Design of "Iris", a Small Autonomous Surveillance UAV

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This paper documents the design process used for a small autonomous surveillance UAV. The most significant requirements for the plane were size (man-packable), endurance (about 1 hour) and cost (essentially disposable). The plane that resulted, named "Iris", is a tailless plane with a 45 cm wing span and a total mass of less than 200g. During flight tests, it achieved an endurance of 52 minutes. The estimated cost to manufacture the planes was $343, excluding the autopilot.

Nomenclature

b	Wing span (m)
C_D	Airplane drag coefficient
C_{Do}	Parasite drag coefficient
C_L	Wing lift coefficient
D	Drag (N)
E	Endurance (s)
K	Induced drag coefficient
L/D	airplane lift to drag ratio
P_{req}	Power required to overcome drag (W)
r	Distance from plane center of gravity to wing aerodynamic center (m)
S	Wing surface area (m²)
S_f	Surface area of winglets (m²)
T	Thrust (N)
V	Velocity (m/s)
V_{VT}	Tail volume ratio
W	Airplane weight (N)
W_b	Battery weight (N)
η	Combined motor and propeller efficiency
ξ	Battery energy density (J/N)
ρ	Air density (kg/m³)

I.   Introduction

ONE exciting technology being developed in the aircraft industry is the ability to remove the pilot from the cockpit, making the aircraft fully autonomous. Airplanes that make use of this technology are called Unmanned Air Vehicles, or UAV's. As UAV technology develops, components used for autonomous control decrease in size and weight. This makes the development of small UAV's (SUAV) possible. SUAV's find numerous applications for reconnaissance purposes with military, border patrol, search and rescue, pipeline monitoring, and traffic reporting. Companies including Northrop Grumman, Boeing, and AeroVironment are among the major developers of SUAV's currently used for military purposes. Fully autonomous UAVs now on the market range in size from the Raven (by AeroVironment) which has about a 6' wingspan to the Predator (by

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Northrop Grumman) which has a 116' wingspan. Recently, a need has arisen for a less expensive, more portable SUAV. This SUAV should be easily carried by a single person, launched by hand with minimal assembly, and be used for flights of up to one hour endurance.

The key functional specifications for the aircraft are as follows:

- Wing span under 60 cm
- Endurance of 1+ hours
- Minimal assembly (no separate parts or tools needed)
- Man-packable (breaks down or is small enough to be carried in a back pack)
- Hand launchable
- Able to fly in 25 mph (12 m/s) winds
- Production cost below $500 dollars (less autopilot)

The purpose of this paper is to provide documentation on the development of the final design and describe how each of the functional specifications was met. Documentation will proceed according to four functional subgroups: Aerodynamics, Components, Propulsion, and Structures and Manufacturing. Each section will contain associated design decisions and metric values associated with these decisions. Following the main body of the report, a short section entitled Prototype Progression will outline the lessons learned from each of the 9 prototypes that were built and flown.

