Guest Editorial for the Special Volume On Unmanned Aircraft Systems (UAS)

Kimon P. Valavanis · Paul Oh · Les Piegl

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Dear colleagues,

This special volume includes reprints and enlarged versions of papers presented in the *International Symposium on Unmanned Aerial Vehicles*, which took place in Orlando FL, June 23–25.

The main objective of UAV'08 was to bring together different groups of qualified representatives from academia, industry, the private sector, government agencies like the Federal Aviation Administration, the Department of Homeland Security, the Department of Defense, the Armed Forces, funding agencies, state and local authorities to discuss the current state of unmanned aircraft systems (UAS) advances, the anticipated roadmap to their full utilization in military and civilian domains, but also present current obstacles, barriers, bottlenecks and limitations to flying autonomously in civilian space. Of paramount importance was to define needed steps to integrate UAS into the National Airspace System (NAS). Therefore, UAS risk analysis assessment, safety, airworthiness, definition of target levels of safety, desired fatality rates and certification issues were central to the Symposium objectives.

Symposium topics included, among others:

AS Airworthiness
UAS Risk Analysis
UAS Desired Levels of Safety
UAS Certification
UAS Operation
UAS See-and-avoid Systems
UAS Levels of Autonomy

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UAS Perspectives and their Integration in to the NAS
UAS On-board systems
UAS Fail-Safe Emergency Landing Systems
Micro Unmanned Vehicles
Fixed Wing and Rotorcraft UAS
UAS Range and Endurance
UAS Swarms
Multi-UAS coordination and cooperation
Regulations and Procedures

It is expected that this event will be an annual meeting, and as such, through this special volume, we invite everybody to visit http://www.uavconferences.com for details. The 2009 Symposium will be in Reno, NV, USA.

We want to thank all authors who contributed to this volume, the reviewers and the participants. Last, but not least, The Springer people who have been so professional, friendly and supportive of our recommendations. In alphabetical order, thank you Anneke, Joey, Gabriela and Nathalie. It has been a pleasure working with you.

We hope you enjoy the issue.

Development of an Unmanned Aerial Vehicle Piloting System with Integrated Motion Cueing for Training and Pilot Evaluation

James T. Hing · Paul Y. Oh

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Abstract UAV accidents have been steadily rising as demand and use of these vehicles increases. A critical examination of UAV accidents reveals that human error is a major cause. Advanced autonomous systems capable of eliminating the need for human piloting are still many years from implementation. There are also many potential applications of UAVs in near Earth environments that would require a human pilot's awareness and ability to adapt. This suggests a need to improve the remote piloting of UAVs. This paper explores the use of motion platforms to augment pilot performance and the use of a simulator system to asses UAV pilot skill. The approach follows studies on human factors performance and cognitive loading. The resulting design serves as a test bed to study UAV pilot performance, create training programs, and ultimately a platform to decrease UAV accidents.

Keywords Unmanned aerial vehicle · Motion cueing · UAV safety · UAV accidents

1 Introduction

One documented civilian fatality has occurred due to a military UAV accident (non-US related) [1] and the number of near-mishaps has been steadily rising. In April 2006, a civilian version of the predator UAV crashed on the Arizona–Mexico border within a few hundred meters of a small town. In January 2006, a Los Angeles County Sheriff lost control of a UAV which then nose-dived into a neighborhood. In our own experiences over the past six years with UAVs, crashes are not uncommon. As Fig. 1 illustrates, UAV accidents are much more common than other aircraft and are increasing [2]. As such, the urgent and important issue is to design systems

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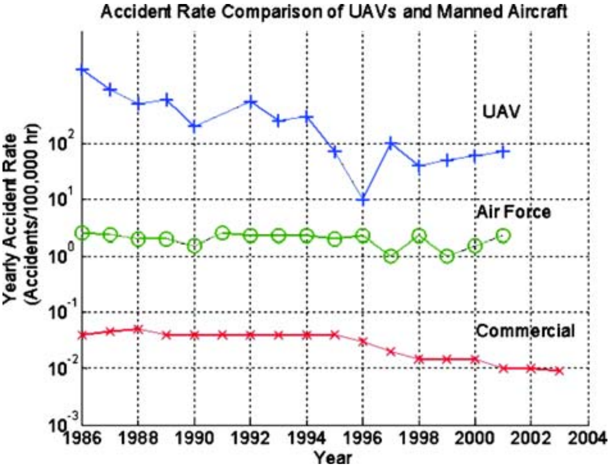


Fig. 1 Comparison of accident rates (data [2])

and protocols that can prevent UAV accidents, better train UAV operators, and augment pilot performance. Accident reconstruction experts have observed that UAV pilots often make unnecessarily high-risk maneuvers. Such maneuvers often induce high stresses on the aircraft, accelerating wear-and-tear and even causing crashes. Traditional pilots often fly by "feel", reacting to acceleration forces while maneuvering the aircraft. When pilots perceive these forces as being too high, they often ease off the controls to fly more smoothly. The authors believe that giving the UAV pilot motion cues will enhance operator performance. By virtually immersing the operator into the UAV cockpit, the pilot will react quicker with increased control precision. This is supported by previous research conducted on the effectiveness of motion cueing in flight simulators and trainers for pilots of manned aircraft, both fixed wing and rotorcraft [3–5]. In this present study, a novel method for UAV training, piloting, and accident evaluation is proposed. The aim is to have a system that improves pilot control of the UAV and in turn decrease the potential for UAV accidents. The setup will also allow for a better understanding of the cause of UAV accidents associated with human error through recreation of accident scenarios and evaluation of UAV pilot commands. This setup stems from discussions with cognitive psychologists on a phenomenon called shared fate. The hypothesis explains that because the ground operator does not share the same fate as the UAV flying in the air, the operator often makes overly aggressive maneuvers that increase the likelihood of crashes. During the experiments, motion cues will be given to the pilot inside the cockpit of the motion platform based on the angular rates of the UAV. The current goals of the experiments will be to assess the following questions in regards to motion cueing:

1. What skills during UAV tasks are improved/degraded under various conditions?
2. To what degree does prior manned aircraft experience improve/degrade control of the UAV?
3. How does it affect a UAV pilot's decision making process and risk taking behaviors due to shared fate sensation?

This paper is part one of a three part development of a novel UAV flight training setup that allows for pilot evaluation and can seamlessly transition pilots into a

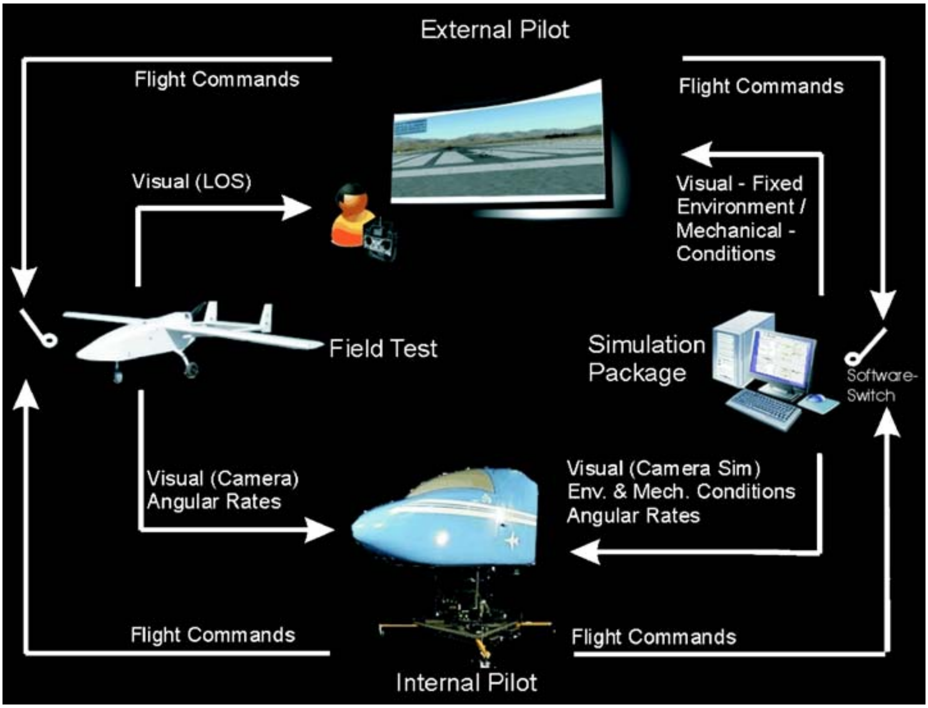


Fig. 2 Experimental setup for evaluating the effectiveness of motion cueing for UAV control. The benefit of this system is that pilots learn on the same system for simulation as they would use in the field

mission capable system. Part two will be the research to assess the effectiveness of the system and Part three will be the presentation of the complete trainer to mission ready system. As such, this paper presents the foundation of the UAV system which includes the software interface for training and the hardware interface for the mission capable system. Figure 2 shows the system and its general parts. This paper explores the use of motion platforms that give the UAV pilot increased awareness of the aircraft's state. The middle sections motivate this paper further by presenting studies on UAV accidents and how these aircraft are currently flown. It details the setup for simulation, training, human factor studies and accident assessment and presents the tele-operation setup for the real-world field tests. The final sections present and discuss experimental results, the conclusions and outlines future work.

