UAV Autopilot Integration and Testing

David Erdos, *and* Steve E. Watkins, *Senior Member, IEEE,*
Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409-0040

***Abstract*—The development of an Unmanned Aerial Vehicle (UAV) platform and the integration of avionics for a search and rescue UAV is examined. The project follows the guidelines for the UAV Challenge – Outback Rescue which is an international aerospace competition. The selection process for a commercial autopilot and avionics package is described. The selected system is integrated into a standard hobby remote control aircraft and configured for autonomous flight and navigation. The autopilot system must be tuned to the aircraft platform and flight characteristics. Flight tests are described for a GPS-based grid search pattern.**

***Index Terms*—UAV (Unmanned Aerial Vehicle), Autopilot, Aircraft Electronics, Aerospace Control, Mobile Robots**

I. INTRODUCTION

The use of UAVs (Unmanned Aerial Vehicles) has skyrocket in the recent years; much development has been due to the rapid adoption of UAV technology by armed forces. UAVs can be used on the battlefield for reconnaissance, target acquisition and tracking, and now some can even deliver weapon payloads. New Defense Department Figures indicate that usage for the 2007 fiscal year of larger UAV systems has reached 258,000 hours, much of which has been in Iraq [1]. The developing capabilities of UAVs have also led to an increasing number of civilian uses.

Today UAVs are finding civilian uses such as environmental monitoring, wildlife population tracking, wildfire monitoring, border patrol, and even shark spotting (in Australia) [2]. Another important potential use for UAVs includes search and rescue operations. Small UAVs could be rapidly deployed without the need for an airstrip and could quickly begin searching an area for a missing person. Using small UAVs as opposed to full-scale human operated aircraft significantly reduces operating costs and can significantly reduce the time taken to begin search and rescue operations. Depending on the specific UAV being used, the mission endurance can also be far greater.

All UAVs have a ground station where they are given commands and where video or aerial images are relayed. A typical ground station provides a simple intuitive user interface allowing the operator to simply drag waypoints on a map and then command the UAV to fly the created path. Most ground stations have a constant data link with the UAV and provide telemetry and positional information.

An international aerospace competition for students, hobbyists, and filmmakers was organized for 2007 with plans for future competitions. The UAV Challenge – Outback Rescue involves the development of a UAV capable of completing a simulated search and rescue mission completely autonomously. Tasks include autonomous takeoff, flight, and landing with associated image processing and control needed to identify a missing hiker in the Australian Outback and deliver an emergency medical package to the hiker [3].

This paper will discuss elements for the development of a UAV that will compete in the 2008 Australian UAV Outback Rescue Challenge. The project is being conducted by the IEEE AESS (Aerospace and Electronic Systems Society) Student Chapter and UAV Team at the Missouri University of Science & Technology (Missouri S&T), formerly the University of Missouri-Rolla. The topic of this paper is the development and integration of the autopilot and avionics package in the UAV platform. The selection process and configuration for a commercial autopilot and avionics package is described. The selected system is integrated into a standard hobby remote control aircraft and configured for autonomous flight and navigation. The tuning process and flight tests of the autopilot system are described for takeoff, landing, and a GPS-based grid search pattern.

II. MISSOURI S&T UAV SYSTEM OVERVIEW

A. Overview

The UAV Challenge competition seeks to encourage innovation in UAV design and application. The Search and Rescue component of the competition involves the development of a UAV that will takeoff, fly a grid that is roughly 3 km by 4 km, search the grid for a defined target (Outback Joe), drop a bottle of water near the target, return to airfield, and land. The flight time is limited to one hour. Competition criteria relate to the ability to perform these tasks autonomously and to document the development and testing process. The vehicles are limited by weight to 100 kg for rotary solutions and 150 kg for fixed wing solutions.

The Missouri S&T UAV team chose the fixed-wing vehicle option [4]. Selection criteria for the airframe were a large payload capacity for the electronics and the water bottle cargo and a minimum of one hour of continuous flight. An "almost-ready-to-fly" solution was desired to allow the development to

The corresponding author is S. E. Watkins. Contact information: Electrical and Computer Engineering Department, Missouri University of Science and Technology, Rolla, MO 65409 USA (phone: 573-341-6321; fax: 573-341-4532; e-mail: steve.e.watkins@ieee.org).