II. Design Description

A photograph of the final design is shown in Fig. 1. A clear coating was applied to the airplane to allow visualization of the components. This plane had an endurance of just less than one hour, a wingspan of 45 cm, and weighed only 193 grams. It can carry the Kestrel 2.0 autopilot with accompanying components as well as a small color video camera for reconnaissance.
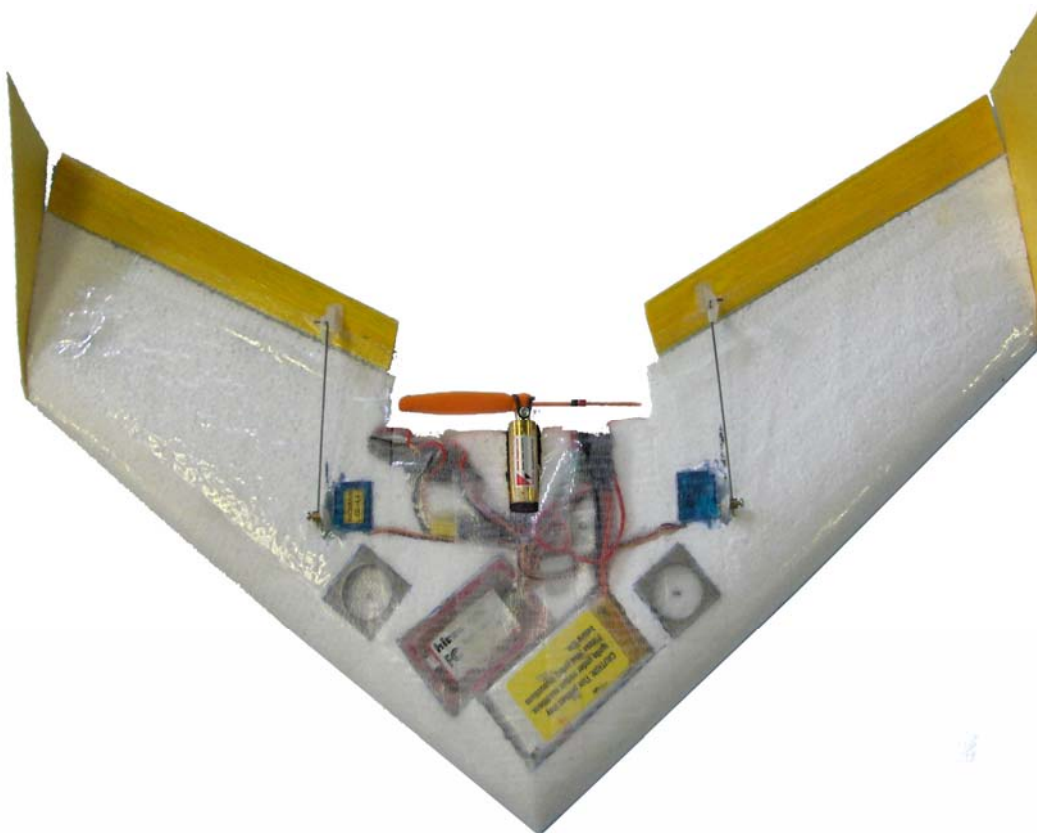
Figure 1   Photograph of the final airplane with components exposed

The proposed design solution includes the following parameters:

- Airfoil: Chipman_Larson
- Quarter Chord Sweep: 30°
- Dihedral: 3°
- Root Chord: 15 cm
- Tip Chord: 12.5 cm
- Elevon Chord: 2.5 cm
- Washout: 2 Degrees
- Center of Gravity Location (measured from leading point of airplane): 10.5cm
- Winglets: Triangle shape with areas of 23 cm^2 each
- Wing Planform Area: 0.065 m^2
- Aspect Ratio: 3.33
- Motor: Feigao 1208436L Motor
- Propeller: GWS 404 Propeller modified to a 4" x 3" propeller
- Speed Control: Phoenix 10
- Receiver: GWS Pico 5 channel
- Servos: Two Bluebird 303, 3.5 gram servos
- Battery: Thunder Power 1320 mAh 2-cell Lithium-Polymer Battery
- 50 gram dummy weight to simulate autopilot and payload

A. Aerodynamics

1. Initial Design

The first step in the plane design was to determine the aircraft configuration. For this project, a tailless swept wing airplane (often known as a flying wing) was chosen because it can be carried without the need to break down any structure. The flying wing design satisfies three critical functional specifications: it requires minimal assembly, it is easy to transport, and it can be set up (from case to flight) very quickly. In order to meet target values, a span of 45 cm was chosen, with a root chord of 15 cm and a tip chord of 12.5 cm. The surface area, weight, and lift coefficient, (C_L), determine the expected speed of the plane. It must be possible to hand launch the plane at its minimum velocity. (Experience shows that it is not generally possible to launch a small airplane by hand at more than 13 m/s). According to Eq. 1:

$$V^2 = \frac{2W}{\rho S C_L},$$
(1)

where W is the weight of the plane, ρ is the air density, and S is the wing surface area. The minimum velocity expected for the plane was 11 m/s.

