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Development of the UIUC Aero Testbed: A Large-Scale Unmanned Electric Aerobatic Aircraft for Aerodynamics Research

Or D. Dantsker,* Miles J. Johnson,† Michael S. Selig,‡ and Timothy W. Bretl§

University of Illinois at Urbana–Champaign, Department of Aerospace Engineering, Urbana, IL 61801

This paper describes the development of a large 35%-scale unmanned aerobatic platform named the UIUC Aero Testbed, which is primarily intended to perform aerodynamics research in the full flight regime. The giant-scale aircraft with a 105-in (2.7-m) wingspan and weight of 37 lb (17 kg) was constructed from a commercially available radio control model aircraft with extensive modifications and upgrades including a 12-kW electric motor system that provides a thrust-to-weight ratio in excess of 2-to-1. It is equipped with an avionics suite that contains a high-frequency, high-resolution six degree-of-freedom (6-DOF) inertial measurement unit (IMU) that allows the system to collect aircraft state data. This information set can be used to generate high-fidelity aerodynamic data that can be used to validate high angle-of-attack flight-dynamic models. Collaboration in this project also led the Aero Testbed to have the capability to fly fully- and semi-autonomously in order to conduct autonomous flight research. A literature review of aerobatic unmanned aircraft used for research is first presented. Then the background and motivations for developing this platform are discussed. This is followed by a description of the planning and development that was involved. Finally, initial test flight results are presented, which include flight path trajectory plots of several aerobatic maneuvers.

Nomenclature

AVI	=	avionics integration
ARF	=	almost ready to fly
$COTS$	=	commercial off the shelf
CG	=	center of gravity
DOF	=	degree of freedom
EEG	=	electroencephalogram
IMU	=	inertial measurement unit
RC	=	radio control

I. Introduction

Numerous unmanned aircraft have been developed in recent years by universities for a variety of tasks. A rather small number of them have aerobatic designs allowing them to perform maneuvers that would be outside the scope of the normal flight regime. Some of these aerobatic unmanned aircraft are used for aerodynamics research while the majority are used for guidance and control research. These aircraft largely vary in size and weight from having a 10-in wingspan and weighing a few ounces to having a 10-ft wingspan and weighing 30 to 50 lb.

The UIUC Applied Aerodynamics Group recently developed and began testing a large unmanned aerobatic aircraft, referred to as the UIUC Aero Testbed. This research platform is a highly-instrumented 35%-scale model of the full-scale Extra 260 aerobatic aircraft. The platform was developed from a commercial off the shelf (COTS) airframe and has a 105-in wingspan and weighs 37 lb. It is powered by a 13-kW electric motor that provides the aircraft with a

*Graduate Research Fellow, AIAA Student Member. dantske1@illinois.edu
†Ph.D. Candidate, AIAA Student Member. mjohns50@illinois.edu
‡Associate Professor, AIAA Senior Member. m-selig@illinois.edu
§Assistant Professor, AIAA Member. tbretl@illinois.edu

thrust-to-weight ratio of greater than 2-to-1. The Aero Testbed is primary used for acquiring aircraft state data for high-fidelity aerodynamics research, but it is also equipped such that it can be used for autonomous flight research.

This paper will first briefly examine other universities' aerobatic unmanned aircraft. The paper will then discuss the background and motivations behind developing the UIUC Aero Testbed. After that is a description of the methodology used in the planning and then the development of the Aero Testbed along with the specifications. Results from initial testing will be presented and finally a summary is given.

Figure 1. A photograph of the UIUC Aero Testbed, which is an electric unmanned 35% scale Extra 260 aerobatic aircraft with a 105 in wingspan, a weight of 37 lb, and is instrumented with an avionics suite that includes a 6-DOF inertial measurement unit, GPS receiver, and pitot probe among other sensors.

A. Literature Review of Aerobatic Unmanned Aircraft Used for Research

Many universities have developed unmanned aircraft for research in a variety of fields. However, focus here is placed on fixed-wing aerobatic aircraft, as this is the area relevant to the aircraft developed. Aerobatic unmanned aircraft used in research vary greatly in size, from a 10-in wingspan and weighing a few ounces to a 10-ft wingspan and weighing 30 to 50 lb. Generally, smaller aircraft are flown indoors and larger aircraft are flown outdoors. These aircraft are sometimes developed for use in aerodynamics research but more often end up being used as test vehicles for hardware and/or control-scheme algorithms.

When performing research with miniature unmanned aerobatic aircraft, state data is collected externally using motion capture systems set in indoor flying spaces with no wind. For aircraft that are flown autonomously, the position data is used to close the loop in the control schemes. This was the case with researchers at the Georgia Institute of Technology, where a miniature indoor aerobatic aircraft was used to demonstrate a guidance controller for transitions into hovering state.[1] Similar work was done at the Massachusetts Institute of Technology[2] and Universit Laval.[3] Using a similar motion capture system, researchers at the University of Illinois parameterized a micro, aerobatic aircraft to determine its aerodynamic characteristics, including lift, drag, and moment curves over a wide flight regime.[4]

Moving onto outdoor aircraft, researchers at the University of Florida used a small outdoor aerobatic unmanned aircraft to investigate aircraft high angle-of-attack flight dynamics, which included stability issues that related to side slip[5] and wing rock[6–8] and later further parameterized the same aircraft in order to design trajectory-following algorithms;[9,10] this aircraft had all sensors and recording equipment on board. However, performing experiments outdoors does come with the problem of external disturbances, the most significant of which is wind. In general, the larger the aircraft, the less the aircraft will be affected by a given amount of external disturbance. Larger aircraft also have the advantage that they are able to carry more weight, without a significant decrease in their flight performance. This is the reason why researchers in ETH Zurich choose the size they did; they used a 10.2-ft wingspan, 61-lb, unmanned aerobatic aircraft to perform a variety of aerobatic maneuvers autonomously.[11] Similar research was done at Stellenbosch University.[12,13] At the Georgia Institute of Technology, researchers used a large, 8.75-ft wingspan, 35-lb, aerobatic unmanned aircraft to perform a variety of tasks including autonomous transitions to hover.[14,15] They also used this aircraft as the flight leader in a vision-based formation flight with a large unmanned helicopter[16] and with another large, 8.5-ft wingspan, 28-lb, aerobatic aircraft.[17]

