Development of a Low Cost Autonomous Indoor Aerial Robotics System V1.0

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Zack Jarrett
Pima Community College
Christopher Miller
Pima Community College
Tete Barrigah
University of Arizona
Huihong Kuang
University of Arizona
Tyler Nelson
University of Arizona
Frank Manning
Pima Community College

[1] ABSTRACT

The Pima Community College UAV Club has designed an autonomous aerial vehicle system to compete in the International Aerial Robotics Competition (IARC). A hovering air vehicle is intended to fly through an open portal and enter a simulated control room of a nuclear power plant. The vehicle travels at eye-level and navigates through a cluttered indoor environment by using a combination of optical flow and SLAM (Simultaneous Location and Mapping). The objective is to locate a control panel and transmit video of the panel to a remote ground station. The vehicle is linked to ground-based computers, and the system is required to be completely autonomous.

[2] INTRODUCTION

[2.a] Statement of the Problem

Pima Community College has an Unmanned Aerial Vehicle (UAV) Club that is entering the International Aerial Robotics Competition. The competition is mounted by The Association for Unmanned Vehicle Systems International in order to "advance the state-of-the-art in aerial robotics" by challenging colleges and universities to successfully complete a mission for which there are no military or industrial solutions in existence. The 2009 mission consists of several tasks, all of which must be completed autonomously within a 10 minute time span: 1) Enter a confined space through a 1 square meter opening; 2) Search the interior of the space and identify a simulated control panel designated by blinking lights and an audible tone; 3) Identify a target gauge on the control panel and transmit continuous video of the target to an operational base.

[2.b] Conceptual Solution to Solve the Problem

This paper describes a conceptual solution that is intended to perform the full IARC mission at a future date. Only a small part of the solution has actually been implemented in hardware and software as of this writing.

The team's approach to the accomplishment of this mission is to deploy a hover-capable aerial robot that utilizes onboard electronic ground avoidance to maintain a constant altitude and horizontal obstacle avoidance to prevent collisions. In addition to basic obstacle avoidance the robot uses an implementation of SLAM to simultaneously traverse and map the environment. The SLAM implementation is based on visual rangefinding with photographs and odometry transmitted wirelessly to a ground station computer that develops the map, amalgamates landmark and vehicle odometry data, and communicates location data and path commands back to the vehicle. Optical flow techniques, such as are implemented in an inexpensive optical computer mouse, are used to collect odometry data onboard the robot. Optical flow is determined by a sensor directed towards the ground.

Outside of the SLAM implementation but within the analysis of photographic data the ground computer actively seeks the control panel and target gauge by continuously monitoring incoming photographic data for the designator, a blue LED. Identification of the LED is accomplished by segmenting image data by color and analyzing each segment for a high blue value. Upon acquisition of the target gauge the path control software will command the vehicle to approach the gauge in order to photograph it specifically.

During the mission JAUS-compatible messages are transitted to a separate station. The information transmitted includes positions of obstacles, target and vehicle.

