The SOAR System: Self Operating Aerial Reconnaissance

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The SOAR system is a student-built Unmanned Aerial System for the sixth annual AUVSI Student UAS Competition. Requirements analysis and a review of existing systems identified a number of areas for improvement. A clean-sheet solution as considered, but the most resource-efficient design was to re-use a previous system. The 2008 SOAR system is based on the Team Hathor design of 2006, but incorporates a new digital camera and datalink system. The camera replaces NTSC analog video with JPEG imagery to achieve improved color and image clarity. The new datalink system uses the 802.11b protocol, but under Amateur Radio rules which permits a high-gain link. These improvements were implemented and proven using a test-driven development strategy, which used the results of lab and flight testing to drive design decisions. The resulting system is capable of achieving the core deliverables of the Student UAS Competition.

I. Introduction

THE Association for Unmanned Vehicle Systems International (AUVSI) Student Unmanned Aerial Systems (UAS) competition is a test of aircraft performance, system autonomy, and visual perception for teams of college students. Contestants must design and build a system that can fly without a pilot, navigate a route, including real-time changes, search an area for visual targets, and report those targets back to the judges within a limited time.

Project SOAR (Self Operating Aerial Reconnaissance), a committee of the AIAA Chapter at Embry-Riddle Aeronautical University, Daytona Beach has taken up this challenge. Using a combination of proven technologies and targeted innovations, The team has built a system capable of performing the core mission, and expandable to perform all elements of the AUVSI Student UAS Competition.

II. Requirements Analysis

The competition rules[1] were analyzed to identify system requirements and figures of merit, for use in selecting technologies and evaluating performance of the mission. Over 40 individual requirements were identified. In addition to safety and general usability, the requirements fell into four areas, as follows:

1. Platform Performance

The aircraft platform has to be large enough to carry the avionics and camera payload, while having sufficient range and performance to complete the competition sortie within the time limit. It also must provide handling characteristics adequate to enable flight control with the avionics and provide a stable base for the camera. Many of these characteristics can be quantified as values to be maximized or minimized, termed *figures of merit*. Examples of the figures of merit for platform performance include higher speed, lower vibration, and less required ground support equipment. A key challenge is wind performance, especially during launch and recovery.

2. System Autonomy

The avionics must be able to control aircraft flight without pilot intervention, navigate the assigned route, and respond to real-time updates to flight speeds and directions. In addition, the combined ground-air system should plan and fly the designated search area, and cue the operators when potential targets are imaged. Examples of figures of merit for system autonomy are lower cross-track error on waypoint routes, higher search area coverage per pass, and higher percentage of correct target cues. The key challenges are efficient route planning, and accurate target recognition.

3. Imagery Performance

The imaging system must be able to quickly provide clear pictures of targets to the rest of the system and to operators. The pictures must provide sufficient detail to identify target characteristics, and include image time, location, and orientation data to enable target location. Figures of merit include higher optical resolution, lower system weight, and higher data rate. The key challenges are providing sufficient area coverage in a timely manner, and integrating with the avionics for location/orientation.

4. Target Recognition Performance

The target recognition system must use the images and location/orientation data to identify and locate targets autonomously. Figures of merit include higher percentage of correct color discrimination, higher percentage of correct shape recognition, and smaller error in target position estimates.

The requirements analysis underscored the need to examine possible solutions as complete systems, rather than a collection of solutions to individual problems. The figures of merit for each system interact with those for other systems, creating a number of possible design spaces for a successful system. Therefore, design choices for each subsystem have been be made with the effects on the overall system performance in mind.

III. System Concept

The requirements analysis was only one of a number of inputs to the design process. A literature review of the journal papers of previous entries was performed, and Embry-Riddle students who had previously participated in the competition were interviewed for insights into the problem as well as the strengths and weaknesses of the existing solutions. From these sources, a picture of the common design solutions emerged, as well as three specific areas of improvement.

Many teams were using modified radio control model aircraft for their platforms. Although these airframes are readily available, they often have structural issues and handling characteristics that make them less than optimal for systems integration and mission performance.

Imagery transmission via analog NTSC video was also common. Since the NTSC protocol heavily compresses color information and is sensitive to phase shifting, it is difficult to get usable imagery without the use of expensive and heavy equipment. The analog transmission scheme is also challenging, with little to no redundancy of information available to permit noise rejection in the video link.