There are several examples of large aerobatic unmanned aircraft being used for risk mitigation research. Researchers at NASA ARC and LaRC used a large scale electric aerobatic aircraft with an 8.25-ft wingspan to perform research in structural fault diagnostics and mitigation, and in electric motor battery health management.[18] Work at the University of Illinois using a 6.5-ft wingspan aerobatic unmanned aircraft involved risk mitigation in the form of failure mode analysis of subsystems and components,[19] particularly fuel management,[20] system fault detection,[21] and object and terrain detection using optical flow.[22,23] The aircraft used by the University of Illinois was also used by Boeing to test distributed communication networks.[24] The University of Kansas has performed extensive testing with their large, 10-ft wingspan, aerobatic unmanned aircraft: researchers have evaluated a COTS autopilot,[25,26] tested a new flight control system,[27,28] performed aircraft and avionics system identification,[29–31] used it as the base aircraft from which a test pilot transitioned to a new unfamiliar airframe,[32] evaluated flight loads using strain gauge measurements[33] and compared moment of inertia estimation methods with experimental measurements.[34]

II. Background and Motivations

The Aero Testbed concept began with members of the UIUC Applied Aerodynamics Group striving to possess an aerobatic aircraft platform that could record high-fidelity aerodynamic data. This platform would allow for research to be done in the full-envelope flight regime, that is, over the full +/-180 deg range in angle of attack and sideslip. It would be able to record high-frequency, high-resolution aircraft state data in regular aerobatic and high angle of attack flight, outside the range of conventional aircraft and in maneuvers only achievable by recently developed unmanned aircraft and high-performance radio control (RC) model aircraft. The state data that this aircraft would record includes three dimensional linear and angular accelerations, velocities, and positions along with airspeed, control surface deflections, and engine performance. Such data could then be used in the validation of aerodynamics methods applied to aircraft stall/spin and upset scenarios, e.g., methods like those used in the real-time flight simulator FS One.[35,36] In order to develop such an aircraft, many decisions would need to be made concerning the desired aircraft performance in terms of airframe and instrumentation specifications.

Figure 2. Simulated spiral maneuver executed by the Aero Testbed in FS One V2.

The UIUC Applied Aerodynamics Group eventually collaborated on this project with the UIUC Robotics and Neuro-Mechanical Systems Laboratory. The Applied Aerodynamics Group was responsible for fabricating the airframe while the Robotics and Neuro-Mechanical Systems Laboratory would develop and integrate an avionics suite into the aircraft using the knowledge gained from developing the Fixed Wing Multi-Role Unmanned Aircraft Vehicle Research Testbed along with previously developed unmanned aircraft.[37] In terms of capability, the aircraft evolved into being a dual-purpose unmanned aerial vehicle. When the Aero Testbed would be used by the Applied Aerodynamics Group, the aircraft would be piloted from the ground using a remote control transmitter, manually performing all types of maneuvers. In the other flight configuration, while it would be flown by the Robotics and Neuro-Mechanical Systems Laboratory, the Aero Testbed would also be used for doing fully- and semi-autonomous flight. In that case, research conducted would include human interface flight, specifically using a neural interface, and autonomous flight such as flying aerobatic patterns, taking-off, and landing using a perching technique. Research using neural interfaces follows several other unmanned aircraft that were successfully flown/controlled by a pilot using an electroencephalogram (EEG) as input and live onboard video as visual feedback.[38,39] All autonomous research would be done using the onboard avionics package in autopilot mode, which would control the aircraft. It is important to note that there would be a pilot capable of remotely taking over control if necessary, via a toggle switch on the transmitter.

III. Planning

In order to develop an unmanned aerobatic aircraft that would serve well in all expected roles, careful planning was required. Planning through all stages of construction and instrumentation and examining how the aircraft would be used prevented or at least diminished the number of problems that arose. This section is separated into several sub-sections, which cover airframe and component selection through proper flight testing.

A. Airframe Size and Construction

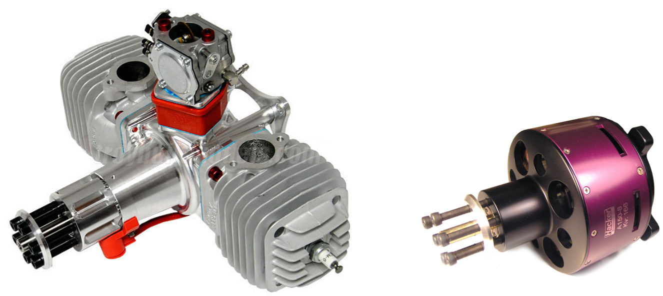
The size of the aircraft that would be developed would need to be determined. In general, a given payload weight will affect a larger aircraft less than it would a smaller one because the percentage weight increase, and therefore the loading increase, will be less due to the higher starting weight. Also, the larger the aircraft, the less it would be affected by environmental conditions such as wind. Increasing the size also makes it easier to work inside the aircraft. However, having a large aircraft does produce a variety of problems and limitations. Larger aircraft are more costly to build and operate than smaller aircraft and require a larger vehicle to transport them from the laboratory to the flying site. The nearest flying site that could facilitate the flight tests is located approximately 25 mi (40 km) away from the University of Illinois campus; this flying site is Eli Field, which is owned and maintained by the Monticello Model Masters RC Club.[40] It should be noted that in order to save valuable time in developing this platform, a COTS airframe would be used, which creates a limitation in terms of available models and their sizes. After considering these factors, it was determined that the most appropriate aircraft size range was 33–40% of full-scale aerobatic aircraft, which yields a wingspan range of 7.5–9 ft (2.3–2.7 m).

Figure 3. A photograph of Eli Field (taken from the Monticello Model Masters RC Club[40]).

Aircraft airframes in the desired size range are predominantly constructed in one of two ways. They are either built-up of plywood structures, sheeted with balsa, and then covered with a light plastic shrink wrap, or they are molded out of composites, which include carbon fiber, fiberglass, honeycomb, and sandwich of composite cloth and light-weight filler. In terms of pros and cons for each building technique, composite construction generally is lighter, yields more rigid structures, and can produce more accurate designs. Composites, however, are more expensive and difficult to repair. Wood built-up designs are relatively low cost, can easily be built, repaired, and modified but are not as rigid. Wooden designs also have the unique problem of bowing when exposed to a significant amount of sunlight, especially if the aircraft is covered by a dark-color film. Bowing is caused by the plastic film covering the aircraft: after being exposed to sunlight for a sufficient amount of time, the film heats up and contracts, which is a problem since only one half of the aircraft receives sunlight. In most cases, the film on the top side of the aircraft contracts and bows the wings and horizontal tail up. It should also be noted that there may be combinations of the two methods available, depending on the airframe, such as a composite fuselage with wooden built-up wings and tail pieces. Given the choice of construction methods, the wooden built-up structure was chosen for its versatility, which in retrospect provided the ability to modify and build off of internal structural elements that became critical in instrumenting the aircraft.

