Virginia Tech Entry to the 2009 International Aerial Robotics Competition

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ABSTRACT

This paper details the Virginia Tech autonomous aerial vehicle to be entered into the 2009 International Aerial Robotics Competition. This paper reviews the problem statement of the competition and the overall system architecture the Virginia Tech team created to solve this challenge. The paper explains the physical design of the vehicle, as well as the sensors and communications used for the mission. Also, the operations of the vehicle are shown and the safety features of the vehicle are explained.

2. INTRODUCTION

2.a Statement of Problem

The 2009 competition mission is to create an autonomous aerial vehicle capable of entering a building through a 1meter x 1meter window, which would then navigate the building and locate a control panel. The control panel is identified by a non-blinking blue LED light. The vehicle must then lock onto a target gauge on the control panel and send back video or imagery enabling the judges to read the gauge.

2.b Conceptual Solution to Problem

To accomplish the task of designing and creating this vehicle, the team split into several sub-teams. Initially the sub-teams consisted of the vision, sensors, and vehicle. The vision team was tasked with designing the camera system and software to identify the control panel and send back video evidence. The sensors team was responsible for evaluation of surroundings and navigation through the environment. The controls team was responsible for developing a flight controller to stabilize and actuate the quad-rotor vehicle. Finally, the Micro Aerial Vehicle (MAV) team was responsible for evaluating and selecting an overall vehicle design. The MAV team was responsible for the design of the flight vehicle, manufacture, and development of test stands to be used by the controls team.

These sub-teams designed the overall system to follow the structure shown in Figure 1. At the highest order, the visual data is collected by the vehicle camera and transmitted to a computer at ground station. This computer determines a proper flight path based on LED detection and vehicle position. This flight path is transmitted by radio back to the vehicle. The flight path information is then passed into the on-board mission controller with ultrasonic distance sensors data. The ultrasonic sensors indicate wall distances and obstacles. From this information the mission controller decides how to translate or rotate the vehicle. This information is passed to the on-board flight controller, along with IMU data. From the immediate IMU data and the higher order translation commands, the flight controller determines the proper thrust for each motor which is then actuated by pulse-width modulation.

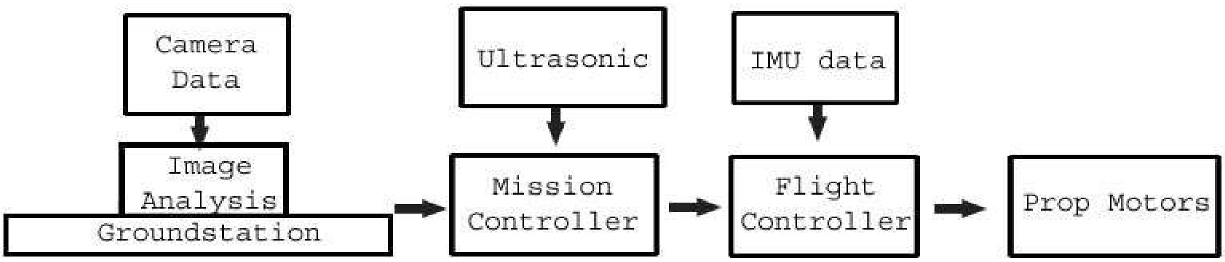

Figure 1.This plot shows the overall system architecture

2.c Yearly Milestones

The vision team successfully detected and the LED and sent back video data with the gauge panel in view during tests. The vision system hardware is also integrated and functioning. The controls team successfully defined the control scheme, based upon the physical equations of motion, and developed three controllers to set vehicle pitch, yaw and roll. These controllers have been tested and require only tuning before the competition. An initial balsa wood vehicle prototype was built and evaluated, and a second prototype was constructed using carbon fiber and aluminum to increase strength.

3. AIR VEHICLE

3.a Propulsion and Lift System

The quad-rotor is driven by four propellers arranged in two counter-rotating pairs. Each propeller is driven by a Hacker electric outrunner motor and a Castle Creations Phoenix series speed controller. A single motor/propeller combination is capable of providing approximately 6 N of thrust. On full battery power, 60% of the total thrust is sufficient for the vehicle to hover.

