ABSTRACT

The objective of this project was to design and implement an avionics system for the Center for Imaging Science at the Rochester Institute of Technology (RIT). The team implemented the necessary modifications to a previously designed Unmanned Aerial Vehicle (UAV), providing the capability to support a 3 lb. (1.36 kg) remote sensing payload. The avionics design incorporates vision guidance, telemetry feedback, and autonomous navigation via stability augmentation hardware. The system architecture utilizes wireless communications for manual flight control, gathering sensor information, and real-time vision guidance. Together these components provide the necessary information for the pilot to successfully complete mission objectives.

INTRODUCTION

The Center for Imaging Science (CIS) at RIT develops state-of-the-art hardware and software for remote sensing applications for both commercial and government clients.

The United States Government, and private industry alike, utilizes UAVs for reconnaissance scenarios both on and off the battlefield. While UAV technology exists for a wide range of military applications, there is a need by the United States Forest Service for UAV technology capable of remote sensing tasks related to wild fires. The goal of this project is to design and build an airborne sensing platform that will allow the CIS to deploy their remote sensing technology.

Important considerations for UAV’s are often payload capacity, endurance and navigation. Also, the sponsor indicated that payload flexibility, future airframe development and commercially available components are the drivers for design decisions. Monetary budget and sponsor requirements were also taken into consideration.

The final design allows a pilot to complete remote sensing tasks at a maximum altitude of 1,000 feet (0.3048 km), and maximum range of 2 miles (3.22 km) from the base station. The platform also has the capability to execute mission objectives autonomously by utilizing its telemetry and stability augmentation hardware. A payload bay is provided to support the 3 lb. (1.36 kg) payload requirement for the CIS equipment.

NOMENCLATURE

- CCD - Charge-Coupled Device
- Cg - Center of Gravity
- CIS – Center for Imaging Science
- I/O - Input/Output
- MHz - Mega Hertz
- N - Newton
- RF - Radio Frequency
- UAV - Unmanned Aerial Vehicle
- V - Volt
- cm - Centimeter
- kg - Kilogram
- km - Kilometer
- lbs - Pounds Force
- psi - Pounds per Square Inch

FINAL DESIGN

Airframe

To evaluate the design of the overall system, it was necessary to analyze the airframe that would carry the telemetry subsystem, vision guidance subsystem and other sensor
subsystems. This included a dynamic analysis of the aircraft produced by the 05008 Senior Design Team, as well as an alternative aircraft. Equations 1-3 were used to determine the airframe handling characteristics.

\[ V_H = \frac{S_T \cdot l_T}{S \cdot c} \]  
\[ V_V = \frac{S_v \cdot l_T}{S \cdot b} \]  
\[ \text{Static Margin} = -\frac{C_{Mg}}{C_{Ls}} \]

We chose two different airframes for implementation in the final design. The first is a modified version of the airframe designed and built by team 05008 (Figure 1). The second is the Senior Telemaster airframe. The plane initially designed and built by team 05008 utilizes a fuselage consisting of carbon fiber and fiberglass. The wing is made from standard wing foam and covered in a fiberglass and carbon fiber shell for added strength and durability. Additional wing supports and access panels were added to allow easy installation and removal of cargo.

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![Figure 1: Team 05008 Airframe](image1)

The team built a Senior Telemaster to provide alternative handling characteristics for the sponsor. The Telemaster fuselage and wing are made from balsa and plywood. These materials provide a high strength to weight ratio, and allow for easy repair and maintenance. Due to the fuselage shape, airfoil and wing configurations, the Telemaster allows the sponsor a trainer type UAV to carry their payload.

![Figure 2: Senior Telemaster](image2)

Furthermore, maintenance and payload flexibility are the major advantages of having two UAV test beds.

### Rail Mounting System

The mounting system for the electronics was based on two 2024-T4 aluminum L-channels with a thickness of 0.1 inches (0.254 cm) and legs of a length of 0.75 inch (1.09 cm). This type of aluminum was chosen because it is typically used in structural applications. The electronic components will be mounted on standoffs to aluminum plates of the same material. These plates will be bolted to each of the rails. This allows alternate placements for the components to modify the center of gravity of the airframe. It also enables each electronic component package to be modular. For cross bracing, the two rails will be connected by two plates at each end. Finally, the entire assembly will be bolted to the bulkheads of the airframe through four L-brackets. An isometric view of the assembly can be seen in Figure 3 above.

![Figure 3: Rail Mount Architecture](image3)

This type of aluminum has a weight density of 0.1 lbs/in³ (2768 kg/m³). Adding all of the aluminum parts, the electronic components, and miscellaneous fasteners resulted in a total assembly weight of approximately 16 oz (0.454 kg). The loading scenario defined for the analysis was a 6G drop. The total force applied will be 6 lbs (26.69 N). This type of loading would be typical in a semi-moderate crash landing.
The worst-case loading scenario on the rail cage itself would be if the total load was borne by a single rail, and it was applied at the opposite corner of the other rail through a rigid plate. This is a conservative modeling scenario because in actuality, the load would be borne by both rails and the plates would also deflect to absorb some of the load.