B. Airframe Propulsion

The next decision in planning the aircraft was what type of propulsion system should be used. There were several choices for an airframe of this size. The default choice was using the gasoline engine recommended for the airframe chosen or a slightly larger one, or on the other hand a large electric motor could be used. There are numerous advantages for each type of propulsion system, in terms of both practicality and data collection. Operational safety must also be considered.



(a) (b)

Figure 4. Examples of aircraft propulsion system options, at approximately the same scale: a) on the left is a Desert Aircraft DA-120 gasoline engine and b) on the right is a Hacker A150-8 electric motor (taken from Ref. 41 and Ref. 42, respectively).

First of all, using an electric motor creates much less vibrations through the aircraft. Having less vibration being transmitted throughout the aircraft decreases the noise recorded by the instruments, thereby yielding better data. In addition, having less vibrations traveling through the airframe will lower the rate of fatigue and thus increase the life of the airframe and avionics. Also, using an electric system results in no center of gravity (CG) shift during flight or weight change from fuel being burnt. Having the aircraft remain the same from takeoff to landing is important factor in examining aerodynamic data because the airframe will always have constant inertial properties throughout the flight and day-to-day. With an electric system, the input power can be measured precisely, and it is much easier to measure propeller speed (RPM) by measuring the current running through poles of the motor instead having to perform optical measurements, which are often difficult in changing light conditions. Moreover, in a practical sense, electric motors have constant performance and need not be tuned, they have much less lag in terms of throttle response than a gas engine, are much easier to install, and have few moving parts, which means they also need less maintenance, and of course they run clean (i.e., the airframe does not become covered with contaminates such as oil and fuel).

Gasoline engines are preferable to electric motors in several categories. First, all airframes in the size range desired are designed for gas engines, which means to use an electric motor requires modifications such as constructing a motor mount and battery trays. Also, an aircraft equipped with a gas engine generally has greater endurance than with an electric motor due to the fact that the fuel required for a given flight time weighs far less than the equivalent amount of batteries. Furthermore, the weight of a gas engine is the same as an electric motor with onboard equipment; however, in terms of gasoline versus batteries, batteries generally yield a 10% increase in the weight of a flight ready aircraft over one that would be fully fueled. Otherwise, electric motors pose a variety of challenges that gas engines simply do not, the most prominent of which is than electric motors use high voltages and currents. For an aircraft in the size range purposed, the motor system at full throttle would run at 50–60 VDC and 200–250 Amps, or about 10-15 kW. In addition, the lithium polymer (LiPo) batteries used are highly volatile and must be handled with care.

In terms of cost between the two options, gas offers pay-per-use while electric propulsion requires that everything is paid upfront. More specifically, the cost of each option with all the required accessories and the peripheral equipment is equal, less the cost of fuel for gas and batteries for electric. However, with the electric system, batteries must be bought ahead of time, and the number of motor battery packs will equal the number of flights that can be flown. Yet, if the motor battery packs are charged at the flying site, the number of flights per day can be increased. With regards to operational cost, given current fuel prices, the cost of one motor flight pack is approximately equivalent to approximately 500 flights worth of gas. This figure does ironically correlate to the optimal number of cycles, or flights, that can be achieved with a battery; however, if battery life is inadvertently shortened, then gas is less expensive.

The last major factor that must be considered is safety. Gas engines require manual starting, specifically by turning the propeller over by hand, which is a major safety concern. However, when a gas engine is off it cannot start by mistake; whereas, whenever the batteries are connected into the motor system everything is armed. To solve the issue of the motor system always being armed when the batteries are plugged in, an inline electronic switch with a “remove-before-flight” indicator can be added to make the state of the motor obvious.

Given all the aspects considered, using an electric motor system was chosen mainly due to the superior aerodynamics data that the platform could yield, which was one of the fundamental reasons for starting the project. Another major reason is that overall it is a more practical system to use and requires less maintenance.

C. Airframe Choice

Provided the choices made for size, airframe construction, and propulsion system, after examining several COTS airframes, the Hangar 9 35%-scale Extra 260[43] was chosen. The 35%-scale Extra 260 is a relatively light and strong design that, once instrumented, has a similar weight to the un-instrumented weight of other airframes in the same size category. In order to convert the airframe an RC model aircraft into an unmanned aircraft, some of the stock hardware needed to be upgraded. Given that the airframe would be instrumented and carry valuable equipment, it is advantageous to improve the overall safety and performance characteristics. These hardware changes include upgrading the servos to stronger and faster models, upgrading all fasteners and linkages, and of course reinforcing the structure. Also a power distribution system would be added, not only to manage power flow sent to servos but to make the flight control system power redundant.

Since the propulsion system was chosen to be electric, certain modifications needed to be made. These modifications include properly mounting the motor and widening the support structure to compensate for the greater torque an electric motor could create compared with a gas engine. Also, battery trays needed to be fabricated and installed such that they provide a sufficient amount of room to change the CG of the aircraft, either to aid the pilot in performing certain maneuvers or to optimize the aircraft for autonomous control.

Figure 5. Stock photograph of the Hangar 9 35%-scale Extra 260 (taken from Ref. 43).

D. Instrumentation

There are essentially two parts making up the platform—the airframe being one and the avionics suite being the second. The avionics suite must be able to perform two tasks: record flight state data while the aircraft is being flown manually, and fly the aircraft either fully- or semi-autonomously. In the case of autonomous flight, the safety pilot at the field must be able to regain control at any time. Otherwise, the goals in selecting an avionics system would to be to maximize safety, maximize logging rate and resolution, minimize complexity, and minimize cost. Several options were discussed during the planning stage. First of all, the method used to operate the avionics in each flight task was examined. One option was to use a stand-alone autopilot and a stand-alone data logger and to run one while the other one is off. The next option was to use an autopilot capable of both flight and logging and to just disconnect the autopilot during manual flight. Either case could be done with COTS hardware or by developing custom electronics. It should also be noted that for any of these operational options a method for reliably switching from autonomous-to-manual control needed to be devised. In the end, the avionics suite chosen to be used on the aircraft was an upgraded version of that developed and used on the Fixed-Wing Multi-Role Unmanned Aircraft Vehicle Research Testbed,[37] with the addition of a separate COTS system to monitor the electric propulsion system.

