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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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J. T. Hing (✉) · P. Y. Oh
Drexel Autonomous Systems Laboratory (DASL),
Drexel University, Philadelphia, PA 19104, USA
e-mail: jth23@drexel.edu

P. Y. Oh
e-mail: paul@coe.drexel.edu

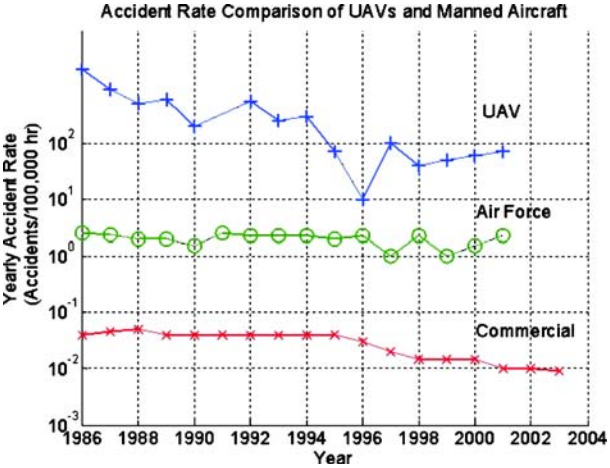


Fig. 1 Comparison of accident rates (data [2])

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

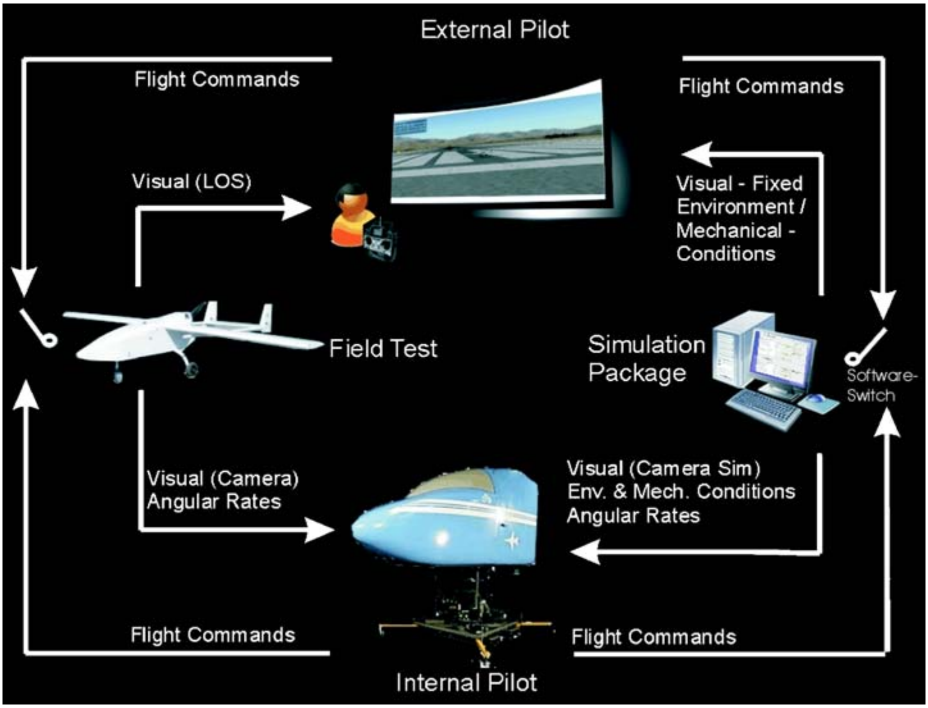


Fig. 2 Experimental setup for evaluating the effectiveness of motion cueing for UAV control. The benefit of this system is that pilots learn on the same system for simulation as they would use in the field

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.

