

Development of a Fixed Wing Multi-Role Unmanned Aircraft Vehicle Research Testbed

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This paper describes the design and construction of a fixed-wing multi-role unmanned aerial vehicle (UAV) that has served as a platform for research on (a) human-machine interface based teleoperation, (b) new autonomous control algorithms, and (c) system identification of aircraft performance parameters. These tasks require capabilities that generalize to a wide range of small scale UAV research. In particular, we believe that sharing our design and construction approaches can benefit the research community. An important criterion in development of a research model is its ability to support testing and development of new technologies in a time- and cost-effective manner. Our work achieved this and can perform multiple tasks without transitioning or replacing hardware. The platform itself is constructed out of commercial off the shelf components, in order to decrease development time and costs, and is also capable of performing aggressive maneuvering, which is unusual for research UAVs at the 1.8-meter wingspan scale. The platform construction details and code are available and can serve as the basis for development of future unmanned aerial vehicles by the research community. Preliminary flight tests provide proof of concept.

Abbreviations

<i>AVI</i>	=	avionics integration
<i>AOA</i>	=	angle of attack
<i>COTS</i>	=	commercial off the shelf
<i>EEG</i>	=	electroencephalograph
<i>GPS</i>	=	Global Positioning System
<i>IMU</i>	=	inertial measurement unit
<i>IR</i>	=	infrared
<i>LIPO</i>	=	lithium polymer
<i>MFG</i>	=	manufacturer
<i>RC</i>	=	remote control
<i>RF</i>	=	radio frequency
<i>RTF</i>	=	ready-to-fly
<i>UAV</i>	=	unmanned aerial vehicle
<i>VTOL</i>	=	vertical take-off and landing

I. Introduction

IN the past decade there has been much development of research oriented unmanned aerial vehicle (UAV) testbeds. These UAV platforms are generally intended for one specific task and are either modified from commercial off the shelf (COTS) aircraft for that task, or are alternately entirely designed and constructed from scratch. In most circumstances, adapting a COTS aircraft is cost prohibitive and/or involves extensive modifications. UAV testbeds can be differentiated into several size and configuration groups, and within these groups certain sets

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of tasks are common. The use of these UAVs also help mitigate the risks inherent in experiments that cannot be done in, or need to be verified from simulation, and would otherwise need to be done in full scale.

In the development of the our UAV, the concept was to create a platform, in the 1.5 to 2.0-meter wingspan size range, that could be used for several tasks. It was specifically equipped so that no modifications need to be made when switching between different tasks. The UAV is primarily intended to be used for human-machine interface based teleoperation, experimental verification of new autonomous control algorithms, and for system identification of aircraft performance parameters; although with slight or no modification it can be adapted to other tasks. In this case, system identification can also include using the platform to understand the full envelope of aerodynamic performance at low Reynolds numbers. Our UAV was the result of several previous platform revisions, each of which yielded results, and therefore new requirements for the next UAV platform. Another aspect of the concept was to use as many COTS components as possible, especially the airframe, which allows for ease of replacement, and decreased development time. To date our UAV platform has completed more than a dozen flights that have yielded multiple sets of data for different tasks, some of which were collected simultaneously.

The paper is organized as follows, first is a study of UAV platforms that have been developed in the past decade, distinguished by size and configuration groups and intended tasks. This is followed by a discussion of past research and platforms, and the consequent requirements for each successive platform. The development of our UAV, including all the modifications done to the COTS airframe, will be discussed next. A discussion of risk mitigation involved in flight-testing of UAVs, as was done with our UAV, will follow. Finally, future capabilities of the UAV will be presented.

A. Literature Review of Recent UAV Testbeds

Over the past decade usage of UAVs has increased, particularly for research purposes, both by academic, as well as government and private institutions. These research oriented UAVs are used for a variety of tasks from control related experiments, to flight dynamics and other types of data collection. The development of most research orientated UAV testbeds is the result of a need for a platform tailored to a particular task. However, since they are designed for one particular task, it is often difficult and economically unfeasible to modify them for other tasks.

To investigate that research oriented UAVs are often suited for a single task, 31 platforms are surveyed and compiled into Table 1. These UAVs are differentiated into 5 categories, which have defined dimension and features. In an attempt to remain relevant to our UAV, only fixed-wing aircraft with constant geometry are examined; no rotor-craft or variable geometry aircraft such as ornithopters or variable-sweep wing aircraft are included. Examination of Table 1 yields the conclusion that most of the UAVs surveyed are only used for one particular task for which they are designed / built; if they are used for multiple tasks, these tasks are coupled.

In the Mini type category, an example is the 30-G UAV platform, developed by Zufferey and Floreono [1] at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Intelligent Systems, was equipped with an electronics package consisting of a microcontroller, two miniature servos, a rate gyro, a radio module, lithium battery, and two cameras, in order to perform the task of autonomously steering in a textured environment. All these components were built into the airframe, making replacement difficult. Since the structure is rather lightweight, additional payload ability is non-existent. The microcontroller and two cameras (sensors) were chosen to nominally satisfy the intended use, and could not easily be otherwise applied. Thus, without major modifications, redesign, or reassembly, the 30-G platform is effectively only able to perform its originally intended task.

Similarly, in the Scale type category, NASA Langley's AirSTAR program constructed a 5.5% scaled dynamics generic transport model (Boeing 757), the GTM-T1 and GTM-T2, in order to study flight dynamics, particularly in attitudes beyond the normal flight envelope, and to develop loss-of-control recovery algorithms [32,33], specifically using L1-adaptive control for flight situations with unknown flight dynamics response. During the development process an avionics suite was integrated into the aircraft that allow for remote piloting, data logging, and telemetry. This allows for the aircraft to house this package while remaining dynamically scaled; it should be noted that the aircraft was tested to satisfy strength requirements within a given flight envelope. Further payload expansion would likely compromise the aircraft in flight.

In the following sections, this paper describes the system we have developed in order to combine the ability to perform several tasks and the capability to perform additional tasks.