E. Flight Testing

An important factor in the development of an unmanned testbed platform is to follow a procedure that allows for all of the systems to be tested while minimizing risk to the other systems. In this case, that meant being able to test the airframe and avionics while minimizing the endangerment of the other. The plan for testing the Aero Testbed was extensively discussed and emerged as the following. The first step to test the platform would occur once the airframe was constructed and flight-readied as an RC aircraft. Then it would be test flown several times to observe if any problems arose. This means that the RC test pilot would run the aircraft through its paces. If any problems were detected, the appropriate modifications would be made. Then the next step would be to put the avionics system together in the aircraft and perform diagnostic tests. Assuming everything checked out, the aircraft would be test flown with the system turned off. Then it could be flown with the avionics running in recording mode. Finally for autonomous flight, the flight testing / risk mitigation method used with the Fixed-Wing Multi-Role Unmanned Aircraft Vehicle Research Testbed[37] would be adopted.

IV. Development

The development process of the Aero Testbed is separated into two stages: aircraft construction and then instrumentation integration. The completed aircraft specification are presented.

A. Airframe Construction

The construction of the Aero Testbed airframe started with a Hangar 9 35%-scale Extra 260 almost-ready-to-fly (ARF) RC airplane kit. The kit came with all major components of the airframe prefabricated along with a variety of hardware from landing gear components to linkages. Generally with ARF airplane kits, a good deal of assembly is required to bring the airplane to flying condition; however, ARF kits are much less time consuming compared with traditional kits where everything, including the structure, must be constructed and then assembled.

Figure 6. All major airframe components that arrived with Hangar 9 35%-scale Extra 260 ARF kit.

As described in the planning section, most of the hardware included with the kit was replaced to better adapt the airframe for use as an unmanned testbed platform. These changes were made to improve flight and longevity characteristics, as well as an overall safety consideration. Most of the stock fasteners included with the airframe were replaced with identically sized fasteners made from stronger materials in order to minimize the risk of failure. Another upgrade included the replacement of the aluminum landing gear with a pair of Graph Tech RC[44] carbon-fiber landing gear that could better handle landings of an airplane that is above its original design weight. The main axles were also replaced in this fashion. The wing and horizontal stabilizer joiner tubes were replaced with a pair of high tensile strength carbon-fiber wrapped tubes. Other upgrades included the replacement of the linkage connectors with heavy-duty Dubro[45] connectors and the steel linkages with stronger titanium linkages. To facilitate the installation of the flight control system components and the avionics, two large balsa/carbon-fiber sandwich trays were fabricated installed in the fuselage. These trays also served to strengthen the area that would experience increased load.

With regard to the RC flight control system, several upgrades and additions were made from what would normally be used on a normal 35%-scale Extra 260. The servos installed for the flight controls were at the top of the manufacturer's range of recommended servos. It should be noted that there are two servos for each aileron and for the rudder, and a separate servo for each of the elevators, to increase redundancy in the system. The RC receiver used (JR R1221X) is the longest range model available, uses 2.4-GHz frequency hopping modulation, and has four redundant antennas. The controller used with this receiver is the JR 12X.[46] A manual override switch was installed to allow shifting control between the RC receiver (that the human pilot would use) and the autopilot. It should be noted that this is a COTS stand-alone unit made by 2icrc that is controlled by a servo channel from the RC receiver, which the test pilot always has control over.[47] A Smart-Fly power distribution unit was installed in the aircraft to both filter and regulate the signals and power available to each servo. It also served to duplicate the servo channels so that they can be recorded; the unit also acts as a redundant power supply by means of two batteries.[48] The two batteries used to power the flight control system are Thunder Power 2S (2 cell / 7.4 V nominal) 5-Ah LiPo batteries.[49]

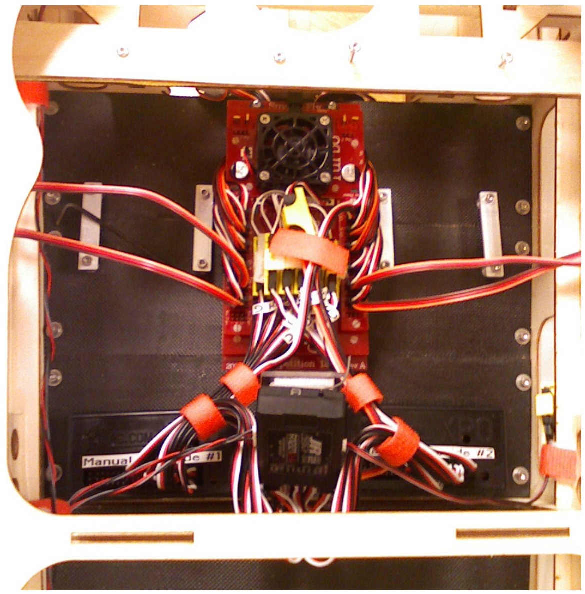


Figure 7. Smart-Fly power distribution unit, JR receiver, and 2irc manual overrides installed on the front balsa/carbon-fiber sandwich tray.

The Aero Testbed is equipped with an electric motor system consisting of a Hacker A150-8 brushless motor running a Mejzlik 27x12TH electric thin-blade propeller[50] and a Hacker MasterSPIN 220 electronic speed controller (ESC).[42] The motor is connected to the speed controller that regulates the rotation rate of the motor by pulsing the motor coils. An EMCOTEC Safety Power Switch was installed in-line between the electronic speed controller and the flight battery and allows the flight battery to be connected without the motor engaging. The switch is triggered using a magnetic pull "Remove Before Flight" flag which was installed on the top of the cowling for easy visibility.[51] The flight pack motor batteries were assembled from four Thunder Power 7S (7 cell / 25.9 V nominal) 5-Ah LiPo battery packs in a 2S 2P configuration, meaning that two packs in series are paralleled with a second set of two packs in series. The flight pack is configured as a 14S (14 cell / 51.8 V nominal) 10-Ah LiPo battery pack. All battery-level interconnects are made using 10-AWG wire and 4-mm gold-plated bullet connectors and run up to 125 A at 29.4 V. All motor power connections, from the switch to the motor are made using 8-AWG wire, or a set of three 12-AWG wires in parallel, and 6-mm gold-plated locking bullet connectors, and run up to 250 A at 58.8 V. The entire system operates using direct current. In order to achieve the proper CG, battery trays were installed in the aircraft where the fuel tank originally sat. The trays were oversized in order to make it possible for the CG to be adjusted.

