Abstract

This paper provides an overview of the University of Arizona’s Unmanned Aerial System (UAS) that is designed to meet the requirements of the 2013 AUVSI Student Unmanned Aerial Systems Competition. The team developed an integrated system that includes a custom built airframe, the JUPITER (Joined-Wing Unmanned Aerial System Providing Intelligence, Targets, and Emergent Reconnaissance, Fig. 1), and a comprehensive avionics system, LAARK (Low-Altitude Aerial Reconnaissance Kit). The aircraft is guided via a Cloud Cap Technology Piccolo II autopilot system with a NovAtel DGPS expansion using a 900MHz radio. JUPITER is capable of accurately navigating a pre-designated flight path of GPS waypoints while capturing high-resolution ground imagery via two gimbaled 10MP IDS uEye cameras. An onboard computer is used to obtain stabilized imagery from the camera system, acquire live telemetry information from the autopilot, and stream data to the ground station over a 2.4GHz 802.11 data-link. The ground station includes a graphical user interfaces to monitor the sensory information, aircraft navigation, and the target reconnaissance provided by a pattern recognition algorithm. Additionally, various safety procedures have been implemented in order to ensure safe operation of the aircraft for the duration of the mission. This paper provides a brief description of the systems engineering methodology utilized to design and construct this complete Unmanned Aerial System. The paper also summarizes the testing that was performed to ensure that the system can safely and successfully compete in the 2013 AUVSI SUAS mission.

Figure 1: JUPITER team with air vehicle.
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Chapter 1

Introduction

1.1 UA Aerial Robotics Club

The University of Arizona (UA) Aerial Robotics Club is a student club in the Department of Aerospace and Mechanical Engineering at the University of Arizona. The club was founded in 2001 and is advised by Professor Dr. Hermann Fasel. The club currently has 15 undergraduate student members with varying backgrounds and academic majors. The club activities combine cutting-edge computer and robotics technology with sophisticated aircraft in order to create aerial vehicles with the ability to autonomously complete missions without human intervention. The main objective is the development of aerial vehicles that meet the requirements of national competitions in order to strive towards excellence in the field of unmanned aerial systems.

1.2 SUAS Competition Mission Requirements

The background scenario for the 2013 AUVSI SUAS competition is as follows:

An earthquake has impacted a small island nation in the Caribbean. Several boatloads of pirates who have been operating in the area have landed and are attempting to take advantage of the ensuing chaos. The overwhelmed local government has put out a call for help and the US Marines have responded. Their tasking includes humanitarian relief and security. Your unmanned aerial system (UAS) is supporting their mission with intelligence, surveillance and reconnaissance (ISR). In order to support them, your UAS must comply with Special Instructions (SPINS) for departure and arrival procedures, and then remain within assigned airspace. It will be tasked to search an area for items of interest, and may be tasked to conduct point reconnaissance if requested. Additionally, the UAS may be tasked to relay data from a third party Simulated Remote Information Center (SRIC). Immediate ISR tasking may be requested outside currently assigned airspace, causing the UAS operators to request deviations.

This simulated real world military mission lays out the requirements for the Unmanned Aerial System. The UAS must autonomously navigate a path of set GPS waypoints at a specified altitude while surveying the ground for targets, one of which will be located up to 60 degrees from the vertical. Once the UAS has completed an en-route target search, it will enter a specified search area with an unknown number of ground targets. The UAS must survey the area as efficiently as possible to locate and identify ground targets in real time while avoiding designated no-fly zones. After surveying the search area, the UAS must be capable of in-flight re-tasking in order to account for an unexpected change in the mission. This may involve flying to an additional waypoint to survey the area for additional targets. During the system design and testing stages more stringent requirements were defined that exceed the AUVSI SUAS requirements to ensure that the final system was very competitive. Extra credit is awarded to teams that stand out with respect to system safety, reliability, and autonomy. Therefore, in addition to the requirements set forth by the competition rules, the team defined additional requirements that address safety and reliability. A functional requirements table was drafted to support the preliminary and critical design stages of the system.
1.3 Brief System Overview

The University of Arizona’s UAS is composed of two main systems, the aircraft (JUPITER) which includes the airframe, propulsion system, and flight control system, and the avionics suite (LAARK) which includes the onboard camera system, autopilot, air-to-ground communications, and ground station systems. The airframe was specifically designed for the 2013 SUAS competition and features a novel joint-wing configuration which reduces structural weight. Together with a modern composite construction and efficient propulsion system the aircraft allows for a flight time of 40min for a mission payload of 8lbs. The mission payload (LAARK) developed for the SUAS competition consists of a Piccolo II autopilot system with DGPS for autonomous flight navigation, takeoff, and landing, and an aerodynamically encased gimbaled camera system with dual 10MP cameras capable of capturing up to 3 frames per second. The dual camera system provides a combined 120 degree horizontal field of vision and is directed vertically towards the ground while the aircraft maneuvers. This is accomplished using a Trossen Robotics pan/tilt gimbal with a MosquitIO gimbal microcontroller. The imaging system is controlled by an onboard FitPC2 computer that streams imagery and telemetry data to the ground station over COTS 2.4 GHz WiFi link. The ground station employs a software suite of image processing software (OpenCV) that corrects for image distortion and performs autonomous target recognition and analysis. The entire system is monitored using a network of three graphical user interfaces to control flight navigation, monitor telemetry data, display ground imagery, and present target reconnaissance results.

