMUs. Consumer electronics have been leveraging inertial sensing heavily for the last decade and the automotive industry for the decade before that. These two large markets have successfully driven the cost and size of IMUs down to the point where a few integrated circuits costing a few dollars can perform well enough (when combined with GPS) to provide reliable state estimation for UAVs.

3.1.3. Magnetometer

Sensing of the Earth’s magnetic field is accomplished with a magnetometer. As with the inertial sensors the magnetic field is sensed in three dimensions. The measured magnetic field is combined with the pitch and roll estimate and a model of the Earth’s magnetic field to compute a heading estimate. This heading estimate is needed when there is inadequate maneuvering to derive the heading from the IMU and GPS. Not all types of UAVs require a reliable heading estimate, for example fixed-wing aircraft can successfully maneuver and navigate without a heading estimate. Hovering vehicles such as multi-rotors or helicopters demand a heading estimate at all times in order to translate guidance commands from the inertial reference frame to the body axis for flight control.

3.1.4. Air data sensors

The set of FMS sensors is typically rounded out with the air data sensors. These are the static pressure, dynamic pressure, and air temperature. Depending on the type of vehicle it is possible to operate without the complete set of air data sensors. In most cases temperature can be determined adequately from the standard atmosphere model. Dynamic pressure is used to compute airspeed, but is not needed for hovering vehicles. Static pressure is used to determine the barometric altitude. Although this is not strictly needed if the GPS is working, it is crucial for integration into any kind of airspace management system (since barometric altitude is the altitude reference used by everyone in the airspace). The barometric altitude is also a useful backup altitude sensor for cases where GPS is unavailable.

3.1.5. Wireless communications

In order to be dynamically re-tasked or deliver real-time results the UAV requires a datalink for two-way wireless communications. The datalink is often, though not always, part of the FMS. The performance requirements of the datalink are mission specific, but in most cases a few tens of kilobits per second of bi-directional command and control data are needed, and in many cases a few megabits per second of downlink bandwidth for delivering video.

3.1.6. Processing

Since the FMS represents the brain of the UAV it requires substantial processing. State estimation, flight control, mission management, communications, and payload tasking all tax the FMS processing system. Some of the processing is real time, such as calculations needed for flight control, and some can be done in a less timely manner, such as terrain lookups or route management. A large store of non-volatile memory is desirable to act as a black-box recorder as well as to hold large datasets such as terrain models.

3.1.7. Airframe integration

The final hardware components of an FMS are the features required to integrate with the airframe. This includes the electrical signals for flight control actuators (for small UAVs these are typically pulse width modulated signals to command model-aircraft style servos), the electrical connections to any peripheral systems such as datalinks, payloads, ranging sensors, and the mounting and vibration isolation system.

3.2. Software components of an FMS

3.2.1. State Estimation

Any FMS must provide some form of state estimation; combining all of the available sensors to provide an estimate of the state of the vehicle with respect to the Earth. The state estimation will typically determine the orientation, velocity, and position of the vehicle in three dimensions, at high rates (typically 50 times per second or more). The state estimation will also resolve and remove some errors in the sensors, such as angular rate bias in the gyros and position and velocity noise from the GPS.

3.2.2. Flight Control

The output of the state estimation is fed to the flight control system. This software is a series of rules using feedback control to drive the estimated state of the system to match a desired state. The flight control is typically built in layers, with the bottom layer working to close inner loops on the body axis and the outer layers commanding the inner layers in order to achieve a guidance target. The output of the flight control system is a set of signals for the control surface actuators.

3.2.3. Communications

The FMS software must also provide a communications resource. Even if the datalink is not directly integrated with the FMS a means of updating commands and receiving telemetry must be provided. Since the communications software must necessarily provide access to the entire range of options provided by the flight control, and must be tolerant to varying degrees of data transmission quality, the communications software is often a complex component of the FMS software stack.

3.2.4. Payload interface

In most cases the FMS software must have some knowledge of the payload (and vice versa). The payload integration could be as simple as relaying user commands to the payload, or as complex as automatically updating the vehicle guidance based on the data from the payload.

4. Components of a smart phone

The modern smart phone is a tour de force of technology integration. The extraordinarily large market for smart phones has produced a product that is exceptionally high quality and low cost. When comparing the hardware components of an FMS with the components of a smartphone the commonality is immediately apparent; raising the idea that a smart phone could in fact be an FMS. For purposes of this discussion the author's Nexus 4 serves as the representative smart phone. This phone runs android 4.4.4 and is available for $200.