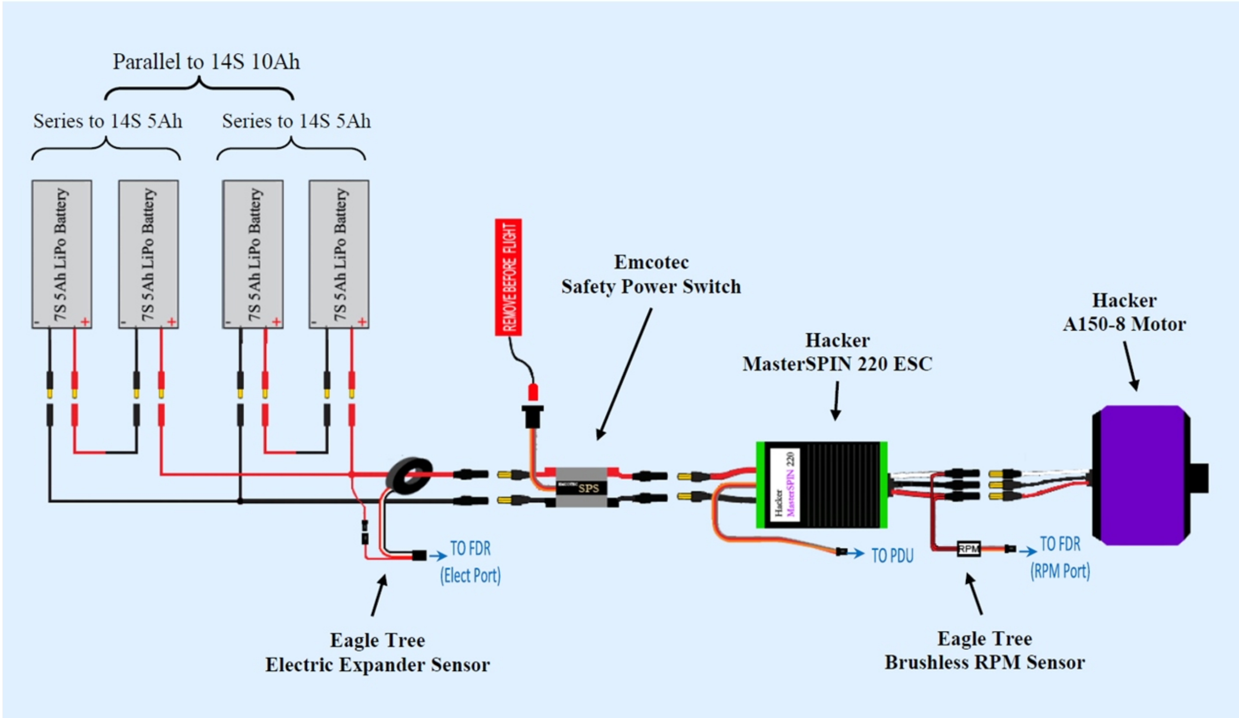


Figure 8. A propulsion system diagram for the Aero Testbed unmanned aircraft.

An Eagle Tree Systems Flight Data Recorder (FDR) was fitted on the Aero Testbed to monitor the propulsion system and the overall state of the aircraft.[52] The Eagle Tree Systems FDR monitors the voltage of the motor flight pack, voltage output of the power distribution unit, current drawn by the motor, motor RPM, temperature of the motor, electronic speed controller, and all motor batteries. Additionally, the flight control inputs sent out from the power distribution unit and the GPS position of the aircraft are recorded. The FDR records all these values at a rate of 10 Hz but can be configured to run at up to 40 Hz. It transmits the information it logs to a ground station via a 2.4-GHz transmitter at a slightly lower rate. The Eagle Tree Systems FDR was primarily installed to allow the propulsion system to be monitored.

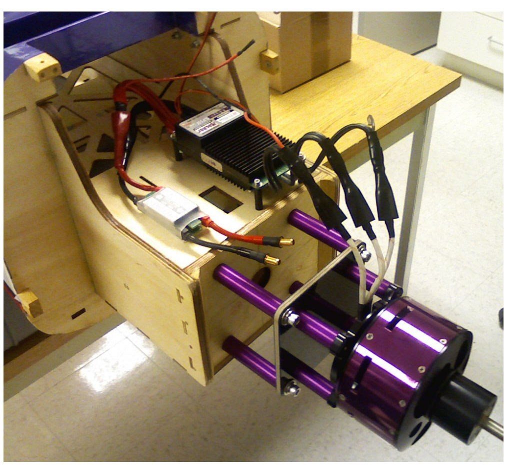


Figure 9. The Hacker A150-8 brushless motor (bottom right), MasterSPIN 220 electronics speed controller (top middle), and SPS safety switch (center left) seen before the cowling, propeller, and spinner were installed.

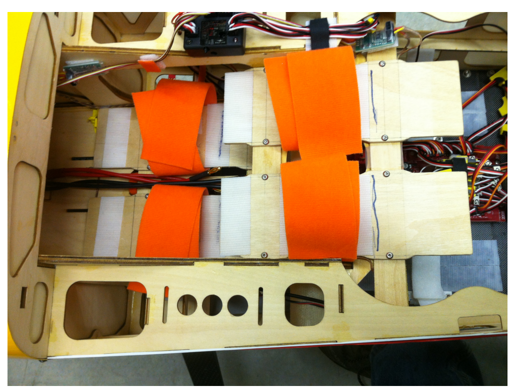


Figure 10. A photograph on the motor battery trays where the Eagle Tree Systems Flight Data Recorder can be seen at the top of the shot.

B. Avionics Integration

The Aero Testbed was equipped with an avionics suite based on the system developed and used on the Fixed-Wing Multi-Role Unmanned Aircraft Vehicle Research Testbed.[37] The avionics suite includes a Gumstix flight computer,[53] an ARM7 microprocessor based Paparazzi autopilot,[54] and a Xsens MTi-G six degree-of-freedom (6-DOF) inertial measurement unit (IMU),[55] along with several other components. This system was first built and tested outside of the aircraft and then was reassembled and mounted in the aircraft.