1.4 Systems Engineering Approach

The JUPITER aircraft and LAARK avionics module were both designed and built in only nine months using a comprehensive systems engineering methodology. Preliminary research was performed to explore existing solutions that met the core requirements of the competition. Thereafter, an in-depth requirements analysis was performed to optimize the preliminary design of each system. This included creating requirement tables that listed each functional requirement desired for each subsystem by priority. Concept of Operations (CONOPS) documents were created for both the airframe and avionics teams that included a statement of work, plan of action, and milestones review. These documents were utilized over the course of work in order to aid in the preliminary and critical design phases, ensure steady progress and development, and evaluate the expected performance of design decisions. The preliminary design phase required the analysis of three potential design solutions that would allow each team to meet the performance objectives outlined in the CONOPS documents. This iterative design stage included trade-off analyses to optimize design decisions and guarantee optimal system performance along with a preliminary design review (PDR) presented in front of university faculty. The critical design stage
focused on the high-level design of each subsystem and its interconnections to other system components. Following the critical design review the final components were selected, the software architecture was diagrammed, and a requirements review was conducted to ensure optimal system performance for the final design. A critical design review (CDR) presentation was conducted in front of university faculty and industry experts to validate the design decisions made by each team. The JUPITER aircraft and LAARK avionics module were constructed in parallel between January and May of 2013. The plans of action developed as part of the CONOPS documents allowed both sub-teams to work efficiently and maintain steady progress. Many of the subsystems, such as the camera system, ground station software, machine vision software, and the air-to-ground data-link were developed first in parallel and then integrated together in the final months of construction. Engineering analysis was conducted through the use of two main software tools, namely the LAARK and JUPITER toolboxes, which included all calculations, analysis methods, and testing results relevant to the design work conducted by each sub-team. The final stage of construction was the integration of the LAARK avionics module into the completed JUPITER aircraft. A rigorous test plan was developed to ensure adequate flight-testing of each system before conducting complete mission simulations with the UAS. Complete mission simulations represent the final stage of testing for the Unmanned Aerial System.
Chapter 2

Aircraft Design

2.1 Air Vehicle Overview

The Joined-Wing Unmanned Aerial System Providing Intelligence, Targets, and Emergent Reconnaissance (JUPITER) aircraft originated from a senior design project at the University of Arizona (Fig. 2.1). It is a joined-wing aircraft that was specifically designed to meet the AUVSI 2013 SUAS competition requirements. The airframe design focused on superior aerodynamic performance and improved structural strength. Both criteria are met by the joint wing configuration. The large inherent stability of the aircraft allows the surveillance system to capture high-resolution images. The airframe was constructed from fiberglass and high density foam resulting in an empty weight of 13 lbs and 7 oz. Static testing showed that the structure could withstand a 4g loading. Two propellers which are driven by electric motors provide 16lbs of thrust and allow the aircraft to perform its mission even on a hot day and when flying at maximum gross weight. The Piccolo II autopilot system which is a military grade device with high accuracy and fast response time was chosen because of its simplicity and adaptability to JUPITER’s unique design. The UAV has successfully completed a thorough flight test program which demonstrated very good good handling qualities during radio-controlled flight.

Figure 2.1: The JUPITER airframe pictured in CAD
2.2 Design Requirements

The design has to successfully meet the objectives of the competition. AUVSI has provided an outline of six key performance parameters (KPP). For each of the six KPPs a minimum requirement and an ideal objective as shown in Tab. 2.2 were provided. The key performance parameters, safety regulations, and technological limitations are the main considerations that were used when interpreting the scope of the mission and determining the required performance of the aircraft and the reconnaissance system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Threshold</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autonomy</td>
<td>During way point navigation and search area</td>
<td>All phases of flight, including takeoff and landing</td>
</tr>
<tr>
<td>Imagery</td>
<td>Identify any two target characteristics</td>
<td>Identify all five target characteristics</td>
</tr>
<tr>
<td>Target Location</td>
<td>Determine target location within 250 feet</td>
<td>Determine target location within 50 feet</td>
</tr>
<tr>
<td>Mission Time</td>
<td>Less than 30 minutes</td>
<td>Within 20 minutes</td>
</tr>
<tr>
<td>Operational Availability</td>
<td>Used one time out</td>
<td>No time outs used</td>
</tr>
<tr>
<td>In-flight Re-tasking</td>
<td>Add an additional way point</td>
<td>Adjust search area</td>
</tr>
</tbody>
</table>

Figure 2.2: Key Performance Parameters Provided by AUVSI.