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focus on the electronics, computing, and sensing functions. The selection of the airframe placed requirements on size and weight for the remaining system components. Also, a choice was evaluated regarding the image acquisition and processing for identifying the pseudo-hiker Outback Joe. If the image processing was to be performed at the ground station, a robust high bandwidth (ideally 5 or more megabits) and long range (5 or more miles) wireless connection would be required. If the image processing was to be performed by the onboard computer, the onboard computing capabilities would need to be more extensive and the processing algorithm tailored to the application. The latter option was selected due to cost, capability, and weight constraints of available high bandwidth link hardware.

Given the selected airframe and the image processing approach, the system was designed with weight, space, electrical power, capability, and cost being the main factors. Fig. 1 is a block diagram of how the various subsystems are interconnected in the UAV avionics, computing, and sensing system. The major components are

- Control Ground Station
- Onboard Computer
- Battery and Power Distribution Board
- Autopilot, Associated Sensors, and GPS Receiver
- Onboard Camera

This work emphasizes the development related to the autopilot.

Selected Constraints

Aircraft Gross Weight (including fuel)	< 7 kg (15 lbs)
Battery Capacity	> 50 Wh
Aircraft Wingspan	< 200 cm (80 in)

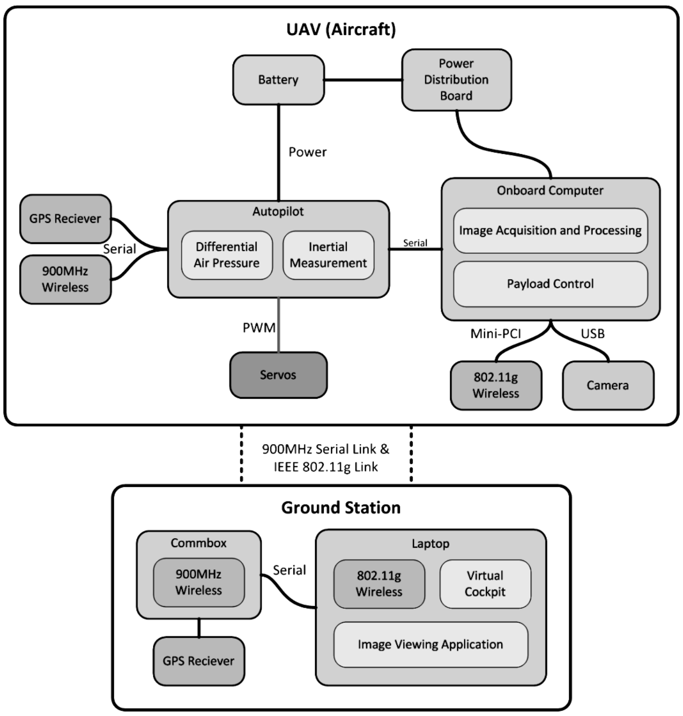

Fig.1 UAV System Block Diagram

B. Autopilot

The Kestrel autopilot manufactured by Procerus Technologies was selected for its combination of desirable features. The Kestrel provides an extremely light-weight (16.65 grams) and tightly integrated solution (Fig. 2). The Kestrel system uses 3 MEMS (Micro-Electro-Mechanical Systems) accelerometers and 3 MEMS gyroscopes to provide 6 Degrees-of-Freedom inertial measurement. It is also equipped with differential air pressure sensors for altitude and air speed measurement, a magnetometer, and an external GPS for guidance and navigation.

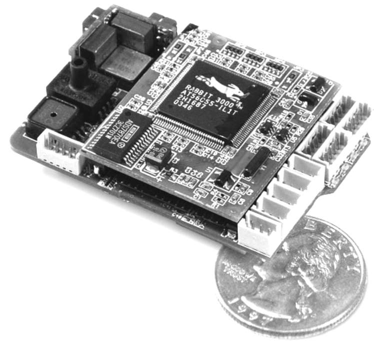

Fig.2 Kestrel Autopilot and a quarter for size comparison
Image Courtesy of Procerus Technologies (www.procerusuav.com)

The Kestrel system uses a 900MHz Maxstream XTend serial modem (not shown in Fig. 1) that, according to the manufacturer, has a range of up to 60 kilometers (40 miles) LOS (Line of Sight), and up to 1W of power output. The serial modem allows communication between the autopilot and the ground station. This communications link is used to upload waypoints and monitor telemetry from the aircraft while in flight or on the ground.