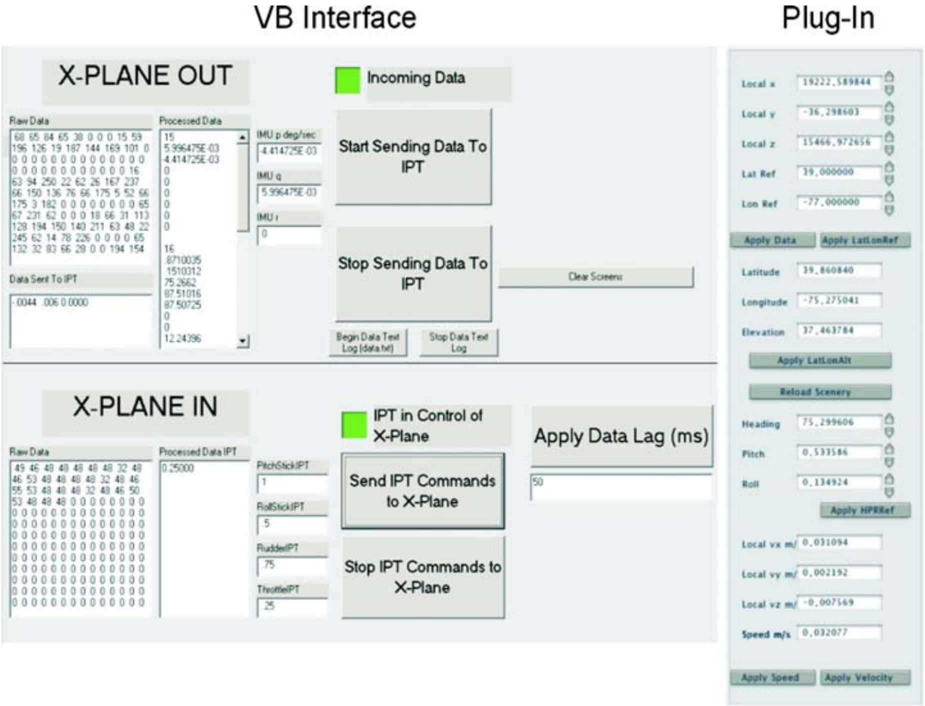
Fig. 4 Simulator screen shots using the Mako UAV model. *Left* external pilot view point with telemetry data presented on screen. In the real world, this data is normally relayed to the pilot through a headset. *Right* internal view point with telemetry data presented. The view simulates a nose camera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

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.

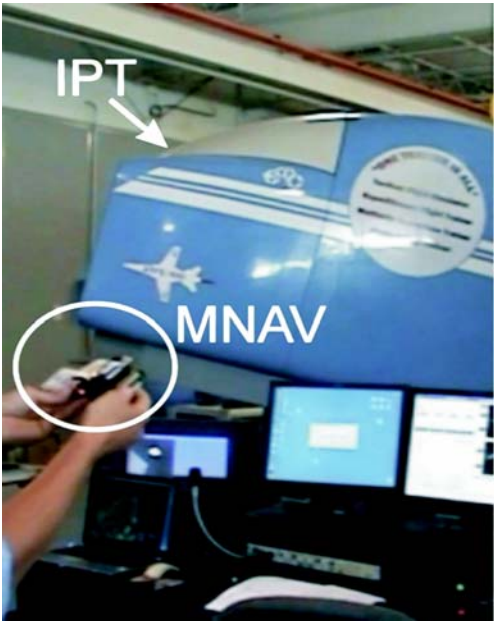


Fig. 6 IPT 4-*dof* motion platform from ETC being wirelessly controlled with the MNAV

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.

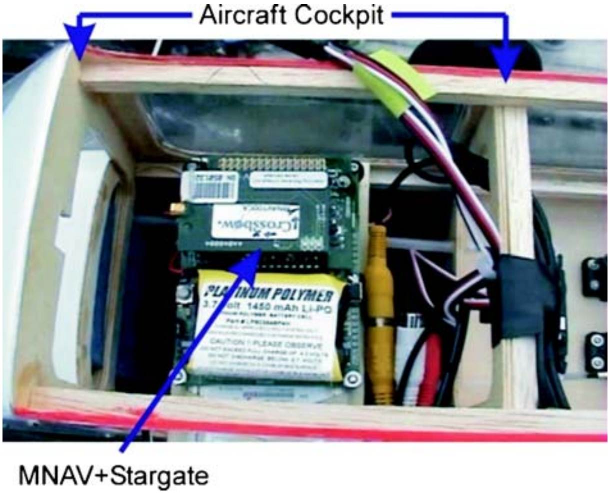


Fig. 8 MNAV and Stargate in the cockpit of the aircraft (top view)