Data links in general were also identified as a challenge. Many existing systems use three or four radio links simultaneously. It is always a challenge to operate multiple radios in close proximity, and doubly so when weight and power constraints limit the use of shielding and power isolation.

With these considerations in mind, the team began a clean-sheet design for an autonomous system capable of meeting the competition requirements. This design concept involved a new airframe design, a different camera selection and a consolidated digital data link.

The proposed new airframe design used a cruciform wing and tail layout to enable maneuvering independent of roll angle. Although this configuration would be aerodynamically less efficient, the ability to keep the camera pointed at the ground during maneuvers would permit an improvement in overall system performance. The airframe would not have landing gear. It is very difficult to fly a light aircraft low and slow in windy conditions, so a typical runway launch and recovery is not optimal. The proposed system would instead use a launcher and a precision parachute recovery system, that would double as a safety parachute.

The proposed camera system would replace the NTSC analog format with a digital format, such as JPEG, which permits control over the level of color compression, and is insensitive to phase shift in the video chain. Analysis of the search phase of the mission indicated that a resolution of about eight megapixel would be optimal.

The proposed datalink would consolidate all radio links into one digital link. The data link would use modified commercial 802.11b hardware. Because 802.11b is licensed under FCC Part 15, modifications to the hardware are heavily restricted. To make the needed modifications, the data link would instead be operated under the FCC Part 97 Amateur Radio rules which have broader privileges in the 2.4 GHz band.

As the project progressed, it became clear that the resources needed to do the detail design and fabricate this configuration within the project time frame were not available. However, components from the Team Hathor system of two years ago were available, so the project team changed strategy from a clean-sheet design to a developmental approach from a baseline design. The development process was driven first by lab tests and then field tests to validate new components and incremental configuration changes. The team repeated this process as many times as possible before the date for configuration freeze. The test-driven approach was risky, but allowed rapid evaluation of changes where analysis resources were limited.

The 2008 SOAR system concept uses the existing airframe and autopilot from Team Hathor, with cost-effective changes to the camera and datalink systems using commercial-off-the-shelf (COTS) hardware adapted to the mission purpose. The next section describes in detail the as-built SOAR system for 2008.

IV. System Description

The complete SOAR system breaks down into 5 major areas:

A. Platform

Figure 1. The Eagle 2 airframe.

The airframe (named Eagle 2) is a modified SIG Kadet Senior. The fuselage has been stretched six inches, and the spruce and balsa structure modified to make room for the avionics and camera system. Other modifications include reinforced aluminum landing gear, and the addition of camera and antenna mounts. The airframe is powered by a Saito FA-100 four-stroke glow engine, fed from a 24 oz fuel tank.

The demonstrated performance of Eagle 2 in flight tests has confirmed that the aircraft configuration is within the competition limits, and has sufficient performance to complete the mission sortie. The vehicle gross weight is 12.5 lbs. The stall speed is 20 mph, and the maximum speed is about 80 mph.

B. **Avionics**

The autopilot system on board Eagle 2 is a Micropilot 2028g. Using integrated air data sensors, gyros, accelerometers, and GPS receiver, the Micropilot provides attitude stabilization, path control and GPS waypoint navigation in a 28 gram package. The control strategy used by the Micropilot is a network of Proportional-Integral-Derivative (PID) feedback loops for the various servo channels, and a state machine to select which loops are active for a particular maneuver or condition. Some loops include feed-forward or cross-reference terms for improved performance.[3]

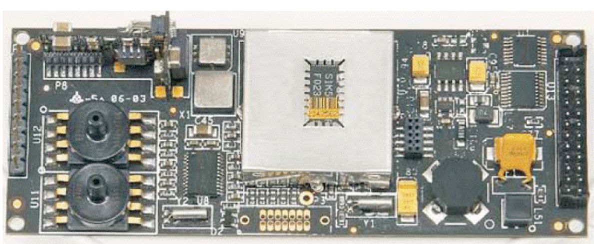

Figure 2. The Micropilot 2028g autopilot.

Manual control is provided by a Futaba T6XA/ R127DF radio control set. This is a standard frequency modulated/pulse position modulated (FM/PPM) radio control system used by radio control hobbyists. Unlike most radio control sets, the unit in Eagle 2 is tuned to the 50 MHz band (RC Channel 01). This band is restricted to Amateur Radio users, reducing the chance of a frequency conflict during tests and competition.