2 UAV Operation and Accidents

While equipment failure has caused some of the accidents, human error has been found to be a significant causal factor in UAV mishaps and accidents [6, 7]. According to the Department of Defense, 70% of manned aircraft non-combat losses are attributed to human error, and a large percentage of the remaining losses have human error as a contributing factor [6]. Many believe the answer to this problem is full autonomy. However, with automation, it is difficult to anticipate all possible contingencies that can occur and to predict the response of the vehicle to all possible events. A more immediate impact can be made by modifying the way that a pilot is trained and how they currently control UAVs [8].

Many UAV accidents occur because of poor operator control. The current modes of operation for UAVs are: (1) external piloting (EP) which controls the vehicle by line of sight, similar to RC piloting; (2) internal piloting (IP) using a ground station and on board camera; and (3) autonomous flight. Some UAV systems are operated using a single mode, like the fully autonomous Global Hawk. Others are switched between modes like the Pioneer and Mako. The Pioneer used an EP for takeoff/landing and an IP during flight from a ground station. The current state of the art ground stations, like those for the Predator, contain static pilot and payload operator consoles. The pilot controls the aircraft with a joystick, rudder pedals and monitoring screens, one of which displays the view from the aircraft's nose.

The internal pilot is affected by many factors that degrade their performance such as limited field of view, delayed control response and feedback, and a lack of sensory cues from the aircraft [7]. These factors lead to a low situational awareness and decreased understanding of the state of the vehicle during operation. In turn this increases the chance of mishaps or accidents. Automating the flight tasks can have its draw backs as well. In a fully autonomous aircraft like the Global Hawk, [9] showed that because of the high levels of automation involved, operators do not closely monitor the automated mission-planning software. This results in both lowered levels of situational awareness and ability to deal with system faults when they occurred.

Human factors research has been conducted on UAV ground station piloting consoles leading to proposals on ways to improve pilot situational awareness. Improvements include new designs for head up displays [10], adding tactile and haptic feedback to the control stick [11, 12] and larger video displays [13]. To the author's knowledge, no research has been conducted in the use of motion cueing for control in UAV applications.

Potential applications of civilian UAVs such as search and rescue, fire suppression, law enforcement and many industrial applications, will take place in near-Earth environments. These are low altitude flying areas that are usually cluttered with obstacles. These new applications will result in an increased potential for mishaps. Current efforts to reduce this risk have been mostly focused on improving the autonomy of unmanned systems and thereby reducing human operator involvement. However, the state of the art of UAV avionics with sensor suites for obstacle avoidance and path planning is still not advanced enough for full autonomy in near-Earth environments like forests and urban landscapes. While the authors have shown that UAVs are capable of flying in near-Earth environments [14, 15], they also emphasized that autonomy is still an open challenge. This led the authors to focus less on developing autonomy and more on improving UAV operator control.

3 Simulation and Human Factor Studies

There are a few commercial UAV simulators available and the numbers continue to grow as the use of UAV's becomes more popular. Most of these simulators are developed to replicate the state of the art training and operation procedures for current military type UAVs. The simulation portion of our system is designed to train pilots to operate UAVs in dynamic environment conditions utilizing the motion feedback we provide them. The simulation setup also allows for reconstruction of UAV accident scenarios, to study in more detail of why the accident occurred, and allows for the placement of pilots back into the accident situation to train them on how to recover. The simulation utilizes the same motion platform and cockpit that would be used for the real world UAV flights so the transfer of the training skills to real world operation should be very close to 100%.

3.1 X-Plane and UAV Model

The training system utilizes the commercial flight simulator software known as X-Plane from Laminar Research. Using commercial software allows for much faster development time as many of the necessary items for simulation are already packaged in the software. X-Plane incorporates very accurate aerodynamic models into the program and allows for real time data to be sent into and out of the program. X-Plane has been used in the UAV research community as a visualization and validation tool for autonomous flight controllers [16]. In [16] they give a very detailed explanation of the inner workings of X-Plane and detail the data exchange through UDP. We are able to control almost every aspect of the program via two methods. The first method is an external interface running outside of the program created in a Visual Basic environment. The external program communicates with X-Plane through UDP. The second method is through the use of plug-ins developed using the X-Plane software development kit (SDK) Release 1.0.2 (freely available from http://www.xsquawkbox.net/xpsdk/). The X-Plane simulator was modified to fit this project's needs. Through the use of the author created plug ins, the simulator is capable of starting the UAV aircraft in any location, in any state, and under any condition for both an external pilot and an internal pilot. The plugin interface is shown on the right in Fig. 5. The benefit of the plugin is that the user can start the aircraft in any position and state in the environment which becomes beneficial when training landing, accident recovery and other in air skills. Another added benefit of the created plugin is that the user can also simulate a catapult launch by changing the position, orientation, and starting velocity of the vehicle. A few of the smaller UAVs are migrating toward catapult launches [17]. Utilizing X-Plane's modeling software, a UAV model was created that represents a real world UAV currently in military operation. The Mako as seen in Fig. 3 is a military drone developed by Navmar Applied Sciences Corporation. It is 130 lb, has a wingspan of 12.8 ft and is operated via an external pilot for takeoff and landings. The vehicle is under computer assisted autopilot during flight. For initial testing, this UAV platform was ideal as it could be validated by veteran Mako pilots in the author's local area. Other models of UAVs are currently available online such as the Predator A shown on the right in Fig. 3. The authors currently have a civilian Predator A pilot evaluating the accuracy of the model. The trainer is setup for the Mako such that an external pilot can train on flight tasks using an external view and RC control as in normal operation seen in Fig. 4. The system is then capable of switching to an internal view (simulated nose camera as seen in Fig. 4) at any moment to give control and send motion cues to a pilot inside of the motion platform.

Fig. 3 *Top left* Mako UAV developed by NAVMAR Applied Sciences. *Bottom left* Mako UAV recreated in X-Plane. *Right* predator A model created by X-Plane online community

3.2 Human Factor Studies

Discussions with experienced UAV pilots of Mako and Predator A & B UAVs on current training operations and evaluation metrics for UAV pilots has helped establish a base from which to assess the effectiveness of the proposed motion integrated UAV training/control system.

The external pilot of the Mako and internal pilot of the Predator systems learn similar tasks and common flight maneuvers when training and operating the UAVs. These tasks include taking off, climbing and leveling off. While in the air, they conduct traffic pattern maneuvering such as a rectangular course and flight maneuvers such as Dutch rolls. On descent, they can conduct traffic pattern entry, go around procedures and landing approaches. These tasks are conducted during training and mission operations in various weather, day and night conditions. Each condition requires a different skill set and control technique. More advanced training includes control of the UAV during different types of system failure such as engine cutoff or camera malfunction. Spatial disorientation in UAVs as studied by [18] can effect both internal and external pilots causing mishaps. The simulator should be able to train pilots to experience and learn how to handle spatial disorientation without the financial risk of losing an aircraft to an accident.