3.b Guidance, Navigation, and Control

3.b.1 Stability Augmentation System

The control system for the vehicle is a Proportional-Derivative velocity controller. The controls software receives a velocity command from the navigation software that will keep the vehicle on track for whichever mode it is in. This command is used as a set point in a Proportional-Derivative control loop. Data from the inertial measurement unit (IMU) is processed by the software to determine the actual response of the vehicle to the set point. The error between the set point and actual response is used to correct the vehicle's response to more accurately follow the navigation commands.

3.b.2 Navigation

There are two aspects of navigation: physical and decision-making. Physically, the quad-rotor navigates by varying the relative speeds of its four motors. For altitude change, the speed of all four motors changes identically. For any other motion however, the speed change of the motors is relative. The same total thrust exists but it is distributed differently. For instance, to move forward, the speed of the front motor decreases and the speed of the rear motor increases. This causes the quad-rotor to pitch forward, which induces forward motion. Translation to the left or right is accomplished similarly by varying the speeds of the left and right motors. To yaw, the motors speeds of the counter-rotating pairs are changed. For instance, to yaw right, the speed of the two clockwise motors is decreased with the speed of the two counter-clockwise motors is increased. This causes the vehicle to rotate about the vertical axis.

The other aspect of navigation is decision-making. The quad-rotor has roughly two decision-making modes –one for searching and one for once the target is located. The search mode uses wall-following to determine the quad-rotors motions. The software uses position data from ultrasonic sensors located on the sides of the vehicle to maintain a safe distance from the wall. Using this method, the vehicle searches the building by tracing the perimeter. The software can account for interior corner and doorways, etc.

Once the vision system has identified the control panel, the quad-rotor responds by entering a hover with no translational velocity. The ground-bases vision system will then be capable of directing the quad-rotor to translate in the direction needed to observe the gauge clearly.

3.b.3 Figure of control system architecture

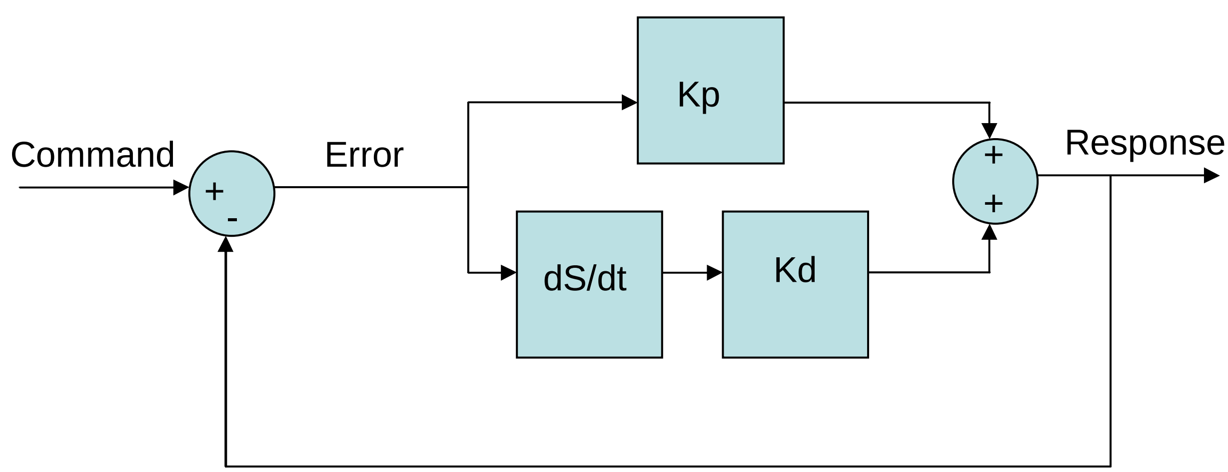

Figure 2. The block diagram representation of a PD control loop. This loop is used to stabilize the vehicle.

3.c Flight Termination System

The flight termination system operates through the ground station through the LabView system monitoring window. A termination button is attached to the computer, with the LabView VI constantly checking the button state. One the button has been depressed, the kill command is relayed to the vehicle through the common serial link. Upon receipt of the kill signal, the flight controller will command all motors to zero percent throttle and cease control loop operation. The onboard computer will also trigger a remote kill switch which terminated the connection between the flight batteries and the motors.