Type:	Config:	Wingspan Size Range: [m]	Payload Capacity: [gr]	Flight Time: [min]	Est. Cost: [\$]	General Aircraft Abilities:	Example: [Aircraft Task ^{REF}]
Mini	Foam or light built. Monoplane or flying wing	0.50-1.25	50-250	2 - 15	100 - 1,000	Indoor/Outdoor. Low payload. Stable or aggressive maneuvering possible.	30-G Indoor visual navigation ¹ ; <i>BYU Flying MAV</i> Visual navigation ² ; <i>gliderUAV</i> Autonomous perching ³ ; <i>SkyEyeV</i> High A.o.A. flight ⁴ & Tail-sitting VTOL ⁵ ; <i>SMAVNET UAV</i> Swarm for communication network ⁶ ; <i>SUMO</i> Atmospheric boundary layer research ⁷ ; <i>Tail-Sitter UAV</i> Tail-sitting VTOL ⁸ .
Trainer / Stable	Monoplane with high wing and dihedral	1.25-1.75	200-1,000	10 - 30	300 - 5,000	Stable. Good preliminary testbed. Impact resistant.	<i>DragonFly</i> GPS/INS integration ⁹ ; Automated formation flight ¹⁰ ; & Hardware-in-the-loop validation ¹¹ ; <i>FASEER</i> General use UAV ¹² ; <i>GT Test Glider</i> Visual only navigation ¹³ ; <i>GTTwinStar</i> Multi-engine system identification ¹⁴ ; <i>KadetUAV</i> Fuzzy adaptive control ¹⁵ ; <i>PennUAV</i> Visual tracking of moving target ¹⁶ ; <i>SkyEye2</i> Vegetation analysis ¹⁷ ; <i>Spirit 100 UAV</i> Ground reconnaissance ¹⁸ .
Aerobatic	Unspecified	1.0-3.0	400-2,000	5- 20	1,000 - 25,000	Aggressive maneuvering. High strength to weight ratio structure.	<i>1/3 Scale Yak 54</i> Autopilot testing ¹⁹ ; <i>ALEAS UAV</i> UAV risk mitigation ^{20,21} ; <i>Cap232UAV</i> Autonomous aerobatic flight ^{22,23} ; <i>Edge 540T</i> 33% UAV Battery health management system ²⁴ ; <i>GTEdge</i> Target leader for autonomous formation flight ²⁵ & Autonomous transition from/to hover ²⁶ ; <i>Mini ShowTimeUAV</i> High A.o.A. flight dynamics ^{27,28} ; 3D path planning ²⁹ ; & Wing rock from tail variation ³⁰ .
Scale	N/A	1.50-	NA	10 - 30	5,000 - 50,000	Scale properties	<i>Aeromot 200S SuperXimango</i> Scaled flight research ³¹ ; <i>AirSTAR GTM-T1 & GTM-T2</i> Subscale testing ^{32,33} & L1 adaptive control for uncertain dynamics ³⁴ ; <i>F/A-18 UAV</i> Damage tolerant control ³⁵ .
Heavy lifter / Long endurance	Unspecified	2.25-6.0	1,000- 20,000	20 - 20 hr	2,500 - 100,000	Stable. Slow movement.	<i>Aerosonde</i> Artic meteorological observation ^{36,37} ; <i>Antex UAVs</i> Costal and environmental survey ³⁸ ; <i>Bramby Mk 3 UAV</i> Cooperative control ³⁹ ; <i>CP-SAR JX-1</i> Electro-magnetic earth observation ⁴⁰ ; <i>DPVolcan</i> Volcanic exploration ⁴¹ ; <i>DSBeast</i> Dynamic soaring ⁴² ; <i>Osprey UAV</i> Visual guidance, control, and navigation ⁴³ .

Table 1. Survey of 31 UAV platforms developed by academic and government research institutions.

II. Past Research, Platforms and Consequent Requirements

The development of our UAV testbed followed a long list of platform revisions starting in 2007. Each testbed developed allowed those involved to gain more experience and better define the requirements for the next platform. This evolution, through a total of 8 airframes, finally led to the creation of our UAV in 2010. All platforms used were developed from COTS almost-ready-to-fly RC model aircraft, which have the advantage of being mostly pre-built and low-cost compared to designing a custom airframe.

A. Early Attempts

In 2007 the Robotics and neuro-Mechanical Systems Lab began experimenting with different COTS RC model aircraft, in order to build a UAV platform that could be teleoperated using a human-machine interface. The avionics used in these airframes was rather basic: a simple open source autopilot with an integrated GPS, a low-cost IMU, IR sensors (for aircraft attitude), a 900 MHz radio modem, and a 72 MHz RC receiver. The initial airframes were electric motor gliders and trainer type aircraft, and all suffered from inadequate thrust availability and therefore lacking in lifting ability.

In early 2008, after several aircraft revisions, a small-scale aerobatic aircraft, a 41-inch wingspan electric Great Planes Yak-54, was successfully flown with the avionics suite. In the testing done with this platform, the GPS, IR sensor, and IMU data were successfully fused to produce the aircraft's state data using Kalman filtering done in the autopilot. The Yak airframe did, however, have problems with overall weight due to lack of sufficient thrust, and was therefore retired.

Then in mid-2008, an electric scaled down, 62-inch wingspan, E-Flite J-3 Piper Cub was chosen as the next platform due to its relatively high cargo space and lifting ability. This testbed allowed for continued development of the avionics suite, including flight algorithms and communications development, which aid teleoperation. During this experimentation, the IMU was forgone in favor of using the GPS and IR sensors, which provided attitude and location data for the given experiments.

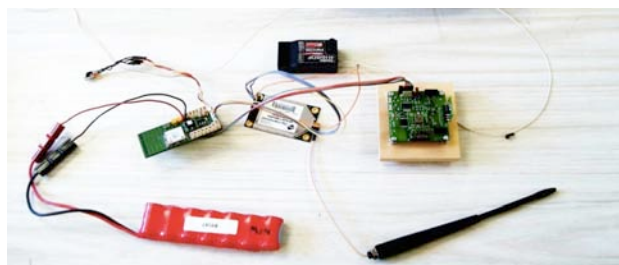


Figure 1. The avionics suite used on early UAV testbed platforms.



