Development of an Autonomous Aerial Reconnaissance Platform at Virginia Tech

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Abstract

The Autonomous Aerial Team at Virginia Tech (AAVT) was formed in the Fall of 2004 with the goal of engineering an aerial vehicle to participate in the 3rd Annual Student Unmanned Aerial Vehicle (UAV) Competition. The Student UAV Competition is directed by the Seafarer Chapter of the Association for Unmanned Vehicle Systems, International (AUVSI) and offers students at the university level unprecedented exposure to the UAV design process and team work as they enter their chosen careers. The current competition is held at the Webster Field Annex in St. Inigoes, Maryland. In less than one year, AAVT has designed and fabricated Xavier, an aerial system capable of successfully competing in the 2005 Student UAV Competition. This report summarizes the steps taken by AAVT in the design and construction of XAVIER including a brief description of the primary vehicle, modifications made to the vehicle, the sensor and control architecture used for autonomous flight, communications, and safety implementations.

Mission Definition

Participants are offered the opportunity to solve real-world problems by applying and combining technologies aimed at providing autonomous surveillance of predefined search areas. The mission initiates by launching a radio controlled (RC) aircraft in either manual or autonomous control. After take off, the craft is transitioned to autonomous mode during which it must navigate a course specified by Global Positioning System (GPS) waypoints. At some point during the flight, the vehicle will enter a search area in which it must locate and identify a number of man-made targets. Image processing techniques must be utilized during the length of the mission in order to not only identify but also report the orientation of these targets. After the targets have been identified the aircraft must then return to the landing point under autonomous control. As in take off, the landing may be performed in manual or autonomous mode.

A radio controlled (RC) aircraft must be equipped with a number of systems to accomplish such a task including a flight navigation and stabilization system, power distribution and management system, a vision system, and finally a data transmission system. Whenever available, the AAVT opted to integrate commercial off-the-shelf (COTS) components in order to maximize test time and reliability. Custom electronics and software are also incorporated resulting in a fully autonomous aerial system. A brief description of each component is presented later in the paper.

Design Process

In Fall 2004 the design team began developing XAVIER by establishing the vehicle's primary design objectives. These objectives focus on creating a safe autonomous system that competes favorably in the Student UAV Competition, promotes awareness of unmanned systems, and provides a reliable platform for future testing and research. To accomplish these goals, the team implemented a design strategy that held customer needs paramount, provided a clear path for project completion, and focused on innovations.

Design Planning Process

A methodical thought process is essential for the successful development of complex systems such as XAVIER. The team used the six-step design method shown in Figure 1 to help guide the design process. Details of this method are described in *Product Design and Development* (Ulrich and Eppinger, 2000). Although the figure indicates sequential steps, the designer is encouraged to return to earlier steps as problems are encountered and as new information becomes available.

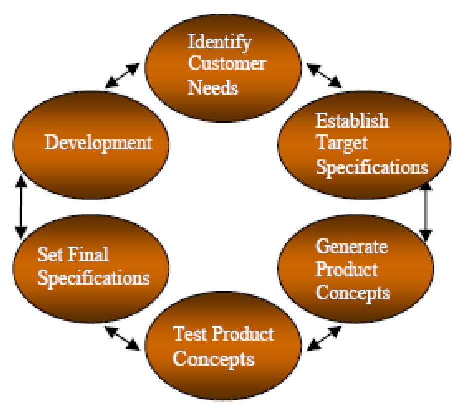

Figure 1: Ulrich and Eppinger's Design Methodology

Identifying Customer Needs

The following primary customers were identified: (1) competition judges and sponsors, (2) the team faculty advisor, and (3) current and future vehicle users. Secondary customers include team sponsors and the autonomous vehicle community. Many of the primary customer needs are expressed in the 3rd Annual Student UAV Competition rules and in the syllabus for our senior design course. The syllabus outlines the faculty advisor's expectations and the course educational objectives.

Team Organization

A majority of the members of the AAVT are senior mechanical engineering students fulfilling a design project required for graduation. However, this mission requires knowledge in the fields of mechanical, aerospace, and electrical engineering. A number of volunteers from these disciplines provided valuable insight and technical knowledge throughout the design process. Goals and milestones are implemented to help the team complete the project in a timely manner.