2.3 Design Tasks

The system was broken down into sub-system and the design of the different subsystems was carried out by different team members:

- Design
  - Aerodynamics
  - Structure

- Construction
  - Materials
  - Manufacturing Methods

- Power System
  - Motors
  - Propellers
  - Batteries
  - Servos

- Autopilot
  - Telemetry
  - Gyros and Accelerometers
  - Navigation
  - Safety
2.4 Design Considerations and Design Choices

In this section the main design considerations and design choices are discussed. A more detailed account of particular critical aspects of the system design is provided in section 2.5. The required mission time and the weight of the LAARK system ask for a lightweight aircraft with low drag, moderate wing loading, and good inherent stability. A lightweight system allows for a larger payload and/or an increased fuel capacity. Similarly, the low drag reduces fuel consumption and increases mission time. The integration of the LAARK system has to be such that the field of vision is sufficient and the aircraft performance is not affected much. Finally, the aircraft has to be sufficiently stable such that the autopilot work load is minimized and the aircraft flight path, velocity and attitude are as constant as possible during the reconnaissance mission. Stability also allows the LAARK system to more accurately recognize targets during flight. Other important considerations are the choice of the power plant, the control surface dimensions, and the overall robustness of the airframe. The choice of the power plant (electric, gas) impacts the ease of use and again the flight time. The control surface dimensions affect the maneuverability of the plane and determine the dimensions of the servos. Robustness is desirable as it increases the overall chances for mission success. Secondary but also important considerations were that the UAS could be easily transported, assembled, and adapted to different types of missions.

Two airframe configurations were considered during the early preliminary design stage in 2012. A single conventional wing configuration was compared to a joined-wing configuration. The joined-wing configuration was chosen because of its improved structural strength and higher aerodynamic efficiency compared to the standard configuration (single wing). The increased structural strength allows for a lighter airframe construction which increases the payload capacity. The increased aerodynamic efficiency (reduced induced drag) translates into a longer flight time. Another advantage of the joint wing configuration is the easy payload integration the large payload space which eases the assembly process.

The aerodynamic wing design was based on XFLR5 and Solidworks CFD simulations. A model airplane airfoil with low drag characteristics (SD7034) was selected to make the plane less draggy. The wing span was fixed at 96 inches with a Mean Aerodynamic Chord of 10 inches for the front wing and 7.6 inches for the rear wing. This resulted in a total wing area of 1,595 square inches. Of particular interest were the tips that join the front and rear wing. It was decided to design tips that transitions linearly from the front wing airfoil to the rear wing airfoil. The CFD analysis showed that this resulted in a minimal distortion of the computed isobaric lines on the top and bottom wing indicating that induced drag was possibly reduced compared to a standard configuration (single wing). Another concern was the separation of the rear wing from the front wing. The horizontal and vertical separation determines how much the aerodynamic performance is affected by the downwash from the front wing. It also determines the stall recovery characteristics. Finally, the placement of the two wings also affects the longitudinal stability characteristics. Based on pencil and paper calculations and supported by the computational analysis (XFLR5) a compromise was found with good stability and performance characteristics. To increase the stability of the aircraft dihedral was included in the design of the front wing.

After establishing the wing aerodynamic design, the control surfaces were dimensioned. Based on aerodynamic analysis and working with estimates for the moments of inertia the control surface size and deflection angles were chosen to obtain angular rates (roll, pitch, yaw) that fulfill the maneuverability requirements for the mission (crosswind takeoff and landing, stall and spin recovery, turn radius, etc.). The maximum deflection angles are 25 deg for the elevator and ailerons and 20 deg for the rudder.

It was decided in favor of an electric propulsion system because of its improved ease of handling (compared to a combustion engine). To improve maneuverability during upset conditions and to ensure laminar flow over the front wing a design with two pusher props was chosen. The prop stream strikes the rear wing control surfaces, which improves control authority. The pusher prop configuration also protects the props which increases the overall robustness of the system. Finally, by placing the props in the rear, the reconnaissance platform has excellent field of view in the direction of flight. The motor was selected based on the estimated drag during the different flight segments and the runway length. The prop was chosen for maximum efficiency at cruise. The maximum calculated thrust at takeoff is 16 pounds which guarantees a short takeoff roll at maximum gross weight on a hot day. Considering the flight time of thirty minutes (including a safety margin), it was determined that four lithium polymer batteries were required to accomplish the mission. Because of their high energy density the battery system does not incur a large weight penalty.

The construction technique determines the weight and strength of the airframe. Traditional designs
(such as the spar and rib construction for the wing) are heavier and do not provide the same structural stiffness and surface quality. For the JUPITER a state-of-the-art composite construction was chosen to make the aircraft light and strong and to obtain a good surface quality. The resulting airframe weighs less than 14 pounds and endures more than 4g.