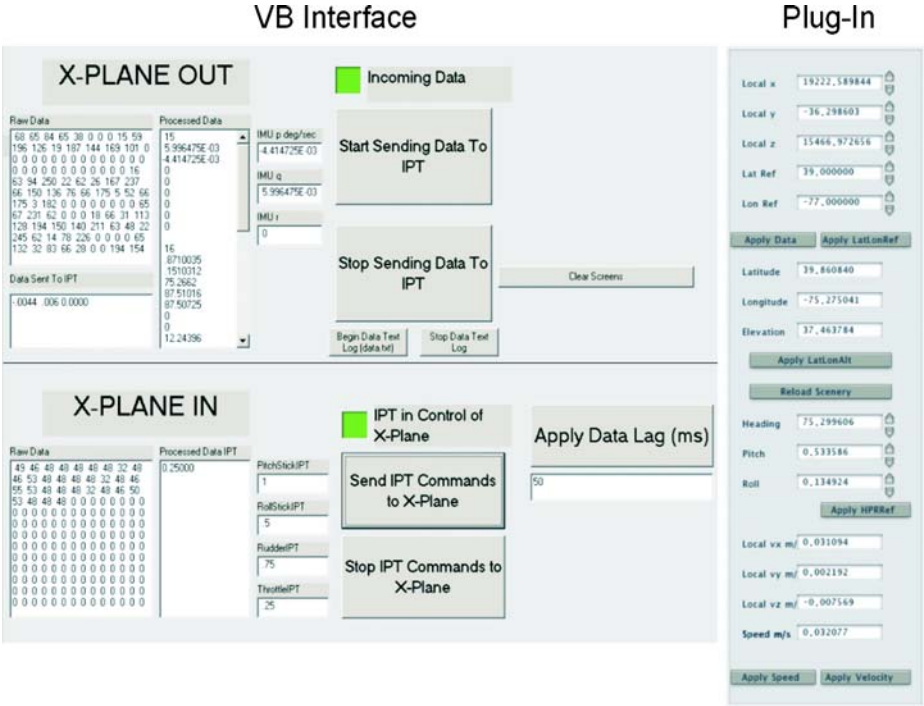
Fig. 4 Simulator screen shots using the Mako UAV model. *Left* external pilot view point with telemetry data presented on screen. In the real world, this data is normally relayed to the pilot through a headset. *Right* internal view point with telemetry data presented. The view simulates a nose camera position on the aircraft and replicates the restricted field of view

Assessing the effectiveness of integrating motion cueing during piloting of a UAV will be conducted by having the motion platform provide cues for yaw, pitch and roll rates to the pilots during training tasks listed earlier. During simulation, the motion cues will be based on aircraft state information being fed out of the X-Plane simulation program. During field tests, the motion cues will be received wirelessly from the inertial measurement unit (IMU) onboard the aircraft. The proposed subjects will be groups of UAV internal pilots (Predator) with manned aircraft experience, UAV internal pilots without manned aircraft experience, and UAV external pilots without manned aircraft experience.

Results from these experiments will be based on quantitative analysis of the recorded flight paths and control inputs from the pilots. There will also be a survey given to assess pilot opinions of the motion integrated UAV training/control system. The work done by [19] offers a comprehensive study addressing the effects of conflicting motion cues during control of remotely piloted vehicles. The conflicting cues produced by a motion platform were representative of the motion felt by the pilot when operating a UAV from a moving position such as on a boat or another aircraft. Rather than conflicting cues, the authors of this paper will be studying the effects of relaying actual UAV motion to a pilot. We are also, in parallel, developing the hardware as mentioned earlier for field testing to validate the simulation. The authors feel that [19] is a good reference to follow for conducting the human factor tests for this study.

3.3 X-Plane and Motion Platform Interface

The left side of Fig. 5 shows the graphical user interface (GUI) designed by the authors to handle the communication between X-Plane and the motion platform ground station described in a later sections. The interface was created using Visual Basic 6 and communicates with X-Plane via UDP. The simulation interface was designed such that it sends/receives the same formatted data packet (via 802.11) to/from the motion platform ground station as an IMU would during real world flights. This allows for the same ground station to be used during simulation and field tests without any modifications. A button is programmed into the interface that allows either the attached RC controller command of the simulated UAV or the pilot inside the motion platform command at any desired moment. This would represent the external pilot control of the vehicle (RC controller) and the internal pilot control (from inside the motion platform) that would be typical of a mission setup. Currently the authors are sending angular rate data from X-Plane to the motion platform ground station and reading back into X-Plane the stick commands from the internal pilot inside the motion platform cockpit. Another powerful aspect of the program interface is that it allows the user to manipulate the data being sent out of and back into X-Plane. Noise can be easily added to the data, replicating real-world transmissions from the IMU. Time lag can also be added to data going into and out of X-plane which would represent real world data transmission delay. For example, Predator and other UAV pilots have seen delays on the order of seconds due to the long range operation of the vehicle and the use of satellite communication links [20]. Inexperienced pilots of the Predator have experienced pilot induced oscillations due to the time lag which has been the cause of some UAV mishaps.



Raw Data

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68 65 84 65 38 0 0 0 15 59
196 126 19 187 144 169 101 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 16
63 94 250 22 62 26 167 237
66 150 136 76 66 175 5 52 66
175 3 182 0 0 0 0 0 0 0 65
67 231 62 0 0 0 18 66 31 113
128 194 150 140 211 63 48 22
245 62 14 78 226 0 0 0 0 65
132 32 83 66 28 0 0 194 154
```

Processed Data

```
15
5.996475E-03
-4.414725E-03
0
0
0
0
0
0

16
.8710035
.1510312
75.2662
87.51016
87.50725
0
0
12.24396
```

IMU p deg/sec: -4.414725E-03
IMU q: 5.996475E-03
IMU r: 0

Data Sent To IPT: -.0044 .006 0.0000

Raw Data

```
49 46 48 48 48 48 48 32 48
46 53 48 48 48 48 32 48 46
55 53 48 48 48 32 48 46 50
53 48 48 48 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Processed Data IPT: 0.25000

PitchStickIPT: 1
RollStickIPT: .5
RudderIPT: .75
ThrottleIPT: .25

Apply Data Lag (ms): 50

Local x: 19222,589844
Local y: -36,298603
Local z: 15466,972656
Lat Ref: 39,000000
Lon Ref: -77,000000
Latitude: 39,860840
Longitude: -75,275041
Elevation: 37,463784
Heading: 75,299606
Pitch: 0,533586
Roll: 0,134924
Local vx m/: 0,031094
Local vy m/: 0,002192
Local vz m/: -0,007569
Speed m/s: 0,032077

Fig. 5 *Left* graphical user interface for communication between X-Plane and IPT ground station. *Right* plugin interface running inside of X-Plane

4 Tele-operation Setup

The tele-operated system is made up of five major parts: (1) the motion platform, (2) the aerial platform, (3) the on board sensors including wireless communication, (4) the PC to remote control (RC) circuit and (5) the ground station.

4.1 Motion Platform

To relay the motion of the aircraft to the pilot during both simulation and field tests, the authors utilized a commercially available 4-*dof* flight simulator platform from Environmental Tectonics Corporation (ETC) shown in Fig. 6. ETC designs and manufactures a wide range of full-motion flight simulators for tactical fighters, general fixed-wing aircraft and helicopters. For initial development, a 4-*dof* integrated physiological trainer (IPT) system was employed because of its large workspace and fast accelerations. These are needed to replicate aircraft flight. The motion system capabilities are shown in Table 1. The cockpit is modified for specific aircrafts offering a high fidelity experience to the pilot. The visual display inside the motion platform can handle up to a 120° field of view. Basic output from the motion platform utilized in this work are the flight commands from the pilot in the form of encoder positions of the flight stick (pitch and roll), rudder pedals (yaw), and throttle.