System Overview and General Mission Strategy

With the problem defined, AAVT endeavored to create an overall approach to accomplish the competition goals. The main components required for this competition are a RC airplane with accessories, flight controller, wireless communications data link, wireless vision system, Ground Control Station (GCS), power management system, and a fail-safe system. Figure 2 outlines a general flow of information and system architecture. The flight controller (FC) is responsible for control and navigation of the vehicle as it executes the mission. A variety of sensors including a pressure altimeter and speed sensor, GPS, and inertial sensors allow the flight controller to determine an estimate of the vehicle's attitude, airspeed, GPS position, and height above terrain. The FC constantly compares the vehicle's current parameters with the desired parameters and actuates servo motors to compensate for the error. All the data pertaining to the vehicle is relayed to the GCS via a serial modem. Operators at the GCS can monitor the electronics and states of the vehicle in real time. Streaming video is also sent back from the vehicle by an analog transmitter. Due to the power and band of the video transmitter, an amateur radio license is required for transmission. The licensee's call sign must be overlaid on the transmission which is accomplished by the video overlay board. A microcontroller, or programmable integrated circuit (PIC), allows the user to specify the text to be overlaid on the video signal. When the video has reaches the ground station, a frame-grabber is used to acquire the video and input it to a computer utilizing object recognition techniques to identify and locate the specified targets.

