The Oakland University Unmanned Aerial Quadrotor System

for the 2008 AUVSI UAS Student Competition

By

Rami AbouSleiman, Dan Korff, Ermal Gjioni, and Hong Chul Yang
Faculty Advisor: Dr. Osamah A. Rawashdeh

Contact Information:
Email: rdabousl@oakland.edu
Web: http://e2r.secs.oakland.edu/
Tel: (248) 370-4936
Fax: (248) 370-4337
Mailing Address:
Aerial Systems Club at Oakland University
Center for Student Activities - Oakland Center
Rochester, MI 48309-4401

Abstract

Oakland University's (OU) unmanned aerial vehicle (UAV) is a four rotor vertical-takeoff-and-landing robot designed for the Sixth Annual Unmanned Aerial Systems Competition. The airframe is commonly known as a quadrotor. The challenging nature and the uniqueness of the design were the main motives behind this project. The complete system was built from scratch; the ground station is a custom made Visual Studio Program and the airframe is a handmade aluminum, carbon fiber, and steel structure. The avionics system is a dual processor design capable of autonomous path navigation and data exchange with the ground station. This challenging and rewarding project is undertaken by the students of Aerial Systems Club at OU.

Table of Contents

1. Introduction

1.1 Overview

A quadrotor is an aerial vehicle that is lifted and propelled by four mechanically independent rotors and is capable of vertical takeoff, vertical landing (VTOL), and hovering. This project included the development of the quadrotor capable of remote control operation, autonomous take-off and landing, as well as autonomous predefined path navigation and image acquisition (Figure 1). In addition to developing the quadrotor, this effort involved the development of a sophisticated ground station with an intuitive graphical user interface that allows the entry, modification, and monitoring of the autonomous flight parameters. Problems addressed in this project include the development of a custom airframe, vehicle stabilization, GPS waypoint navigation, wireless communication, camera stabilization and control, and target recognition ability. The project has been pursued by the students of the Aerial Systems Club at Oakland University (OU) competing in the annual international Unmanned Aerial Vehicles competition hosted by the AUVSI. It will serve as the building block for future improvements and motivation for OU's aerial robotics research.

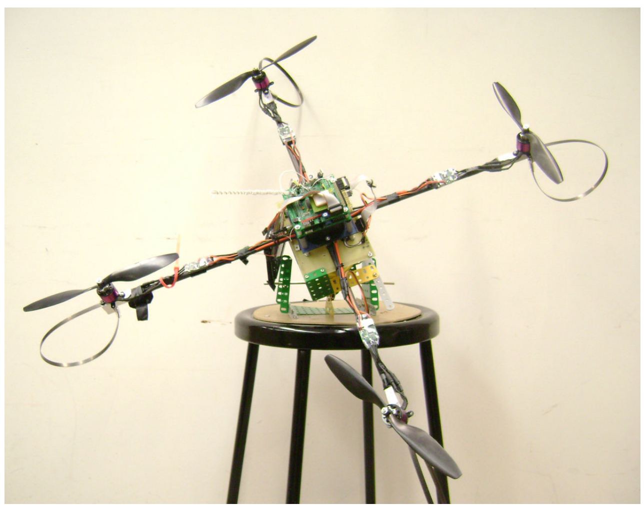

Figure 1: The OU Quadrotor System

1.2 Why Quadrotors?

Controlling a quadrotor is very complex and virtually impossible without modern computer-based control systems. The availability of sensors and high performance small size microcontrollers have resulted in the revival of the quadrotor concept. A few quadrotors are currently being designed to be used as UAVs mainly for surveillance applications. Recently, commercially available quadrotors became available that do not exceed 80 x 80 cm in size and can carry about 300 grams of payload. However, there is still a limited amount of information on the hardware and software of quadrotors.

VTOL vehicles have several advantages over fixed-wing planes. They are capable of hovering and slow flight speed which is advantageous for surveillance and targeting applications. In addition, the vertical takeoff and landing ability of VTOLs allows their deployment in almost any terrain while fixed-wing aircraft require a prepared airstrip for takeoff and landing. Finally, a VTOL vehicle can move in any direction in its lateral plane.