Competition rules require the aircraft to fly 1 nautical mile to the search area [3], and the greatest distance the link will have to reach is approximately 7 kilometers (4.5 miles), i.e. the distance from the starting location to the farthest corner of the search grid. With the use of a directional antenna on the ground, reaching this range will not be an issue. The radios selected provide a 115,200 bps 256-bit AES encrypted link ensure secure communications between the UAV and the ground station at all times.

C. Airframe

The airframe chosen was the Sig Kadet Senior (Fig. 3) [5]. This hobby remote-controlled aircraft is a popular “almost-ready-to-fly” aircraft for remote-controlled flight due to its inherent stability and stable flight characteristics. It is also a relatively slow flying aircraft that gives time for autonomous reaction and good image acquisition. As manufactured with balsa and plywood inner structures, the covered airframe without engine weights 2.95 kilograms (104 ounces). The 164.5cm (64.75-in.) fuselage also has plenty of space for the electronics and camera. A camera can be installed with an unimpeded view from the bottom of the fuselage. Despite a large as-manufacture total weight capability, a custom main wing is used. This modification was needed to enable the airframe to handle the extra-large payload of the electronics, batteries, a camera, and extra fuel. During initial testing the wing provided by the manufacturer failed catastrophically causing the aircraft to crash. For this reason a custom wing was designed that would be significantly stronger and provide higher cruise speeds (allowing grid to be searched faster).

A four-stroke glow fuel engine was chosen as the power source for the aircraft. This glow fuel engine provided extended flight capability and more power for the aircraft as opposed to brushless electric motor options.

Fig.3 The airframe in the flight-ready configuration.

D. *Image Acquisition and Processing*

The image acquisition and processing components, along with the autopilot, determined the main requirements on the onboard computing power and the base station link capacity. High-resolution still imagery was selected for hardware cost benefits and processing simplicity. A 10-megapixel digital camera provides 3-cm resolution at a cruising altitude of 122 m (400 ft.).

E. *Onboard Computer*

In addition to computing power, the onboard computer requirements were to fit within a 10.16-cm x 12.70-cm x 17.78-cm compartment, to operate from a 5-v power supply, and to have low power needs. The JRex-PM 3.5-in SBC (Single Board Computer) computer manufactured by Kontron was selected. The main board is shown in Fig. 4. The JRex-PM is equipped with a 1.8GHz Intel Pentium M processor and 1GB of DDR-RAM and has the maximum power consumption of about 35 W. The JRex-PM is also equipped with a compact flash slot allowing flash memory to be used instead of a standard hard drive, which is particularly important due to the high levels of vibration present in the aircraft under full power.

To minimize overhead and for ease of installation, Ubuntu Linux was selected as the operating system. Linux was installed on a 4GB compact flash card that attaches directly to the bottom of the SBC. For communication to the ground station a Mini-PCI IEEE 802.11g/b wireless card was also installed and additional storage for images and data will be added as a USB flash drive.

The computer interconnects to the autopilot, the camera, the wireless ground link (for imagery), and storage. It also provides control for the payload relay. Again, the water bottle must be dropped once the pseudo-hiker is identified. Also, the system must allow for manual override and flight control to meet safety requirements.

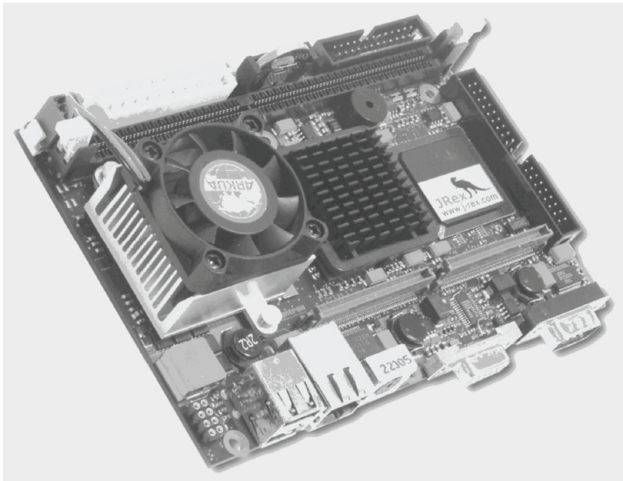

Fig.4 JRex-PM Single Board Computer
Image Courtesy of Kontron (www.kontron.com)

III. Autopilot Configuration and Integration

A. *Installation*

The installation of the autopilot was rather straightforward due to the provision of thorough documentation by the manufacturer. Once the autopilot and the ground station were powered, communication between the two was instantly initiated and the Virtual Cockpit ground station software began to display live telemetry from the autopilot including GPS location, attitude information (pitch, roll, and yaw), battery voltage, and current draw from the power source.