2. Airfoil

An airfoil was developed to meet the particular needs of a tailless aircraft. For a flying wing configuration, it is important to have a positive moment about the wing aerodynamic center. In order to develop an airfoil with sufficient positive moment, the computer program "Xfoil" was used. "Xfoil" is free to download and can be found at http://raphael.mit.edu/xfoil. As inputs it takes data points for the airfoil, a Reynolds number, and an angle of attack. The program returns the airfoil lift coefficient, drag coefficient, lift to drag ratio, and moment coefficient along with the pressure variation over the airfoil.

Research was conducted on 400 different airfoils. Each of these airfoils was tested separately through the following process:

1. The airfoil coordinates were loaded into Xfoil.
2. The anticipated Reynolds number was entered (for cruise velocity Re= 120,000).
3. The airfoil was then analyzed at angles of attack from 0 to 10°.
4. The resultant coefficients for lift, drag, and moment were noted. If the pitching moment was more negative than -0.02, the airfoil was eliminated.

Only 20 airfoils returned pitching moments greater than -0.02. Of these 20 the airfoil with the highest lift to drag ratio, the Eppler 520, was chosen. This was used for the first three prototypes. Because prototype planes built using the Eppler 520 performed poorly, it was suspected that the airfoil was experiencing flow separation due to the low Reynolds number effects. Further analysis using Xfoil confirmed this and more airfoils were researched. Two airfoils specifically designed for flying wings at low velocities, the S6071 and the S6079, were analyzed and tested on planes. The S6071 had a higher lift to drag ratio (L/D), but had a negative moment coefficient. Both airfoils were tested on planes, with comparable performance. A new airfoil, called Chipman-Larson, was also developed using Xfoil in an attempt to improve upon these airfoils. The new airfoil had a positive moment coefficient (0.02) as well as a high L/D (47 at 10 degrees angle of attack) at the low Reynolds number the plane would be flying at. It was decided that the Chipman-Larson would be used on the final plane because this positive moment coefficient would decrease the amount of elevon deflection required to maintain stable flight.

3. Winglets

Winglets provide yaw stabilizing moments. Winglets were sized using the tail volume ratio defined as:

$$V_{VT} = \frac{2S_f r}{Sb} \, ,$$ (2)

where S_f is the surface area of the winglets, r is the distance from the center of gravity of the plane to the aerodynamic center of the winglet, and b is the wing span. Nickel and Wolfhart[1], suggest that the tail volume ratio should range from 0.03 to 0.05. For this design, 0.04 was used. For a triangular shaped winglet, this gives the result that each winglet, attached at the 10 cm tip of the wing (the wing tip chord was 12.5 cm, of which 2.5 cm was the elevon), should be 4 cm tall.