Different components of the aircraft, such as the winglet and wing-sets, were tested individually prior to integration. After the integration various field tests were completed. Static loading tests, range tests, and taxi tests were done prior to RC flight tests. The RC flight tests were followed by autonomous flight tests. The UAS testing and evaluation procedures and results are discussed in chapter 4.

JUPITER was designed with an intelligent surveillance capability. A spherical clear dome was chosen to house the LAARK system. The dome was located at the bottom of the fuselage between the landing gear and nose gear. This location provides maximum protection and prevents glare from the sun. The location also allows the camera to have a maximum view of the environment. Flying at an altitude between 100 feet and 500 feet, allows the computer to identify targets even when they are not directly in the flight path. The target finding method has been re-coded to prevent distraction by targets that are far away. A cruise speed of 45 knots and a dash speed of 60 knots not only ensure a clear image but also allow the aircraft to complete the mission swiftly.

2.5 Critical Design Considerations

2.5.1 Configuration Selection

In UAV flight, high aerodynamic performance is very desirable as it increases endurance and thus allows for longer missions. High-aerodynamic performance is typically accomplished by increasing the aspect ratio to reduce induced drag and by employing laminar airfoils and reducing parasitic drag. A good example are gliders which typically have very long and slender wings. A problem typically encountered for aircraft with very large aspect ratios is the increased moment arm between the center of lift and the wing root which leads to high bending moments a the wing root. This trend is usually counteracted by reinforcing the wing-fuselage connection point. A joined-wing aircraft with similar wing area as a conventional single wing aircraft does not suffer from the same weight penalty because the overall wingspan is smaller and the joint wing configuration is structurally stiffer. The shorter wing span reduces the moment arm and thus decreases or completely eliminates the need for heavy reinforcements at the wing root. This reduction in structural weight allows the aircraft to carry more payload which is very important for meeting the AUVSI objective. This distinct advantage was the foremost reason why a joined-wing design was selected over a conventional single wing designs.
2.5.2 Performance

JUPITER has a takeoff weight of 24 pounds and a wingspan of 96 inches. The endurance was calculated based on the power-plant. Based on the structural limit and the field view of the camera the minimum turning radius, minimum turning velocity and the corresponding load limit factor were calculated. The following formulas were used for the calculations:

\[
\nu_{R_{\text{min}}} = \sqrt{2 - \frac{4KC_D}{T^2}} \tag{2.1}
\]

\[
V_{\infty R_{\text{min}}} = \sqrt{\frac{4K}{\rho \infty T^2 W}} \tag{2.2}
\]

\[
R_{\text{min}} = \frac{V_{\infty}^2}{g\sqrt{\nu_{R_{\text{min}}}^2 - 1}} \tag{2.3}
\]

Here, \(C_D\) is the drag coefficient, \(W\) is the aircraft weight, \(S\) is the planform area, \(T\) is the thrust, and \(R_{\text{min}}\) is the minimum turning radius. The system performance parameters are listed in Tab. 2.3.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Weight</td>
<td>22 lbs.</td>
</tr>
<tr>
<td>Wing Span</td>
<td>96 in</td>
</tr>
<tr>
<td>AR</td>
<td>12.4</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>67.5 ft./sec</td>
</tr>
<tr>
<td>Max Speed</td>
<td>101.3 ft./sec</td>
</tr>
<tr>
<td>Endurance</td>
<td>30 min</td>
</tr>
<tr>
<td>Min. Turn Radius</td>
<td>47.6</td>
</tr>
<tr>
<td>Min. Turn Velocity</td>
<td>39.1 ft./sec</td>
</tr>
<tr>
<td>Min. Load Limit Factor for Turn</td>
<td>1.41</td>
</tr>
<tr>
<td>Max. Load Limit factor</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 2.3: Predicted performance parameters for JUPITER.

2.5.3 Airframe Construction

The JUPITER airframe was constructed using modern composite manufacturing techniques. The fuselage mold was fabricated by first making a balsa wood plug which was then wrapped with fiberglass. The fiberglass copy was then removed and served as a negative mold for the fuselage. The fuselage shells
were manufactured by performing composite layups on the negatives. The wings were constructed by performing a composite layup over a foam core that was cut to the precise shape of the wing using a hotwire. Due to the sandwich construction of the wings, spars were not necessary. Each composite layup consisted of a series of different materials that resulted in lightweight yet strong skins (Fig. 2.4). All shells were joined with epoxy with micro balloons. The internal structure of the aircraft was designed to be extremely strong and lightweight while withstanding the expected aerodynamic loads.

2.5.4 Servos
Taking into account the weight and torque requirements, Hi-Tech HS-645MG servos were selected for the Ailerons and rudder, whereas Hi-Tech HS-5085MG servos were selected for the elevator. The servos are powered by Zippy Flightmax 5000mAh SS1p 15C batteries.