The largest hurdle in the entire process was to tune the PID control loops for the specific airframe and aircraft configuration; this process must be done for every specific aircraft. The manufacturer outlines four flights that must be completed to tune the control loops for the autopilot. The first flight consisted of simply verifying that all the sensors were functional and that the autopilot was capable of communicating with the ground station properly. The subsequent flights involved tuning the lower level control loops and then enabling higher and higher level control loops.

This process of tuning the control loops began with trips to the local RC airfield where the flights that the manufacturer outlined were completed within the pilot-in-the-loop mode. To tune the control loops the pilot would disturb the aircraft from level flight and depending on which control loops were enabled, the aircraft would respond and return the aircraft to straight and level flight. As per the manufacturer’s recommendations tuning was performed by setting a small value for the proportional gain and slowly increasing it until instabilities were noticed, the gain was then reduced by 25% (later integral and/or derivative gain was also added if proportional did not provide sufficient performance). One loop at a time, the PID parameters were tuned from the ground station. This process was rather time consuming and it was often difficult to gauge how well the loops were tuned from the ground. Having the autopilot control loops tuned to the specific airframe is critical to allow accurate and smooth navigation of waypoints.

B. *Flight Performance*

The autopilot performance must satisfy the needs for autonomous takeoff, landing, and a GPS-based grid search pattern. Also, information must be relayed to the ground station to monitor progress and provide for safety assurance, e.g. the aircraft must not travel out of approved airspace. The performance tasks are:

- Autonomous takeoff and landing, especially when fully loaded with fuel and the water bottle payload,
- Adherence to the defined flight path and altitude while traveling to and from the search area, and
- Navigation by set waypoints for the GPS-controlled grid search.

The autopilot sensor and control performance is examined with regard to the ability of the autopilot to adhere to the desired flight parameters (roll, pitch, airspeed, and altitude).

The Kestrel autopilot logs all telemetry sent between it and the ground station, this information can later be reviewed and used to analyze the performance of the aircraft and autopilot in specific situations. This data was used to analyze the performance of the autopilot regarding the specific flight parameters mentioned above (roll, pitch, airspeed, and altitude).

IV. Discussion

A. *Roll Performance*

The flight performance of the aircraft is examined below. Roll performance is shown in Fig. 5. Ideally, the graphs of the desired and actual roll should line up exactly, but in practice this close match is not always feasible. In this case the performance of the autopilot is very good. The graph shows that the actual and desired roll are quite close, although the actual roll does lag the desired roll slightly, but this behavior is to be expected.

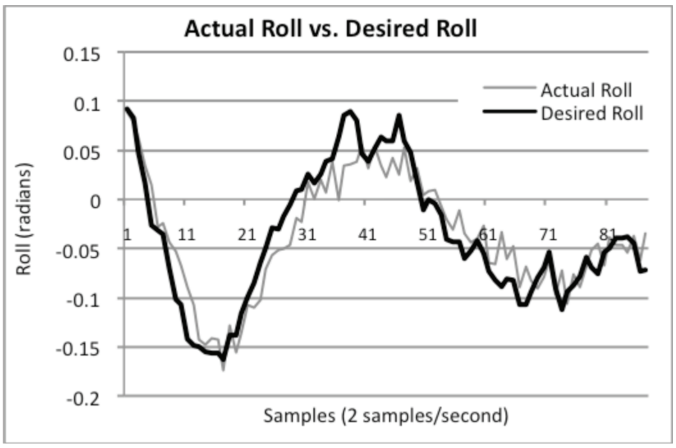

Fig.5 Roll performance of the autopilot.

The ability of the autopilot to maintain the desired roll is particularly important in obtaining accurate images of ground below. Being able to maintain a roll command accurately is also important when the aircraft is turning, which it will have to do reliably in order to search the search area in the shortest time possible.

B. *Pitch Performance*

Pitch performance is shown in Fig. 6. The performance of the pitch control of the autopilot was not as effective as the roll. There is significant lag in the pitch response of the aircraft to a step input as seen in Fig. 6, but with more tuning and analysis the pitch response time could be improved (by adjusting the integral and derivative gains of the pitch PID loop). Other than the lag in the pitch response there do not appear to be oscillations or other instabilities.