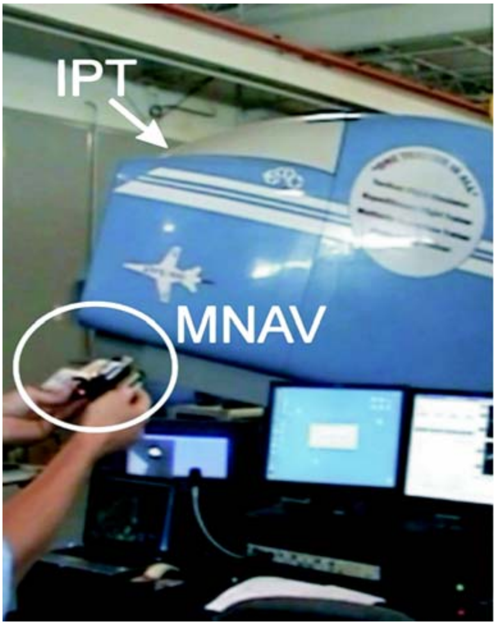


Fig. 6 IPT 4-*dof* motion platform from ETC being wirelessly controlled with the MNAV

The motion platform generates the appropriate motion cues to the pilot based on the angular velocities that it receives from the ground station. Motion cues are brief movements in the direction of acceleration which give the sensation of constant motion to the pilot but are "washed out" before the motion platform exceeds its reachable workspace. Washout algorithms are commonly used by the motion platform community to return the platform to a neutral position at a rate below the threshold that humans can sense [21]. This allows the platform to simulate motions much greater than its reachable workspace. For the IPT motion platform in particular, angular rate data streaming from the MNAV is filtered and then pitch and roll rates are washed out. The yaw rate is fed straight through due to the continuous yaw capabilities of the IPT motion platform.

4.2 Aerial Platform

The authors are particularly interested in UAV rotorcraft because they are well suited to fulfill missions like medevac and cargo transport which demand hovering, pirouettes and precision positioning. For proof of concept, the immediate goal was

Table 1 Select ETC GYRO IPT II motion system capabilities

Degree of freedom	Displacement	Speed	Acceleration
Pitch	±25°	0.5–25°/s	0.5–50°/s^2
Roll	±25°	0.5–25°/s	0.5–50°/s^2
Continuous yaw	±360° continuous	0.5–150°/s	0.5–15°/s^2

For complete specs please see ETC website

Fig. 7 The Sig Giant Kadet model aircraft used as the testing platform

to ensure a master-slave setup where the UAV's motions can be reproduced (in real-time) on a motion platform. To build system components, a fixed-wing UAV was used for initial demonstrations.

Rather than start with a Mako which costs on the order of thousands of dollars, the Sig Kadet offers a much cheaper, and quicker crash recovery solution for initial tests. With the Sig Kadet, the proper sensor suite and communication issues can be worked out before switching to an aircraft like the Mako shown in the earlier simulation section of this paper. The Sig Kadet shown in Fig. 7 is a very stable flight platform and is capable of carrying a sensor suite and camera system. It uses five servo motors controlled by pulse position modulated (PPM) signals to actuate the elevator, ailerons, rudder and throttle. With its 80 in. wingspan, it is comparable in size to the smaller back packable UAVs like the FQM-151 Pointer and the Raven [17].

4.3 On Board Sensors

On board the aircraft is a robotic vehicle sensor suite developed by Crossbow inertial systems. The MNAV100CA (MNAV) is a 6-*df* inertial measurement unit (IMU) measuring on board accelerations and angular rates at 50 Hz. It is also capable of measuring altitude, airspeed, GPS and heading. The MNAV is attached to the Stargate, also from Crossbow, which is an on board Linux single board computer. The Stargate is set to transmit the MNAV data at 20 Hz to the ground station via a wireless 802.11 link. As shown in Fig. 8, the MNAV and Stargate fit inside the cockpit of the Sig Kadet close to the aircraft's center of gravity.

On board video is streamed in real time to the ground station via a 2.4 GHz wireless transmission link. The transmitter is held under the belly of the Sig Kadet and the camera is located off the left wing of the aircraft. The current camera used has a 70° field of view and is capable of transmitting images at 30 FPS and 640 × 480 to a distance of 1.5 miles (AAR03-4/450 Camera from wirelessvideocameras.net). This is relatively low quality as compared with high definition camera systems but it is inexpensive, making it a decent choice for initial tests. Future tests will include much higher resolution cameras for a better visual for the pilots and a more strategic placement of the camera to replicate a pilot's on board view.

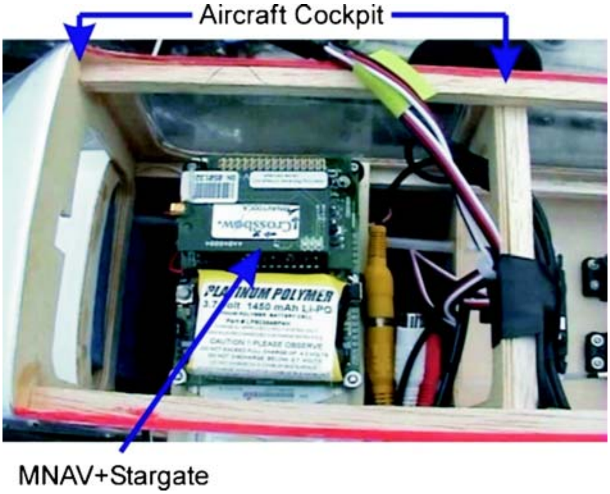


Fig. 8 MNAV and Stargate in the cockpit of the aircraft (top view)

4.4 PC to RC

Encoder positions of the flight stick, rudder pedals, and throttle inside the motion platform are transmitted via an Ethernet link to the ground station. The signals are then routed through a PC to RC circuit that converts the integer values of the encoders to pulse position modulated (PPM) signals. The PPM signals are sent through the buddy port of a 72 MHz RC transmitter which then transmits the signal to the RC receiver on board the aircraft. The PPM signals are routed to the appropriate servos to control the position of the ailerons, elevator, rudder, and throttle of the aircraft. The positions of the IPT flight controls are currently sent through the PC to RC link at a rate of 15 Hz.

4.5 Ground Station

The ground station used for the tele-operation system is a highly modified (by the authors) version of the MNAV Autopilot Ground station freely distributed on SourceForge.net. The modified ground station does three things. (1) It receives all the information being transmitted wirelessly from the MNAV and displays it to the user operating the ground station. (2) It acts as the communication hub between the aircraft and the motion platform. It relays the MNAV information via Ethernet link to the motion platform computers and sends the flight control positions of the motion platform to the PC to RC circuit via USB. (3) It continuously monitors the state of the communication link between the motion platform and the MNAV. If something fails it will put both the motion platform and aircraft (via the MNAV/Stargate) into a safe state. Determining if the ground station responds to an IMU or X-Plane data packets is set by assigning either the IP address of the IMU or the IP address of the simulator in the IPT ground station.

4.6 Field Tests

Current field tests have been conducted at a local RC flying field with the aircraft under full RC control. The field is approximately a half mile wide and a quarter mile deep. Avionics data such as angular velocity rates, accelerations and elevation was collected and recorded by the MNAV attached to the aircraft during flight. Video from the onboard camera was streamed wirelessly to the ground station and recorded. During each flight, the RC pilot conducted take off, figure eight patterns and landing with the Sig Kadet.

5 Initial Test Results and Discussion

As of writing this paper, the simulation portion was coming to completion and preparing for pilot testing and verification. In this section, the authors will present initial test results from the hardware control portion of the UAV system. In this prototyping stage, development was divided into three specific tasks that include: (1) motion platform control using the MNAV, (2) control of the aircraft servos using the IPT flight controls and (3) recording of actual flight data from the MNAV and replay on the IPT.

5.1 Motion Platform Control with MNAV

Aircraft angular rates are measured using the MNAV and this information is transmitted down to the ground station via a 20 Hz wireless link. Task A demonstrated the MNAV's ability to communicate with the ground station and the IPT. The MNAV was held in hand and commanded pitch, roll and yaw motion to the IPT by rotating the MNAV in the pitch, roll and yaw directions as seen in Fig. 6 (showing pitch).

Motions of the MNAV and IPT were recorded. Figure 9 shows a plot comparing MNAV and IPT data. The IPT is designed to replicate actual flight motions and therefore is not capable of recreating the very high angular rates commanded with the MNAV during the hand tests in the roll and pitch axis. The IPT handles this by decreasing the value of the rates to be within its bandwidth and it also filters out some of the noise associated with the MNAV sensor. Overall, the IPT tracked the motion being commanded by the MNAV fairly well. The IPT is limited by its reachable work space which is why the amplitude of the angular rates does not match at times.

Of considerable interest is the lag between the commanded angular rates and the response from the IPT motion platform, particularly with the yaw axis. This may be a limitation of the motion platform and is currently being assessed. Minimal lag is desired as significant differences between the motion cues from the IPT and visuals from the video feed will cause a quick onset of pilot vertigo.