Figure 2. The 41-inch wing span Great Planes Yak-54 testbed platform with instrumentation.



Figure 3. The 62-inch wing span E-Flite J-3 Piper Cub testbed platform with instrumentation.

B. Further Platform Revision and Success

In order to advance beyond initial experiments, and achieve the task of teleoperating a UAV using a human-machine interface, more specific guidelines, in terms of testbed requirements, had to be made. The aircraft must be able to fly with all additional weight associated with avionics, and should be able to fly slowly in order to allow more time for recovery in case of loss of control. A wingspan larger than that of the Piper Cub platform was desired in order to increase visibility. It was also preferred that the new airframe be able to sustain minor crashes without damage. It was decided that a camera should also be added to the platform so that the subject involved in the human-machine interface experiment would be able to have first person video (FPV) from the aircraft.

In early 2009, the airframe chosen to suit these broad requirements was the Multiplex Cularis, a 103-inch wingspan motor glider. The structure of the Cularis is made from a composite foam, which is made of expanded polystyrene (EPS) and polyethylene (PE) foam, with carbon fiber tube reinforcements-which allows the aircraft to take repeated minor crashes and poor landings without breaking. The Cularis was assembled per the manufacturer's recommendations and then modified and equipped with the avionics suite. Modifications to the airframe included a larger flight battery for longer endurance, a separate battery to power the RC receiver and avionics, the addition of a camera fixed below the fuselage behind the wings and pointing down at a 45 degree angle, a 2.4 GHz video transmitter, and a pitot probe. All other components in the avionics system remained the same, with the exception of some wiring changes. The final ready-to-fly (RTF) specifications of the Cularis, in MFG and AVI configurations, can be found below:

	MFG	AVI
Wing Span [in] [mm]	102.75 (2160)	
Length [in] [mm]	49.6 (1260)	
Weight [oz] [g]	59.26 (1680)	89.0 (2522)
Wing Area [in ²] [dm ²]	863 (55)	
Wing Loading [oz/ft ²] [g/dm ²]	9.89 (30.5)	14.9 (45.9)

Table 2. Summary of the final RTF specifications for the Multiplex Cularis UAV platform in MFG and AVI configurations. Note that the AVI weight includes all modification made before platform retirement.

During flights with the Cularis platform, it was discovered that the added weight allowed the platform to be more stable, especially in winds up to 15 mph. However, due to the additional weight, the power available for climb or acceleration was quite limited. As a result, the takeoff procedure of hand launching the aircraft became problematic because the aircraft was no longer able to pull out of steep launch AOA's, and would stall and likely impact the ground. Thus, the launch AOA window narrowed to approximately ± 15 deg; anything lower would cause the Cularis to strike the ground before being able to climb. Another problem that arose as a result of increased weight was that, during bank angles of greater than 30 deg, the wings would bend to an undesirable amount, hinting at the possibility of in-flight structural failure. Of similar concern, after landings cracks would aggregate in the fuselage, especially near the wing jointer.

During experimentation, the IR sensors and the low-cost IMU were replaced with a commercial grade IMU and GPS, with built-in Kalman filtering; the IMU also uses an integrated magnetometer to aid in heading determination. This change allowed for quicker and more precise state determination compared to the older sensors. This combination also facilitated a superior response from the autopilot to environmental disturbances, such as wind, and allowed it to receive improved feedback. Another improvement made to the Cularis platform during later experimentation was the addition of bright green and orange paint, to the right and left flight surfaces of the aircraft, to improve visibility at great distances and especially in hazy conditions.

However, more problems arose during experimentation such as a decrease in effective manual control RC range and interference encountered by the RC receiver. This issue was quite severe, especially during landing, when the safety pilot would often lose control of the aircraft momentarily or unintended control surface input would occur, requiring immediate correction. These issues were most likely the result of the close proximity between all the systems



Figure 3. The 103-inch wing span Multiplex Cularis testbed platform with instrumentation, during early experimentation.

on board, due to low internal volume, which created on-board interference. Several incidents where loss of control occurred within 100 m (300 ft), well within the RC transmitter's range, support this conclusion. The RC transmitter used in late experimentation with the Cularis UAV Platform is the Futaba T14MZ in 72 MHz FM mode, which has a line-of-sight range of approximately 4.5 miles. Other related issues, such as possible overheating of other systems during extended usage, are probably also the result of low internal volume. There were also repeating problems with the video system.



Figure 3. The Cularis UAV platform with instrumentation, during late experimentation. Note the addition of an IMU and GPS, mounted externally.



Figure 4. The final avionics configuration in the Cularis UAV platform.

Nevertheless, the Cularis UAV platform allowed for continued development of algorithms and communications protocols for teleoperation to occur. During later experimentation, the Cularis platform was able to fly for an average of 15 minutes, depending on wind conditions. In August-September 2009, the first successful sets of human-machine teleoperated flights occurred, which incorporated the use of a brain-machine interface to allow human subjects to give commands to the aircraft using their thoughts.

In this interface, the human pilot's brain activity was measured by an electroencephalograph (EEG) that was used to distinguish between left- and right- hand motor imagery. These correlates of motor intent provided a binary input at approximately 1 Hz with noise. Mapping these inputs directly to control signals, as would be done with a joystick, was not feasible. Because of the low input rate and inherent noise, the pilot's inputs (motor imagery) were used to select a desired path for the aircraft. The currently chosen path was shown to the pilot. The display showed the video from the aircraft's onboard camera and annotated it with the chosen path. The selection of the path was as follows: Upon observing a left-motor imagery, the interface chose a path that turns more left than the current chosen path. Similarly, upon observing a right-motor imagery, the interface chose a path that turns more right than the current chosen path. The details of how this process, in particular the path chosen by the interface, are described in [44]. The path is transmitted to the aircraft sequentially using the wireless radio. The onboard computer implemented trajectory following and low-level stabilization algorithms follow the path chosen by the human pilot.