Using the principle of superposition, this problem can be decoupled into an asymmetric beam bending and a torsion problem. The results of each can then be added to provide a total solution. Asymmetric beams add to the complexity of stress prediction because the cross moments of inertia are no longer zero. This introduces coupling between the two directions of the cross-section. The first step in completing this type of analysis is to locate the centroid of the cross-section using Eq. (4-6). Then each of the second area moments of inertia can be calculated using Eq. (7).

\[
\bar{y} = \frac{1}{A} \sum A_i \cdot \bar{y}_i
\]

\[
\bar{z} = \frac{1}{A} \sum A_i \cdot \bar{z}_i
\]

\[
I_{\text{parallel axis}} = I_{\text{centroid}} + A \cdot d^2
\]

\[
\sigma_x = c_2y + c_3z
\]

The maximum shear force is in the y direction and has a value of 6 lbs. The maximum transverse shear will occur in the thinner portion of the cross-section. Using Eq. (9), where \( V \) is the shear force, \( Q \) is the first area moment of inertia, \( L \) is as previously defined, and \( b \) is the thickness of the section under examination. \( Q \) is defined by Eq. (10) and is calculated to be 0.0138 in³ (0.266 cm³). The transverse shear at point A is calculated to be 114 psi, and at point B is 15 psi (10.55 kN/m²).

Based on the placement of the load, the torque applied (\( T \)) is 19.7 in-lbs. (2.226 N-m). A closed form solution for the shear stress due to torsion for the cross-section that we have defined does not exist. A good approximation is given by Eq. (11), where \( b_1 \) is the leg length and \( t \) is the thickness of the cross-section.

\[
\tau_{\text{max}} = \frac{3\tau}{2b_1t^2}
\]

\[
\tau_{\text{fill}} = 1.74 \cdot \tau_{\text{max}} \cdot \frac{3L}{r}.
\]

The maximum shear stress due to torsion is 3940 psi (2770 kN/m²). A torsional stress concentration will exist in the fillets of the cross-section. The stress concentrations are calculated using the Trefftz criteria defined by Eq. (12). Given our thickness to radius ratio of 1:1, the stress concentrations will have a value of 6860 psi (4823 kN/m²).

The Von Mises failure criteria, which is typical to use for ductile materials such as aluminum, is given by Eq. (13).

\[
\sigma_{\text{VM}} = \sqrt{\frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + 6\sigma_1\sigma_2 + 6\sigma_1\sigma_3 + 6\sigma_2\sigma_3}{2}}
\]

Calculating the Von Mises stress for point A and point B results 10.48 ksi (7368 kN/m²) and 12.04 ksi (8465 kN/m²). The yield strength of 2024-T4 Aluminum is 47 ksi (33040 kN/m²). This gives us an overall static margin at point A and point B of 450% and 390% respectively. This analysis clearly shows that we have considerable margin over the worst-case expected loading of the electronics mounting structure.

Communication Scheme

A communication system is required to meet the project specifications, and allow the exchange of telemetry, instrument, and control data between the base station and airborne platform.

The communication systems were over-engineered to ensure a quality link at two miles. The link budget equations (Appendix A) were used to design a system that had at least +30 dB of margin. This accounted for possible path loss due to trees, buildings, RF interference and other sources of attenuation.

The final communication scheme utilized a 900 MHz MaxStream transceiver, which is easily integrated with the AP50 hardware and Auto Pilot Ground Control Station software. A 2.1 dBi half-wave (dipole) antenna was used to maximize the omni-directional transmission range, while maintaining a small-form factor onboard the plane. The wave propagation pattern for a half-wave antenna is illustrated below in Figure 4.

Figure 4: Dipole Antenna Wave Propagation
Size restrictions were far more lenient at the base station side of the communications architecture; therefore, a 6 dBi omnidirectional antenna was incorporated.

The vision guidance system uses a 439.25 MHz amateur TV (ATV) transmitter. This transmitter is an off-the-shelf 1.5 watt frequency modulation (FM) transmitter offered by Hamtronics, Inc. FM ATV bandwidth and spectrum power density requirements are generally much greater than amplitude modulation (AM) ATV. Also, standard TV sets utilize amplitude modulation. Several adjustments were made to bypass the FM stage of the ATV transmitter; therefore, an AM modulator was used to prepare the camera output for transmission. The vision guidance system broadcasts the video signal on cable channel 60.