5.2 Control of Aircraft Servos

Transmitting wirelessly at 15 Hz, no lag was observed between the instructor's flight box commands and the servo motor response. This is significant because it means

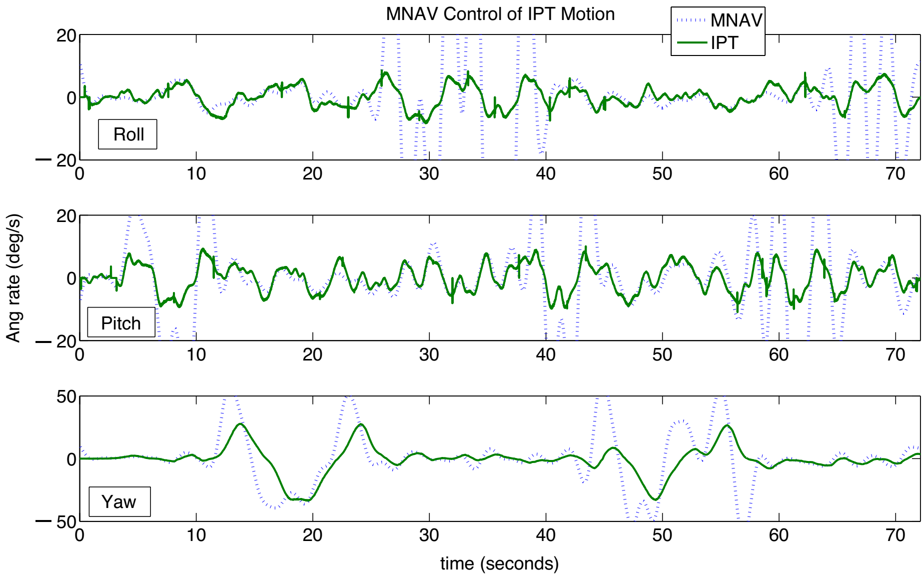


Fig. 9 Comparison of the angular rates during MNAV control of the IPT

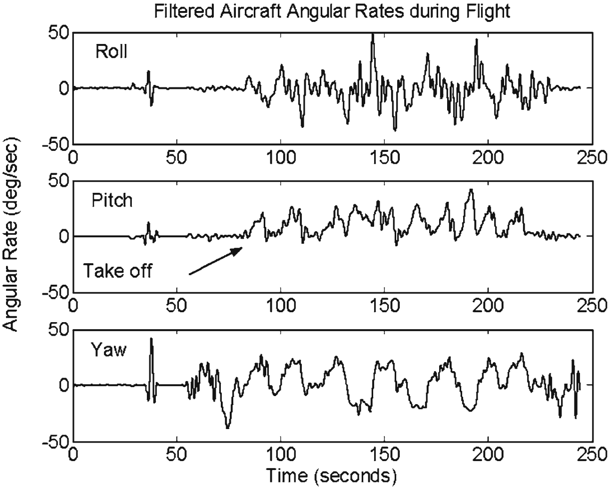
that the pilot sitting inside the motion platform can control the aircraft through the RC link. This underscores fidelity; the aircraft will respond as if the pilot was inside its cockpit and flying the aircraft. This has only been tested during line of sight control. RC is limited in range and as stated earlier, satellite communication links for long range distances can introduce delays in data transfer. However the authors imagine near-Earth UAV applications will be conducted with groundstations near the operation site.

5.3 Record and Replay Real Flight Data

Task A demonstrated that the MNAV is able to transmit motion data to the IPT. During this task the MNAV was subjected to extreme rates and poses. Such extremes are not representative of actual aircraft angular rates but serve to demonstrate master-slave capability. To test the IPT's ability to respond to actual aircraft angular rates being sent from the MNAV, angular rate data was recorded directly from a field flight of the Sig Kadet. This data was replayed on the IPT along with on board flight video. The recorded video and flight data simulate the real time streaming information that would occur during a field tele-operation experiment. An example of the recorded angular rates from one of the field tests is shown in Fig. 10 and a still shot of the on board video recording is shown in Fig. 11.

Initial results showed errors in the angular rates between the observed motion and the recorded data. For example, the pitch rate (Fig. 10), while it is oscillating, rarely

Fig. 10 Filtered angular rates during actual aircraft flight



goes negative. This means that the sensor is measuring a positive pitch rate during most of the flight. Comparison of the rates with onboard aircraft video shows the error varying throughout the data so it is not a simple offset fix. This was consistently the case for multiple flights. The authors emphasize that this phenomenon was only seen during flights. Hand held motions always produced correct and expected angular rates. The recorded flight data was replayed on the IPT motion platform. This caused the IPT to travel and remain at its kinematic joint limits as was expected because of the aforementioned positive pitch rate.

The IMU was re-visited to output angular rates that reflect the bias correction made in the Kalman filter for the rate gyros [22]. A plot of the biases during a real flight is shown in Fig. 12. The resulting biases were very small and did little to fix the positive pitch rate phenomenon during flights. Alternative IMUs are thus

Fig. 11 Onboard camera view off of the left wing during flight

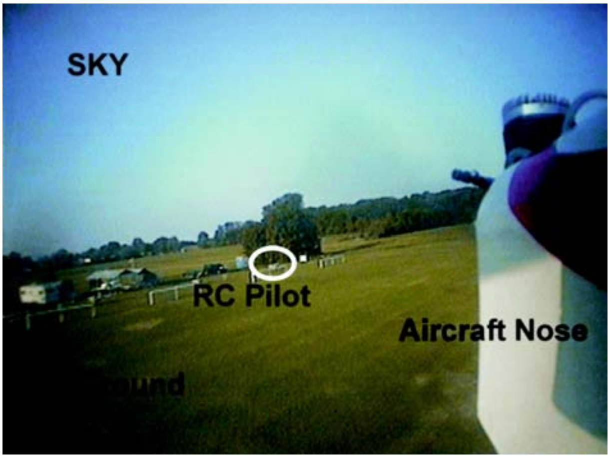
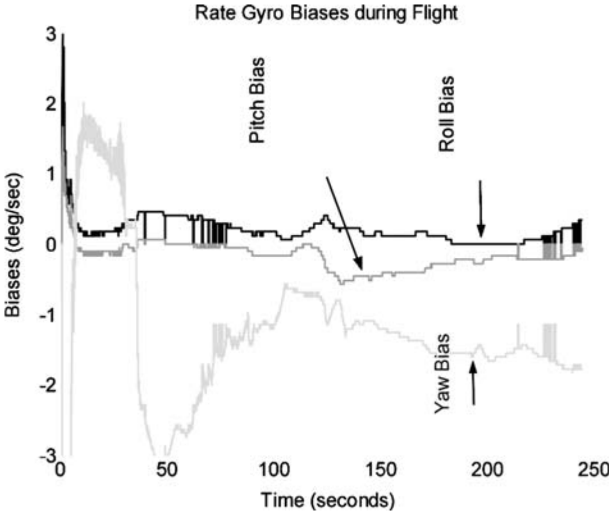


Fig. 12 Rate gyro biases during actual aircraft flight



being explored at this prototyping stage. None the less, the integration of an IMU and motion platform was successfully developed. This underscores that the wireless communication interface and low-level avionics work as designed.

Fig. 13 UAV cargo transport in a cluttered environment using a radio link that slaves robotic helicopter motions to the motion platform. Through a "shared fate" sensation the pilot flies by "feeling" the UAV's response to maneuvers commanded by the pilot

6 Conclusion and Future Work

While the future of UAVs is promising, the lack of technical standards and fault tolerant systems are fundamental gaps preventing a vertical advance in UAV innovation, technology research, development and market growth. This paper has presented the development of the first steps toward a novel tele-operation paradigm that employs motion cueing to augment UAV operator performance and improve UAV flight training. This method has the potential to decrease the number of UAV accidents and increase the applicability of unmanned technology.

Leveraging this work, future development includes research to eliminate, reduce, or compensate for the motion lag in the motion platform. Also to be examined are additional cues like sight, touch and sound that may improve UAV control. Utilizing the system for accident reconstruction will also be assessed. The net effect is that from such understanding, one can analytically design systems to better control UAVs, train UAV pilots and help eliminate UAV accidents.