The standard configuration of the radio control link and the Micropilot is for the Micropilot to be plugged in series between the R127DF receiver and the servos that operate the control surfaces. This is a risky configuration, because if the Micropilot should fail or hang up, all control of the aircraft is lost. To prevent this, a Reactive Technologies Rx-Mux input selector, was instead connected to the servos, and the RC receiver and Micropilot were each connected to a set of inputs. The RC transmitter selects which set of inputs is active.

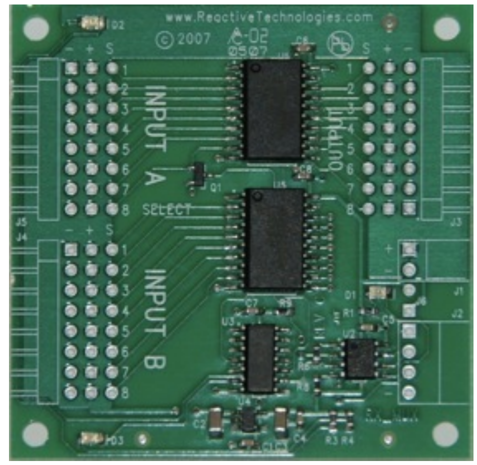

Figure 3. The Rx-Mux input selector.

Power for the avionics is provided by three 6.0 v 1100 mAh nickel/cadmium batteries. Bench tests have demonstrated that this amount of power is sufficient to complete the competition sortie.

C. **Visual Imaging**

The camera selected for visual image gathering is an Axis 207W wireless network camera. It is an inexpensive security camera designed for indoor locations where a wired connection would be inconvenient. Although the camera's resolution is less than optimal (640 x 480 pixels), the integrated 802.11b transceiver and light weight (38 grams) made it a compelling choice for easily switching to an all-digital imagery and telemetry link. More detail on the wireless features of the camera will follow in the data links section.

Figure 4. The Axis 207W wireless network camera.

The camera uses a 1/4 inch CMOS imager to generate 640x480 pixel images. Using the supplied 4.0 mm lens at 200 feet altitude, this equates to a field of view of 180 x 135 feet. This field size gives each pixel a field of view of 3.325 x 3.325 inches, placing 6 inch features within the limit of resolution for the camera.

Figure 5. A lab test image using sub-scale targets. The targets and range are scaled to simulate 48 inch targets at 250 foot altitude. This test demonstrated that the camera and lens were a feasible solution for the mission requirements.

The camera can provide color MPEG-4 format video, motion JPEG, or individual JPEG images. The image capture software for the project currently captures individual images, at a rate of about 5 per second. Although the JPEG format does store color information at lower resolution than the luminance data, the compression is less severe and is not further degraded by analog transmission to the ground station.

The other source of difficulty for getting acceptable imagery is unwanted camera motion. Single-cylinder internal combustion engines generate considerable vibration when operating. To get the camera further away from the engine, and to make room for a planned recovery system, the camera was mounted in the left wing of Eagle 2. Initial tests showed that despite this mounting location, there was an unacceptable horizontal shake in the imagery, due to camera motion during the data transfer time from the CMOS imager. The motion showed as a horizontal wave in the image. To resolve the problem, the team built a compliant mount using latex foam pads captured in balsa brackets. The compliant mount reduced the shake to acceptable levels at cruise throttle settings.

The camera mount has a fixed point of view. Selecting or building a gimbal mount for the camera was deemed inconsistent with the goal of developing a future fixed-wing platform that is optimized to position a camera directly. Off-axis imaging may not be possible until maneuvers can be developed to position the camera with the current Micropilot firmware and Eagle 2 airframe.

Flight tests with 44-inch color targets demonstrate that the camera has adequate performance to image all but the smallest specified targets in in the competition sortie.

Figure 6. An example flight test image taken from 213 foot altitude. The 44-inch color targets are easily recognized, and the horizontal distortion due to vibration is acceptably low.

The power system for the camera is a 9.6 volt 600 mAh Ni/Cd battery driving an LM7805 voltage regulator to provide the regulated 5.0 vdc supply required by the camera. Although this is not a very efficient power system, performance is adequate for the needed flight time.