2.5.5 Power Plant Selection
The JUPITER power-plant needed to provide the aircraft with a high dash speed and low cruise speed while providing sufficient clearance for the nose-mounted camera system. For these reasons, a twin pusher configuration was selected. The power-plant consists of two Hacker A50-12S motors mounted on the trailing edge of the front wings. The twin motors are controlled using two Hacker X-70SB electronic speed controllers and are powered by 2500 mAh lithium ion batteries. The propellers were selected using the MotoCalc software. Two two-bladed 14 x 8.5 electric motor propellers turning at approximately 7000 RPM were selected based on the motor specifications and performance requirements. The propellers are counter rotating to balance torque and reduce pi-factor effects. The configuration provides up to 16 pounds of thrust.

2.5.6 Final Design Parameters
The JUPITER aircraft was designed to exceed the flight requirements of the 2013 AUVSI SUAS competition and provide an optimal platform for the LAARK avionics payload. The airframe is aerodynamically efficient, easily transportable, and was designed using modern analysis methods. The final design parameters are summarized in 2.5.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Empty weight (lb)</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight with maximum battery (lb)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Maximum payload (lb)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Optimal Wing Loading (g/cm²)</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>Maximum takeoff weight (lb)</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Designed G loading</td>
<td>-3.2</td>
</tr>
<tr>
<td>Speeds</td>
<td>Takeoff speed (15 degree flaps) (knots)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Takeoff speed (no flaps) (knots)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Cruise speed (knots)</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Stall speed (knots)</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Maneuvering speed (knots)</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Best L/D speed (knots)</td>
<td>40</td>
</tr>
</tbody>
</table>

| Cruise Performance | Best L/D | 24.5 |
|                    | Cruise C, | 0.4 |
|                    | Maximum flight endurance (min) | 40 |
|                    | Maximum range (miles) | 38 |
|                    | Optimal turn rate (degrees/seconds) | 360/19 |
|                    | Service Ceiling (ft) | 8000 |

| Power and Control Systems | Motors (2) | Brushless, 515 rpm, 90% efficiency |
|                          | Electronic Speed Controller (2) | 70 amp burst, 55 amp continuous |
|                          | Operating power (total) | Up to 2000 Watt burst, 1400 Watt continuous |
|                          | Batteries (5 to 6 packs) | 5.6 cell 18.5-22.2V, 25,000 mAh capacity |
|                          | Control surface actuation | Hitec HS-565MR Servos |
|                          | Servo strength | >150 oz-in of torque at 4.8 volts |

Figure 2.5: Final design parameters.
Chapter 3
Avionics Design

3.1 Data Link

The air-to-ground data-link is the most critical part of the onboard system and has therefore been carefully designed with extensive engineering analysis. The onboard camera system acquires an immense amount of imagery data that must be streamed to the ground station quickly and reliably at all times during the mission. The camera to ground subsystem consists of an onboard Wi-Fi data-link between the FitPC2 and the 2 ground station access points. The Wi-Fi data-link utilizes a custom multithreaded client-server program to transfer images and data to the ground for processing using the industry standard TCP/IP protocol. The onboard antenna was specially designed for a wide field of vision (to compensate for uncertainties with respect to the aircraft orientation, Fig. 3.1). It was constructed using a 12cm radius aluminum plate (1mm thick) with an N-type coaxial connector placed in the center and a 3cm
12-AWG wire connected to the center pin as the vertical radiator. For the ground station, a keyhole pattern was constructed in order to cover the far end of the field and the takeoff area. This was done using a Ubiquiti Wireless Bullet M2 with a Comet SF-245W vertical antenna as the omnidirectional access point, and a Ubiquiti Nanostation M2 as the sector access point. To facilitate roaming between these two access points (AP), a custom-roaming algorithm was devised.

Figure 3.2: Ideal antenna pattern and omnidirectional antenna coverage.

3.2 Payload

3.2.1 Onboard Avionics

The JUPITER aircraft was designed for optimal integration with the LAARK avionics package. The LAARK system configuration (Figure 3.2) was designed for ultimate performance. The design features powerful, cutting edge technology components that achieve all of the functional requirements set forth in the CONOPS documentation. The LAARK module includes an onboard Piccolo II autopilot, gimbaled dual-camera system with up to 20MP combined resolution, onboard computer, and 250mW long-range 2.4 GHz 802.11 card for reliable data transmission. The pan/tilt gimbal is controlled by an ATMega168 microcontroller board which receives commands from the FitPC2 computer. The onboard computer also runs a client-server set of applications which acquire time-synchronized imagery-telemetry data for reliable ground transmission.

3.2.2 Piccolo II Autopilot System

The Piccolo II autopilot subsystem is an industry standard and consists of the onboard Piccolo II autopilot, the Ground Station and the Piccolo Command Center. Waypoint navigation, override controls, and flight sensory data is commanded via the Piccolo ground station. Transmission is sent and received over 900MHz channel to the onboard autopilot via the ground station. The onboard autopilot module connects via RS-232 (serial port) to the aircraft’s onboard computer. A custom autopilot data parser \texttt{(autopilot)} runs onboard. This program is run upon the kernel detection of the autopilot’s RS-232 to USB adaptor, and is terminated upon device removal, via a \texttt{udev} script that identifies adaptor serial number and manufacturer.