4. Elevons

Elevon sizing affects the airplane's pitch and roll rates. The greatest pitching moment occurs at an elevon chord ratio of about 0.2 (elevon chord divided by wing chord). With this ratio, and the knowledge that the greatest roll moment is provided by the elevons further from the root chord, a geometry was chosen for the elevons of 2.5 cm near the wing tips to 2 cm near the wing root section.
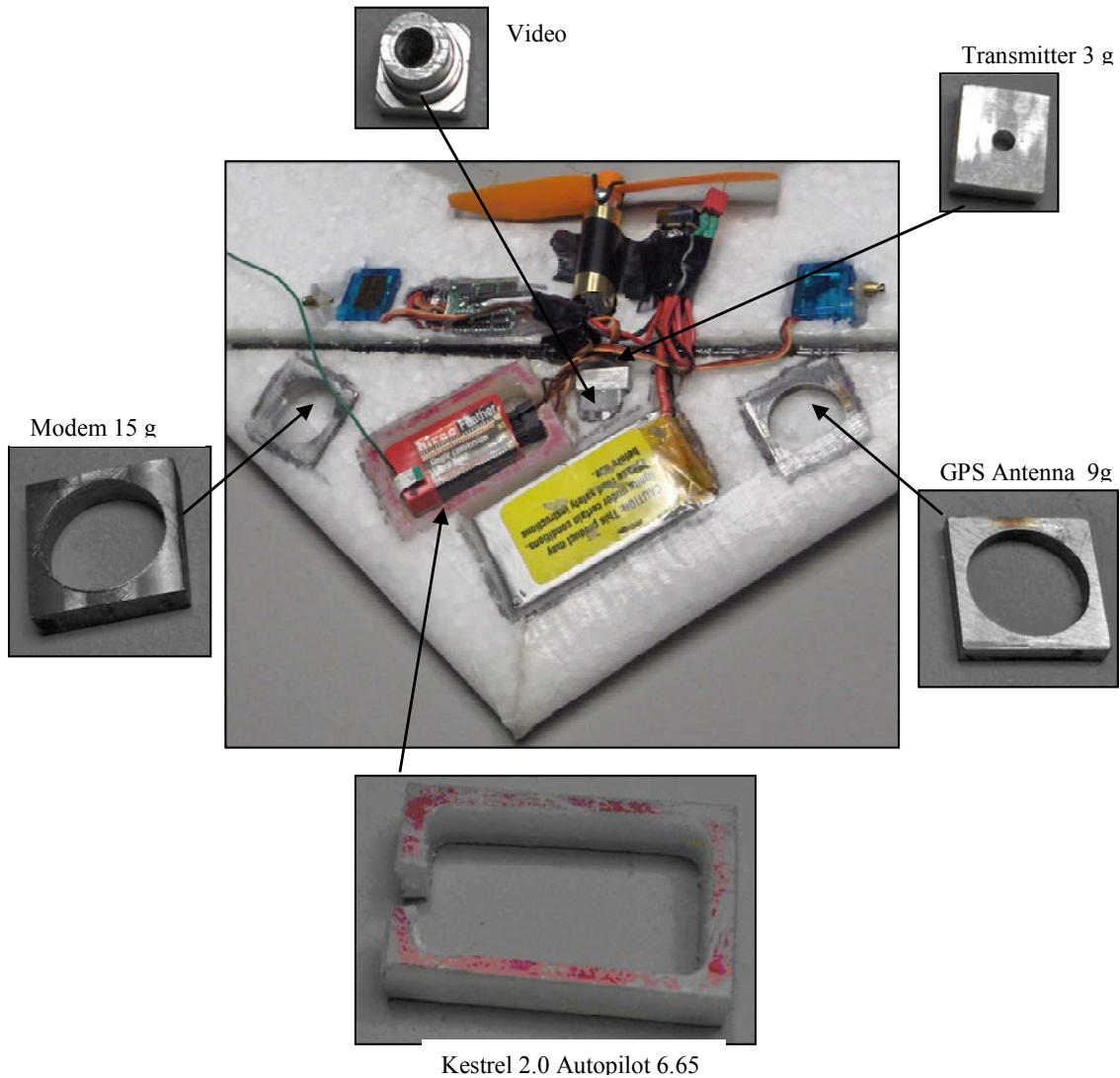
B. Components

The choice of components was largely determined by weight. In order to fly within the prescribed velocity envelope, the total weight of the aircraft was limited to no more than 250 grams. In order to achieve this, the lightest components that still accomplished the mission were used. A listing of the chosen components and their masses is given in Table 1.