D. Data Link

The other function of the Axis 207W wireless network camera is to provide an 802.11b network connection to the aircraft to support imagery and the command and telemetry links. This is possible because the 207W incorporates an 802.11b transceiver, and because the firmware uses the Linux operating system and the Busybox multi-service application. The camera's hardware includes both the 802.11b port and and a 100Base-T ethernet port. Like all Linux computers with multiple ports, the 207W can be configured to route packets between its ports.

A Lantronix XPort Direct is used to connect the serial port of the Micropilot 2028g to the network, converting the serial connection to IP packets. The Xport Direct takes 3.3 vdc power, so a voltage divider from the 5v supply is used.

Figure 7. The Lantronix XPort Direct serial to ethernet adapter.

The 802.11b port has a typical power output for an FCC part 15 device (~20 dBm peak), which is inadequate for the ranges required during the competition sortie. To increase the signal strength of the link, a bidirectional amplifier (sourced from Fleeman, Anderson, and Bird) has been added to the 207W camera. To achieve this, the stock antenna has been removed, and a short coaxial adapter cable used to connect the Hirose U.FL connector inside the 207W to the RP-SMA connector on the bidirectional amplifier.

Figure 8. The 802.11b bidirectional amplifier. The amplifier is specified for 1000 mW output, and 16 dBi input gain.

Because the angle of the aircraft relative to the ground station is always changing, the aircraft antenna must be relatively omnidirectional. Therefore, a simple 2 dBi collinear dipole antenna was connected to the amplifier output.

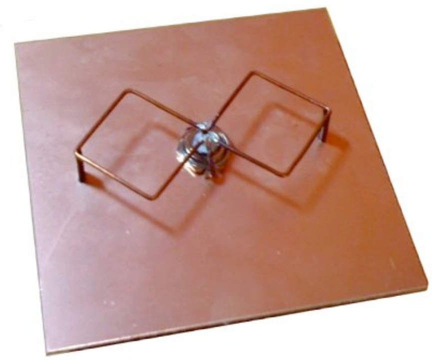

Figure 9. The biquad high gain antenna.

The ground station antenna wis more directional. An 18 inch dish antenna was initially tested, but it was not feasible to track the aircraft manually with sufficient accuracy to maintain a reliable link. Instead, the biquad feed antenna is used by itself. This configuration provides approximately 10 dBi of gain, with a 40-degree beam width. The biquad antenna was fabricated in the lab, with a kit from wardrivingworld.com.

The ground station antenna feeds one of the antenna inputs of a modified Linksys WRT54G wireless router. The router has been flashed with the open source DD-WRT firmware, giving greater control over the radio settings of he 802.11b transceiver. The router hardware has also been modified to improve cooling and allow operation at higher power levels.

Figure 10. The WRT54G wireless router.