[2.b.1] Figure of Overall System Architecture

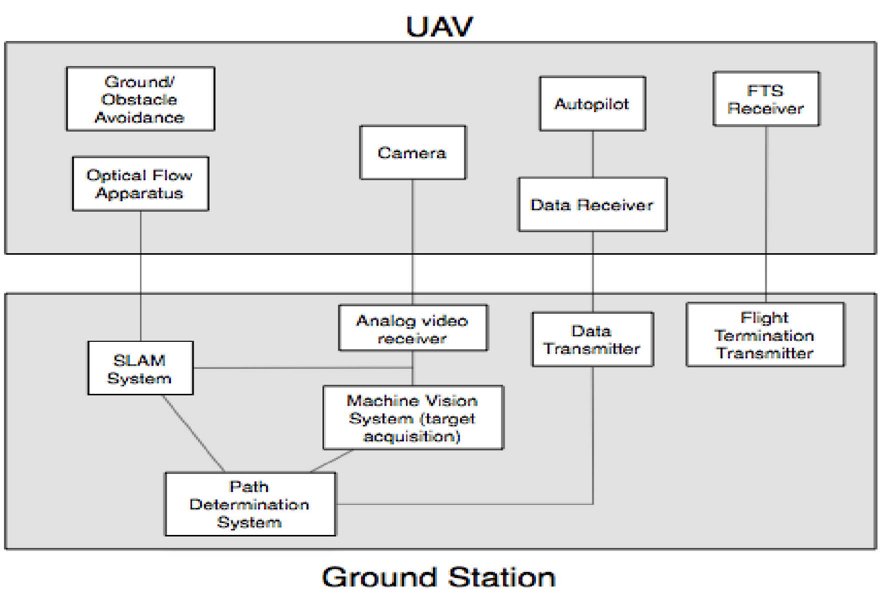

Figure 1. Overall system architecture.

[2.c] Yearly Milestones

For the 2009 competition the Pima team developed an onboard ground and obstacle avoidance system using electronic gyroscopes, ultrasonic range finders, and an onboard microcontroller. In addition, an entirely passive stabilization system was developed that simplified the implementation of ground and obstacle avoidance.

For the 2010 competition the Pima team is focused on implementing a robust SLAM system using binocular analysis of sequential images taken by a single onboard camera. An integral part of this will be the development of an optical flow system in order to provide accurate robot odometry.

[3] AIR VEHICLE

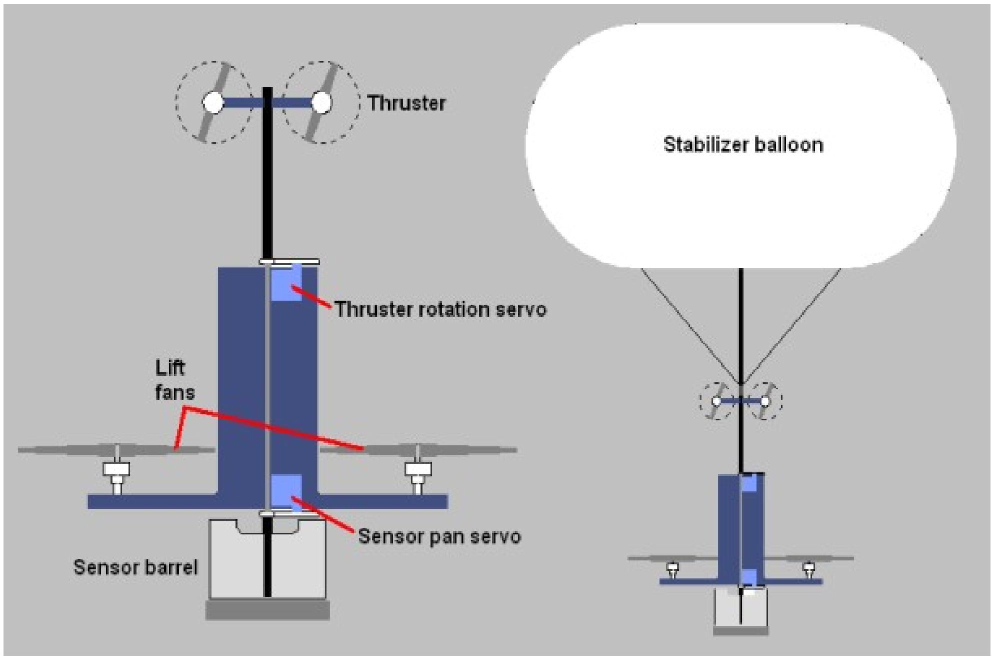

Figure 2. Air vehicle.

[3.a] Propulsion and Lift System

The vehicle uses a jellyfish configuration. Suspended beneath a balloon stabilizer are two contrarotating fans for lift, plus a separate thruster for propulsion.

Horizontal propulsion is provided by a thruster consisting of two small brushed motors driving contrarotating propellers. Each motor is reversible. The thruster propellers are fixed pitch, two-bladed propellers with a diameter of 50 mm. The thruster can be rotated a full 360 degrees about the vertical axis, allowing thrust vector control in any arbitrary direction in the horizontal plane. The thruster was cannibalized from an off-the-shelf blimp. The thruster is located close to the vehicle's center of mass in order to minimize attitude oscillations as thrust is varied.