The shared fate and motion cueing will have tremendous benefit in near-Earth flying. Figure 13 depicts a notional mission involving cargo pickup and transport through a cluttered terrain to a target location. The motion platform can be used to implement a virtual “shared fate” infrastructure to command a robotic helicopter. The visuals from the helicopter’s on board cameras would be transmitted to the motion platform cockpit. Added cues like audio, vibration, and motion would enable the pilot to perform precision maneuvers in cluttered environments like forests or urban structures. Future work demands the look at rotorcraft because their potential applications extend beyond the capabilities of current fixed wing UAVs. There are still a number of beneficial, life saving applications that are unachievable with current UAV methods. Among these are applications such as search and rescue and fire fighting. Even cargo transport is still very difficult to achieve autonomously in non-optimal conditions and cluttered environments. These tasks require quick, precise maneuvers and dynamic mission plans due to quickly changing environment conditions and close quarter terrain. To date these missions can only be flown by experienced, on board pilots, who still incur a great deal of risk.

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Networking Issues for Small Unmanned Aircraft Systems

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Abstract This paper explores networking issues that arise as a result of the operational requirements of future applications of small unmanned aircraft systems. Small unmanned aircraft systems have the potential to create new applications and markets in civil domains, enable many disruptive technologies, and put considerable stress on air traffic control systems. The operational requirements lead to networking requirements that are mapped to three different conceptual axes that include network connectivity, data delivery, and service discovery. The location of small UAS networking requirements and limitations along these axes has implications on the networking architectures that should be deployed. The delay-tolerant mobile ad-hoc network architecture offers the best option in terms of flexibility, reliability, robustness, and performance compared to other possibilities. This network architecture also provides the opportunity to exploit controlled mobility to improve performance when the network becomes stressed or fractured.

Keywords Unmanned aircraft system · UAS · Airborne communication networks · Controlled mobility · Heterogeneous unmanned aircraft system · Mobile ad-hoc networking · Delay tolerant networking

1 Introduction

The proliferation of small unmanned aircraft systems (UAS) for military applications has led to rapid technological advancement and a large UAS-savvy workforce poised

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to propel unmanned aircraft into new areas and markets in civil domains. Small unmanned aircraft systems have already been fielded for missions such as law enforcement [29], wildfire management [34], pollutant studies [10], polar weather monitoring [11], and hurricane observation [26]. Proposed UAS span numerous more future civilian, commercial, and scientific applications. A recent study concluded that in 2017 the civil UAS market in the USA could reach $560 M out of a total (civil plus military) UAS market of approximately $5.0 B [32]. That study projects 1,500 civil UAS will be in service in 2017 and that approximately 85% of those will be small UAS.

As the number of fielded small UAS grows, networked communication will become an increasingly vital issue for small UAS development. The largest current barrier to the use of unmanned aircraft in the National Airspace System (NAS) of the USA is satisfaction of Federal Aviation Administration (FAA) regulations regarding safe flight operations and Air Traffic Control (ATC). In particular, the FAA requires almost all aircraft operating in the NAS to have a detect, sense, and avoid (DSA) capability [3] that provides an equivalent level of safety compared to manned aircraft [1, 33]. While onboard sensors are expected to be a component of future DSA solutions, communication to ATC and operator intervention will also be required, either from a regulatory or practical perspective. Thus, one of the primary concerns of the FAA regarding the ability of UAS to meet safety regulations without conflicting with existing systems is the availability and allocation of bandwidth and spectrum for communication, command, and control [2]. Although the particular regulations just mentioned refer to operation in the USA, similar concerns apply to the operation of small UAS anywhere.

Small unmanned aircraft (UA) are defined here to encompass the Micro, Mini, and Close Range categories defined in [5]. This classification means small UA have maximum takeoff weight less than or equal to 150 kg, maximum range of 30 km, and maximum altitude of 4,000 m mean sea level (MSL). The weight limit effectively means small UA can not carry the equivalent weight of a human operator. The altitude limit taken here means small UA cannot fly into Class A airspace (the airspace from 18,000 to 60,000 ft MSL where commercial aircraft fly). Although it may be possible for vehicles in this category to fly at higher altitudes, the regulatory issues are significantly more challenging and it is reasonable to assume most small UA will not fly in that airspace. In fact, most small UA would probably fly substantially closer to the ground. Likewise, the maximum range of 30 km represents typical operational limits on this class of aircraft and there can be notable exceptions [11]. Finally, note that a small UAS can be comprised of multiple heterogeneous small UA with highly varying capabilities.

Unlike larger unmanned aircraft, small UAS are in a unique regime where the ability to carry mitigating technology onboard is limited yet the potential for damage is high. Given the size and payload constraints of small UAS, these unmanned aircraft have limited onboard power, sensing, communication, and computation. Although the payload capacity of a small UAS is limiting, the kinetic energy stored in a 150 kg aircraft can cause significant damage to other aircraft, buildings, and people on the ground. Furthermore, the limited sizes of small UAS make them accessible to a wider audience (e.g. a variety of universities already have small UAS programs [4, 9, 16, 21, 28]) than larger systems and the percentage of small UAS deployed in the future will likely be high relative to larger unmanned aircraft systems [32]. The limited capabilities of small UAS lead to unique operational requirements compared to larger UA that can more easily assimilate into the existing ATC framework (e.g. larger UA can carry the same transponder equipment as manned aircraft).

This paper explores networking issues that arise as a result of the operational requirements of future applications of small unmanned aircraft systems. These requirements are derived from a set of representative application scenarios. The operational requirements then lead to networking requirements (e.g. throughput, which is the rate at which data can be sent over a communication link, and latency or delay) that greatly exceed those of current manned aircraft. Further, the networking requirements are mapped to three different conceptual axes that include network connectivity, data delivery, and service discovery. The location of small UAS networking requirements and limitations along these axes has implications on the networking architectures that should be deployed.

Of the existing possible network architectures for small UAS, only delay-tolerant mobile ad-hoc networking architectures will provide the needed communication for the large number of small aircraft expected to be deployed in the future. Since small UA are relatively cheap, future UAS will likely deploy multiple vehicles coordinated together. Many small UAS applications will require quick response times in areas where permanent supporting communication infrastructures will not exist. Furthermore, current approaches using powerful long-range or satellite communications are too big and expensive for small aircraft while smaller radios fundamentally limit the small UAS operational envelope in terms of range, altitude, and payload. The delay-tolerant mobile ad-hoc network architecture offers the best option in terms of flexibility, reliability, robustness, and performance compared to other possibilities. This network architecture also provides the opportunity to exploit controlled mobility to improve performance when the network becomes stressed or fractured.

2 Communication Requirements

2.1 Operational Requirements

This work is motivated by the Heterogeneous Unmanned Aircraft System (HUAS) developed at the University of Colorado as a platform to study airborne communication networks and multivehicle cooperative control (Fig. 1 shows the various small UA included in HUAS). Specific applications studied to date include the impact of mobility on airborne wireless communication using off the shelf IEEE 802.11b (WiFi) radios [7]; net-centric communication, command, and control of small UAS [16]; sensor data collection [22]; delay tolerant networking [6]; and a framework for controlled mobility that integrates direct, relay, and ferrying communication concepts [13].

As an example application consider a UAS to track a toxic plume. In this scenario a toxic plume has been released in an accident and the goal is to locate the plume extent and source [17]. To characterize the plume, multiple small UA fly while sensing the plume with onboard chemical sensors. Different sensors may be in different UA because it may not be possible or desirable for every small UA to carry every sensor. UA with the same chemical sensors onboard need to find each other to form gradient seeking pairs. Chemical gradients can be defined by sharing sensor

Fig. 1 The HUAS vehicle fleet includes (*clockwise from top left*) the CU Ares, the CU MUA, the Velocity XL, the MLB Bat 3, the CU ground control station, and the Hobico NextGen

data and the UAS can cooperatively track boundaries or follow the gradients to the source. UA can potentially move far away from their launching ground stations and each other. In this example, the UAS consists of potentially many heterogeneous UA. They need to fly freely over a large area and be able to dynamically form associations autonomously without relying on a centralized controller.