Quadrotors specifically have multiple advantages over helicopters, the most important of which is the reduced mechanical complexity and higher safety. Advantages may be summarized as follows:

- No gearing required between the motor and the rotor.
- No variable propeller pitch required for changing the angle of attack.
- No rotor shaft tilting required.
- 4 smaller rotors instead of one big rotor resulting in less stored kinetic energy and thus less damage in case of accidents.
- Minimal mechanical complexity, quadrotors require less maintenance compared to both helicopters and planes.

Due to these significant advantages and the availability of computer control that is capable of stabilizing the inherently unstable airframe of a quadrotor, these vehicles are increasingly being developed for applications in various fields. Research aimed at lowering the cost and increasing the performance of these VTOLs is currently underway.

2. Structure

2.1 Frame

Weight and power consumption are critical issues in the design of quadrotors. In comparison with other types of aerial vehicle such as fixed wing airplane, the payload of the quadrotor capacity is significantly smaller. To meet the competition requirements, the quadrotor was equipped with sensors and electrical devices such as GPS, radio transceivers, video camera and transmitter. The weight, size, power requirements, and performance of all components were therefore carefully researched. The resulting system has the following physical characteristics:

- Total Weight: Approximately 1400 grams.
- Frame Width * Length: Approx. 40 * 40 cm (without propellers).
- Structure: Hand-made carbon fiber, aluminum and steel frame.
- Payload: Approx. 600 grams.

The carbon fiber used has a tensile strength of 200,000 psi and a density of 0.054 lb/in ^{3} or 1.49 gr/cm ^{3}. Because of its characteristic, the frame is mainly constructed with carbon fiber. aluminum holdings, and steel saws serving as a flexible base. Figure 2 shows the quadrotor in its initial stages, only the frame, motors, motor controllers, base, and propellers are shown. Carbon fiber structure is conductive thus caution was practiced to make sure that no wiring came in contact with the frame under any circumstance.

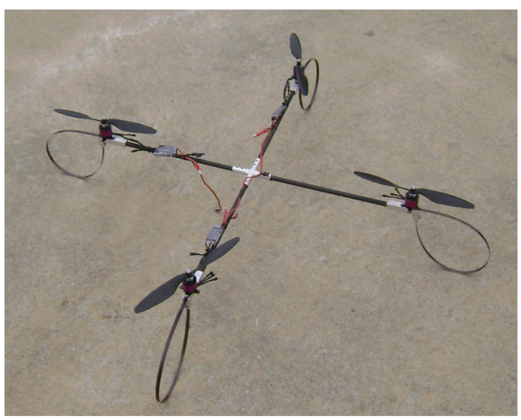

Figure 2: The Quadrotor Frame and Motors

2.2 Motors

Four Hacker A20-20L brushless motors were used to drive the system. These motors are outrunner motors that are characterized by their high efficiency. Each motor weighs around 57g and can generate up to 150 watts of power. This motor features oversize bearings, curved neo-magnets, and high efficiency stator design. The A20-20L was originally developed for 12-18 oz. Parkflyer models. The 12 pole "Outrunner" type design creates significant torque and can thus drive direct props without the need for a gearbox.

2.3 Propellers

The quadrotor system requires two pusher and two puller propellers. The availability of the pullers and pushers of the same type and size is narrowed to only one brand which is the MAXX1045 propeller. Other options would lead to the use of wood propellers or extra small blades used in commercially available quadrotors. The main aim for our design was to use a 10’’ by 4.7‘’ propeller but the unavailability of this model lead us to use the Maxx 10’’ by 4.5’’ propellers. The lower pitch angle lead to less torque per turn thus more spin speed.

Using the selected motors and propellers the quadrotor is capable of maximum theoretical liftoff weight of 2.8 Kg.

2.4 Batteries

Lithium polymer batteries were used due to their exceptional power to weight ratio. Four FlightPower Evolite 2100 3S were installed. The total battery package weighted 640 grams which comprises around 50% of the total weight. The package has a 8400 mAh capacity which is capable of providing around 15 minutes of flight time.

3. High-Level Architecture

The quadrotor features a dual microcontroller unit (MCU) designed to share the processing load of the system. The *telemetry* MCU is responsible for data monitoring and collection from the sensors. The collected data is shared with the *control* MCU, which is responsible for vehicle stabilization and navigation, as well as wirelessly transmitting data to the ground station. The monitoring function, on the other hand, allows the detection of failures in the system (e.g., low battery, excessive altitude change rate, and vehicle instability) and initiates emergency landing procedures when warranted. Figure 3 shows the general flow chart of the complete system.