The Cularis UAV testbed platform was soon to be retired and replaced as winter set in, due to all problems encountered. Over the little more than half a year of operation, the Cularis flew a few dozen flights.

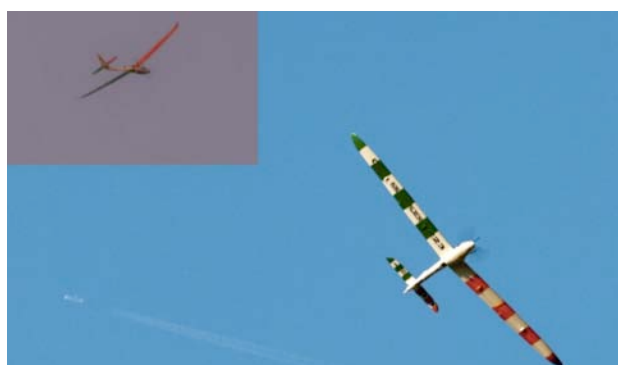


Figure 5. The Cularis UAV platform, flying autonomously, is easily visible in the different lighting and attitudes due to the added paint scheme.



Figure 6. The Cularis testbed platform on final approach for landing with the safety pilot in the foreground.

C. New Requirements and the Next Platform

The next step forward towards consistently replicating the results achieved with the Cularis UAV platform was to develop a new platform without the deficiencies the Cularis had. So given the experience learned from the Cularis UAV, new requirements were formulated for the next platform. One problem encountered with the Cularis platform was the way the autopilot was set up by default: it was required to be on in order to switch to manual control, and when it was on, all signals passed through it. If the autopilot were to fail in mid-flight, as it had done several times on the ground, there would be no way to regain control of the aircraft, or even cycle power to restart the autopilot. Therefore, a manual override-multiplexer was introduced into the avionics system of the next platform, which would be completely independent of all autonomous components.

Also, in order to introduce more safety features into the avionics system of the next platform, a new power scheme was to be adopted. A set of batteries powers the servos, manual override, and RC receiver, while an independent battery powers autonomous part of the avionics system. The power for the servos, manual override, and RC receiver would conveniently be allocated by a COTS power distribution unit, which would save weight overall, in comparison to large arrangements of wires. The battery for the motor would remain separate from the other batteries, and would still provide 15 min of flight time, if not more.

Additional payload weight would come in the form of a further upgraded autopilot system from that of the Cularis platform. This would be in the form of a flight computer in parallel to the autopilot and would run higher-level processes. Beyond improved processing power, the RC receiver and transmitter would be upgraded to resist more interference. And in order to prevent issues resulting from the close proximity of all the systems, the avionics bay would have a much higher volume than in the Cularis.

Further improvements would come in the form of a propulsion system that could provide greater than a 1:1 thrust to weight ratio, which would allow the safety pilot to get the aircraft out of potentially troubling attitudes with more ease. The propulsion system should remain electric in order to prevent an increase in vibration, especially to the IMU. Another improvement to the platform would be a higher quality downlink video camera than that used on the Cularis. The final, most practical, improvements to the platform would be that the aircraft could fly in winds of up to 20 mph and that it could be transported in the same vehicle as the Cularis was, requiring it to be in the range of 50 inches in length.

The airframe chosen to fill the requirements for the next UAV platform was the Sebart Angel 30. The motivation behind this choice was that it is a neutrally stable aerobatic design with a lightweight reinforced structure, using some composites, and is only 55 inches long. It is also much larger in volume than the Cularis and thus could store all the avionics with more ease. Also, since it is an aerobatics design, it could stand up to large accelerations, as it might face during aggressive RC aerobatics thus it could handle the increased load that the avionics would add. The Angel was first flown un-instrumented in early 2010, and was soon afterwards equipped with all avionic systems. The RTF specifications for the Angel platform in MFG and AVI configurations can be found below:



Figure 7. The Sebart Angel 30 UAV testbed platform without instrumentation, during early flight tests.

	MFG	AVI
Wing Span [in] [mm]	50.4 (1280)	
Length [in] [mm]	52.4 (1330)	
Weight [oz] [g]	49.38 (1400)	91.8 (2602)
Wing Area [in ²] [dm ²]	519.3 (33.5)	
Wing Loading [oz/ft ²] [g/dm ²]	13.7 (41.8)	25.5 (77.7)

Table 3. Summary of the final RTF specifications for the Sebart Angel 30 UAV platform in MFG and AVI configurations. Note that the AVI weight includes all modification made.

The Angel UAV platform was equipped with upgraded avionics systems as outlined in the requirements. Importantly, the 72 MHz RC receiver for manual flight from the Cularis was replaced with a Futaba R6008HS 2.4 GHz receiver; likewise the 72 MHz RF module in RC transmitter was replaced with a 2.4 GHz module. Also, in order to better prevent interference, the RC transmitter/receiver RF band change forced the video downlink, previously on 2.4 GHz, to be exchanged with 5.8 GHz.

As all the avionics systems were upgraded, the weight of the aircraft increased, as expected. However, to satisfy the other requirements, mainly endurance and thrust-to-weight ratio for the added weight, the motor and flight batteries needed to be upgraded. The motor was upgraded from the MFG recommended Hacker A30-14L 500 Watt motor to a Hacker A40-10S 900 Watt motor. The increase in motor size increased the thrust produced from 84 oz (2381 g) to 150 oz (4252 g), which was more than enough in order to pull out of dangerous situations. In order to support the upgraded motor, the battery also had to be exchanged. The original MFG recommended battery, an 11.1 V (3 cell) 2150 mAh LiPo battery, was replaced to a 14.8 V (4 cell) 5000 mAh LiPo battery.