Maintaining the pitch of the aircraft reliably is important in order to maintain a constant altitude, and in turn maintaining a constant altitude is important in order to stay within the mission parameters (the altitude must not exceed 400 feet [3]). A constant pitch is also important in order to obtain images with the proper orientation from the camera.

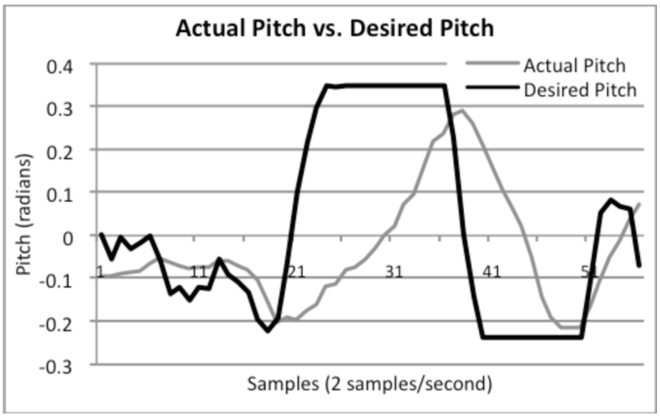

Fig.6 Pitch performance of the autopilot.

C. *Airspeed Performance*

After the amount of control tuning that was performed, performance of the control loops in charge of maintaining airspeed were still rather poor (Fig. 7).

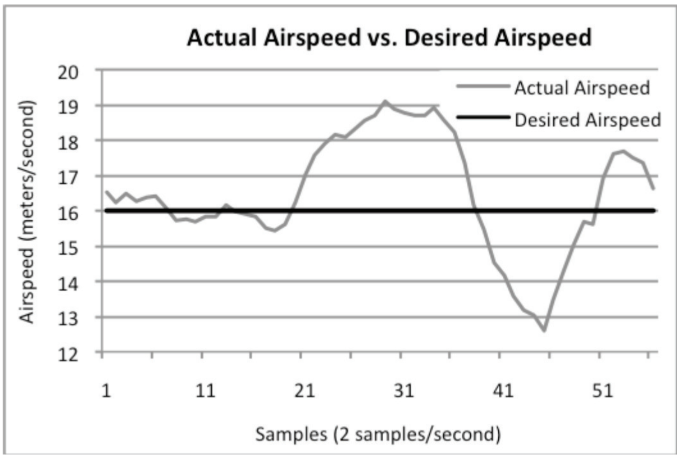

Fig.7 Airspeed performance of the autopilot.

The commanded airspeed was maintained within ±3 meters per second. From Fig. 7 oscillations can be seen in the actual airspeed which was also quite noticeable from the sound of the aircraft.

D. Altitude Performance

The final control loops that are examined are the altitude tracking control loops. As seen in the Fig 8, the altitude tracking exhibited oscillations centered along the commanded altitude, up to ±10 meters.

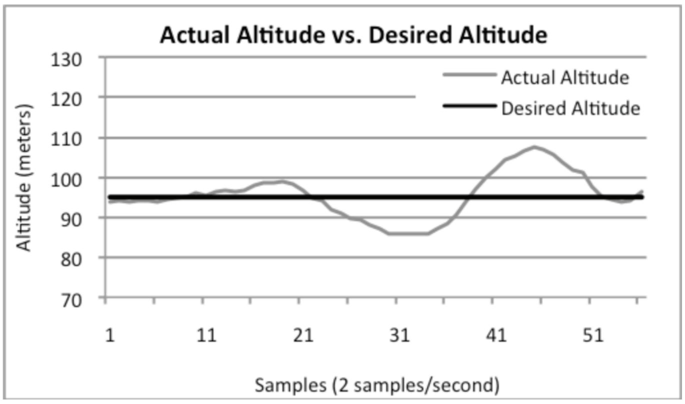

Fig.8 Altitude performance of the autopilot.

Oscillations in the altitude were significantly worse at the beginning of the process, up to ±20 meters, but after more tuning and testing they were reduced to the levels seen in Fig. 8 (±10 meters). Ideally the oscillations should be reduced to a maximum of ±3 meters or eliminated completely. More tuning and adjustment of the autopilot control parameters may be needed.