4. PAYLOAD

4.a Sensor Suite

For autonomous flight the 3DM-GX2 was selected as the inertial measurement unit (IMU). It was picked for its support of many different protocols (wi-fi, usb) and because the 3DM-GX2 provides supplementary information beyond altitude and acceleration, that can be used for frame translation and positioning. For target detection the KX141 Black Widow high resolution color camera will be used; while the Maxbotix LV Maxsonar EZ series sensors will be used on the vehicle for wall and obstacle avoidance, as well as sensing altitude. There are two EZ sensor types that will be used: the narrow beam width EZ-4 and the wide beam EZ-0.

To detect the non-blinking LED and lock on to the target gauge the KX141 camera was used. This camera is connected to an independent transmitter which sends visual data directly to a ground station running LED detection software. The camera focus is set at roughly 2 feet, which must be calibrated before flight manually.

Figure 3 shows the basic set up of the sensor package for the quad-rotor. To control the quad-rotor, two sensors facing the wall keep the vehicle orthogonal with the wall. These two sensors control the yaw of the vehicle. To detect walls and obstacles, sensors are located 32° between the front and wall side of the vehicle, see Figure 3. The sensors at 32° also locate corners and door openings. Another sensor is placed at the rear of the vehicle to determine how far away the vehicle is from the opposite wall. These sensors have a very narrow range of visibility. Wide range visibility sensors, visibility represented in yellow in Figure 3 are used for detecting obstacles in front of the vehicle. To allow the vehicle to follow the wall in either direction, wide range sensors are located on both sides of the vehicle.

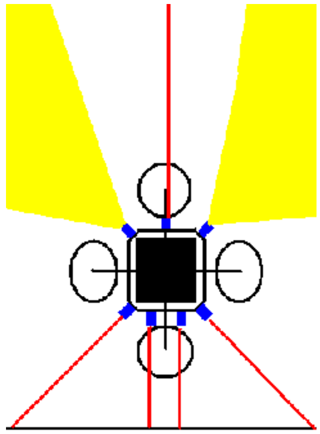

Figure 3. The red lines indicate the narrow range sensors, and the yellow areas indicate the wide range sensors. The black line at the bottom is the wall.

To control this system it has been decided to use a Robostix Atmel AVR processor, which runs using an ATMega128 processor chip (“Robostix”, 2009). The processor comes with eight A to D pins allowing for the 8 sensors to be attached. The coding for this processor is written in AVR studio, which is a program provided by Atmel, similar to C code.

A test bracket was made in order to hold the sensors at the necessary positions, mount onto the vehicle, and connect the sensors together, shown in Figure 4. Dimensions for this bracket are shown in Figure 4. Reading from the schematic, the top bracket has four narrow range sensors (EZ-4) and the bottom has two wide range sensors (EZ-0) and one EZ-4. The top bracket angle of 32° was experimentally found by having the sensor read a surface perpendicular to it. Then the angle was gradually increased by rotating the sensor in one direction. Relative to the starting point, any angle greater than approximately 32° yielded inaccurate results. This was due to the sound signal from the sensor being unable to be bounced back to the source. However, the same was not true for the EZ-0 sensors, since they were wide beam. Therefore, the bottom bracket was not limited to the same range.