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

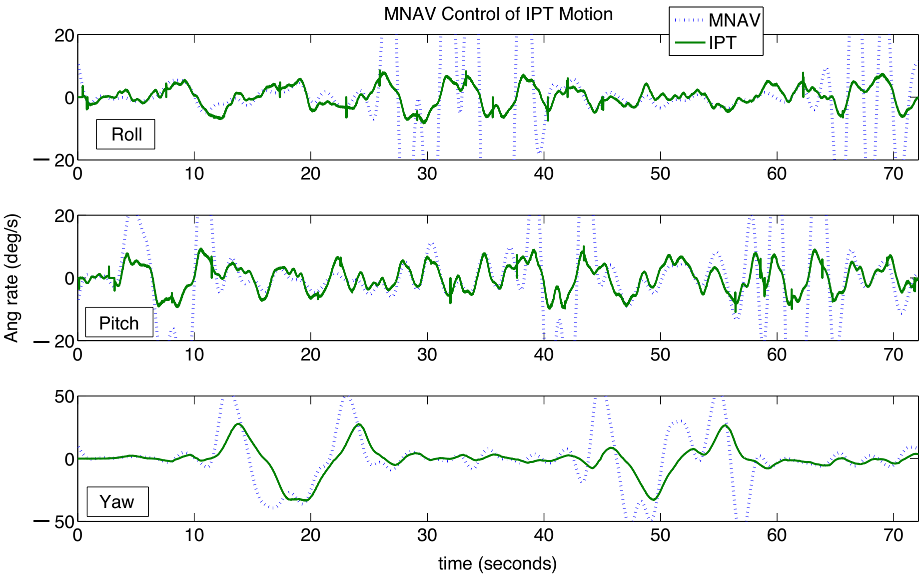


Fig. 9 Comparison of the angular rates during MNAV control of the IPT

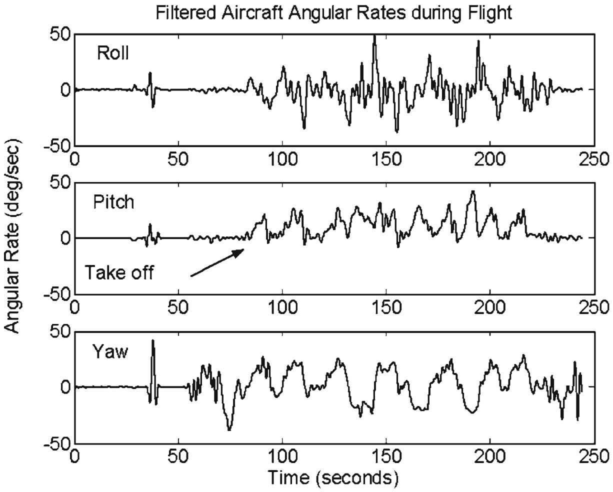
that the pilot sitting inside the motion platform can control the aircraft through the RC link. This underscores fidelity; the aircraft will respond as if the pilot was inside its cockpit and flying the aircraft. This has only been tested during line of sight control. RC is limited in range and as stated 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