Programming of the Piccolo system is done in the \texttt{C} language and flight data can be requested from the onboard aircraft computer. Among the accessible Piccolo data is GPS location, flight altitude, heading, pitch, roll and yaw. The data are made available to the gimbal controller and camera client systems via ZeroMQ sockets. ZeroMQ sockets were chosen for their robustness, simple API and speed. Implicit packet backlogging allows for connection drop and reconnect to be seamless (no change in programming model).

Autonomous aircraft navigation is accomplished through the proprietary Piccolo Flight Command Center from CloudCap Technology (Fig. 3.3). The command center allows the pilot operator to plan and execute flight plans. The pilot may also re-task the aircraft to meet changing mission objectives and monitor all available aircraft sensors. The controller attached to the ground station interface allows the pilot to manually override the autopilot in case of an emergency. The PCC interface displays the...
aircraft’s current position overlayed over USGS maps using either a 2D overhead view or a 3D elevation relief view.

3.2.3 Gimbaled Camera System

The onboard camera system features two IDS uEye LE Machine Vision cameras (UI-1495LE-C) equipped with Edmund Optics Tech-Spec 4.5mm fixed focal length lenses. The board-level cameras have a resolution of 10MP each and are controlled using Linux drivers running on the FitPC2 onboard computer’s Linux platform. The cameras are positioned at an angle optimized to provide a 120 degree horizontal field of view with minimal image distortion.

The cameras are mounted onto a pan-tilt gimbal that is controlled by an external MosquitIO (AT-Mega168 board) gimbal micro-controller that receives aircraft Euler attitude data from the aircraft’s FitPC2 via a gimbal control program (gimbalctl). The gimbal control program is written in ANSI C and is automatically run whenever the Linux kernel recognizes the RS-232 connection to the gimbal microcontroller. This detection takes place via custom udev scripts that match manufacturer and serial number of the USB devices. If at any time the gimbal device disappears, the gimbal controller program is terminated until the device reappears.

Aircraft altitude information is received from the autopilot data parser via a ZeroMQ socket. The gimbal controller needs no special handshake or memory locking due to the socket-style programming approach. The gimbal polls the socket for new telemetry data and continually positions the camera system orthogonal to the ground. Each image taken by the camera is bundled with flight sensory data and immediately sent to the ground station via 802.11n.

The entire imaging assembly (gimbal, cameras, and lenses) is concentrically placed within a hemispherical acrylic image dome using a team-built carbon fiber optics mount. The spherical shape of the dome reduces aerodynamic disturbances and minimizes parasitic drag.

3.3 Autonomous Data Processing Method and Supported Target Types

The capability to carry out autonomous data processing is an important design feature of the LAARK imagery system. Without autonomy the Intelligence Officer would be required to closely investigate every potential target. This would not only incur a large work load but also increase the error margin. LAARK autonomously processes imagery in real time as it is received from the aircraft. Objects of high interest are removed from the large image and processed through a feature pipeline. High interest objects that have certain characteristics are then presented to the Intelligence Officer for confirmation.

3.3.1 Filtering and Identifying Objects

It is often necessary to filter results from a classifier to determine the characteristics of the targets. In this section a case-study is presented that serves as a good example for explaining the method for the filtering of the targets as described in the previous section.
Figure 3.4: Six stages of progressive chip analysis.

<table>
<thead>
<tr>
<th></th>
<th>CPU</th>
<th>GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GHz Core 2 Duo / GT 430</td>
<td>2078 ms</td>
<td>348 ms</td>
</tr>
<tr>
<td>3.4GHz i5 / GTX 580</td>
<td>1012 ms</td>
<td>112 ms</td>
</tr>
</tbody>
</table>

Table 3.1: CPU vs. GPU OpenCV remap performance on 3264 x 2448 dimension image.

Object recognition can be characterized by the output from the object classifier. At this part of the chip analysis pipeline, it was assumed that an image chip was available for processing. This is represented by the leftmost image in Figure 3.4. Next, filtering on the background was used to remove noise and provide a clear representation of the target. A simple mean and standard deviation of chip corners filtered out pixels which fit within the constraint. Stages three and four then performed a binarization technique to remove remaining interior colors for object detection. Colors were binned by HSV which then allowed easy filling, masking and extraction. The final stage, shown as the rightmost chip in Figure 3.4, was generated by analysis on contours via decision trees and/or approximation.

### 3.3.2 CUDA–Accelerated Tangential and Radial Distortion Correction

LAARK accurately determines the location of targets from imagery using spatial transformations. Once a target is located in the imagery its secondary spatial location can be determined from the transformed imagery as pixels can now be easily mapped to a physical length scale. The distance from a centroid where the plane is located is calculated and then added to the GPS location at which the imagery was taken. This data is then provided in the user interface.