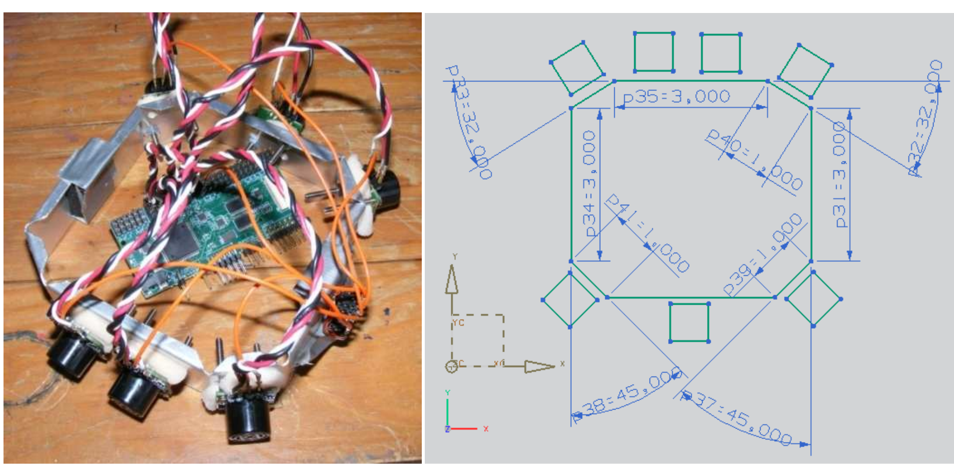

Figure 4. A picture and diagram of the test sensor bracket. The dimensions are shown (right) and the current state is shown (left)

4.b Communications

The communications system is a 'point to multi point' system, illustrated in Figure 5. This type of system will work in conjunction with the base stations, the vehicle, the judges, and the ground control system allowing communication between all parts via the ground control. The transceivers used are the 9XTend™ OEM RF Modules. These transceivers are spread spectrum and can travel 370 meters in urban areas according to the data sheet ("9XTend™", 2008). The 370m range is with the device setup to transmit at 500mW. The transceiver can transmit up to 1W, where the transmit power is software selectable. This transceiver was chosen for its long range in urban areas, spread spectrum capabilities and its ease of use. A spread spectrum device operates over a range of frequencies, is robust to outside interference and cannot be intercepted by devices not included on the network. Each prototype board has a serial connector attached, which is what the systems use for communication. The antenna for use on the various base stations is a 900 MHz Maxrad antenna ("Antennas", 2009).

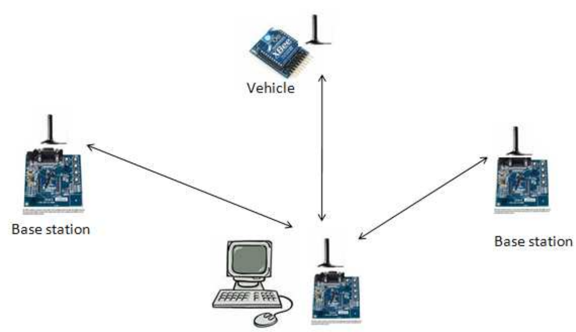

Figure 5. This shows 'point to multipoint' used for data communication systems. It will be necessary to add another point that will be with the judges for the JAUS protocol.

4.c Power Management System

A converter board takes the battery voltage (7.4V) and steps it down to a desired output voltage that is suitable for a specific component on the vehicle. On this vehicle a 7.4V battery will be used for everything on board except the prop motors. There are components requiring 5V and 3V needed to run the devices listed in TABLE 1. To get both 5V and 3V on the vehicle, a DC to DC converter is used. A total of 3 DC to DC converter boards are used to convert the 7.4V (2C) 910maH Thunder Power battery to 5V and 3V. One of the DC to DC converter boards is used for the 3V emergency shutoff system (433 MHz transmitter). The other two boards are used for the rest of the payload devices. The 5V items will be separated into two boards as follows: one board is used to power the vision and controls systems, and the other 5V board powers the localization Robostix processor, 900 MHz XTend transceiver, and ultrasonic sensors.

TABLE 1.POWER CONSUMPTION OF COMPONENTS ON 7.4V(2C) THUNDER POWER BATTERY

Group	**Item**	**Quantity**	**Voltage (V)**	**Current (mA)**	**Total Draw (mA)**
Vision	KX-141 Camera	1	5	150	150
	2.4 GHz, 500mW Transmitter	1	5	350	350
Controls	Robostix & IMU	1	5	300	300
Localization	433 MHz Transmitter	1	3	5.1	5.1
	Robostix	1	5	50	50
Data Comm	Xtend 900 MHz transmitter 500mW	1	5	500	500
Sensor	Ultrasonic MaxSonar	8	5	2	16
Total:					1371.1

We decided on the 7.4V (2C) 910 mAh Thunder power battery. To calculate the life of the battery,

$$B = \frac{A}{D} * 60\ min/hr \tag{1}$$

Where B is the battery life in minutes, A is the rated amount of energy stored in a battery in mAh, and D is the total draw of the system in mA as listed in TABLE 1. For the battery chosen, the battery life is about 40 minutes