Table 1 Components and masses

Component	Name	Mass (g)
Autopilot	Kestrel 2.1	16.7
Modem	Aerocom 4490-100 1x1	15
GPS Antenna	Commlinx Solutions Patch	9
Camera	Micro Color CMOS	3.3
Transmitter	Spy Stuff SDX-22	3
Servos	Bluebird 303	3.4
Motor	Feigao Brushless	17
Speed Control	Phoeniz-10	6
Batteries	Thunder Power	62

The total mass of the non-propulsive components found in Table 1 is 54 grams. These components were intended to provide the plane with full autonomous capabilities at a range of up to 1 mile. Because it was not included in the scope of this project (largely due to funding) to actually perform fully autonomous flights, the physical components were not installed in the airframe. However, in order to demonstrate the plane's ability to house these components, dummy components of appropriate size and mass were created and were carried by the final prototype as shown in Fig. 2. All prototypes were flown using radio control only.

Video

Transmitter 3 g

Modem 15 g

GPS Antenna 9g

Kestrel 2.0 Autopilot 6.65

Figure 2 Autonomous simulation components and masses

Because material must be removed from the body of the plane to make space for each component, their placement affects not only the center of gravity but the structure of the entire plane. In order to make the plane strong enough, a carbon spar was added to the plane. The final placement of components is shown in Fig. 2. At the end of the development, the structure had noticeable weak points. More work needs to be done in the future to eliminate these points of potential structure failure.

C. Propulsion

1. Method of Propulsion

Endurance is affected by many factors. These include aerodynamic factors such as airfoil characteristics (Lift to Drag ratio), and propulsive efficiency. Propulsion design decisions will now be described.

It was decided early on that propulsion for the Iris plane would be provided by a battery, an electric motor, and a propeller. This decision was made due to the high efficiency, simplicity, and reliability of an electric system at the small sizes and weights that were needed. Each propulsive component was carefully chosen to best meet the mission requirements of one hour endurance, and V_{min} and V_{max} of 10 and 20 m/s, respectively.

2. Battery

In order to select the best battery, specific energies (kJ/N) were compared for many batteries. Three popular battery types were specifically compared: Nickel Cadmium, Lithium Polymer, and Zinc Air. Specific energy values for these three battery types are listed in Table 2.

Table 2 Battery type and specific energy

Battery	Specific Energy (kJ/N)
Zinc air	128
Li Poly	48
NiCad	20

As can be seen, the specific energy of Zinc Air exceeds the other two. However, Zinc Air batteries are expensive and cannot be recharged. It was felt that although rechargeability is not specifically a mission requirement, it is a necessity for the prototyping of the plane. For this reason, Lithium Polymer batteries were chosen for the plane. However, it is recommended that as Zinc Air batteries, be considered as an option to improve endurance of the airplane.

Now that the battery type had been selected, it was necessary to predict the battery capacity required for a one hour flight. Battery weight fraction can be found from the equation:

$$\frac{W_b}{W} = \frac{VE}{\xi \left(L/D \right) \eta},$$
(3)

where W_b/W is the battery weight fraction, E is the plane endurance, ξ is the battery energy density (J/N), and η is the combined efficiency of the motor, propeller and electronics. It was found that the battery to total plane weight percentage would be no greater than 25%. Since the total plane was constrained to 250 grams, this limited the battery to about 60 grams. It was found that the maximum capacity available within that weight limit was a ThunderPower 2-cell, 1320 mAh battery which has a mass of 62 g.

3. Motor

As mentioned previously, the motor needed to provide sufficient power to enable the plane to achieve a maximum velocity of 20 m/s. An analysis was performed on the plane to find the amount of power that would be needed. The coefficient of drag, C_D, is:

$$C_D = C_{Do} + KC_L^2,$$
(4)

where C_{Do} is the parasite drag coefficient and K is the induced drag coefficient. K is found from the wing aspect ratio and the Oswald Efficiency factor (e). The coefficient of drag is used to find the drag on the plane, or thrust from the motor using Eq. 5:

$$D = \frac{1}{2} C_D \rho S V^2 = T.$$
(5)

Thrust is used to find the required power using Eq. 6:

6

$$T \times V = P_{req} \,. \tag{6}$$

P_{req} is the power required from the propeller to overcome drag. A flight velocity vs. required power curve was generated. This plot is seen in Fig. 3. At cruise velocity, 15 m/s, power required is 5.1 W, and at max velocity, 20 m/s, power required is 11.6 W.