The nexus 4, disassembled courtesy of iFixit

4.1. Components in common with a traditional FMS

The sensors that a smart phone has in common with an FMS are:

- GPS for location based services. Once per second update rate.
- Three axis rate gyro for motion based gaming. 200 Hz update rate with a ±1000^0/sec limit.
- Three axis accelerometer for portrait/landscape sensing, and for motion based gaming. 200 Hz update rate with a ±4g limit.
- Three axis magnetometer for heading determination to enhance location services. 50 Hz update rate.
- A barometer for aiding position when GPS is poor. 33Hz update rate. Note that the barometer is not currently a typical sensor, as the Nexus 4 is one of the only phones to have it, but is expected to be commonplace in the future.

Notice that the only FMS sensors that the phone lacks are air temperature and dynamic pressure. However for hovering vehicles the lack of these sensors is not a problem. For fixed wing applications dynamic pressure would have to be added as an externally connected peripheral.

The other hardware components of an FMS are also present in a smart phone. There is ample processing power and volatile and nonvolatile memory. More significantly there is an integrated datalink system. For operations in non-rural environments the mobile phone network provides fast and reliable communications. Performance is typically adequate both for command and control and for real time delivery of compressed standard definition video. Modern mobile phone networks are internet-protocol (IP) capable and therefore the other end of the datalink could be any internet connected device.

Interface to the remainder of the airframe can be accomplished through the USB system. Some custom hardware is required to be developed to convert the USB interface to the PWM signals necessary to drive the actuators. This can be accomplished with relatively modest circuit boards employing a single USB enabled microcontroller. This circuit board could also host the necessary power electronics to drive the flight control actuation system.

Mention should be made of the camera system. The smart phone typically has two cameras: a large format camera with variable focus for taking pictures, and a small format camera with fixed focus for video conferencing. These cameras, while not having a direct corollary in the traditional FMS, can be employed as payloads or vision based sensors in a low cost UAV.

4.2. Components not common to a traditional FMS

Although smart phone hardware overlaps in many areas with the traditional FMS there are components of a smart phone that have no corollary in a traditional FMS. However there are ways in which some of these components can be employed effectively in a UAV system.

- Touchscreen display. The touchscreen display is not useful for prosecuting the UAV mission but it does provide a handy way to facilitate pre-flight operations. Simple commands can be input and status information can be displayed; substantially streamlining the preflight operation.
- Speaker. Similar to the touchscreen the speaker can be used to facilitate preflight status checks. There are a number of operations for which audio feedback would be very useful. One simple example would be performing the traditional pitch, roll, yaw sensor check; where the user manipulates the orientation of the UAV while the phone announces the changes made as confirmation of correct sensor operation. There are other safety related aspects to the speaker. For example prior to engine start the phone could announce “clear prop!” to warn bystanders to move away.
- Microphone. The microphone has the potential to be used as a payload and/or sensor. Given the signal processing ability of the phone the microphone could be used to detect (loud) signals of interest, such as gunshots. In combination with the speaker the microphone may also be able to determine basic ranging information. The speaker would chirp high frequency signals and the microphone would listen for the echo. Simple time of arrival arithmetic then provides a crude ranging sensor. Experimentation would be needed to determine the useful range of this solution, but it may be enough to provide a simple landing/takeoff proximity sensor. Finally the microphone can be used to measure the RPM of the engine or rotor system.
- Wi-Fi. Wireless Ethernet is suitable for short range flying (indeed some hobby oriented multi-rotors use Wi-Fi as the primary datalink) although any real UAV mission is likely to exceed the usable range of Wi-Fi. However there is a niche mission to utilize the tethering feature of the phone to provide data communications services from a hovering vehicle to people or devices below in an occluded area.
- Ambient light sensor. This is used to control the screen intensity of the phone. If operating free from obstructions such as buildings this sensor could be used (in combination with time of day information) to determine cloud cover.
- Proximity sensor. This is used to determine when the phone is held close to the user’s body as in a phone call, prompting the phone to disable response to touch events. Since the range of the proximity sensor is typically only 5 cm it has no use as a payload or FMS system.
- Bluetooth is only useful over short ranges (less than 10 meters) and is slower than USB so is not likely to be useful for a UAV system, either as a payload or a peripheral connection.
- NFC. Near field communication suffers from the same limitations as Bluetooth.

5. The case for a smart phone autopilot

Integration and packaging of complex electronics is ultimately driven by market size. When the market size is measured in the billions (users or dollars) extraordinary investment takes place in product development. Examples include microprocessors, automobiles, and smart phones. The integration and performance-to-cost ratio of these products is a result of their enormous market and the resulting competitive pressure.