The wide-angle lens of the LAARK imagery system, coupled with non-orthogonal mounting angles to provide 120° field-of-view, caused considerable tangential ("keystone") and radial ("barrel") distortions in the imagery (Fig. 3.5). The correction of the optical aberrations required the following transformations:

\[
\begin{align*}
x_i^{(t)} &= 2 p_1 x_i y_i + p_2 \left( r_i^2 + 2 x_i^2 \right) \\
y_i^{(t)} &= p_1 \left( r_i^2 + 2 y_i^2 \right) + 2 p_2 x_i y_i \\
x_i^{(r)} &= x_i \left( k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6 + \ldots \right) \\
y_i^{(r)} &= y_i \left( k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6 + \ldots \right)
\end{align*}
\]

(3.1)

(3.2)

where old pixel coordinates \((x_i, y_i)\) are mapped to new pixel coordinates \((x'_i, y'_i)\) through the respective transformation pair. Here, \(p_1\) and \(p_2\) are the tangential distortion coefficients, and \(k_1\), \(k_2\) and \(k_3\) are the radial distortion coefficients. These parameters are assembled into a five-element vector. The remap function in OpenCV then corrects the image.

The process of applying the remapping projection to images of 3000 x 2000 pixels and larger presented a problem for real-time UAV imagery. Each image remap would take longer than the transmission time of a single image and thus caused a backlog of data on the ground station side. As a cluster of computers was not a practical solution, the OpenCV CUDA™-assisted API was investigated.

LAARK has been developed using both open source libraries and custom written code to efficiently analyze streaming imagery in real time. The LAARK system has been tested in software in the loop.
(SIL) simulations on three separate imagery databases. LAARK is able to detect targets and find their shape, location, color and alphanumeric character on 95% of the targets in the image database. Once confirmed by the Intelligence Officer no false positives remain in the system. Based on the testing it is expected that LAARK will perform equally well in the field at identifying and locating targets with any alphanumeric character, basic geometric shape, and color.
Chapter 4

UAS Test and Evaluation Results

4.1 Aircraft Flight Testing

Prior to physical flight-testing, software simulations were performed to approximate the flight behavior of the aerial vehicle. An AVL model was created for the JUPITER aircraft to be used with the Piccolo Command Center Simulator. AVL is a program developed for aerodynamic and flight-dynamic analysis of rigid aircraft of arbitrary configuration. It employs an extended vortex lattice model for the lifting surfaces, together with a slender-body model for fuselages. It simulates a number of general nonlinear flight states. Additionally, the flight dynamic analysis combines a full linearization of the aerodynamic model about any flight state, together with specified mass properties. This program was used to obtain preliminary data for the flight behavior of the JUPITER and is a crucial part of implementing the Piccolo autopilot for autonomous control of the UAS.

A rigorous flight-testing timeline was developed to ensure that adequate flight-testing was done to familiarize both the manual pilot and autopilot with the performance characteristics of the JUPITER airframe. Initially, the aircraft was manually flown at its minimum takeoff weight without the imaging dome. The aircraft was found to have an excellent climb rate, stability, and maneuverability, as well as high glide ratio. The unusual joined-wing configuration was not found to cause any unexpected performance abnormalities. Some slight pitch insensitivity was addressed by enlarging the elevator control surface.

The next flight test focused on validating the predicted endurance of the aircraft and flight envelope with the imaging dome and complete payload installed. Additionally, in-flight control performance tests were conducted to investigate the vehicle at low speed, high speed, and stall conditions. A RC pilot performed normal maneuvers with the fully loaded airframe, including climbs, descents, and level flight, all of which were stable. Battery usage during these procedures was recorded to project endurance capability during competition conditions, with expected flight times in excess of 30 minutes with a load of four 5000 mAh, 5 cell lithium polymer batteries. Increasingly tight turns were performed, with no unusual behavior. This also loaded the structure of the aircraft to near its 3 g design point, and post flight inspection showed that this had caused no negative effects on the composite structure. Stalls were performed at high altitude with both power on and power off, with a response identical to that of a conventional aircraft, indicating correct CG placement and wing loading. Slow flight was achieved easily, and brief doublet pulses on each control channel confirmed control effectiveness.

After manual flight-testing confirmed the viability of the design, the Piccolo II autopilot was installed in the JUPITER and used to conduct autonomous flight plans. All autonomous flights were conducted with the precaution of a manual override pilot prepared to re-take control should a safety issue arise. Control and tracking gains were adjusted to optimize vehicle responses, as demonstrated in Figure 4.1 below, where angular rates are recorded by the Piccolo during test maneuvers.