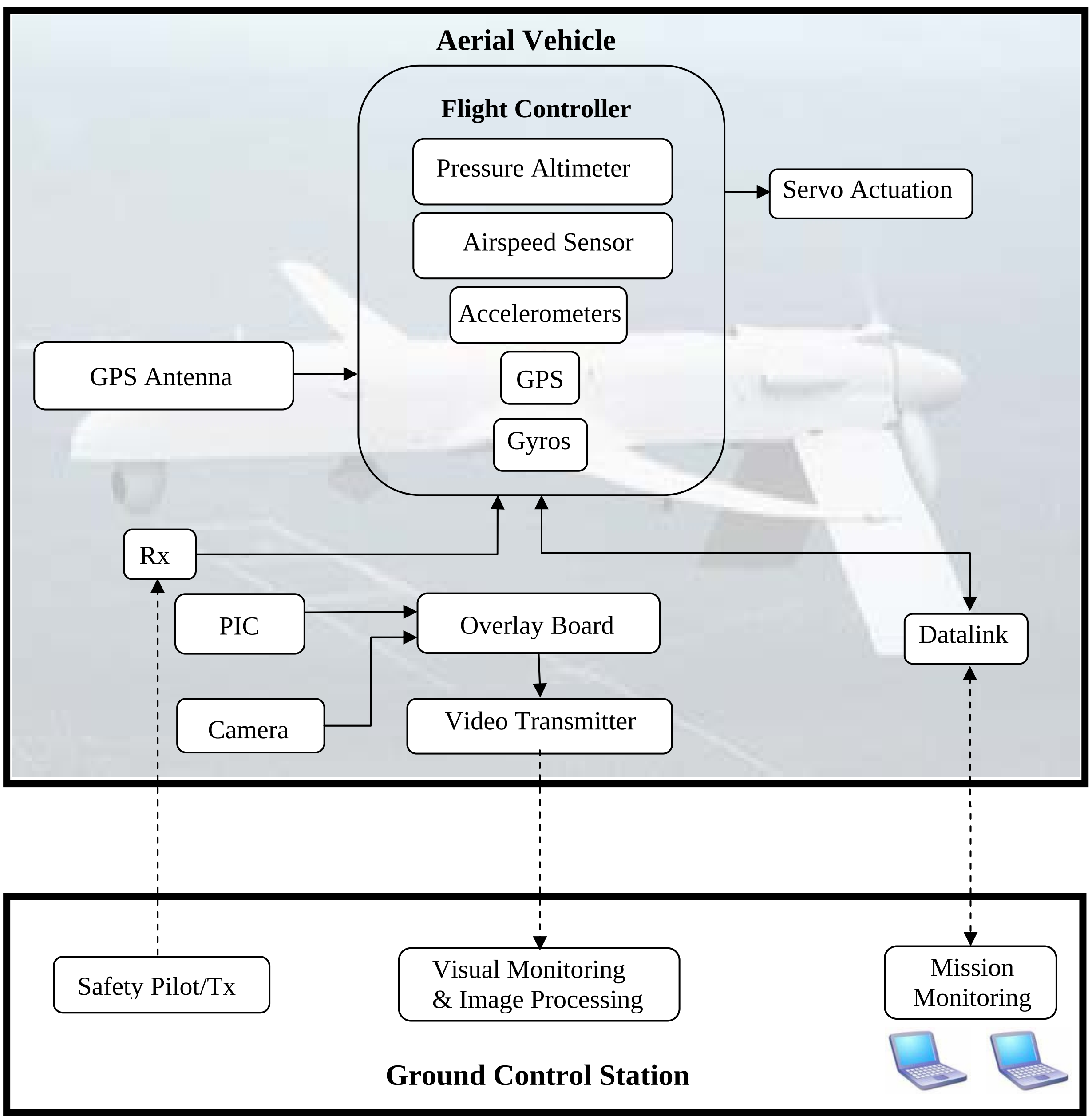

Figure 2: System Architecture

Safety

Safety is a paramount concern in UAV operation. A number of factors contribute to a successful and safe flight including power levels, radio connection with the safety pilot, wireless communication with the ground station, electro-magnetic interference, and mechanical integrity. A constant consideration is that one of these components fails or malfunctions, resulting in uncontrolled flight. In order to minimize safety risks of XAVIER, AAVT incorporated a number of safety characteristics including:

1. The safety pilot and GCS has authority to switch between autonomous and manual flight; and,
2. If the radio link between the safety pilot and aircraft is lost or the FC voltage drops below a minimum specified level, the plane will dive as specified by the competition rules.

Hardware Overview

Airframe

After familiarization with the competition rules and requirements, the AAVT generated a list of possible vehicle platforms and weighed the advantages and disadvantages of each as they related to the competition. With safety held as a constant concern, other factors included controllability, size, expandability, and payload capacity. Of these items controllability and payload capacity emerged as the dominant factors. The standard trade-off for controllability in aircraft is speed and maneuverability, both of which AAVT was willing to sacrifice for a aircraft stability.

However, before an airframe, or engine, could be selected a list of on-board avionics was generated in order to provide a payload estimate. Table 1 outlines the required components and their weight.

Table 1: Weight Summary

Component	Weight (gr)
Micropilot MP2028g	28
RC Receiver	40
Video Transmitter	39
Video Overlay Board	27.7
Battery (2)	480
Serial Modem	200
Camera	20
Servos (5)	186
Fuel (22 oz.)	665
Misc. Electronics/Hardware	454
Total (grams)	2139.7
Total (pounds)	4.7

Each of these components will be discussed in greater detail throughout the paper. A pound of miscellaneous components was added to provide a factor of safety in determining the required payload capacity of the aircraft. With a payload estimate, the team continued its search for an aircraft and discovered a number of viable solutions. After careful analysis couple with recommendations from a number of seasoned pilots, the Sig Kadet Senior was chosen as the main aerial platform. The Kadet is a trainer craft boasting a wingspan of 80.5 inches and a lift surface of 1180 square inches. The wing has a flat bottom which increases the lifting capacity and ensures a smooth, controlled flight.

Kadet Specifications	
Wingspan	80.5 inches
Wing Area	1180 square inches
Length	64.75 inches
Weight	6 pounds

Figure 3: The Sig Kadet Senior serves as the main platform

Engine Selection

The Kadet Senior is a 0.40 size trainer. The team decided to oversize the engine to ensure payload ability and compared the O.S. 46 AX and O.S. 61 FX non-ringed engines. Performance specifications for each engine are summarized in Table 2. The engines are similar in performance, with the 0.61 weighing 6.2 ounces heavier but producing 0.25 more horsepower. Although, the power density of the 0.61 is also lower than the 0.46 the team opted to use the 0.61 in order to provide a buffer for the estimated payload.

Table 2: Engine Comparison

	O.S. Engine Model	
	0.46 AX	**0.61 FX**
Displacement (cu in)	0.455	0.607
Engine Speed (kRPM)	2 - 17	2 - 17
Power Output (hp)	1.65	1.9
Weight (oz)	13.2	19.4
Power Density (hp/oz)	0.125	0.098

Avionics and Sensors

Flight Controller

Two flight controller options were available to AAVT. The first was to design and fabricate a custom controller, including hardware and software. The second was to purchase a COTS unit. Given the timeframe and complexity of the competition AAVT decided to purchase the Micropilot MP2028g flight controller because it best supported AAVT's design goals and exhibited a friendly user interface. A substantial competition discount also contributed to this decision. The Micropilot controller is responsible for all control and stabilization of the aircraft. Inertial and pressure sensors, as well as a GPS unit, are used to estimate the current states of the vehicle and position. These estimates are then compared to desired states and position through a PID controller with a 30 Hz update rate. The resultant correction signal actuates servo motors in the appropriate manner. Use of Micropilot's Horizon software provides a graphical user interface for the GCS. Monitors at the GCS can dynamically load and reload flight paths consisting of GPS points to the controller as well as command air speed and altitude. A number of important parameters, including battery power level and strength of the radio link are also sent to the GCS. Figure 4 illustrates a screen shot of the Horizon graphical user interface (GUI).