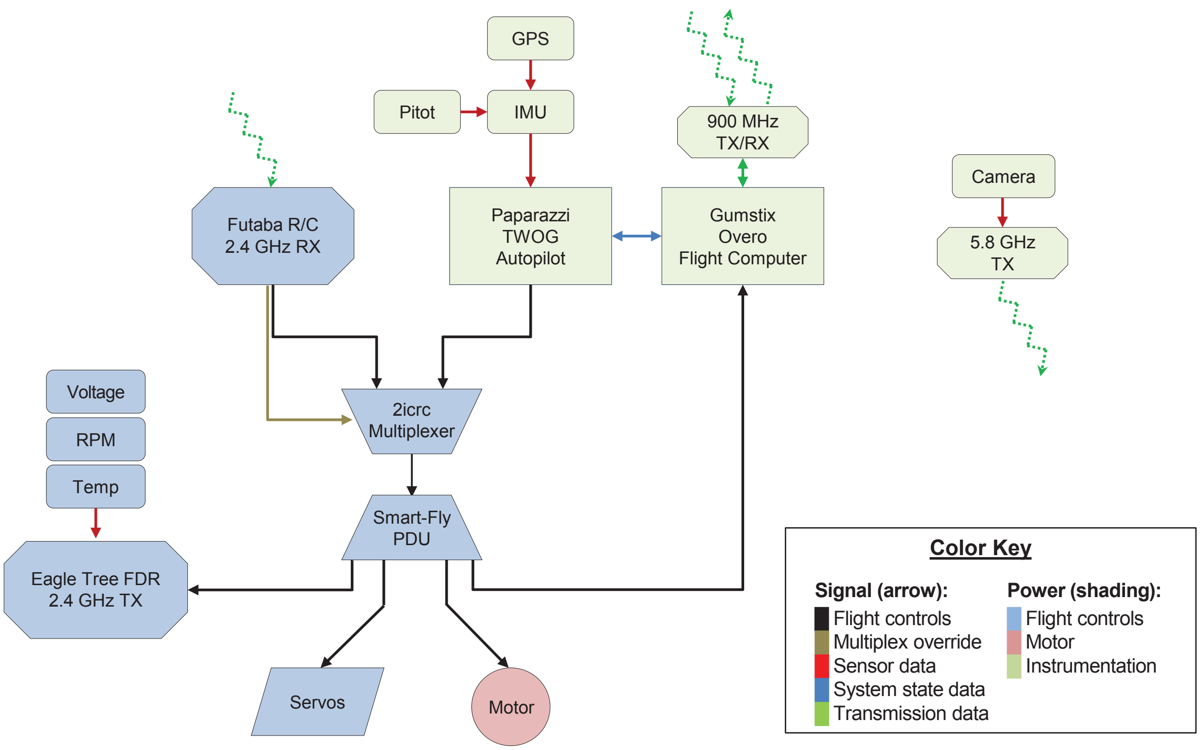


Figure 11. A flowchart diagram of the avionics suite showing a top-down view of flight control signals, multiplex the override command signal, sensor inputs, instrumentation communication, and transmission routes.

The IMU is a MEMS-based 6-DOF inertial measurement unit that has an internal barometric pressure sensor and an internal GPS receiver along with two 16-bit analog-to-digital converters. The IMU has an onboard Attitude and Heading Reference System (AHRS) and Navigation processor that runs a real-time sensor-fusion algorithm using a proprietary extended Kalman filter to output minimal drift, GPS-enhanced, 3D orientation and position data at a rate of up to 120 Hz. The IMU uses this filter to couple inertial measurements from the accelerometer, gyroscope, and magnetometer that update at 512 Hz with a 4-Hz GPS and a static pressure sensor that updates at 9 Hz. The GPS receiver is connected to an antenna that was mounted on top of the fuselage behind the canopy hatch area. GPS altitude readings are aided by the barometric pressure sensor. The IMU is also able to output all the unprocessed sensor readings, which is useful because body-frame accelerations and rate-of-turn can be logged. The airspeed of the aircraft is measured by a pitot probe connected to an All Sensors 20cmH2O-D1-4V-MINI differential pressure sensor,[56] which is integrated into the system through one of the two IMU analog-to-digital converters.

The flight computer and autopilot continuously communicate over a serial line. The flight computer was setup such that it records aircraft state data independent of whether or not the aircraft is being flown manually or autonomously. When the aircraft is being flown autonomously, it performs all the high-level flight-plan calculations. The autopilot on the other hand is used primary as input/output device in that it passes data from the IMU to the flight computer and uses the flight plan commands from the flight computer to run low-level control loops to output the proper control-surface servo commands via its servo output ports. The flight computer and autopilot operate at a rate of 100 Hz; however, the autopilot outputs servo commands at a rate of 60 Hz. The avionics suite is also equipped with an XTend 900-MHz transceiver,[57] which is connected to the flight computer via a serial line, allowing the avionics system to communicate with a ground station where the ground-station operators can both monitor acquired data and control the aircraft if needed.

Physically, the majority of the avionics system, which includes the flight computer, autopilot, autopilot-to-IMU signal conversion board, avionics power regulators, and avionics batteries, were mounted on the rear balsa/carbon fiber tray. The avionics are supplied with power from two regulators—the first made by Smart-Fly redundantly inputs power from two batteries and lowers the voltage to 6.5 V and the other made by Castle Creations,[58] which is connected to the first regulator and lowers the voltage further to 5 V. Power originates from two Thunder Power 2S (2 cell / 7.4 V nominal) 900-mAh LiPo batteries.

The remainder of the avionics components lay throughout the rest of the aircraft. The IMU was mounted as close as possible to the CG (right above the wing tube of the aircraft). This placement was done in order to minimize the accelerations created by aircraft rotation, which is important in an aircraft that is able to produce large angular accelerations. The pitot probe was mounted on the left wing tip, while the differential pressure sensor was mounted halfway through the wing. The avionics transceiver was mounted halfway into the tail to minimize possibilities of interference with other equipment.

After several test flights with the aircraft instrumented, a passive high-definition video camera was added to the canopy of the aircraft in order to record a pilot's eye view. This video greatly aids in recognizing maneuvers and their timing during the post processing of data. In order to facilitate human-machine interface-based autonomous flight, the aircraft has space available for a gimbaled video camera that can be downlinked using a 5.8-GHz transmitter, allowing interface subjects to have point-of-view visual feedback.

Figure 12. The avionics suite components, starting on the top left and going clockwise: a) the IMU is mounted as close as possible to the CG, b) the pitot probe is mounted on the left wingtip, c) the GPS antenna is mounted atop the fuselage behind the canopy, and d) the rear balsa/carbon fiber sandwich tray with the flight computer, autopilot, IMU signal conversion board, and two regulators.