Given the relative size of their markets there is no chance that the traditional FMS builder can make a product as well integrated or as inexpensive as the smart phone. For those UAVs where the smart phone can replace the traditional FMS cost advantages, and increased mission capabilities, can be achieved.

In addition the rapid development pace of the smart phone has another advantage: the triumph over obsolescence. For traditional FMS makers leveraging the ever increasing computing performance being delivered by today’s silicon is difficult. Market size again limits the pace at which any FMS builder can evolve their hardware platform. Without the large market size and attendant investment in ongoing research and development an FMS builder can at best update their platform a few times per decade. In contrast the computing power (and sensor performance) of the smart phone is increasing at a pace similar to traditional personal computing, i.e. doubling every two years. Most smart phone makers are launching a new platform every year, with major updates to existing platforms every six months.

The smart phone FMS enjoys another advantage over the traditional FMS: the software stack. The traditional FMS builder has a lot of software to integrate before they even begin thinking about flight management: operating system, board support package, sensor drivers, datalink interfaces, etc. All of this is already integrated in the smart phone operating system; and the development tools to create new software are readily available and well documented with a large community of existing developers.

6. Challenges for the smart phone FMS

Although it should be clear by now that a smart phone can make a fine FMS there are some short comings that need to be considered.

6.1. Hardware Challenges to the smart phone autopilot

The ideal platform for the smart phone FMS is a small low cost UAV, operating in a non-rural environment at low altitude (less than 1000 ft.) in order to leverage the integrated camera and communications. Because of the small size of such vehicles there is a penalty to any excess weight, and the smart phone is carrying weight that a traditional FMS can avoid; in particular the glass display and the battery. These represent more than half the weight of the smart phone, and preclude the phone from being used in the smallest vehicles, those less than a few pounds. However it should be noted that effective outdoor operation requires enough mass and power to operate in the wind, and this implies that the weight penalty of the smart phone can be tolerated.

A traditional FMS is rich in input and output (I/O) features; with dedicated interface hardware for control actuators, peripheral sensors, and payloads. The smart phone is restricted to a single USB interface. Hence integration with the airframe will require custom electronics to provide the necessary I/O features. Fortunately a number of inexpensive off the shelf solutions exist for using a smart phone in general purpose robotics and these can be leveraged to provide the needed I/O.

The smart phone is intended to be held in the user's hand and so lacks any native means of mounting to the airframe. Custom mounting hardware must be fabricated for this purpose. Such hardware can be similar to the snap on plastic hard covers available for protecting the phone. In high production quantities the airframe itself can simply have a receptacle for the phone to 'snap' in. No matter how it is mounted particular attention will need to be paid to the vibration environment. A traditional FMS will utilize a high sampling rate (typically 1000Hz or more) in order to prevent propulsion frequencies from aliasing the inertial sensors. The typical smart phone only provides 200Hz inertial sampling, and so passive vibration isolation must be good enough to prevent vibration frequencies above 50Hz from getting to the phone[1].

6.2. Software challenges to the smart phone FMS

A typical FMS will utilize a real time operating system to guarantee that specific software routines, such as sensor sampling and flight control, are run on deterministic schedules. A smart phone operating system will not natively provide this capability. Nevertheless the latencies typical of modern smart phones are adequate for control of conventional UAVs. If more determinism is required then the smart phone operating system would need to be customized. This is a daunting but not impossible task, as many smart phones use open source operating systems that can be modified by someone skilled in the art.

One of the strengths of the smart phone platform is also a negative: the pace of development. Major phone vendors spend enormous amounts of money to advance their software stack for competitive purposes. This rapid pace of development can levy a heavy burden on the FMS developer to keep up.

6.3. Communications challenges to the smart phone FMS

One of the major advantages of the smart phone autopilot is the native high speed internet-protocol (IP) based cellular communications system. However there is a problem with this system. Ideally each mobile device would have a globally visible IP address and any device could send data to any other. The reality is somewhat different. Most devices connect to the internet via a network-address-translator (NAT). The NAT is designed to allow the device to initiate a connection to a publicly visible server, but not the reverse.

The net effect is that in order to reliably send and receive data from a mobile device over the cell network the other party must be a server on the public internet. In order to perform device to device communications an intermediate publicly visible server must be used. Each end point then connects to this "rendezvous server" which relays at least addressing information and at most the data itself. The

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[1] This particular limitation can be overcome by customizing the operating system software. Some smart phones, like the Nexus 4, use open source operating systems, whose inertial sensor drivers could be modified to deliver higher data rate sampling.

creation, maintenance, and bandwidth provisioning of this server represents a significant barrier to smart phone communications.