5. OPERATIONS

5.a Flight Preparations

check batteries
check bumper connections
initialize speed controllers
verify emergency shut-off
verify program

5.a1 Checklist(s)

check structure
check surrounding areas
ensure observers have proper safety equipment

5.b Man/Machine Interface

To control the quad-rotor manually, there is a joystick designed to control the roll, pitch, yaw, and throttle in the same manner a typical RC controller would. A joystick designed for use with flight simulators was used and plugged into the ground station computer to use the same communication system between the ground station and vehicle that was already in place. The joystick is run into a Labview program which has built in functions to translate the movement of the joystick into numeric values. The numeric values are then translated into commands to send to the flight controller. The commands mimic the format used by the mission computer for roll, pitch, and yaw, and the altitude PD controller for altitude. Since the format will be the same for the commands from manual control or autonomous control, the flight controller will be able to translate them into motion the same way.

6. RISK REDUCTION

6.a Vehicle Status

The first prototype was primarily used for testing vehicle stability and control. The second prototype, constructed of carbon fiber, is more lightweight and will be able to accommodate the payload more efficiently without exceeding the weight limit. Currently, the first prototype, shown in Figure 6 is being used for testing and the second prototype is under construction.

Figure 6. Photograph of the first vehicle prototype.

6.a1 Shock/Vibration Isolation

There were multiple measures taken to reduce the amount of shock and vibrations felt by the components on the vehicle. Memory foam is used to mount some of the critical components such as the IMU and the mission computer to reduce the vibration on the components. This will help reduce errors in the readings from the IMU. To reduce the amount of vibration picked up by the distance sensors they are placed on the body of the vehicle instead of the arms. The vehicle experiences less vibration than the arms that absorb the vibrations from the motors. The bumpers on the corners of the vehicle protect the blades from damage if the vehicle runs into an object, but they also are designed to absorb some of the shock from the sudden change of direction so that that shock is reduced to the rest of the vehicle.

6.a2 EMI/RFI Solutions

To avoid interference, data is transmitted using a spread spectrum transceiver. Since the importance of receiving and transmitting data between the vehicle, base station and judges is critical to the success of the mission, a spread spectrum device is used. The emergency shutoff is on a 433 MHz transmitter, which is a less used frequency and has sufficient strength to receive the shutoff signal if necessary. The video transmitter does not have the same protections against interference but transmits at a high link margin on its own channel. It was decided that video transmission was not as important as data and emergency shutoff transmissions and can still identify the target gauge with some interference.

The link margin calculation is used to verify that the signals transmitted from the vehicle will be received 100 meters away, as requested for the competition. The required signal to noise ratio was assumed to be 21dB or 99.9999 % reliability (Site 2002). From the calculations shown in Equation 2, the video link margin is 64dB, the data link margin is 53dB, and the emergency shutoff link margin is 73 dB. Using a fade margin calculator obtained online, the video link margin is 57.9 dB, data is 52.5 dB, and emergency shutoff is 55.8 dB (Fade 2009). The online calculator gave lower results because of a high free space loss. The noise figure and noise bandwidth are included in the receiver's sensitivity measurement and left out of the link margin equation. Unlike the 900 MHz XTend transceiver and 433 MHz LINX receiver, the sensitivity of the 2.4 GHz video receiver was not given in the specs. The sensitivity is assumed to be 100 dB, which is the same as the XTend transceiver. The link margin is calculated as:

$$L = P_T + A_T + A_R - S_R - \log_{10}\left[\left(\frac{4\pi R}{\lambda}\right)^2\right] - \log_{10}(kT) - M - N \qquad (2)$$

Where,

P_T	=	Transmitter Output Power (dB)
A_T	=	Transmitter Antenna Gain (dB)
A_R	=	Receiver Antenna Gain (dB)
S_R	=	Receiver Sensitivity (dB)
R	=	Distance between antennas or desired range (m)
λ	=	Wavelength of radio (m)
k	=	Boltzman Constant (1.3054 x 10^-23 J/K)
T	=	Temperature (K)
M	=	Misc losses, concrete wall, (6 dB)
N	=	Required signal to noise ratio (21dB)

<u>Video: 2.4Ghz 500mW Transmitter</u>
L = 2.699 + 3 + 14 – (-100) – 8 – 20.4 – 6 – 21 = 64 dB