As a second example consider a UAS deployed to act as a communication network over a disaster area. Here, normal communication infrastructure has been damaged but various entities on the ground such as first responders, relief agencies, and local inhabitants require communication in order to organize a coordinated response. An unmanned aircraft system flying overhead can provide a meshed communication architecture that connects local devices, e.g. laptops with wireless networking or cell phones, with each other or back to the larger communication grid. Since communication demand will vary as the severity of the disaster is assessed and relief efforts are mounted, the UAS must be able to reposition itself in response. Since the actions of the ground units are in direct response to the emergency situation, the actions of the UAS must be dependent on them and not limit their efforts. Also, the UAS will likely operate in the vicinity of buildings and other manned aircraft so obstacle and collision avoidance will be critical.

The two scenarios described above share properties with many other potential small UAS applications and lead to communication requirements for the UAS itself. In particular, these communication needs can be broadly classified into platform safety, remote piloting, and payload management (Fig. 2). In general, the UAS will communicate with multiple external parties that could include ATC, the pilot, and payload operators who may be in widely separate locations.

2.1.1 Platform Safety

From a regulatory perspective, platform safety is the most critical component of an unmanned aircraft system. Like a manned aircraft, the pilot of the UAS must communicate with ATC in most controlled airspace [33]. This communication may be mediated by the UAS whereby the UAS communicates via conventional radio

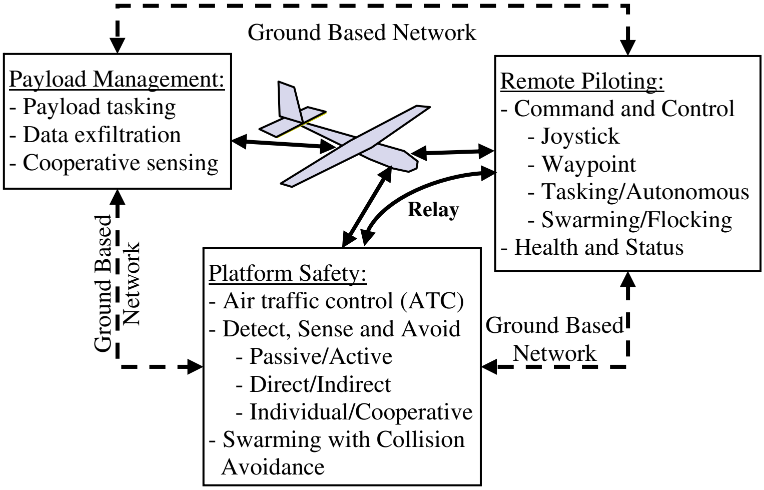


Fig. 2 Types of communication in an unmanned aircraft system

to the ATC and this communication is then backhauled to the pilot. This implies an inherent inefficiency. A single ATC radio channel is shared by all planes in an area. But, each UA requires a separate backhaul to its respective operator, and multiplies the communication requirements. Future non-voice approaches to managing aircraft are being contemplated [14]. In principle, ATC commands (e.g. to change altitude) could be acted upon directly by the UA without pilot intervention obviating the need for the inefficient backhaul. However, it is likely that a pilot will always be expected to be "on the loop" so that UAS operations are completely transparent to ATC. Future communication system analysis estimates the average ATC voice and data rates to be about 10 kbps per aircraft particularly in autonomous operations areas typical of UAS operations [14].

Other platform safety communication is related to detect, sense, and avoid requirements which generally require the UAS to have equivalent ability to avoid collisions as manned aircraft [1, 33]. This may require onboard radar (active sensing), backhaul of image data (passive sensing), transponders, or cooperative sharing of information between UA. The communication requirements here can depend significantly on the approach. The least communication demands are required when the aircraft uses active sensing, only reports potential collisions to the operator, and autonomously performs evasive maneuvers when collisions are imminent. The communication requirements here are negligible. More demanding systems send full visual situational awareness to the operator which can require 1 Mbps or more (e.g. Fig. 3).

The communication requirements for small UAS are simplified in many instances. Small UAS often fly in uncontrolled airspace. No transponders are required, nor is communication with ATC. Small UAS can operate directly in uncontrolled airspace without the need of an airport. They are often catapult or hand launched and can have parachute, net, or snag recovery systems. Small UAS generally fly over smaller regions than larger UAS. Small UAS are still subject to DSA requirements, however, for very short ranges, the pilot or spotters on the ground can provide the see and

Fig. 3 Situational awareness provide by imagery from onboard a small UA

avoid. For larger ranges active or passive techniques are required. The smaller platform size limits the ability to carry onboard autonomous DSA systems.

Small UAS participating in the example scenarios described in Section 2.1 will clearly be operating in environments with significant other air traffic so platform safety will be important. Manned aircraft for emergency response and from news agencies will surely operate in the environment where the UAS will be deployed. The UAS pilot will require significant communication with ATC to coordinate operation with these other aircraft. From the perspective of network or radio bandwidth and throughput, the requirements for this communication traffic are low since messages are limited in size (or length) and are sent sporadically. However, the safety critical nature of this traffic will require high reliability with low latency.

2.1.2 Remote Piloting

Remote piloting of the vehicle has requirements that vary with the type of flight control. On one extreme is direct joystick control of the aircraft. This requires low delay and high availability. At the other extreme, tasking commands are sent to the aircraft which are autonomously translated to flight paths (Fig. 4 shows the user interface for the Piccolo autopilot that allows for point and click commands [31]). Here delays can be longer and gaps in availability can be tolerated. The UA to

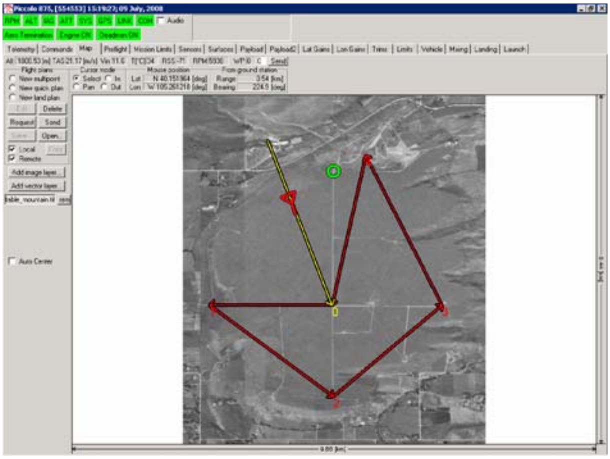


Fig. 4 Cloud cap technologies piccolo autopilot command center [31]

pilot link contains not only commands from the pilot to the UA but also essential health and status information from the aircraft back to the pilot. As examples, on the joystick end of the spectrum commercial digital radio control (R/C) links have data rates below 10 kbps and one-way delays below 100 ms are preferred. On the autonomous end of the spectrum, an Iridium satellite link is sufficient for waypoint flying of the Predator UAS. Iridium has 2.1 kbps throughput, delays of 1–7 s, and has gaps in connectivity with 96% average availability [25].

Small UAS are lower cost and are more likely to operate in cooperative groups. There is a strong push to enable one-to-many pilot-aircraft interactions for UAS [27]. This mode of operation would require increased amounts of UA autonomy with the pilot in charge of higher level mission planning and tasking. As such, UA must be capable of autonomous collision avoidance and therefore plane-to-plane communication becomes another significant communication component. Collision avoidance between two UA will also have low data rate and low latency requirements. However, the presence of multiple vehicles all performing plane-to-plane communication complicates the networking and introduces the need for bandwidth and congestion control. The possibility of varied capabilities and aircraft attrition also necessitates dynamic service discovery routines whereby system capabilities can be updated internally.

2.1.3 Payload Management

Communication with the payload can range from a few bits per second for simple sensor readings to megabits per second for high-quality images (Fig. 5). For instance, the Predator uses a 4.5 Mbps microwave link to communicate payload imagery when in line-of-site of the ground station [23]. The types of payload communication needed by small UAS can be highly varied. For example, depending on the type of chemical plume being tracked, real-time data assimilation may not be needed. In that case large amounts of data can be stored at intermediate nodes and transmitted opportunistically back to the end user. In contrast, if a toxic substance is released in an urban setting, source localization could take priority over all other requirements including DSA. Using multiple UA to provide information to multiple dispersed users also necessitates dynamic service discovery routines.

In summary, the communication requirements for UAS are modest for ATC communication and remote piloting while UAS can potentially require data rates in the megabits per second for payload management and DSA. It is this requirement for multiple connections, some of which are at high data rates, that distinguishes UAS from manned aircraft communications. There are also other considerations

Fig. 5 High quality payload imagery from the MLB Bat small UAS [24]

than data rates, latency, and availability. ATC, remote piloting, and other flight safety communication will likely be required to operate in protected spectrum that is not shared with payload and non-essential communication [14, 20].