Figure 4: Screen-shot of the MP2028g GUI

Utilizing the Micropilot flight controller greatly simplifies the mission for AAVT. Given the robustness of the FC, the design team is responsible for tuning PID gains and adjusting flight parameters as needed. The Micropilot package also allows the operator to easily change PID gains and adjust flight parameters allowing one to tailor the flight controller to the aircraft in question.

Datalink Communications

In order to maintain datalink communications with the GCS, XAVIER utilizes a MaxStream 900 MHz serial modem. This unit provides a compact, simple, and reliable solution. In its current configuration a maximum line-of-sight range of 5 miles is possible. A flow diagram of the communications system is shown in Figure 5.

Figure 5: Flow diagram of wireless communications from XAVIER to the GCS

Reconnaissance System

The camera, overlay board, PIC, video transmitter/receiver, frame grabber, and object recognition algorithm constitute the reconnaissance system. Figure 6 illustrates the process. A single analog camera was shock mounted to the underside of the airframe and positioned to look straight down, allowing the maximum field of view. The video signal is passed through a video overlay board where an Amateur Radio Licensee's call sign is overlaid as required by the Federal Communications Commission. The overlaid message is extremely flexible and is commanded via a microcontroller through a RS-232 connection. A one watt, 2.4 GHz transmitter from Black Widow AV then sends the signal to the GCS where a television set displays the raw video signal. The video is also ported to a computer where the image is analyzed using AAVT's object recognition algorithms. Results of the image processing are displayed on the computer's monitor, allowing the judges and operators to easily evaluate mission performance in real time.

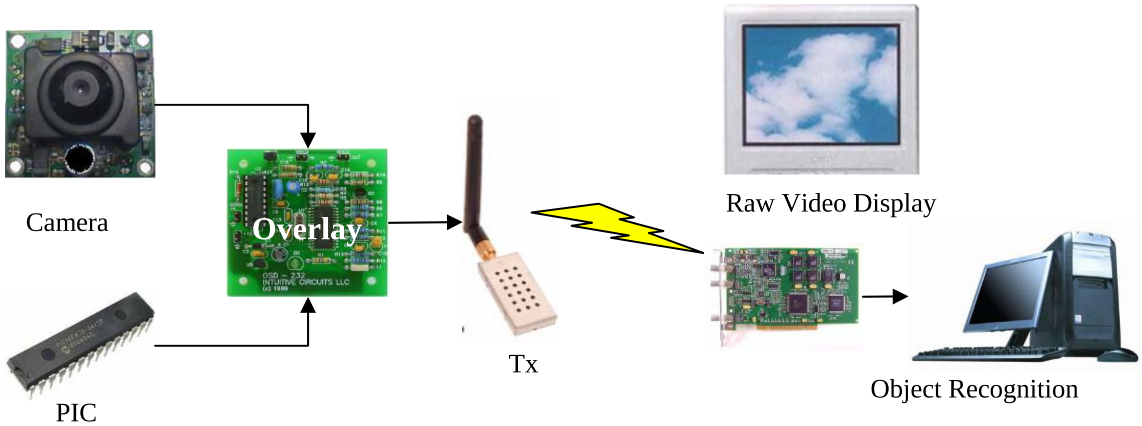

Figure 6: Reconnaissance System

Power Management

Once the on-board components were specified, AAVT compiled a list of power specifications and chose batteries to operate the electronics. Table 3 summarizes the required power for each component. An estimated power consumption of 10.8 watts was determined from this analysis.