Lift is generated by a combination of lift fans plus helium, with the fans providing 60% to 70% of the lift. The lift fans are driven by Park 180 brushless outrunner motors. Each lift fan consists of a three-bladed propeller with a diameter of 127 mm. The lift fans provide a peak static thrust of 1.57 N (5.6 oz).

The main purpose of the balloon is to provide passive stability about the roll and pitch axes. Stability is primarily due to aerodynamic drag generated by the balloon. It happens to be convenient to fill the balloon with helium, which provides 0.51 N (1.8 oz) of lift due to buoyancy. Buoyancy has only a minor effect on stability, and in fact the vehicle can be made stable if air is used in place of helium.

A secondary purpose of the balloon is to enclose a high-gain directional antenna that might be needed due to the 10 dB link margin listed in IARC requirements.

[3.b] Guidance, Navigation and Control

[3.b.1] Stability Augmentation System

The UAV is stabilized on its pitch and roll axes by a gas filled ellipsoidal balloon which is suspended above the robot by a rigid member connected to the airframe. Stabilization is provided entirely passively through aerodynamics. When the airframe is perpendicular to the earth the force from the lift fans is directed collinearly antiparallel to the gravity vector, thus sustaining vehicle altitude.

As the robot pitches or rolls, the force from the lift fans, relative to an earth-fixed inertial frame, takes on a horizontal component. This horizontal force causes a horizontal acceleration of the vehicle. As velocity increases in this direction a drag force is produced on the balloon. This drag force acts well above the center of mass of the vehicle, causing an aerodynamic moment that tends to restore pitch and roll angles to their equilibrium values.

[3.b.2] Navigation

Outside of basic obstacle avoidance navigation of the robot is handled entirely by the ground station. As the robot travels onboard optical flow electronics collect odometry data and a camera takes photos. The photos and odometry data are regularly transmitted to the ground station where a SLAM implementation analyzes them to build and update a map. The SLAM results are analyzed to determine the optimal path for the robot and this path is communicated by radio to the robot by three data points: heading, distance, and speed. The robot follows the command while simultaneously gathering and transmitting data to the SLAM system and awaiting new commands.

The onboard obstacle avoidance system has the ability to stop the robot and leave it in a safe hover state should it determine that following a command would result in a collision. When this state is reached additional photos and odometry data are transmitted to the SLAM system until a new command arrives.

[3.b.3] Figure of Control System Architecture

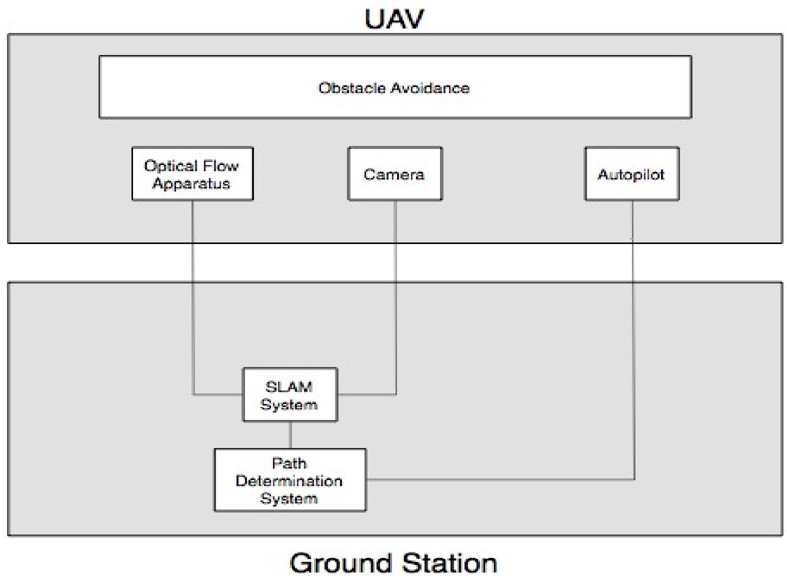

Figure 3. Control system architecture.