Figure 8. The Angel UAV platform with avionics. Left: note the pitot probe attached to the left wing and the IMU (orange) behind the flight battery.

A few problems were encountered with the Angel UAV platform, during testing. Due to the overall weight increase, the wing loading increased, therefore the aircraft needed to fly faster in order to stay in steady level flight; an increase from 55 mph to 70 mph for cruise was necessary. The weight increase also meant that takeoffs and especially landings had to be performed at higher speed; landings also needed to be done at higher AOAs. As a result, during landings, the landing gear would deform 30% in width at initial touch down, implying that a significant amount of shock was being applied to the airframe.

Another significant problem encountered was that the GPS had trouble acquiring a signal, and once it acquired a signal, the recorded altitude might vary by as much as 20 m (60 ft) during steady level flight, and thus the autopilot would try to adjust. This problem seemed most likely the result of the GPS receiver being mounted internally. Once it was moved externally, the issues subsided. Also, the magnetometer in the IMU seemed to have problems correctly determining the heading of the aircraft, a result of the IMU being located directly behind the flight battery. While the battery was being discharged, a magnetic field was induced from the current, thereby acting on the magnetometer. Since it was very impractical to move the IMU, due to location constraints in the aircraft, the magnetometer was simply turned off, and heading information was be attained from a combination of the gyroscope in the IMU and the GPS.



Figure 10. The Angel UAV platform flying autonomously.

D. Motivation and Requirements for the Development of a New Testbed Platform

In mid-2010, as flight experiments were under way with the Angel UAV platform, it was decided that a new platform be developed for a variety of reasons. The most important motivation was that, since there was only one Angel platform, any extensive maintenance required, or worse yet, a loss of the aircraft would result in all experiments being halted until the aircraft was restored to flight ready status, or another platform could be built. Another factor involved was an overheating issue with the motor, which occurred as the weather got warmer.

Otherwise, the Angel platform performed as desired in-flight and allowed for the development of new algorithms for the improved avionics suite. Therefore, due to the stellar performance of the aircraft design in the air, disregarding all problems caused by the introduction of the avionics, the next testbed platform would come from Sebart (the MFG of the Angel 30), however it would be larger.

In the meanwhile, several other tasks and increased capabilities desired for human-machine interface based teleoperation were envisioned for the next platform. For human-machine interface based teleoperation, an increase in aircraft endurance and operational range was desired. An increase in endurance should extend the flight time to approximately 20 min, or more if possible, without detrimentally increasing the overall weight of the aircraft. This was a fault of the Angel platform; approximately 40% of the weight increase was the result of extending endurance. The operational range increase would come in the form of an increase in video system range, RC transmitter/receiver range, and the ability to manually recover the aircraft beyond the line-of-sight, assuming complete autonomous failure. Another feature desired for human-machine interface based teleoperation was a gyro stabilized camera that would make it easier for the subject pilot to guide the aircraft, without being distracted by the aircraft's attitude changes, such as during a banked turn.

Other tasks envisioned for the new platform were experimental verification of new autonomous control algorithms and systems identification of aircraft performance parameters. These added tasks require vastly different features from the testbed, as compared to its usage for human-machine interface based teleoperation, and therefore would make it a multi-role platform. Thus, due to its multipurpose nature, it would be named the Fixed Wing Multi-Role Unmanned Aircraft Vehicle Research Testbed. For new control algorithm research, it is preferred that the aircraft should have as little coupling between the control surfaces as possible and it be neutrally stable. Additionally, the UAV platform would preferably have a low wing loading, unlike the increase that occurred with the Angel platform, whilst still having a 1.5:1 thrust-to-weight ratio, which would aid pulling it out of trouble as was demonstrated several times with the Angel platform. For system identification of aircraft performance parameters, as well as for new control algorithm development, the UAV platform should preferably be fully aerobatic, as are all Sebart models available, and therefore have low wing loadings and high thrust-to-weight ratios. It would also be important to reduce the motor vibration transferred to the aircraft, by further isolating the motor, to decrease IMU noise. Additional desired features for the UAV platform would be the ability to fly in high winds, of around 30 mph (50 km/hr), and have sufficiently large avionics bay(s), which would allow for the components to be spaced further from each other.

In late-mid 2010, the Angel UAV testbed platform was lost during a routine test flight when part of the horizontal stabilizer disintegrated in flight. The Angel was flown under manual control at full throttle into the wind, while testing a new collection method for IMU data. The right elevator half separated from the aircraft when the hinges sheared; the right elevator half was never recovered. At approximately the same time, the main spar of both stabilizer halves broke and the linkage control horn in the remaining elevator half was sheared from its mount, thereby eliminating any pitch control. The steel control linkages, for both the elevators and the rudder, were also found to have bent during the descent. The Angel then uncontrollably executed an outside half loop, remained inverted momentarily, stalled, went into an inverted spin, and then impacted terrain. Fortunately the impact was at low speed, only 30 mph (50 km/hr), and in the nose-in direction, thereby resulting in minimal avionics damage since most of the avionics were in the rear of the aircraft. The airframe had severe damage in the forward part and was therefore practically and economically un-repairable. It was determined that the loss the Angel UAV was most likely the result of material fatigue, due to the increased airframe weight, in either the horizontal stabilizers or right elevator half, and one initiated the damage to the other.

The loss of the Angel platform did spawn imperative requirements. There should be redundant flight controls on the new UAV platform, at the very least on the elevators and either the ailerons or rudder to prevent similar losses. The control linkage horns should be made out of a stronger material and be adhered better to each control surface. The control linkages should be made out of a stronger material than the ones used on the Angel, especially on a larger airframe. The structure of the next platform should also be reinforced for the addition of weight, as is the result of integrating the avionics suite. The avionics should also be placed in the rear of the aircraft, especially near the wing, therefore limiting any possible damage if similar loss of aircraft should occur. An important feature that would be desired in the new platform is having sufficiently large control surfaces that can be used to compensate for the loss of a flight surface or control surface, in the event that would occur.