<u>Data: 900Mhz 500mW XTend Transmitter</u>
L = 2.699 + 3 + 2 – (-100) – 7.15 – 20.4 – 6 – 21 = 53 dB

<u>Localization: 433Mhz Transmitter</u>
L = 4 + 1 + 10 – (-112) – 6.52 – 20.4 – 6 – 21 = 73 dB

6.b Safety

The main physical safety feature is the aluminum bumpers preventing the four props from direct contact with walls or obstacles, shown in Figure 7. The independent electronic kill switch is also a key feature, which cuts power to the motors immediately after the switch is activated. This allows for termination of the vehicle flight even during a loss of autonomous control. The radio equipment on the vehicle and at the ground station is also heavily powered, to maintain the highest quality of connection as possible. This high quality during transmission and reception minimizes the possibility of noise or missed signals which could cause the vehicle to lose autonomous control or disrupt flight stability.

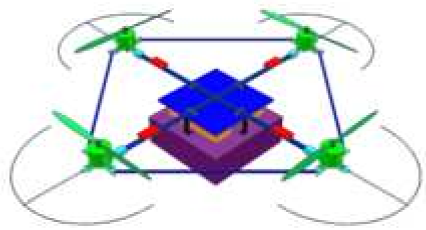

Figure 7. This is a diagram of the aluminum safety bumpers on the quad-rotor

6.c Modeling and Simulation

Modeling and simulation was used for the flight controller design. A simulation was created in Simulink to test the stability of the system and controller and was translated into Labview for gain adjustment during testing. Through the Labview simulation loose gains were obtained for all of the degrees of freedom. These gains were used for the single degree of freedom testing of the control system and reduced the amount of time it took to get suitable gains for stable flight.

6.d Testing

6.d1 Vision Testing

The camera hardware and software were tested independently and then as a complete system. The LED detection software and higher order decision making software were tested by feeding a sequence of images (simulating a possible flight) into the software and monitoring the performance. The camera hardware was assembled on a portable platform and tested for range, clarity of signal, and rate of power consumption. These two systems were then tested together and the live video was fed from the hardware to a laptop continuously running the vision software. This was performed for a variety of indoor lighting conditions and surfaces, including natural sunlight, bright, med and low lighting, reflective surfaces, intense points of light, intense areas of light in dim background, etc.

6.d2 Sensor Testing

The sensor package for the quad-rotor was chosen based on the results for testing for many sensors. Various infrared and ultrasonic sensors were tested to select the best sensor to use for navigating the vehicle. Things considered during testing included reflectivity of the walls, sensitivity to vehicle vibration and accuracy of sensor through turbulent air under propellers. Testing determined that seven ultrasonic sensors were ideal for this application.

6.d3 Navigation Testing

The navigation software used by last year's team is applicable to this competition so much of that logic is being re-used. Results from last year show that this is an effective navigation method so little other testing was done. A few changes were made, such as the second mode for once the control panel was located, and those remain to be tested.

6.d4 Controls Testing

To test the controls system the vehicle was tested on single degree of freedom test stands. First, the altitude controller was tested on a stand that only allowed for vertical motion. Next, the pitch and roll testing was completed on a test stand. Yaw was tested on a rotating platform. Finally, tethered testing provided all the degrees of freedom to be tested simultaneously, without causing damage to the vehicle if it were to become out of control. Free flight testing was done after stability was confirmed on the tethered test stand.

7. CONCLUSION

In conclusion the Virginia Tech team has designed a quad-rotor helicopter to complete the 5th mission of the International Aerial Robotics Competition. The quad-rotor flight controller uses velocity based controllers together with IMU data to maintain flight stability. Obstacle avoidance and search decisions are made by the mission controller using ultrasonic range data and high order commands. These high order commands are issued by the ground station software, which uses LED detection software to analyze visual data from the vehicle digital camera. To protect this overall system and the people nearby, the quad-rotor has aluminum bumpers installed to prevent prop damage or injury. Also, a manually operated kill-switch will both reduce thruster output to zero and disconnect the motors from the batteries. With this overall system Virginia Tech will compete in the 2009 International Aerial Robotics Competition.