2.2 Operational Networking Requirements

The communication needs can be explored along three axis (Fig. 6). The first is connectivity. In traditional networks, node connectivity is well defined; a physical wire connects two nodes. These links are designed to be reliable with rare transmission errors. Further, the links and nodes are stable with only rare failures. This yields a well defined network topology with clear notions of graph connectivity that is consistent across network nodes. In a small UAS, the links are less reliable wireless links with connectivity that ranges from good when nodes are close to poor for nodes that are further away. Even when connectivity is good packet error rates are high relative to wired standards. The transmission is broadcast and can reach multiple receivers so that connections are not simple graph edges. Further, broadcast transmissions interfere with each other so that the ability of two nodes to communicate depends on the other transmissions at the same time. As we add UA mobility, connectivity becomes dynamic and as UA speeds increase relative to the nominal communication range different UA may have inconsistent notions of connectivity.

The second axis is data delivery. In traditional networks, connectivity is well defined and stable so that data delivery is based on an end-to-end model. For instance, with TCP protocols the source and destination end points manage data delivery over a presumed reliable and low latency network. As these connectivity assumptions break down this model of delivery is not possible. As already noted, small UAS connectivity is unreliable and dynamic. Furthermore, small UAS may become spread out over a mission so that end-to-end connectivity simply does not exist for data delivery.

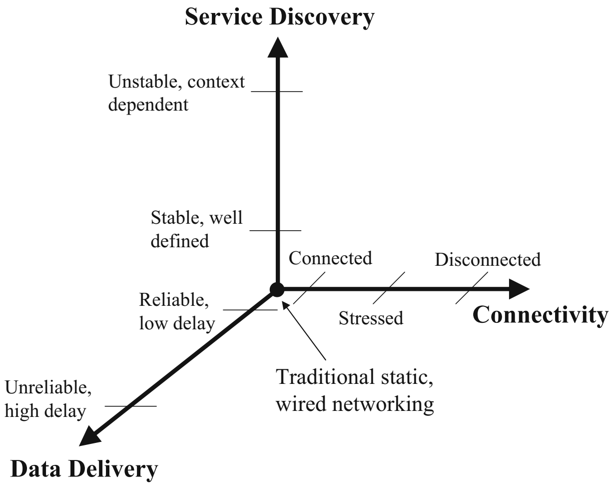


Fig. 6 Communication requirements can be characterized along three axes

The third axis is service discovery. In traditional networks, resources are stable and can be found through well defined procedures. To find a webpage, we use a URL (e.g. http://www.springer.com), this is translated by the DNS service into a network address, and we request the webpage from the server at that address. In contrast, with small UAS nodes, services, and users can come and go over the life of a mission and the resources sought may be ephemeral or context dependent. Each UA may have different capabilities (e.g. the chemical sensors in the plume tracking example) and onboard capabilities may be available for use by other UA (e.g. coordinating cameras for stereo imaging). As small UAS spread out these resources, even when they exist, may be difficult to discover. This concept of service discovery can be pushed down from aircraft to the subsystems aboard the aircraft. By connecting onboard subsystems via local subnets to the external meshed network, dispersed operators as well as other aircraft in the UAS can discover and communicate directly to different components of the aircraft avionics system.

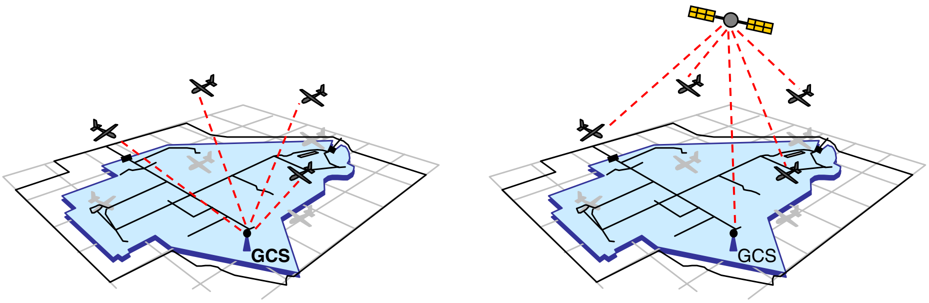
3 Networking for Small UAS

The goal of small UAS networking is to address the communication needs given that small UAS differ from traditional networks along the connectivity, data delivery, and service discovery axes. To this end, this section describes the merits of different communication architectures and introduces the delay tolerant networking delivery mechanism. It also discusses how the mobility of the small UAS can be exploited to improve networking.

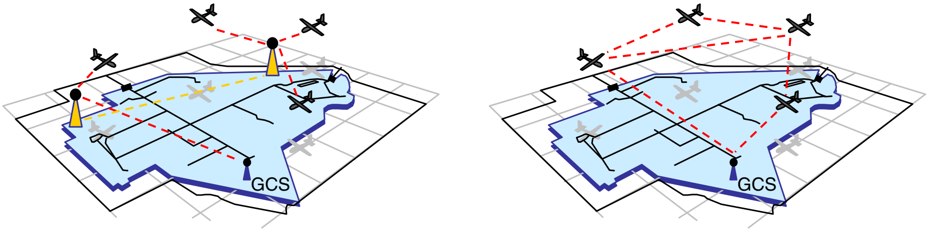
3.1 Communication Architectures

There are four basic communication architectures which can be used for small UAS applications: direct link, satellite, cellular, or mesh networking (Fig. 7). Each has advantages and disadvantages which we outline here. A direct link between the ground control station and each UA is the simplest architecture. It assumes connectivity is maintained over dedicated links to each UA and therefore data delivery is reliable with low latency. Since the ground station communicates to each UA, service discovery is easily managed by a centralized agent at the ground station. Unfortunately the direct architecture is not suited for dynamic environments and non-line-of-sight (NLOS) communication. Obstructions can block the signal, and at longer ranges the UA requires a high-power transmitter, a steerable antenna, or significant bandwidth in order to support high data rate downlinks. The amount of bandwidth scales with the number of UA so that many UAS may not operate simultaneously in the same area. Finally, plane-to-plane communication will be inefficiently routed through the ground control station in a star topology and not exploit direct communication between cooperative UA operating in the same area.

Satellite provides better coverage than a direct link to the ground control station. As a result, the UAS network can remain well connected, however this connectivity would still be provided by routing data through a centralized system. Data delivery is relatively poor using satellite. Lack of satellite bandwidth already limits existing UAS operations and will not scale with the increasing demand of 1,000s of small UAS operations in a region. For high data rate applications, a bulky steerable dish antenna mechanism unsuitable in size, weight and cost for small UAS is necessary.



(a) Direct (b) Satellite



(c) Cellular (d) Mesh

Fig. 7 Four basic communication architectures for small UAS. The ground control station (GCS) represents the operator or end user

Further, the ground control station requires a connection to the satellite downlink network. The ground control station may have obstructed satellite views because of terrain or clutter. Finally, multiple UA operating in an area will suffer high delays if their communication is mediated by satellite.

Cellular refers to an infrastructure of downlink towers similar to the ubiquitous mobile telephone infrastructure. The cellular architecture has several advantages that can provide good levels of network connectivity and reliable data delivery. First, coverage can be extended over large areas via multiple base stations. UAS would hand-off between different base stations as needed during flight. Second, the multiple base stations provide a natural redundancy so that if one link is poor another link may perform better. Third, a limited bandwidth can be reused many times over a region and capacity increased as needed to meet demand. The reuse can grow by adding more base stations as the number of users grows. Fourth, the infrastructure can be shared by different UAS. Once installed, many UAS can each pay for the fraction of the infrastructure that they use. These advantages must be weighed against the cost. A typical mobile telephone base station is expensive for the tower, tower site, radio equipment, and associated networking infrastructure. Such a solution applies where the infrastructure investment can be amortized across frequent and regular UAS flights. Examples might include agricultural monitoring or border surveillance. Such architecture is not suited for applications like wildfire management or polar climatology where demand is transient. The existing mobile telephone infrastructure is not designed for air to ground communication. A single UA transmitter can blanket a large area with its signal degrading system performance. Therefore, small UAS operations may require a dedicated cellular infrastructure.