As mentioned earlier, the new UAV platform would be constructed from a COTS airframe from Sebart. The relevant options available are compared below:

	Angel 30		Angel 50		Miss Wind 50		Wind 110		WindS Pro 2M	
	MFG	AVI	MFG	AVI	MFG	AVI	MFG	AVI	MFG	AVI
Wing Span [in] [mm]	50.4 (1280)		62.2 (1580)		62.2 (1580)		68.5 (1740)		74.0 (1880)	
Length [in] [mm]	52.4 (1330)		65.0 (1650)		62.2 (1580)		70.9 (1800)		78.3 (1880)	
Weight [lb] [g]	3.09 (1400)	5.74 (2601)	6.07 (2573)	7.98 (3619)	6.62 (3030)	8.53 (3869)	9.13 (4138)	10.9 (4930)	10.5 (4757)	11.6 (5272)
Wing Area [in ²] [dm ²]	519 (33.5)		710 (45.8)		1008 (65)		899 (58)		1008 (65)	
Wing Loading [oz/ft ²] [g/dm ²]	13.7 (41.8)	25.5 (77.6)	19.7 (60.1)	25.9 (79.0)	15.1 (46.2)	19.5 (59.5)	23.4 (71.3)	27.9 (85.0)	24.0 (73.2)	26.6 (81.1)
Wing Loading per Wing Span [(g/dm ²)/cm]	0.326	0.606	0.380	0.500	0.292	0.377	0.410	0.489	0.389	0.431
Weight Increase	85.7%		31.5%		28.8%		19.1%		10.8%	
Servos per Control Surface Type										
Aileron	2				4		2			
Elevator	1						2			
Motor Power [W]	500	900	1250		1250		1650	1900	2200	
Power-to-Weight Ratio [W/lb]	170	227	156		147		152	175	189	
Total Cost [\$]	1472		2050		2162		3520		5420	

Table 4. Comparison of all relevant COTS airframe choices. The Angel 30 UAV platform is listed for comparison.

It is assumed that the additional weight in the form of the avionics suite will be approximately 800 g. However in the case of the Angel 30 through the Miss Wind 50 airframes, there will be additional payload to support the avionics and satisfy all requirements, such as endurance. Note that all airframes used one rudder servo.

The rows in Table 4 that would impact the choice of airframe are: the wing loading, the wing loading per wing span, the weight increase percentage, the number of servo per control surface type, the power-to-weight ratio and the total cost. Per the requirements of our new UAV platform, the wing loading must remain low. However, each design's wing loading is proportional to its size. Thus, in order to make the comparison independent of size, the wing loading per wing span is used. The wing loading per wingspan, sometimes called a cubic loading, gives a size-independent comparison of wing loading following the cubic dimension-volume growth ratio, where weight grows as a function of the cube of the length and thus is compared in that matter. In order for an aircraft to fly as agile as possible, it must have the least cubic loading, while in order for it to be able to fly in as high winds as possible, it must have the greatest cubic loading. The weight increase is optimally minimized in order to lessen the relative rate of fatigue that the aircraft encounters. The number of servos per control surface type must be maximized in order to gain the greatest amount of redundancy and independence between each control surface per type. The power-to-weight ratio must be maximized in order to achieve the greatest thrust to weight ratio. The total cost would optimally be minimized.

Following these comparisons, the Wind 110 was chosen to be the new UAV platform. It has the second lowest increase in weight while having a middle wing loading per wing span. It also has twin independent ailerons and, more importantly, twin independent elevators, and has the second highest power to weight ratio of the platform choices. In terms of total cost, the Wind 110 was chosen over the WindS Pro 2M because the significant cost increase only yielded a slight improvement in the other categories while yielding no improvement in the servos per control surface type.

Otherwise, the Wind 110 was chosen because it is a RC pattern precision aerobatics design that has been well tested in RC aerobatic competitions. There have also been several cases where one part of the Wind airframe

malfunctioned, such as a control surface jam, and the aircraft was recovered successfully. Moreover, other aircraft of this type have returned after in-flight collisions where a large portion of their flight surfaces were destroyed, such as after losing most of a wing. The Wind 110 had also been reported to fly in 30 mph winds without significant affect in cruise. There is also minimal control surface coupling on the Wind, a result of the combination of horizontal stabilizer anhedral and wing dihedral.

III. UAV Construction

Construction began on the Wind 110 airframe soon after it was chosen as the new UAV testbed platform. The airframe would be built as an RC model airplane and then modified as our UAV. While building it as an RC airplane, many modifications were made to improve flight and longevity characteristics, as well as overall safety. These included the replacement of the MFG linkages and connectors with stronger and higher quality titanium linkages and ball link connectors. The MFG phenolic control horns were replaced with higher strength custom cut carbon fiber horns and were mounted using an epoxy adhesive with an especially high shear strength to prevent pull out, as occurred on the Angel UAV. Most of the stock fasteners throughout the airframe were also replaced with identically sized fasteners made from stronger materials and meeting specification ratings, to minimize the risk of failure.

The motor was also replaced, following a need for increased thrust and isolation from the airframe, as per the requirements of the new UAV platform. The MFG recommended motor was a Hacker A50-16L, which is an outrunner design brushless motor in which the magnets and housing rotate with the shaft around the motor coils. The motor was replaced with a Hacker C50-14L, which is a competition grade inrunner design brushless motor, where the rotor, shaft with magnets attached, rotates inside of the motor coils. Since it is of competition grade, higher tolerances are met and the motor is rated for high rotation rates and torques. The C50 uses a planetary gear box in order to transform its greater rotation rate into increased torque. With an 18x12 APC-E propeller, as recommended for the airframe by Sebart, the C50 is able to drive the propeller at higher rotation rates, therefore producing more thrust, than the A50, and, if needed, allow for greater flight speeds. It should be noted that for the same rotation rates, the C50 is more efficient than the A50 at producing thrust. That is, it uses less current and thus less power per thrust output, therefore allowing for greater endurance per given battery capacity. As a result of this, it will also run much cooler than the A50 due to the decrease in current used.