Table 3: On-board Power Requirements for XAVIER

Component	Voltage (V)	Current (mA)	Power (W)
Camera	12	100	1.2
Video Transmitter	12	450	5.4
Maxstream	12	200	2.4
Servos	5	2	0.05
Receiver	5	10	0.05
Micropilot	12	80	0.96
PIC	5	4	0.02
Overlay Board	12	60	0.72
Total Required Power			**10.8**
Battery Power (2)	7.4	2000	29.6
Effective Battery Power			**25.16**

Two 7.2 V, 2000 mAh nickel-metal hydride (NiMH) batteries tied in series power the entire system and allow for flight times of over two hours. All of the components require either 12 or 5 VDC. Two DC-DC buck converters with 85% efficiency are

employed to this end and the necessary power is supplied to the appropriate systems as shown in Figure 7.

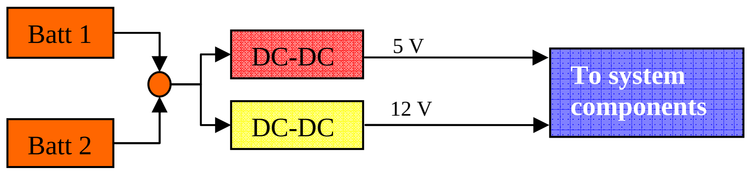

Figure 7: Basic Power schematic showing power redundancy to the FC

Mission Management

With the airframe, engine, and avionics selected and operational, completing the mission includes several steps.

- A preflight and safety checklist of XAVIER is performed.
- A path of GPS waypoints is loaded into the FC and altitude and air speed parameters are set.
- XAVIER is launched under manual control and transitioned to autonomous control when in flight. As soon as the transition occurs streaming video will be sent back to the GCS and passed through the object recognition algorithms.
- Once the vehicle enters the search area it will perform a predefined flight pattern, systematically searching the area for the targets. XAVIER will perform this search twice, in order to assure all targets are identified.
- Once the area has been searched, XAVIER will begin its return flight and land under manual control.

During the length of the flight, mission controllers will be closely monitoring the electrical and vehicle states in order to ensure a safe flight. The judges or team can forfeit the mission at any point if they feel the vehicle is uncontrollable.

Testing and Evaluation

Airframe Testing

Extensive component testing was performed before integrating the units into the final product. The Sig Kadet Senior was tested first in order to determine flight time and verify payload capability. Testing with the stock fuel tank resulted in a flight time of approximately 10 minutes with no load. Adding a load of 5 pounds saw little degradation in flight time, yielded a flight of 9 minutes. Since the allowable mission time is 40 minutes, including preflight and data analysis, AAVT chose to double the fuel tank resulting in an estimated loaded flight time of 20 minutes.

Flight Controller Testing

Systematic testing was performed in order to ensure FC performance and reduce the risk of a crash. Software simulations were performed with the Micropilot simulator allowing one to test PID gains and flight parameters. Ground testing was conducted during which team members “walked” the plane through a GPS course to verify correct servo actuation and FC GUI recognition as XAVIER approached the GPS points. After this ground testing, XAVIER was flown with the FC in manual mode to ensure steady flight. Finally, a course was flown autonomously.

Figure 8: XAVIER during one of its test flights

Reconnaissance Testing

Initially, a low power video transmission system was tested which resulted in poor reception and a range of only one-third a mile. A more powerful, one watt, 2.4 GHz transmitter and receiver were then purchased and integrated into the system. The results were clear transmissions for over one mile.

EMI Concerns

Electro-magnetic interference is a major safety concern for AAVT. Three different frequencies are employed on XAVIER: (1) RC transmitter at 72 MHz, (2) serial modem at 900 MHz, and (3) the video transmitter at 2400 Mhz. Interference or power flooding on the servo lines can inhibit the safety pilot's ability to regain manual control and pilot the aircraft. The receiver is shielded in an aluminum box and a low pass filter is added to inhibit everything above 400 Mhz from interfering with the RC transmitter.

Vibration

Vibration problems appeared in the early stages of testing. In particular, the FC's sensors and camera are susceptible to engine vibration. A quick and light weight solution to this problem was to isolate each component from the airframe with foam padding.

Conclusion

XAVIER is an autonomous air vehicle that was designed and fabricated by students at Virginia Tech. XAVIER was engineered using the latest design and simulation tools, resulting in a reliable, compact, and safe product. The AAVT believes XAVIER will provide and adaptable and reliable for this and future competitions.

Acknowledgements

The AAVT would like to acknowledge the generous support of its volunteers and sponsors. Appendix A lists the AAVT's sponsors.

Appendix A: Sponsor List