The airborne platform utilizes a custom ½ wave (dipole) antenna. This is constructed using standard 22-gauge solid wire. Each radiating element of the dipole antenna was cut to ¼ of the RF wavelength, which is 16.2 cm. The equation used to obtain this length is shown below in Eq. (14)

$$\lambda = \frac{c}{frequency} \times Velocity \ Factor \ \ \ \ (14)$$

Where c is the speed of light, and the velocity factor is 95%. Again, base station size restrictions were more lenient; therefore, a 12 dBi omnidirectional antenna was purchased for the base station.

A laptop acting as a base station receives all communication data. The base station uses the Auto Pilot Ground Control Station software to display GPS and other navigational cues to the pilot. The video is displayed using a Hauppauge USB receiver and the associated WinTV.

**Vision Guidance System**

The final design for the vision guidance system implements a small board mounted CCD black and white camera with 420 TV lines of horizontal resolution, 3.6mm lens, and a 92° angle of view. The camera is integrated with the aforementioned 439.25 MHz communication equipment. The camera is mounted in the nose of the fuselage to provide the pilot with a reference to the horizon, as well as, a view of the ground. The vision guidance sub-system design incorporates a 14.8V lithium polymer battery, CCD camera, and 440MHz transmitter coupled with an ATV receiver at the base station antenna.

**Control, Navigation and Stability Augmentation**

The team used a Futaba 72MHz radio controller to permit piloted control of the UAV. This radio has an associated 9 Channel Futaba receiver. This allows the pilot to actuate the control surfaces of the UAV and to adjust the throttle and brake for take-off, landing, and in-flight scenarios. The radio/receiver pair was selected to provide extra channels because this will allow the sponsor to exercise additional control options for future onboard sensors and control algorithms.

Furthermore, to meet the project requirements and to enhance the capabilities of the UAV the team implemented an AP50 AutoPilot system. The AP50 Autopilot uses GPS and inertial measurement information and Radio Frequency (RF) communication to allow autonomous navigation for the UAV.

GPS waypoints are programmed via the base station to provide the UAV with mission path information, as well as, target location and loiter. In addition, accelerometers provide inertial data that allow the software to provide dynamic control and stability augmentation when combined with velocity measurements taken from a pitot-tube and pressure transducer.

The hardware connects to the servos that actuate the control surfaces and to the 900 MHz transmitter to provide wireless communication and autonomous navigation.

The AP50 Autopilot will allow the sponsor more flexible options for future upgrades. The onboard and base-station software is customizable and comes with a development kit. Thus, CIS can fine tune their current and future UAV’s based on dynamic characteristics of the airframe and payloads. Also, the AP50 Autopilot provides additional I/O ports. This provides a means to execute control and sensor algorithms for future sensor packages.

**TESTING**

**Experimental Setup**

In order to fully test out various sub-systems onboard the UAV. Several experiments and tests were conducted both in the lab and in the field. Lab tests were conducted on the motor, battery, airframe and communication equipment. Then field testing was done on the communications equipment and integrated UAV to ensure proper function and range.

The test setup for the motor, battery, and radio can be seen in Figure 5. The motor was mounted to a sled allowing for thrust measurements to be acquired through LABView. The motor was connected to a force transducer that was calibrated such that the output voltage of the force transducer was directly correlated to thrust measured in lbs. ± 0.010 lbs. (.044 N). The output of the force transducer was logged using LABView to provide a measurement for maximum thrust of the motor, as well as, thrust at various throttle positions on the 72 Mhz Radio Controller. Battery life and performance were also observed during this process to ensure the endurance requirements were met.
Range Test

A range test was performed on the MaxStream transceivers. The airborne platform radio was powered by a small 12 Volt battery, and used the 2.1 dBi half-wave antenna. A laptop was used to monitor the received signal strength indicator on the base station radio. Figure 6 shows the test configuration.

Airframe

In addition, load tests on the airframe and field testing of the integrated UAV were conducted to determine overall system functionality and interference characteristics. Field testing included ground handling tests, a low-speed high-alpha loiter stability test, a stall recovery flight test, a glide slope flight test with feathered propeller, command signal in-flight range test, and verification of hand launch takeoff and landing methods.

RESULTS

The test results found in the lab demonstrated a maximum thrust from the motor of 5.51 lbs. (24.51N). Also, excellent response characteristics of the throttle on the radio controller were seen.

During this testing phase the mission endurance was found to be 60 minutes based on the take-off, loiter and landing scenario tested in the lab.

After the initial test of the airframe designed and built by team 05008, sensitivity in pitch was observed. A tail redesign followed. The new tail design gave the UAV enhanced stability and handling characteristics. The CIS payload tested during this flight was 3.1 lbs (1.4 kg) plus avionics.