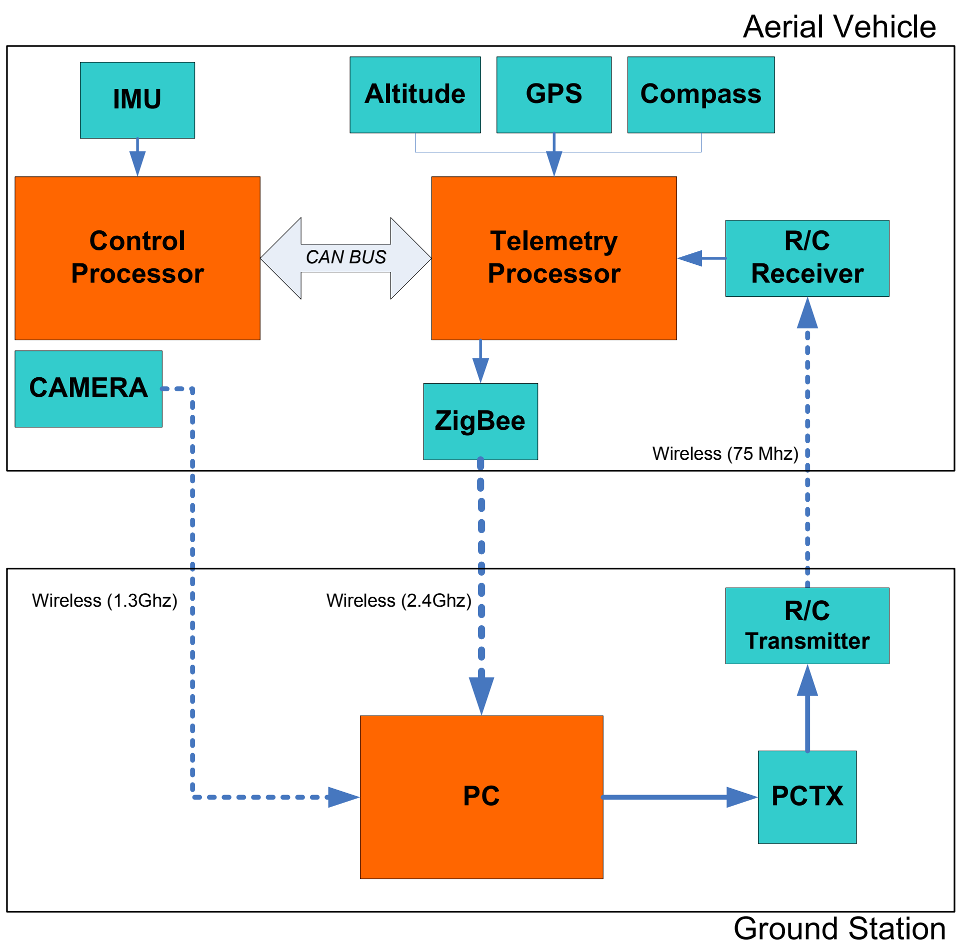

Figure 3: General System Overview

To ensure reliable communication between the two MCUs, a 1.5 Mbps controller area network (CAN) interface is used. The advantage of using CAN is the robust design in addition to the availability of message buffers that can hold data until it is needed by the MCUs.

For wireless communication between the vehicle and the ground station, a Zigbee module is used to relay data. The telemetry packets are 77 byte frames and contain all the vehicle flight data (i.e. IMU, GPS, Altitude, etc.) in addition to a checksum sequence for redundancy and to ensure fault tolerance.

3.1 Aerial Vehicle

3.1.1 IMU

IMU (Inertial Moment Unit) is the heart of the quadrotor's control loop. The MicroStrain's 3DM-3X1 module was selected for this task. This is a very sensitive modules that incorporate both accelerometers and gyros to find orientation based on inertial movement. This particular module also features a compass and a temperature sensor. The IMU can output a variety of data types and formats but only the gyro stabilized Euler Angles are used in the system. These angles estimate the absolute yaw, roll and pitch of the vehicle. Because the IMU data is gyro stabilized, the outputs are very steady and thus are suitable for vibration intensive aerial applications. This module has excellent vibration absorption capabilities and it was observed that even under high frequency vibrations the outputs were steady and the noise was filtered. The IMU outputs its data on the serial bus and a 38400 bps connection is used to read the data and process by the control MCU. A higher baud rate was possible but the medium speed was chosen as a balance between reliability and speed. There are 11 bytes of data including a start byte and a checksum byte that are sent from the IMU for the gyro stabilized Euler Matrix. A bit can be set on the IMU's internal EEPROM and it will send the data continuously at the maximum possible rate. For the gyro stabilized Euler-matrix this is done every 13ms. Furthermore it takes ~2.5 ms for the serial data to be completely shifted, which leaves 10.5 ms for our control loop.