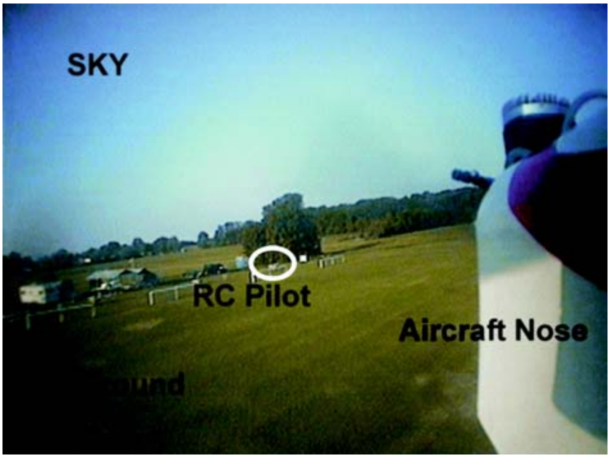
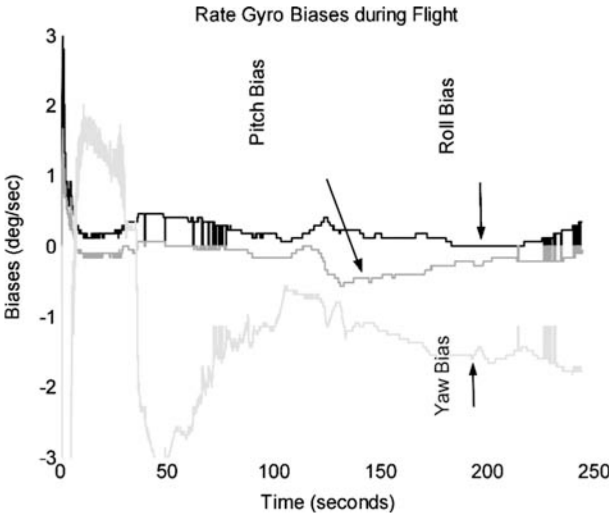


Fig. 12 Rate gyro biases during actual aircraft flight



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.

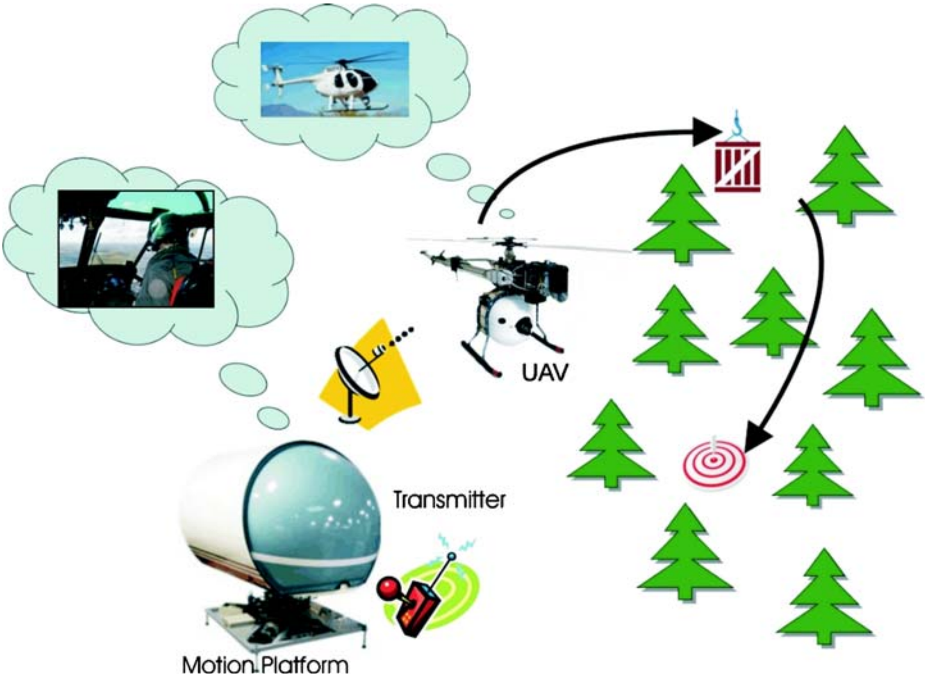


Fig. 13 UAV cargo transport in a cluttered environment using a radio link that slaves robotic helicopter motions to the motion platform. Through a "shared fate" sensation the pilot flies by "feeling" the UAV's response to maneuvers commanded by the pilot

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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