The airspeed and altitude control loops are the two of the most difficult control loops to tune on this specific autopilot. Airspeed is controlled by two control loops, the pitch from airspeed PID loop, and the throttle from airspeed PID loop, likewise the altitude is controlled by the pitch from altitude PID loop and the throttle from altitude PID loop. Tuning these control loops to a satisfactory level proved more difficult than anticipated due to the difficulty of determining whether or not the aircraft was performing as expected from the ground. Although with more testing, analysis and tuning these issues encountered are expected to be resolved.

E. Navigation Performance

The primary purpose of having all of these control loops tuned properly is to enable the autopilot and the aircraft to navigate a designated path autonomously. In order to upload a path to the autopilot the ground station's Virtual Cockpit software is used to create a flight plan. The user can program waypoints and loiters that set the intended flight path of the UAV. To test the performance of the control loops a simple loop was created using six waypoints (Fig. 9) and then the aircraft was commanded to fly the path.

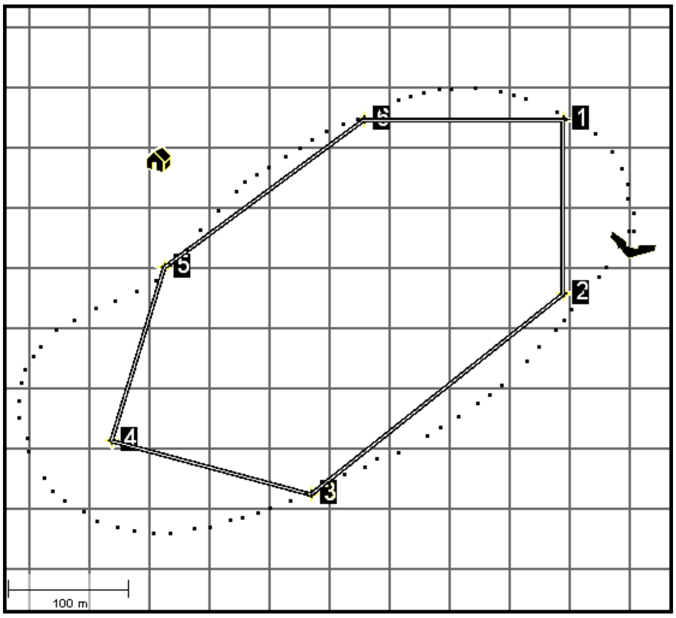

Fig.9 Navigation performance of the autopilot.

In the figure above (Fig.9) the path of the aircraft is shown by the dotted line, while the waypoints are represented by the numbers. As can be seen from the figure above the navigation performance of the UAV was not particularly good. After analyzing the flight shown above, it appears that the waypoints chosen are too close together for the autopilot to navigate cleanly; if these waypoints were moved further apart the navigation performance would be improved. This hypothesis (that moving the waypoints further apart will improve navigation performance) was also validated in later flights.

V. Conclusion

The Sig Kadet Senior aircraft provided a good platform for the development of a UAV system. Its flight characteristics and physical dimensions meet needed criteria with reasonable constraints. Autopilot, imaging, image processing, and onboard computer subsystems are key elements in the design. The autopilot promotes UAV usage and provides appropriate communication with the ground station.

After the tuning of the control loops was completed, the overall flight performance of the autopilot and aircraft was reasonable and sufficient for the initial testing phase of this project. Several areas still need improvement, primarily the altitude and airspeed tracking control loops. Some of the navigation parameters could benefit from more fine-tuning. With more testing and tuning of the existing configuration, a significant improvement in performance is expected.

Overall the process outlined in this paper, of integrating the Kestrel autopilot into the selected airframe, was a success and this systems integration will allow the further development of the UAV platform to be used in the 2008 Australian UAV Outback Rescue Challenge.

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David Erdos is a junior undergraduate majoring in electrical engineering at the Missouri University of Science and Technology (formerly University of Missouri-Rolla). He is President of the Missouri S&T Student Chapter of AESS.

Dr. Steve E. Watkins is Professor of Electrical and Computer Engineering and Director of the Applied Optics Laboratory at the Missouri University of Science and Technology (formerly the University of Missouri-Rolla). He was a 2004 IEEE-USA Congressional Fellow, a visiting physicist at Kirtland Air Force Base, and a visiting scholar at NTT in Japan. He is a member of IEEE (senior member), SPIE, OSA, and ASEE. His Ph.D. is from the University of Texas at Austin.