3.1.2 Altimeter

Altitude is determined using a SMD500 Barometer Breakout Board, this board is very light around 1.5g and it features an I2C interface. The altimeter data is sent through an I2C interface to the telemetry processor.

3.1.3 GPS

The GPS is a crucial part of the system. Most GPS modules have the same performance - precession is actually aceived by a good antenna mounting. Thus our focus shifted to find the GPS module with the lowest weight. Two designs are available from Ublox the C04-4H and the C05-5H. The C04-4H was chosen because testing showed that the C04-4H has higher precession than the C05-4H. The C04-4H has a low weight and a smartly designed antenna that does not use much space. The GPS module has 37 x 37 x 9.0 mm dimensions.

3.1.4 Telemetry Processor

The telemetry processor has multiple responsibilities. It basically is a Freescale HCS12 development board that reads the GPS, altimeter, compass, and the PWM capture from the RC receiver and assembles a data frame to be sent back to the base through the

Zigbee link for control feedback. The processor also sends command signals through CAN to the control processor.

3.1.5 Control Processor

The control processor has the main task of stabilization; it reads the Euler Angles from the IMU and control signals from the telemetry processor and performs PID control loops. The stabilization system is necessary to drive the quadrotor because it is a very unstable vehicle in nature; the implementation of stabilization control algorithms has not been possible until very recently with the development of fast small sized microcontrollers. In this project, four PID (Proportional-Integral-Differential) control loops are used to stabilize and control the vehicle (Figure 4). The motor speed is controlled by the PID control-loops according to the throttle, pitch, roll and yaw values received by the IMU, GPS unit and altimeter. The error of the closed-loop system is calculated by subtracting the desired values from four PWM reading and the actual values from the IMU (roll, pitch and yaw), and GPS (height). In the PID control loops, the current errors are calibrated with PID gain constants Kp, Ki and Kd to generate the proper motor adjusting values where Kp, Ki and Kd are the proportional, integral and differential gain constants. The PID gains are found experimentally, and our system allows the updating of the PID gains to optimize the performance wirelessly, in real-time.