C. Completed Specifications

The completed specifications of the UIUC Aero Testbed are given in this section. First the aircraft physical specifications are given in Table 1. Then the airframe specifications are given in Table 2. Finally the avionics specifications are given in Table 3.

Table 1. Aircraft Physical Specifications

Geometric Properties	
Overall Length	98 in (2489 mm)
Wing	
Span	105 in (2667 mm)
Area	2003 in^2 (129 dm^2)
Airfoil	Symmetric - 10.5% Thick
Aspect Ratio	5.50
Taper Ratio	0.45
Dihedral	0.00 deg
Incidence	0.00 deg
Sweep	$<$ 1 deg
Aileron Area	20.0% of Wing Area
Horizontal Stabilizer	
Area	449 in^2 (29.0 dm^2)
Airfoil	Symmetric - 11% Thick
Aspect Ratio	4.90
Taper Ratio	0.55
Dihedral	0.00 deg
Incidence	0.00 deg
Elevator Area	45.4% of Horizontal Stabilizer Area
Vertical Stabilizer	
Area	214 in^2 (13.8 dm^2)
Airfoil	Symmetric - 11% Thick
Rudder Area	72.0% of Vertical Stabilizer Area
Inertial Properties	
Weight	
Empty (w/o Battery)	31.3 lb (14.2 kg)
14S LiPo Battery	6.2 lb (2.8 kg)
Gross Weight	37.5 lb (17.0 kg)
Wing Loading	40.3 oz/ft^2 (123 gr/dm^2)
CG Location	35.8% of Wing Mean Aerodynamic Chord
Moments of Inertia	
Roll	1.13 slug-ft^2 (1.53 kg-m^2)
Pitch	3.58 slug-ft^2 (4.86 kg-m^2)
Yaw	4.47 slug-ft^2 (6.06 kg-m^2)

Table 2. Airframe Specifications

Construction	Built-up balsa and plywood structure, foam turtle deck, carbon fiber wing and stab tube, carbon fiber landing gear, fiberglass cowl, fiberglass wheel pants, and styrene canopy.
Flight Controls	
Controls	Aileron, elevator, rudder, and throttle
Transmitter	JR 12X DSM2
Receiver	JR R1221 DSM2
Servos	(8) JR DS8711 Ultra Torque
Power Distribution	SmartFly PowerSystem Competition 12 Turbo
Receiver Battery	(2) Thunder Power ProLite 20c 2S 5000 mAh (redundant)
Propulsion	
Motor	Hacker A150-8 Outrunner
ESC	Hacker MasterSPIN 220 Brushless Speed Controller
Propeller	Mejzlik 27x12TH
Spinner	TruTurn 4.5-in Ultimate with Lite Backplate & Blue Anodize Alum.
Motor Flight Pack	(4) Thunder Power ProPower 30c 7S 5000 mAh in 2S2P config.
Motor Power Switch	Emcotec SPS 120/240
Static Thrust & RPM	76 lb at 6,936 RPM at standard day at 770 ft altitude
Static Thrust / Weight	2.05:1 ratio
Flight Time	8-12 min

Table 3. Avionics Specifications

Onboard Systems	
Flight Computer	Gumstix Overo Water with Summit expansion board
Autopilot	Paparazzi TWOG v1.0
Sensors	
IMU	XSens Mti-g 6-DOF IMU with Wi-Sys WS3910 GPS Antenna
Airspeed	Pitot-static probe using an All Sensors 20cmH2O-D1-4V-MINI differential pressure sensor
Transceiver	Digi 9X Tend 900-MHz card
Power	
Regulators	Smart Fly SportReg & Castle Creations CCBEC
Batteries	(2) Thunder Power ProLite RX 2S 900 mAh (redundant)
Data Storage	MicroSD card up to 8 GB
Data Log Rate	Up to 100 Hz

V. Initial Flight Test Results

During the spring, summer and fall of 2012, the Aero Testbed was flown in its fully-instrumented configuration several dozen times. Initially, simple circuits were flown, and as the flight days progressed, maneuvers were added to the flight plans as a higher level of familiarity with the aircraft and the safety procedures were gained. The Aero Testbed was flown through a variety of aerobatic maneuvers, specifically including spins, which became of particular interest.[59,60] These maneuvers were performed to test the avionics system because of their relative simplicity and safety compared with more complicated maneuvers. The avionics were initially set to log at 5 Hz, and then this was increased to 25 Hz. A handful of rudimentary aerobatic maneuvers that were performed are shown in in Fig. 13. As can be seen in several of the trajectories, the flight paths become jagged when the aircraft attitude is rapidly changing. The jaggedness is the result of filtering problems occurring in the IMU processor due to temporary GPS and magnetometer sensors faults following the rapid course changes. These issues will be solved by performing additional post-processing of raw sensor data.