The initial tail design provided horizontal and vertical tail volume coefficients of 0.21 and 0.01, respectively. Previous experience acquired over three years of design empennage and control surfaces for SAE Heavy Lift aircraft in this size shows these coefficients to be too low. Daniel P. Raymer also suggests these coefficients to be low for such a small scale aircraft.

A more detailed analysis using software developed for previous SAE Heavy Lift aircraft designs and modified for the CIS aircraft shows a static margin of roughly 10%. This was determined to be too low for flight within a turbulent region. The equations utilized by this software are cited in the Appendix of this document. A least-squares optimization routine embedded in the software was used to derive optimal tail volume coefficients of 0.3 and 0.06 in order to maintain a static margin of 15-20%. These passive stability characteristics provide excellent handling qualities suitable for a remote sensing platform.

Link signal strength data was collected at several key distances to ascertain the ability to meet project specifications. The testing showed that the link quality is more than sufficient at a range of two miles. Most testing was completed in line-of-sight conditions; however, some links had minor tree interference. There was no major degradation in signal quality under these conditions. The results are shown below in Table 1.

<table>
<thead>
<tr>
<th>Distance</th>
<th>RSSI*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>-62.4</td>
</tr>
<tr>
<td>0.82</td>
<td>-66.6</td>
</tr>
<tr>
<td>1</td>
<td>-68</td>
</tr>
<tr>
<td>2</td>
<td>-70.8</td>
</tr>
</tbody>
</table>

Table 1: Range Test Results

(*RSSI Received Signal Strength Indicator)

The signal strength indicator has values from -40 to -110, where -40 is the best signal strength.

ACKNOWLEDGMENTS

The team would like to thank our advisor Dr. Kevin Kochersberger for his insight and mentoring on the project. Also, the team would like to recognize Jason Faulring, Don Mckeown, and the CIS for their remote sensing expertise and invaluable assistance with the communications aspect of the project. Professor John D. Wellin assisted the team throughout senior design with his extensive knowledge of data acquisition and design of experiments assistance. Another important contributor to the project that went over and above to assist the team was Derek Miller. He was a valued resource for airframe information and construction techniques, as well as, a superb pilot during the testing phase of the project. Without his help and the assistance of the Aero Design Team this project would have been nearly impossible.

REFERENCES


Appendix A

Path Loss Calculations

\[ \text{Tx / Antenna Power} = (\text{Tx Power}) + (\text{Tx Antenna Gain}) \]

\[ \text{Cable Loss} = \frac{\text{Loss}}{\text{ft}} \times \text{Length} \]

\[ \text{Connector Loss} = (\text{Number Of Connectors}) \times \left(0.1 \sqrt{\text{Frequency in GHz}}\right) \]

\[ \text{Free Space Loss} = 35.56 + 20 \log_{10} (\text{Frequency in MHz}) + 20 \log_{10} (\text{Link Length in Miles}) \]

\[ \text{Tx Power Budget} = (\text{Tx / Antenna Power}) - (\text{Cable Loss}) - (\text{Connector Loss}) \]

\[ \text{Rx Power Budget} = |\text{Sensitivity}| + (\text{Antenna Gain}) - (\text{Cable Loss}) - (\text{Connector Loss}) \]

\[ \text{Margin} = (\text{Tx Power Budget}) + (\text{Rx Power Budget}) - (\text{Free Space Loss}) \]

Longitudinal Stability

\[ C_{\text{Mgwl}} = C_{\text{Mcw}} + C_{\text{Lw1}} \left( \frac{x_{\text{cq}} - x_{\text{acw1}}}{c(\cos(\alpha_{w1}))} \right) + C_{\text{Dw1}} \left( \frac{x_{\text{cq}} - x_{\text{acw1}}}{c(\sin(\alpha_{w1}))} \right) + C_{\text{Lw1}} \left( \frac{z_{\text{cpw1}}}{c(\sin(\alpha_{w1}))} \right) - C_{\text{Dw1}} \left( \frac{z_{\text{cpw1}}}{c(\cos(\alpha_{w1}))} \right) \]

\[ C_{\text{Mgw2}} = C_{\text{Mcw}} + C_{\text{Lw2}} \left( \frac{x_{\text{cq}} - x_{\text{acw2}}}{c(\cos(\alpha_{w2}))} \right) + C_{\text{Dw1}} \left( \frac{x_{\text{cq}} - x_{\text{acw2}}}{c(\sin(\alpha_{w2}))} \right) + C_{\text{Lw1}} \left( \frac{z_{\text{cpw2}}}{c(\sin(\alpha_{w2}))} \right) - C_{\text{Dw1}} \left( \frac{z_{\text{cpw2}}}{c(\cos(\alpha_{w2}))} \right) \]

Downwash Incidence Angle

\[ \Gamma = \frac{1}{2} a_0 V_w c (\alpha - \alpha_i + \theta_i - \alpha_0) \]