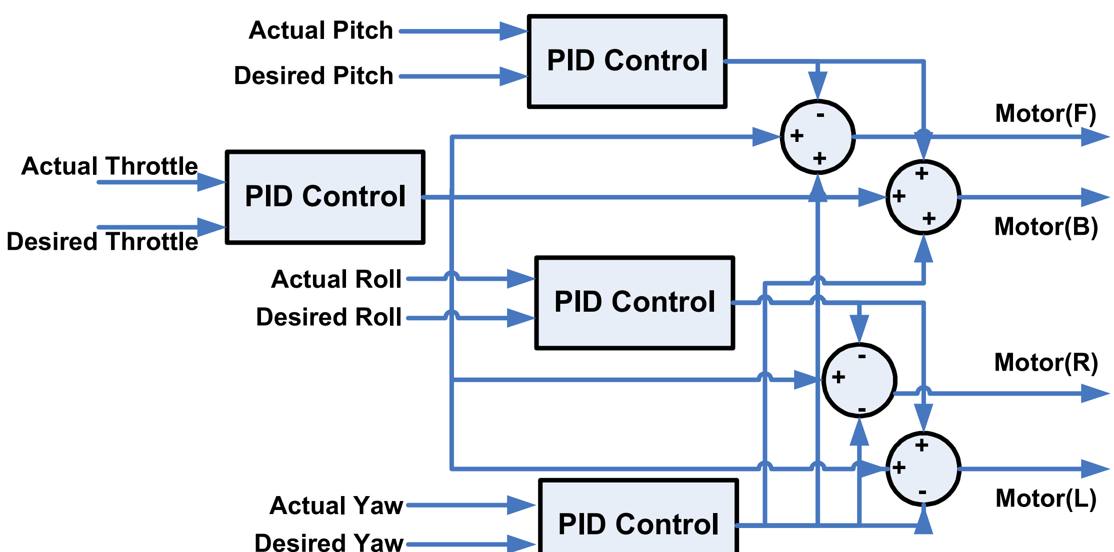

Figure 4: Control Diagram

3.1.6 Video System

The video system is based on a 380 horizontal lines resolution color camera, which is a very light system, featuring a 1/4" Sony Super HAD CCD camera and a 1.3 GHz 300 mW transmitter system. The video system has an intelligent tracking antenna, which follows of the quadrotor at all times. The video signals are received by a receiver at the ground station and sent to the computer through a Dazzle video to USB converter. The PC is then responsible for monitoring and recording the video stream. The stream will be manually inspected by team members for target detection. GPS data is stored and correlated with the video recording by the ground system to allow for position estimation of sighted targets.

3.2 Ground Station Software

The PC ground station software (Figure 5) is primarily responsible for navigation, image processing, and serves as the user interface. The PC will be used to receive GPS and heading data from the serial port, perform some processing, and output signals from an RC transmitter which is connected to the PC through a PCTx module. The software provides a user friendly interface of setting up a flight path and viewing various data being received from the quadrotor. All PC software was written in C# using Visual Studio 2005. Microsoft's .Net framework was chosen for its speed and easy compatibility with external hardware which was necessary for communicating with the camera, joystick and serial port, and PCTx.