[3.c] Flight Termination System

The purpose of the flight termination system is to cut off the supply power to the vehicle immediately by a radio transmitter in an emergency situation to prevent the vehicle from injuring people.. The team's flight termination system is comprised of two components. The first component is a Spektrum DX6i RC transmitter, the second a Spektrum AR6300 RC receiver and a Texas Instruments MSP430 microcontroller connected to a field effect transistor that acts as a switch (see figure 4 below). Flight termination can be achieved by simply flipping the kill switch on the transmitter.

1) A Spektrum DX6i RC transmitter sends a 2.4 GHz Pulse Width Modulated (PWM) signal that represents the state of the kill switch

2) This signal is received by a Spectrum AR6300 RC receiver and is recreated at the output of the receiver.

3) Next, a TI MSP430 microprocessor is used to detect and analyze the PWM signal, the PWM signal is fed in to an internal timer module of the MSP430 where the microcontroller examines the rising and falling edges of the PWM signal to determine the duration of the pulse.

4) When the when the kill switch is in the up position the PWM signal transmitted is longer than 1.5 ms. When the microprocessor detects this, the output on an I/O pin (pin P1.7) is set high (3.3 V). When the kill switch is in the down position a PWM signal of less than 1.5 ms is transmitted and P1.7 is set low (0 V).

5) Finally, an N-type MOSFET is connected to act like a switch between the batteries and speed controllers for the vehicle. P1.7 is connected to the gate of the MOSFET and acts as the control for the switch, when P1.7 is high electricity flows from the battery to the speed controllers and then through the MOSFET back to the negative terminal of the battery. If P1.7 is brought low then the circuit is opened and electricity can no longer flow to the speed controllers thus terminating flight.

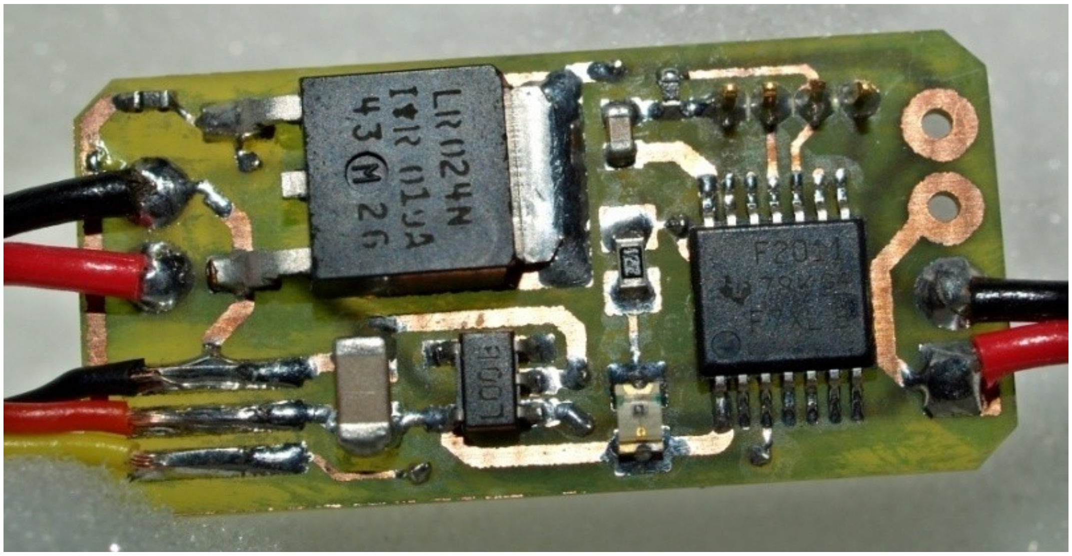

Figure 4. Flight termination system processor.