Since the C50 is an inrunner design rather than outrunner, it requires a different mount than that of the A50. A special vibration isolation mount was designed and built into the nose of the aircraft. The vibration isolation mount suspends the motor from the nose of the aircraft using neoprene rubber. The C50 also has an overall weight advantage over the A50, where the weight of the C50 motor and vibration isolation mount are less than the weight of the A50 by 63.4 grams. This reduction of weight in the nose allows for a larger capacity / heavier flight battery to be used, which lies in the forward part of the aircraft behind the motor, without affecting the center of gravity. This allows for the endurance of the platform to be increased without an overall weight increase.

The rest of the propulsion system was also modified for increased safety and endurance. The electronic speed controller, which controls the motor, was upgraded from the MFG recommendation to a larger sized Castle Creations Phoenix ICE HV 80, with a larger heat sink and a built-in data logger. A safety switch was also installed in-line between the electronic speed controller and the flight battery and allows the flight battery to be connected without the motor engaging; this switch also has spark suppression system to prevent corrosion of the battery leads. The 8 cell LiPo battery was also to be upgraded from MFG recommended capacity of between 4500 mAh to 5000 mAh to a capacity of 6600 mAh, therefore allowing for greater required endurance.



Figure 11. The upgraded linkages on the UAV. The carbon fiber horn can be seen on the left connected to a ball link, then a titanium pushrod, then another ball link and finally the servo arm.

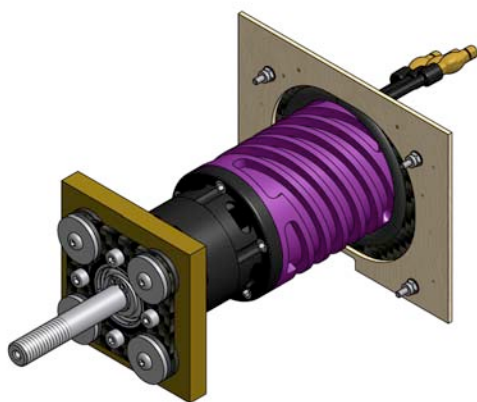


Figure 12. The UAV's upgraded propulsion system. Left: the CAD model of the Hacker C50-14L motor assembled into the aircraft, at the firewall (yellow) and rear retainer (tan), using the vibration isolation mount. Right: the nose of the UAV. The motor, electronic speed controller (green), safety unit (clear heat shrink), and the flight battery (silver).

Following the test flight of the un-instrumented UAV, the avionics suite was installed, mainly in the rear of the aircraft. The Wind 110 airframe features large open areas, where in some of them there is open airflow, specifically in the forward half of the fuselage. Therefore, the avionics components that need airflow were installed under the battery tray and the rest of the components were installed behind the air deflector in the mid-rear of the aircraft. The IMU was strategically placed as far rear as possible to prevent any effects induced by electronic components, such as a current induced magnetic field affecting the IMU's integrated magnetometer. The effect of the IMU being behind the center of gravity (center of mass) will be counteracted with software built into the IMU. The GPS was mounted externally on the top of the fuselage right behind the canopy.



Figure 13. The internal layout of the UAV.

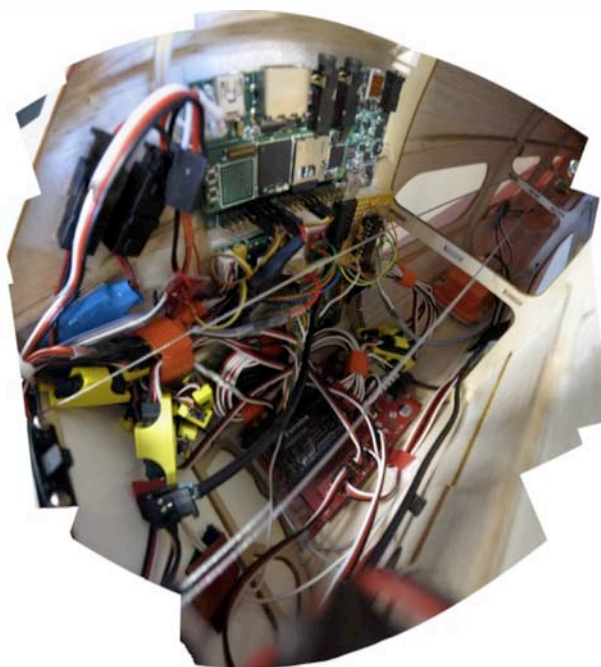


Figure 14. The avionics bay in the UAV. Note the placement of the IMU (orange), far from any other components.

The permanent camera mount from the Angel UAV was upgraded to a gimbaled three degrees of freedom (3DOF) mount, which can roll and yaw ± 60 degrees from center, and it can pitch from the horizontal 120 degrees in the downwards direction. The camera is mounted on the bottom of the fuselage in the front of the aircraft, between the landing gear to protect it from harm. The camera is automatically stabilized by the autopilot using the state data from the IMU. For human-machine interface experiments, the autopilot will keep the camera at 45 degrees below the horizon and level, with respect to roll, during the entire flight. Otherwise it can be prompted to change direction. For safety purposes the camera can easily be locked into an aircraft body stationary 0 degrees roll, pitch, and yaw, thus aiding the safety pilot in recovering the aircraft at beyond the line-of-sight locations.



Figure 15. The 3DOF gimbaled camera on the UAV platform.

Our UAV platform has to date been able to fly fully autonomous without any incident. It has been flown in winds up to about 35 mph (60 km/hr) without very much affect to the performance of the aircraft. A recovery via the onboard camera has been demonstrated possible, yet never used. Some of the other communication components have been upgraded, giving the aircraft the ability to fly within an expected range of 5 miles (8 km). The overall weight of the aircraft, including all modifications, is 5028 grams, which is only 1.9% over the initial estimate.



Figure 16. The UAV platform with avionics in flight-ready status.