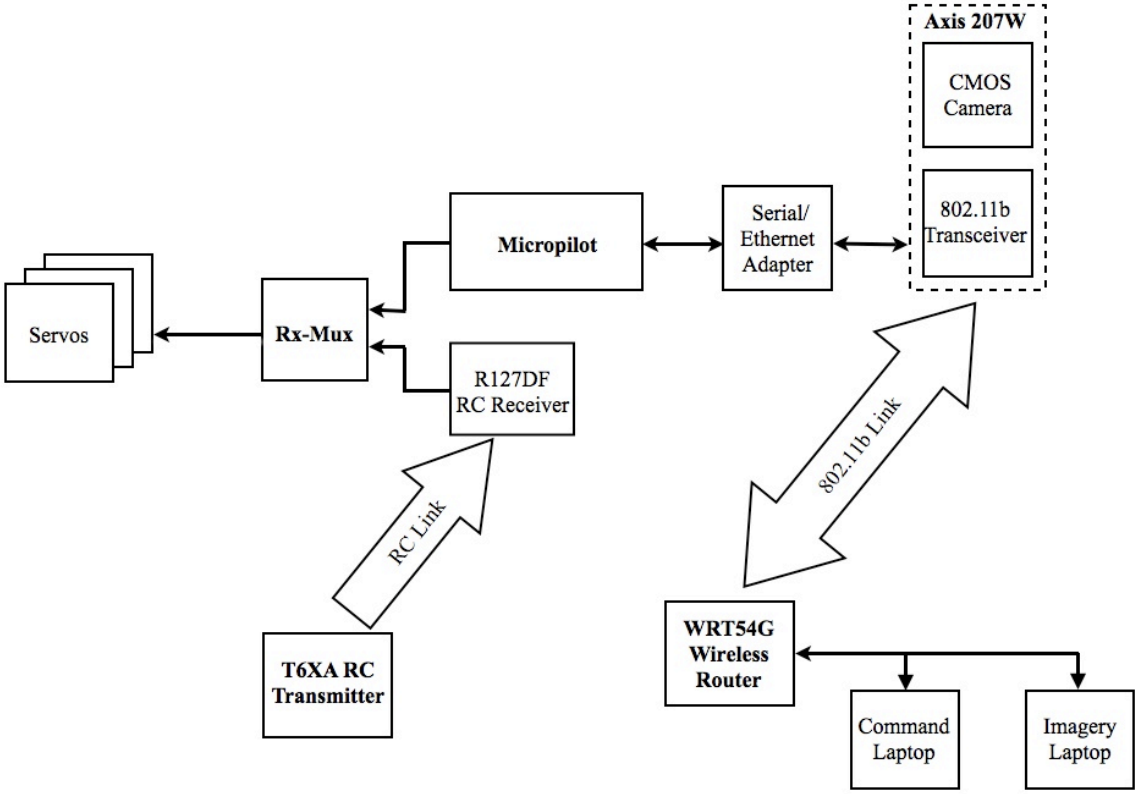

Figure 11. The logical arrangement of the SOAR system components.

These modifications are inconsistent with operation under the FCC Part 15 rules for which the router is designed -- therefore it is operated instead under FCC Part 97, Amateur Radio rules. To comply with the station identification requirement under Part 97, the SSID of the router is set to the call sign of the licensee (KB9RMK).

E. **Ground Support Equipment**

The Linksys WRT54G router is connected to two laptop computers. One laptop is for the Micropilot Horizon application which provides telemetry and control for the Micropilot. The other laptop is for the fetch_touch imagery application, written by the SOAR team to receive pictures from the camera and interpret them. Each laptop has a custom-built sunshade to permit easy viewing of the laptop displays by the operators.

For the airframe, the tools and materials needed are kept in a radio control flight box. The primary components are the fuel supply, glow-plug power, and starter motor. Spare parts and repair tools are also included.

In the unlikely event of an accident or injury, a fire extinguisher and first aid kit are included in the ground support equipment. The fire extinguisher is an ABC type, capable of handling liquid fuel, electrical, and small grass fires. There are no Lithium batteries in the system, so light-metal extinguishing is not required.

F. **Operating Procedures**

The increasing restrictions by the Department of Homeland Security (DHS) and the Academy of Model Aeronautics (AMA) have closed many previously-available test sites for small unmanned aerial systems. Since the nearest site that is both safe and unrestricted is a two hour drive from the Daytona Beach campus, careful planning is required to ensure that trips to the test site are not wasted. A pre-departure packing list is used to ensure that no critical components are left behind. Pre-departure, set up, pre-flight, post-flight, and takedown checklists reduce wasted time and the risk of a configuration error.

Each flight test is has specific test objectives, and when appropriate, test cards are used to ensure that the test conditions are achieved. Imagery and datalogs are taken from the system and backed up after each flight, to secure the maximum information for analysis of each flight. A flight test report that is written after each trip summarizes lessons learned, and informs what changes will be made for the next iteration of the test-develop cycle.

V. Conclusion

The 2008 SOAR system is an important first step to a new configuration to better complete the objectives of the AUVSI Student UAS competition. The COTS autopilot from Micropilot provides autonomy and waypoint navigation, with basic in-flight re-tasking afforded by the Horizon ground control software. The Eagle 2 aircraft fits within the size constraints and has sufficient performance to complete the competition sortie within the time limit. The digital camera and datalink systems provide superior imagery performance, maximizing the performance of the custom imagery software to locate and identify targets.

The new systems improve overall system performance, and can be carried forward into a future configurations incorporating these and other changes to fully complete the challenge posed by the competition.

The test-driven development model fostered rapid progress on the new configuration, and helped the team gain experience with traveling with the system and using test time efficiently. Practical needs have been identified, and changes evaluated in a close analog to the competition environment.

The as-built system has been shown to be capable of flying autonomously, imaging targets, and returning imagery to the ground station, fulfilling the goals of the sixth annual AUVSI Student UAS Competition.

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