[4] PAYLOAD

[4.a] Sensor Suite

[4.a.1] GNC Sensors

- MEMS gyro for yaw rate
- Sonar rangefinder for altitude control
- Optical flow sensor for odometry data
- Video camera for SLAM

The UAV carries a single small wireless video camera that is mounted such that it rotates independently of the vehicle airframe. The camera measures 22 mm x 22 mm x 25 mm and weighs about 11 grams. The power input to the camera is 5 VDC at about 110 mA. The camera has the capability to transmit 30 frames per second. Each frame is 320 x 240 pixels.

In an effort to minimize payload weight, reduce sensor complexity, and decrease the quantity of data transmission the team chose to use a single sensor, the camera, to perform multiple functions. The camera is one of several sensors for guidance and navigation but is the sole sensor for mission sensing and target identification.

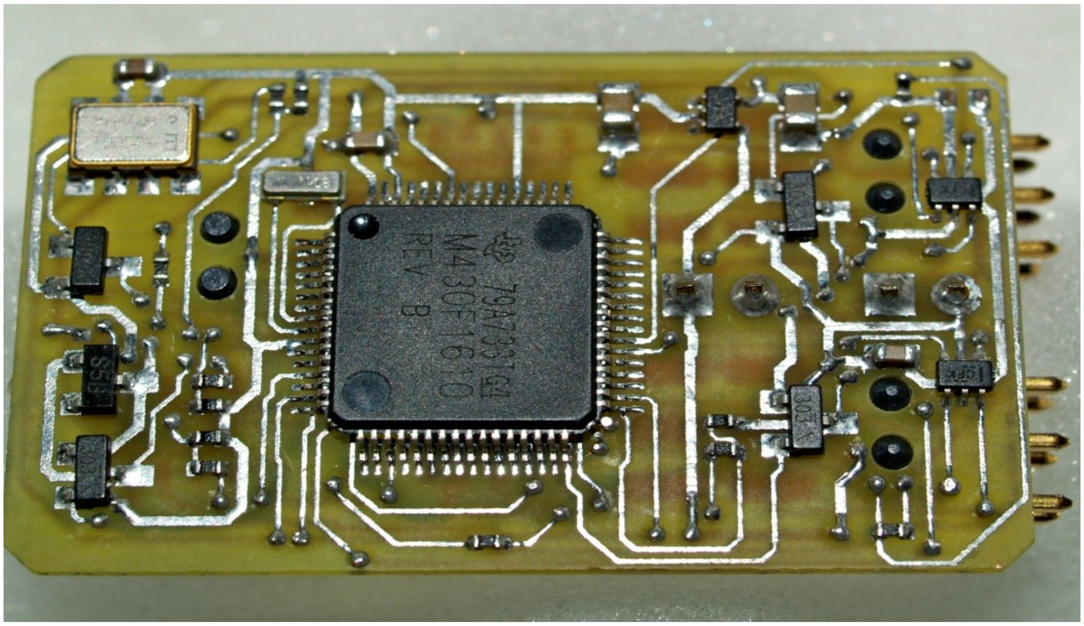

Figure 5. Autopilot.

The vehicle's autopilot (Figure 5 above) was designed by three of us (Kuang, Barrigah and Tyler) and is based on a Texas Instruments MSP430 processor. The autopilot receives data from the vehicles sensors and controls the lift and propulsion systems.

[4.a.2] Mission Sensors
A video camera is used for control panel identification.

[4.a.2.1] Target Identification
A video camera is used for target identification.

[4.a.2.2] Threat Avoidance
Sonar rangefinders are used for obstacle avoidance. The single greatest threat to the vehicle is the collision of a rotor with a stationary object in the environment. In order to minimize this threat forward, rear, and side to side sonar rangefinders are coupled to an onboard microcontroller that will take evasive action if such a collision is imminent.

Because of the hazard of sonar devices interfering with one another no two horizontal rangefinders are operating simultaneously. Rather, the range finders are pulsed individually in order to avoid conflicts.