It was then necessary to decide which motor could supply the power required. The power rating of a motor is typically the shaft power of the motor. This is related to the power available from propulsion by the propeller efficiency. Assuming a propeller efficiency of 70%, the shaft power required at maximum velocity would be 15 W. Many motors were analyzed. Five of the most probable candidates based on weight (<50 grams) and reported power are shown below. Note that the power given is not power output of the propeller, but shaft power.

Table 3 Motor Specifications

Motor	Power (W)	Mass(g)
Mighty Micro	60	49
Firefly (x2)	14	20
Medusa 4000	40	15
Medusa 5300	48	15
Feigao 1208436L	33	17

The Feigao was chosen for the final prototype. The Medusa motors were not selected because they were newly developed and inaccessible. In order to simplify motor and propeller efficiency analysis, pre-existing software called "Mprop" was used along with an iteration routine. Analysis was performed on the Feigao motor with many different propeller parameters.

4. Efficiency Analysis

Mprop takes motor, propeller, and battery parameters, along with flight conditions as input and predicts current draw and throttle setting required to produce the needed thrust at the given airspeed. Along with the throttle setting, Mprop predicts the efficiencies of the propeller, motor, and overall efficiency of the system. The program was used to analyze many different propellers until a satisfactory propeller was found. An acceptable propeller would yield a combined motor and propeller efficiency of about 50% at Vcruise = 15 m/s and produce enough thrust to fly at Vmax = 20 m/s.

For cruise velocity, the following parameters and values were entered as inputs:

Motor specifications:
    Motor voltage constant   4122 rpm/V
    No load motor current   0.3 Amps
    Motor armature resistance   0.585 Ohms
    Motor Gear Ratio   1:1
Battery specifications:
    Battery voltage   7.4 V
    Battery internal resistance   0.25 Ohms
Propeller specifications:
    Propeller diameter   Iterative
    Propeller Pitch   Iterative
    Number of Propeller blades   2
Flight Conditions:
    Air Density   1.23 kg/m^3
    Air speed   15 m/s

In order to quickly analyze many different propellers, a program was written that would run Mprop iteratively, changing the propeller diameter and pitch. Output data was obtained containing the throttle setting

and the efficiencies of the motor and propeller. The maximum system efficiency of 0.517 occurs for a propeller with a diameter of 3.5", a pitch of 1.75", and at cruise velocity. However, this efficiency occurs at a 100% throttle setting. Even though the 3.5X1.75 propeller was most efficient, it was rejected because it could not achieve the maximum desired velocity. The system efficiency of a 4 x 3 propeller at 60% throttle was still fairly good, 0.48, and there was still enough excess power to achieve maximum velocity. The current draw at this setting and prop combination is 2.2 Amps. Once the efficiencies were obtained, it was possible to generate a power available curve. This curve is seen in Fig. 3. It was found that the power available was sufficient to achieve a velocity of 20 m/s.
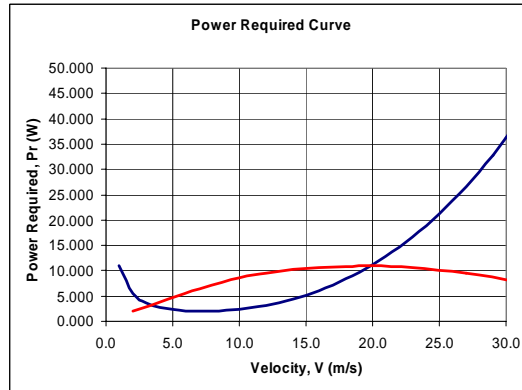
Figure 3 Power required and power available vs. velocity (darker line is power required; lighter line is power, available)