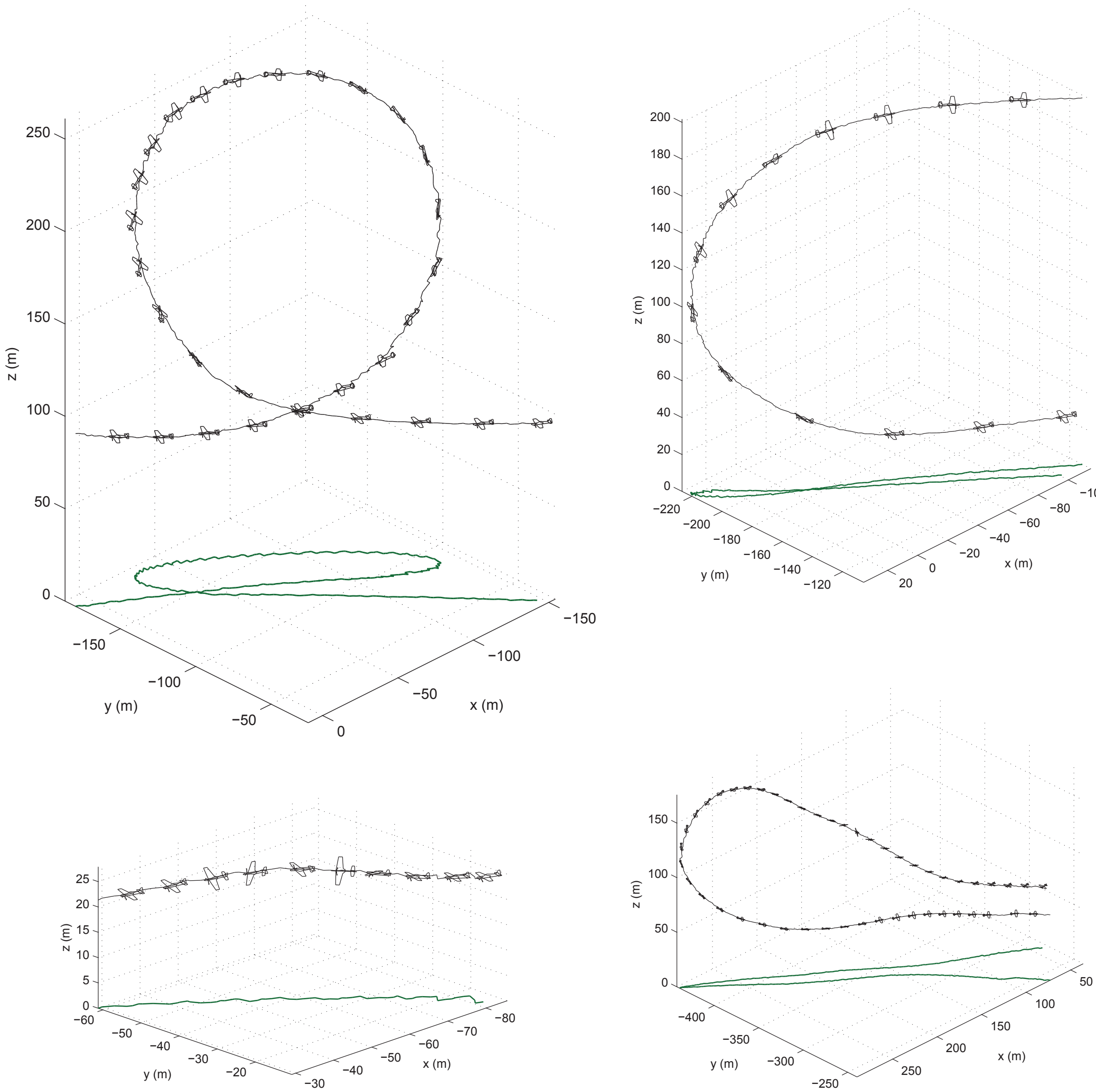


Figure 13. Trajectory and ground trace plots of aerobatic maneuvers, starting on the top left and going clockwise: a) loop, b) Immelmann, c) roll, and d) half Cuban-eight.

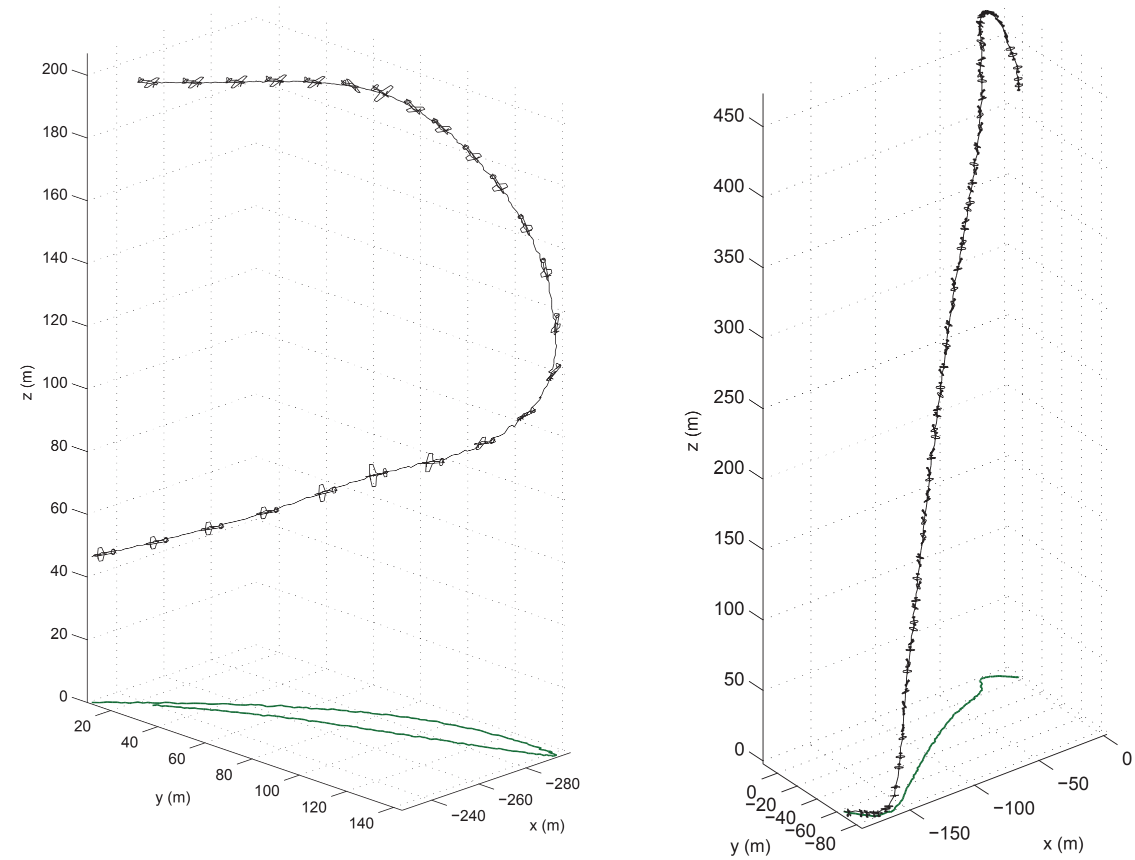


Figure 13. [continued] e) spilt-S and f) spin

VI. Summary

This paper described the development and initial testing of the UIUC Aero Testbed, which is a large unmanned aerobatic aircraft primary intended to perform aerodynamics research in the full flight regime. The aircraft, which has an 105-in wingspan and weighs 37 lb, is powered by a 12-kW electric motor that provides the aircraft with a thrust-to-weight ratio in excess of 2-to-1. The aircraft is equipped with an avionics suite that can be used to generate high-fidelity aerodynamic data using a high-frequency, high-resolution 6-DOF IMU. This aerodynamic data will used to validate high angle-of-attack flight-dynamics models along with allowing stall/spin upset conditions to be studied. To date, the Aero Testbed has flown several dozen times, each time with an increasing amount of rudimentary aerobatic maneuvers. Once the logging and processing of these maneuvers can be perfected, more complicated maneuvers will be performed and analyzed, particularly in the high angle-of-attack regime.

Figure 14. The Aero Testbed flying inverted.

Figure 15. The Aero Testbed landing.

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