[4.b] Communications
Camera -- a Swann Blackhawk MicroCam is used to capture and return video from the vehicle. The camera consists of a CCD connected to a 2.4 GHz transmitter that drives a 100 mW amplifier and is then fed in to an 11 cm vertical dipole antenna. The camera weighs 11 grams and operates at 5 volts and draws 110 mA of current. The camera is designed to start transmitting

video as soon as it is connected to a 5 V power supply. Because of this a MOSFET and microcontroller is used to remotely power on and off the camera. The MOSFET is connected in series between the positive power lead of the camera and the positive 5 volts power supply, when power is applied from P1.3 to the gate of the MOSFET the camera is turned on.

Control -- control of the UAV is provided by a Spektrum DX6I RC transmitter connected to a computer and a Spektrum AR6300 RC receiver connected to the microcontroller. A 50 Hz PWM signal is generated by the remote control that represents the control inputs from the ground station computer. These signals are received by the UAV's receivers and are translated back in to electrical pulses by the receivers. These signals are then delivered to and interoperated by the microcontroller. The microcontroller uses this information to control all of the servos and motors onboard the UAV.

[4.c] Power Management System

The vehicle is powered by a 7.4 V lithium polymer battery. All power is routed through the flight termination system to twin Electronic Speed Controls (ESCs) for the lift fans. Each ESC has a built-in 5 VDC regulator, both of which are connected in parallel to provide power to the rest of the system, including autopilot, servos, sensors and camera. The autopilot is able to control power applied to sensors and camera.

[4.d] Subvehicles

No subvehicle is used.

[5] OPERATIONS

[5.a] Flight Preparations

[5.a.1] Checklists

The use of checklists is critical for safety and reliability. Failure to use checklists consistently has lead to numerous problems in the past.

[5.b] Man/Machine Interface

One important factor in the man/machine interface is in getting access to internal equipment in air vehicles. Most equipment installed on the vehicle is relatively exposed and easy to get access to.

[6] RISK REDUCTION

[6.a] Vehicle Status

Vehicle status is monitored by means of data returning from the onboard camera and odometry sensor.

[6.a.1] Shock/Vibration Isolation

Shock isolation of the UAV is provided by polypropylene foam landing pads at the base of the UAV airframe. These polypropylene pads absorb the majority of shock in an unexpectedly hard landing. The passive stabilization system has displayed in lab testing the benefit of keeping the vehicle in a nearly vertical orientation at all times with the resulting benefit of ensuring that the shock of landing is absorbed first by the polypropylene pads.

Vibration isolation is provided through several mechanisms. First, the design of the passive stabilization system of the UAV makes the entire vehicle very stable. Second, the propellers for the lift fans and thrusters are carefully balanced in order to eliminate this common source of vibration. Third, the majority of the airframe is constructed of medium density plastic foam, which material has a dampening effect on vibration.

[6.a.2] EMI/RFI Solutions
RFI and EMI are minimized in the following ways:

- Both the remote control system and video system operate around 2.4 GHz. Because of this care must be taken when selecting the appropriate frequency over which to transmit video. Video is transmitted on 2.432 GHz while the control signals are transmitted at 2.402 MHz allowing roughly 30 MHz of bandwidth between the signals. The video bandwidth is 20 MHz and the bandwidth of the control signal is 2 MHz. To avoid interference the space between the signals must be greater than at least half of the bandwidth of the signals.

- Physical proximity between transmitters and receivers can also contribute to RFI in the form of front end overload. Front end overload occurs when a strong signal (or a weak one that originates close to the receiver) is demodulated directly in the receiver. This can occur even when the receiver is not tuned to the frequency of the unwanted signal. This problem can be avoided by placing the R/C transmitting antenna as far away as possible from the video receiver. The extra distance will reduce the chance that the control signal will overload the video receivers' front end.

- Ferrite beads are installed on all wires that connect to the video receiver. These devices essentially turn the wire in to a one-turn inductor. If a signal of infinite frequency is passed through an inductor it will appear as though there is an open circuit. This principle is used to block interference from entering our video receiver. Any RF that is traveling down these wires will be choked out at this point and will not pass in to the receiver.