7. The smart phone as UAV payload

While a hobbyist may operate an autonomous flying vehicle for enjoyment, most UAVs will require a payload to be useful. The smart phone has several peripherals that can act as payloads.

7.1. Large format camera

The large format camera can be used exactly as intended by the phone manufacturer: providing wide angle situational awareness pictures which would be useful for agricultural or real estate survey. However with some simple software the camera can be made to do more.

The traditional UAV payload is a mechanically stabilized standard definition video camera with zoom lens. Typical smartphone camera resolutions are 3264 x 2448 (8MP) or greater[2] with a field of view of 60 degrees horizontally. If a standard definition frame (640x480) is selected from the large format image then an effective zoom of 3264/640 = 5x is possible, giving a field of view of approximately 12 degrees. In this mode of operation the image can be electronically gimbaled anywhere in the field of view to emulate a stabilized video camera. Experience indicates that a standard definition stabilized video camera at 12 degrees field of view can be used to track a car from 1000 feet away or a person from 250 feet away.

In most cases the smart phone will lay flat in the host vehicle, naturally pointing the camera downwards where it is most useful as a payload. However the camera orientation could be modified using a mirror integrated into the airframe. For example if the goal is to track fixed or moving targets it may be desirable to deflect the camera line of sight forward or to the side depending on the host vehicle kinematics[3]. The mirror could be curved to effect magnification and possibly mechanically gimbaled to extend the electronically gimbaled range of the imager.

7.2. Web camera

Most smart phones have a second camera which is used for video telephony (aka the webcam or the “selfie” cam). This camera is fixed focus, has fewer pixels (1.3MP), and is generally not useful compared to the performance of the large format camera. However the web camera does make possible a nice feature in the smart phone autopilot: the pilot camera.

In traditional UAV flight operations it is often desirable to see the view as a human pilot would see it. This is so useful that the ground control station may use synthetic vision software to emulate this view. If the web camera is combined with a 45 degree mirror (again assuming the smart phone lays flat in the host vehicle) then the image (after flipping) is the pilot view. Since the camera in question is very small

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[2] Latest camera resolutions are 16MP however one must account for the lens quality and focal plane size before assuming that all 16 million pixels provide useful data.

[3] Fixed wing vehicles that maintain constant forward flight would favor one side over the other so as to maximize the ability to hold the target in the field of view while orbiting.

the mirror needed is also quite small, and could be integrated into the airframe, or directly adhered on the phone.

The pilot camera provides utility for remote pilot in the loop operation, or for situational awareness monitoring, or (when combined with advanced onboard image processing) the ability to detect obstacles in the flight path.

7.3. Microphone

As already mentioned the microphone can be used to measure interesting data on the vehicle such as engine or rotor speed. However it can also be used as a payload to listen for specific signals. In the case of law enforcement applications listening for gunshots is the obvious application. Most smartphones contain multiple microphones for noise suppression purposes, however it is not possible (which is to say the author could not find a way) to simultaneously access the individual microphones for the purpose of determining the bearing to a noise source. However if multiple vehicles are in the area it would be possible to triangulate the location of a sound by comparing time of arrival information to the different platforms.

In addition all smartphones support connecting external microphones. The external microphone could be much more capable, even directional. This would allow a hovering vehicle (for example) to hear conversations below it. In addition to the obvious surveillance application one could imagine controlling the vehicle through voice commands!

7.4. Wi-Fi sniffer or data relay

The wireless Ethernet radio of a smartphone can be used to find other Wi-Fi networks, and to estimate their distance from itself (using the radio signal strength).

The Ethernet radio can be used to provide data relay. So called “tethering” is already a supported feature of most smart phones. In urban or rural canyons a hovering vehicle could be deployed to an altitude appropriate to reach cell service and then provide wireless internet access to anyone below in the canyon. The utility of this is limited by the phones useful Ethernet range which is of the order of 100 meters.

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Before founding Five by Five Development in 2013 Bill was co-founder of Cloud Cap Technology. While at Cloud Cap he (and partner Ross Hoag) developed the Piccolo flight management system, an extremely capable and popular proprietary FMS. Bill oversaw the software development of the Piccolo from its original concept into a market leading FMS. The Piccolo remains one of the most successful small UAV FMSs in use, with many thousands of units shipped and hundreds of thousands of hours of operation in military and civil applications.