5. Endurance

After the combined efficiency ($\eta_p * \eta_m$) was found, the expected endurance of the plane was calculated. This was done by defining a battery efficiency, η_b, defined as the ratio of the actual to expected capacities. For the 1320 mAh Thunderpower batteries, this was found experimentally to be 0.97. Flight endurance was calculated by Eq. 7:

$$\text{Endurance} = \frac{\eta_p \eta_m \eta_b \times \text{Capacity} \times \text{Voltage}}{P_{req}} \tag{7}$$

The predicted endurance was found to be 62 minutes. Prototype 8, which did not contain the autonomous simulation weights, achieved an endurance of 58 minutes. This value is slightly less than predicted especially considering it was a lighter model than what the design analysis had assumed. This may be due to various effects, including: wind, cold batteries, under-predicted parasite drag, power loss during turns, and over-predicted efficiency. By adjusting the overall efficiency from .48 to .45, the prediction was changed to match with the actual value. This made it possible to accurately predict future endurance tests. The final prototype was not fully endurance tested, due to inclement weather. However, a reasonable prediction was made. With the autonomous dummy weights, the final prototype was slightly heavier than prototype 8. This resulted in more power required, and thus a lower endurance. It was predicted that the plane would be able to fly for 50 minutes. Although a full endurance test was not possible, energy consumption was obtained for a 20 minute flight. With knowledge of the total energy available, the endurance was calculated to be 45 minutes. It can be reasonably supposed, then, that a final endurance for the Iris plane, fully loaded, is between 45 -50 minutes.

D. Structures and Manufacturing

A manufacturing process needed to be chosen. Using a solid foam wing was selected over a composite hollow structure due to cost. The concept selected was to produce foam wing cores with pockets ready cut for the components. Early on, several options were explored; however, three different options proved to be most cost effective and efficient, depending on the size of the production run. The three processes considered were

expansion foam molding, steam mold outsourcing, and CNC wire cutting combined with CNC milling to cut component cavities.

1. Cost Analysis

Time was spent researching costs associated with facilities, machines, tooling, molds, manufacturing materials, labor, and shipping costs for two different run sizes of 1000 planes and 10,000 planes. Experts and manufacturing companies were interviewed to obtain cost values for the two run sizes. The results in cost per plane (less electronic components) for the two run sizes are shown in Table 4.

Table 4 Cost Analysis for Manufacturing
(components cost not included)

Manufacturing Process	Cost per plane for 1000 units ($)	For 10,000 units ($)
Expansion foam method	257	152
Wire cutting method	203	92
Steam mold outsourcing	80	65

As can be seen, for both production runs, steam mold outsourcing proves to be the lowest cost method. This is obviously the best option. It saves more than 100 dollars per plane (over the other processes) on a run of 1000 planes because there is no machine, tooling, or facility cost associated with it. The overall cost of one plane was then calculated. Table 5 shows the costs per part of the previously established components for 1, 1000, and 10,000 units. For a run of 10,000 planes, the total cost of the components, without the autopilot, is estimated to be $343.

Table 5 Components Cost

| Component	Cost per unit, 1 unit ($)	Cost per unit, 1000 units ($)	Cost per unit, 10,000 units ($)
AutoPilot	5000	3025	2468
Modem	50	26	24
GPS Antenna	17	9	8
Video Camera	80	41	38
Video Transmitter	395	201	190
Servos	17	9	8
Motor	40	20	19
Propeller	2	1	1
Speed control	60	31	17
Batteries	36	18	17
Total	**5697**	**3389**	**2811**

III. Prototype Progression

Nine prototypes were built to test design assumptions. All of these prototypes were radio controlled. With each prototype, lessons were learned and used to improve subsequent prototypes. Below is presented the progression of prototypes and the lessons learned for each.