- All cables used to connect the receivers and transmitters are made of the highest quality shielded cable available. The metal braid surrounding the conductors in a shielded cable act in the same way that a Faraday cage does. Any RFI or EMI that strikes the cable is converted in to an electric signal that is dissipated to ground thus keeping the wires from carrying the interference further in to the radio.

- A band pass filter is connected inline with the video receiver so that only the desired signal approximately 2.415 – 2.430 GHz to pass. All other signals (such as our control signal) will be greatly attenuated thus reducing their effect on the receiver.

[6.b] Safety
Safety is achieved primarily by the light weight of the vehicle, which reduces power required to drive propellers in the lift and propulsion systems. Small, low-power propellers are

comparatively less hazardous than propellers required for heavier vehicles. In addition, a helium balloon further reduces propeller loads, and the drag on the balloon tends to limit hazardous velocities that can otherwise occur with an out-of-control vehicle.

[6.c] Modeling and Simulation

The team designed an autopilot for the vehicle. The following circuit components were modeled and simulated in Orcad Pspice. Devices were connected to a TI MSP430F1610IPM microprocessor used in the autopilot.

Sonar – the MaxSonar EZ1 ultrasonic sensor is capable of detecting range from 152 cm to 645 cm (6” to 254”) operating at 42 kHz, and can be powered at 5 V with typical 2 mA current draw, and has interface output of PWM, analog voltage and serial digital. The weight is 4.3 grams which is suitable for constructing this obstacle avoidance system within the weight specification.

Gyro – an ultra-miniature size XV-8000CB gyro sensor is used to measure the vehicle's rotation angle around its center of mass, the yaw being one of three critical flight dynamic parameters. The gyro’s rotational velocity is very important to control the vehicle’s yaw during flight. The XV-8000CB gyro is operated at 5 V typical 4 mA draw, and the maximum rotational velocity is 60 degree to the left or right along a reference direction with a scale factor of 25 mV per degree.

IR Rangefinder – the Sharp GP2Y0A02YK Infrared Sensor is a long distance measuring sensor with a range from 20 cm to 150 cm (8” to 59”), and it can operate at 5 V with typical 33 mA current draw. It only has an analog output.

[6.d] Testing

Testing of the system was done throughout the entire build. First, each part was tested by powering it up and checking the output. Then, the circuit was tested after it was built by running small programs and testing the output of the ports using digital multimeters and oscilloscopes. The sensors for distance were each tested by holding them a measured distance from an object and checking the voltage output of the sensor with a digital multimeter. Next, the sensors were integrated into the circuit and the software was tested by running it and checking the outputs using the JTAG and its accompanying software. . Then, the PID controller software was added into the system and verified. The vehicle was turned on and run to see if it would hover at the correct altitude. It was then checked to see if it would hold a constant heading. After that, the collision avoidance software was added to the system and the vehicle was run again. Each time that the vehicle passed the test, another part was integrated into the system until it was fully functional and met all of the requirements of being able to autonomously search a building.

Altitude control testing – the sensors for the altitude control were tested individually first before their integration into the system. Each altitude sensor was tested by holding it at a measured distance from an object and checking the voltage output of the sensor with a digital multi-meter. Next, the sensors were integrated into the circuit and the software was tested by running it and checking the outputs using the JTAG and its accompanying software. After the integration of the PID controller software, the vehicle was turned on and run to check if the altitude controller was working properly. Using the tracker software all the outputs were recorded at different distance during each flight simulation. This data was then used to recalculate the coefficients of the PID controller. Using Matlab, we calculated the coefficient of the PID controller, graphed the root locus, and the logarithmic plot to find the 3 db point. The root locus is the locus of the poles and zeros of a transfer function as the system gain k is varied on some interval. We also plot some the data using *Excel*. The root locus is a useful tool for analyzing single input single output (SISO) linear dynamic systems. A system is *stable* if all of its poles are in the left-hand side of the s-plane (for continuous systems) or inside the unit circle of the z-plane (for discrete systems). In addition to determining the stability of the system, the root locus was also used to identify the damping ratio and natural frequency of a system. Where lines of constant damping ratio can be drawn radially from the origin and lines of constant natural frequency can be drawn as arcs whose center points coincide with the origin. By selecting a point along the root locus that coincides with a desired damping ratio and natural frequency a gain can be calculated and implemented in the controller.