Control surface doublet maneuvers are performed by the autopilot in one axis while the other axes are set to track a straight course throughout the doublet. As seen in Fig. 4.1, initially over-damped controls in the first test are later lowered to the point where the angular rates remain steady in all axes except the one that is being actuated for the doublet. These tuning adjustments allow the autopilot to better track the desired flight paths without deviation or human intervention. Another example is seen below in Figure 4.2, where Euler angles are measured. During a pitch doublet, drift is initially seen in
the yaw and roll axes, but with increased gains, the disturbance is seen to be correct and the desired flight path is reestablished.

Thereafter, autonomous takeoffs and landings were performed and tuned. These followed careful procedures to ensure repeatability and safety of autonomous vehicle operations, including using a complete checklist before takeoff, during flight, and after landing. The Piccolo settings related to landing, including descent rate, flare height and strength, and rotation speed at takeoff were adjusted based on observations and recordings of manual pilots. Repeated takeoff and landing tests were conducted in a range of weather conditions to guarantee success.

4.2 Data-link Testing

The Wi-Fi data-link was tested both in and out of the aircraft. Initially, the data-link was tested between tall rooftops to simulate the distances that would be encountered during flight. These tests were performed in order to validate our theoretical analysis with real test data. At a distance of 0.6 miles (the maximum lateral distance predicted to be encountered at Webster Field, and a frequency of 2407 MHz, the free-space loss was determined to be 99.8 dB. With a transmission power of 22 dBm and an antenna gain of 7.2 dBi, the estimated receive signal (RSSI) is 70.6 dB. The manufacturer of the aircraft’s long-range Wi-Fi transceiver (jjPlus) claims full bandwidth (150 Mbit/s) at this signal...
level with a 7 dB headroom until performance degrades. After preliminary manual flight-testing of the aircraft, the LAARK payload will be installed into the JUPITER and the data-link will be flight-tested both with and without disturbances introduced into the system. The bandwidth and signal strength will be confirmed to be sufficient and reliable at varying flight distances.
Chapter 5

Safety Considerations and Flight Test Procedures

The JUPITER and LAARK systems have been designed with safety as a top priority during all phases of the development and testing. This approach was taken to guarantee that the system was not compromised due to an overlooked detail and that neither individuals nor facilities were exposed to any unnecessary risk. Each of the safety requirements described in the official 2013 AUVSI SUAS Competition Rules have been met by the system presented in this paper.

5.1 Checklists

Detailed checklists were developed to ensure highly repeatable successful and safe operation of the UAS.

5.2 Manual Safety Pilot Override

The Piccolo II autopilot system allows for a manual safety override pilot to take control at any time during flight operations with the simple flip of a transmitter switch. This is critical in ensuring that the vehicle is closely monitored and under control at all times. This feature is also an essential part of autopilot testing and integration into the UAS. Autopilot integration is an involved process that requires the fine adjustment of many parameters and gains to ensure successful operation. The manual override pilot is there at all times to ensure that the vehicle is operating in a safe manner in regards to itself and its surrounding environment when operating autonomously. For example, should the aircraft ever enter the no-fly zone, the safety pilot will take control of the aircraft and reroute it back to the mission area.

5.3 Loss of Signal

In the case of a loss of transmission signal, the aircraft is configured to respond according to the 2013 AUVSI SUAS Competition Rules. If a loss of signal occurs for more than 30 seconds, the autopilot is programmed to return home and loiter until communication is reestablished. If a signal loss occurs for more than 3 minutes the aircraft will terminate flight. The return home and flight termination protocols can be activated by the manual safety pilot at anytime during flight operations.

5.4 Flight Termination Procedure

If the transmission signal is lost for 3 minutes, the flight termination procedure will be activated. During flight termination of the JUPITER aircraft, the vehicle will cut throttle and deflect the control surfaces such as to maintain a constant low-energy controlled spiral to ground. This is done by deflecting full up elevator, full right rudder, and full right aileron. The flight termination procedure will be demonstrated during the System Safety Overview and Pre-Mission Briefing on competition day.
5.5 Flight Procedures for Competition Day

Every mission has to follow a number of well thought-out steps in order to ensure success (Fig. 5.1). Once the specific mission objectives are known, a flight plan can be created along with the airspeed and altitudes at every point in order to deliver the aircraft to the desired locations. The mission priorities and what-if scenarios have to be determined in order to best complete the mission within the allotted time limit. Prior to mission start, a number of tasks must be completed. The tasks include safety checks such as servo checks, range check, motor test and autopilot checks. Then the aircraft is put onto the runway and the coordinates are recorded in order to create reference points for takeoff and landing patterns. After takeoff, the next step is the execution of the mission. During flight, the aircraft will be sent on its given flight plan. However, a number of mission aspects can change that will affect performance. In the case of a requirement change, the aircraft can be sent to an orbit while the flight plan and priorities are modified. Once the mission is completed or the time limit is reached the aircraft will be sent to its landing pattern so that the mission can end.
Figure 5.1: Team Member Responsibilities and Procedures
Chapter 6

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