Prototype 1
-Add dihedral to improver roll stability (>2 deg)
-Improve craftsmanship of winglets to reduce yaw instability (make them flat)

Prototype 2
-Validated winglet sizing method (see Winglets section of this report)
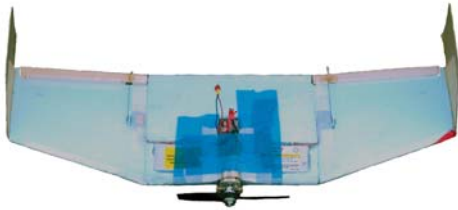
Prototype 3
-Increased washout was necessary to reduce wing tip stall (use 2º)

Prototype 4
-Sweep was added to the wing to allow for a more aft Center of Gravity

Prototype 5
-Elevons must not be in a region of flow separation
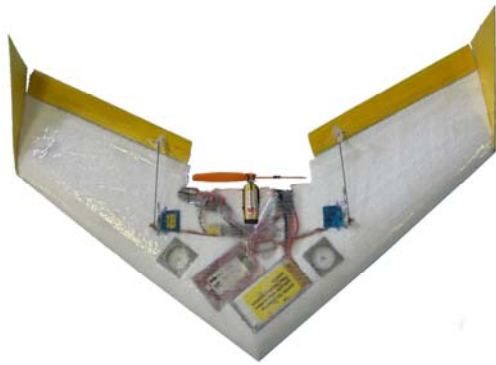-Airfoil was changed to eliminate flow separation

Prototype 6
-Static Margin between 3-6% is crucial for longitudinal stability

Prototype 7
-Achieved an endurance of 25 minutes
-Good pitch, roll and yaw stability

Prototype 8
-Achieved an endurance of 58 minutes without the required payload
-Good pitch, roll and yaw stability

Prototype 9
-Simulated payload and autopilot included
-No full endurance flight test done due to weather
-50 minute expected endurance (extrapolation from 20 minute endurance test)

IV. Conclusion

The goal of this project was to produce a man-packable UAV capable of autonomous flight, while achieving flight endurance of up to one hour. This goal has been largely achieved, as can be seen in Table 7, which is a list of metrics, target values, and achieved values. The 45 cm wingspan allows for easy portability. Sixteen out of the 19 original target values were achieved, two have yet to be measured (#7 – adverse wind conditions, #18 – climb rate), and the endurance of the plane is about 80% of target intended value.

Table 6   Metric versus Target and Achieved Values

	Metric	Units	Target Value	Acceptance Test	Achieved Value
1	Total Flight Time	Minutes	60	Flight-test	50
2	Set-up (from case to flight)	Seconds	300	Time test	180
3	Broken Down Max Dimension	cm	60	Measured	45
4	Carrying Case Dimensions	cm^3	4800	Measured	4680
5	Minimum Flight Velocity	m/s	10	Flight-test	11
6	Maximum Flight Velocity	m/s	18	Flight-test	20
7	Wind Speed (stability in adverse winds)	m/s	10	Flight-test	YTBD*
8	Payload Capacity	g	50	Measured	50
9	Structure Cost	$	20	Financial Analysis	5.5
10	Components Cost (less autopilot)	$	100	Financial Analysis	343
11	Production Time	Man-hours	2	Financial Analysis	1.5
12	Production Cost	$	20	Financial Analysis	60
13	Total Cost (less autopilot)	$	500	Financial Analysis	408
14	Range	km	30	Flight-test	33
15	Total Weight	kg	0.3	Measured	0.195
16	Peak Altitude	m	150	Flight-test	150+
17	Life Expectancy	# Flights	10	Flight-test	10
18	Climb Rate	m/s	2.6	Flight-test	YTBD*
19	Number of People to Operate	People	1	Flight-test	1

*Yet to be determined – these metrics must be measured with instruments contained in the autopilot.

References:

1. Nickel, K., and M. Wohlfahrt, *Tailless Aircraft in Theory and Practice,* AIAA, 1994.