A SD flash memory card was integrated into the system such that extensive flight test data was stored on the card and downloaded for later analysis. In figure 6 (below), the data was used to make plots of altitude and motor speed vs. time. Similarly plots of motor speed and vehicle heading could be made to better understand yaw control (figure 7 below). This data proved to be very useful for tuning PID loops for altitude and yaw control.

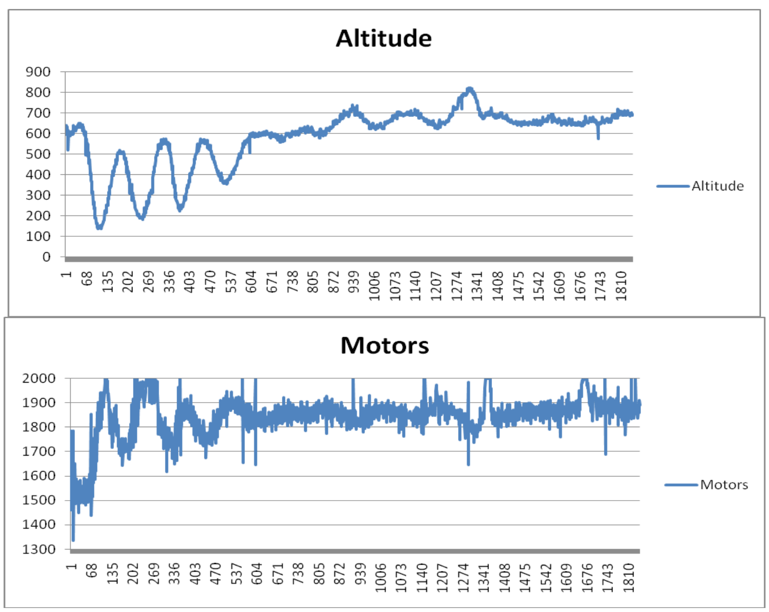

Figure 6. Altitude and motor speed vs time.

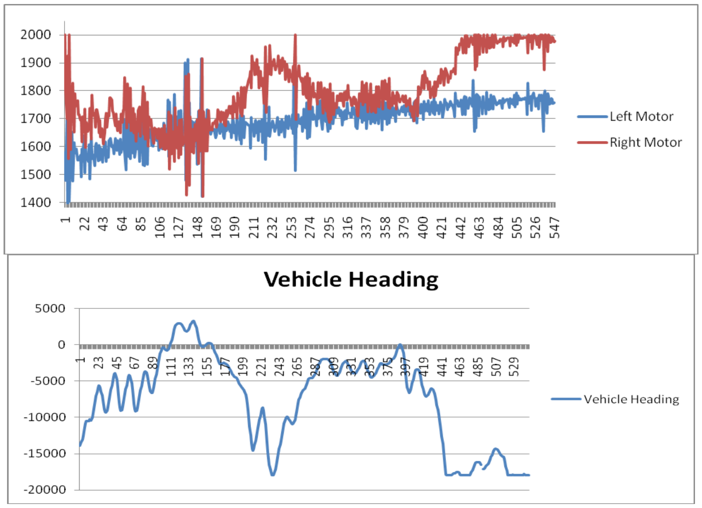

Figure 7. Motor speed and heading vs. time.

[7] CONCLUSION

An aerial robotics system was conceptually designed to perform IARC Mission 5 using a vehicle of simple, low cost design. A hovering vehicle with a passive stability system is capable of navigating through a cluttered indoor environment.

Acknowlegements – we would like to thank Pima Community College for support of this project, and especially Tony Pitucco as PCC faculty advisor. We'd also like to thank David Coombs for his invaluable support and advice regarding building electronic and mechanical parts for our system.

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