IV. Risk Mitigation Strategies followed in our UAV's Testing and Experiments

An important factor in the development of a UAV testbed platform, and subsequent usage in experiments, is risk mitigation. The significance of risk mitigation was recently highlighted in NASA's AirSTAR program, where the researchers went through a series of aircraft in order to train their pilots, and to test their avionics [32,33]. In our case, the current safety pilot has almost a decade of RC piloting experience with a variety of aircraft, so training was not a concern. However, the concern in advancing with larger UAV testbed platforms was that each successive platform can cause increasingly more bodily injury and property damage. The our UAV weighs approximately 11 lb and has been measured to fly at speeds, in 'controlled' full throttle level flight, of up to 110 mph; in a full throttle dive, the UAV will reach even higher speeds. Therefore, a careful process need be undertaken before a platform such as our UAV is allowed to fly, either autonomously or teleoperated, especially beyond the line-of-sight. The process, outlined as following, was used to minimize the risk of losing our UAV and is described generally.

The first step in testing a new UAV platform is to construct and flight-ready an airframe as an RC aircraft and to perform several flight tests without avionics. At this point, any modifications to the airframe should be made, while there should still be no avionics whatsoever on board. This allows the safety pilot to become familiar with the aircraft's flying characteristics, especially bad tendencies. This aircraft status reduces the stress induced on the safety pilot as compared to flying the airframe as a fully equipped platform for the first time; it also entirely prevents the loss of any avionics assuming any malfunctions are to occur.

Next, the platform would be equipped with full instrumentation. All systems should be thoroughly tested on the ground to ensure that there has been no miswiring of any sort, and that the safety pilot can still assume full control at will. This would be followed by several manual, safety pilot controlled, flights where, again, the safety pilot can familiarize oneself with the aircraft and become familiar with any bad tendencies. At this point it is also useful for the safety pilot to narrow down the optimal center of gravity of the aircraft from the MFG provided range; this is easily done with aerobatic airplanes by watching if the nose of the aircraft rises or descends significantly during roll. Once the center of gravity is correctly adjusted, which is normally done by moving the flight battery, the aircraft should be able to perform an axial mid-speed roll, of around 180 degrees per second. At this point, the aircraft would be ready for system identification of performance parameters.

For autonomous or teleoperated flight, such as experimentally verifying new autonomous control algorithms and being teleoperated using a human-machine interface, the aircraft must go through several more steps, especially if it is to fly beyond line of sight. For both these tasks, the UAV platform is to demonstrate flight in straight lines and curves of different radii, and combinations of the two; and finally be able to autonomously recover itself. Following these, the UAV platform can be used for autonomous flight beyond the line of sight.

However, in the case of the human-machine interface teleoperation of our UAV, the platform must go through a few additional steps. These extra steps are necessary because the teleoperation of our UAV is done through a 3G data connection, from the neuroscience laboratory to the flying site, a distance of 25 miles. The UAV needed to be flown at the field using a keyboard based interface, which simulates commands generated from the EEG interface, within the line of sight. This process is to be repeated beyond the line of sight with the keyboard interface. Following that, EEG teleoperation is to occur within the line of sight. Finally, the teleoperation can be done beyond the line of sight. This process reduces the risk of encountering communications errors between our UAV and the ground station, and of encountering problems due to the 3G connection.

V. Further Platform Capabilities and Possible Extensions

To date, our UAV has performed flawlessly in all tasks rendered. Currently the platform can also be implemented for a variety of other applications. One example is the capability of our UAV to perform reconnaissance type tasks such as mosaic image collection by using its IMU stabilized onboard camera. Mosaic image collection is regularly done using low cost UAVs with fixed cameras by computing a trajectory about the area desired in order to vector the camera. This can become quite problematic in unsteady environmental conditions, such as shifting winds and turbulence. Iscold *et al* [18] demonstrated that this task can be accomplished in unsteady conditions with a small UAV using a novel guidance strategy; with the video captured, they stitched together a mosaic image of a highway. By replacing the fixed camera with an IMU stabilized camera that can be aimed at a desired location, as installed on our UAV, a similar mosaic photo can be created by continuously sweeping an area, without regard to aircraft heading or steadiness. This system can also be applied to monitoring a fixed location while the aircraft is aggressively maneuvering.

Our UAV can easily be expanded to fill other roles, although some existing avionics components may be a constraint. The current communication components used limit the platform to relatively short ranges, only 5 miles or so. Beyond this distance, the components will likely lose reception. These communication components can be upgraded on the current UAV platform without much, if any, modification. As an example, with the current 5.8GHz video system, which only has 0.5W of power, the downlinked video will begin to get fuzzy after about a kilometer or so. This system can be swapped out for a 2W or greater power system without significant increase in weight. As an aside, the 3DOF gimbaled video mount on the UAV can also be replaced with a better mount, which would provide smoother motion based on the design of a swash plate in a helicopter rotor head, rather than bridged servos.

The development procedure for our UAV can be adapted to other similar airframes in order to develop similar multi-role platforms. The advantage of using our UAV, as opposed to task specific UAV platforms, is that a user has the ability to transition the aircraft from one role to another without making any hardware changes. This saves the user significant effort with respect to the development and maintenance of multiple platforms. However, if an additional task is required of our UAV, or a similar platform, it can be adapted to carry the required avionics. For example, the aircraft can be adapted for use in swarm applications by equipping it with additional networking communication devices, as used by the SMAVNET project [6], without noticeable performance changes. Furthermore, if our UAV was developed from the WindS Pro 2M airframe, instead of the Wind 110, the platform would be able to fly with similar characteristics and could carry 1500 grams of payload, rather than 800 grams, without increasing the weight addition percentage past that of the Wind 110 derived UAV. This design concept can be applied to larger airframes to produce similar multi-role UAV platforms. Our future plans are to create a platform similar to our current UAV, which would be in the size range of 2.5 to 3.0-meters, with similar aerobatic performance.



Figure 16. The UAV platform during landing.

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