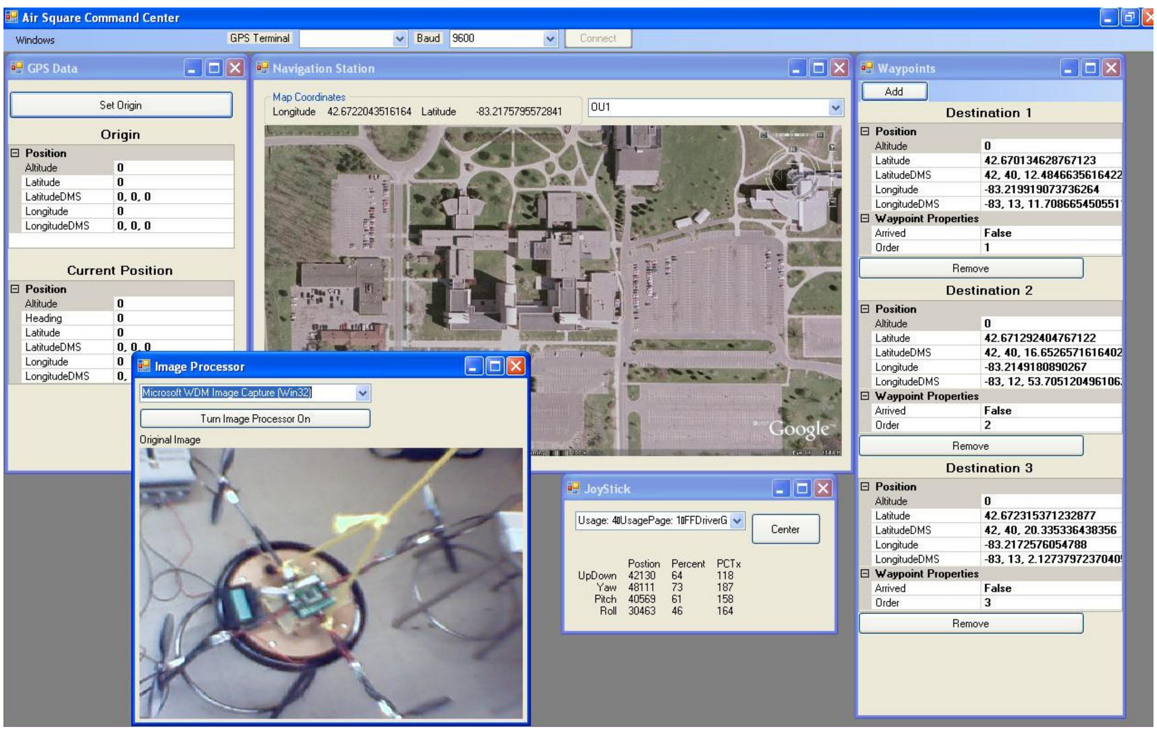

Figure 5: Screenshot of the Ground Station System

Figure 6 provides a high-level view of the overall organization of the software. The system is grouped into two sets of modules; the back-end code (left side) that provides the primary functionality, and the set of form modules (right side) that make up the interface. The back-end functionality is organized into a set of static objects that can be accessed by any module at any time. The objects include the GPS processor, waypoint collection, navigator, joystick, and map. The GPS processor is used to receive and process data coming from the quadrotor. It contains a terminal for serial communication and exposes properties such as current position and heading. The waypoint collection is the end result of a hierarchy of classes which represent position and waypoints. The collection contains the list of waypoints, origin, and next destination. The navigator is used to maintain the state of navigation, as well as perform the processing necessary to adjust the flight path as the quadrotor moves through waypoints. The joystick object is used to connect to a joystick and receive signals from it; this object also encapsulates the functionality of the PCTx. The map object is used to load an XML file which contains maps and coordinates. It is also used to scale latitude and longitude coordinates into linear distances.

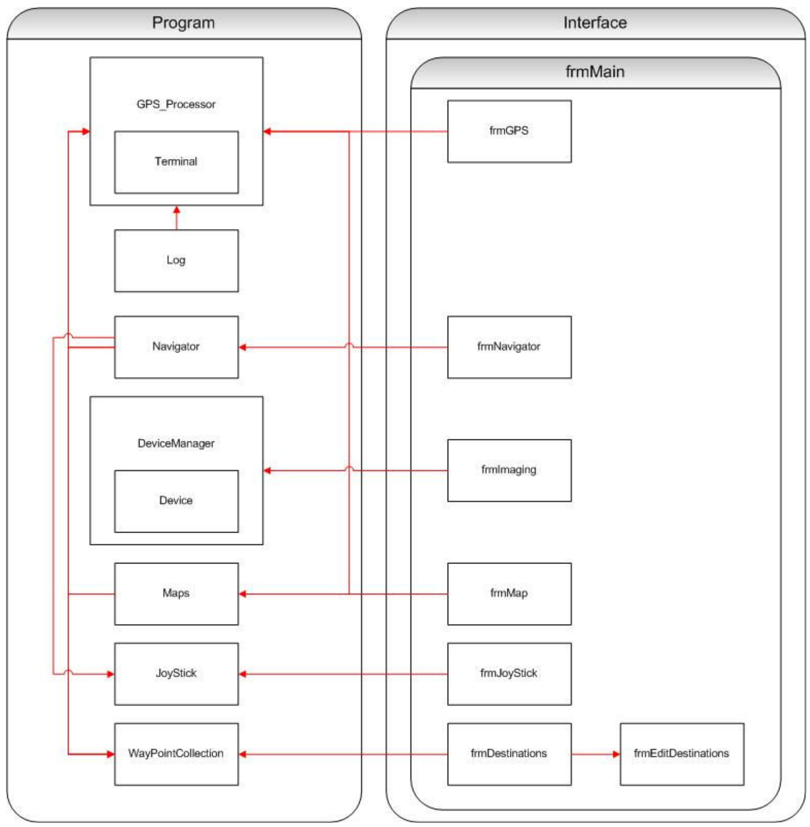

Figure 6: Software Architecture

The interface is organized as a set of child windows inside an MDI form. The windows operate independently of one another and are updated by call-back functions tied to the back end modules. The child windows include forms for GPS data, image processing, map, joystick, navigation, and waypoints. The GPS Data form is used to view the current position and origin position of the quadrotor. The Image Processor form is used to connect to a camera, view and incoming video stream and optionally add filters to the incoming images. The Map form loads a map and bounding coordinates from an XML file, it can then be used to set waypoints and view the current position of the quadrotor. The Joystick form is used to connect to a joystick and view its input values as well as the corresponding output values of the PCTx; this is used mostly for calibration and testing. The Waypoints form is used to add, edit and view the set of waypoints that the quadrotor will navigate through. The navigation form offers start, stop, and pause buttons to begin or end navigation.

4. Safety

As the quadrotor is a heavy flying object equipped with four blades spinning at thousands of revolutions per minute, safety was an important concern in its design. The quadrotor is controlled by a standard RC transmitter that is overridden by commands from the PC. In the event of an emergency the signals coming from the PC can be switched off and the quadrotor can be controlled manually by the same RC transmitter. Also, if at any time the quadrotor stops receiving a signal from the RC transmitter, it will slowly power itself down and land safely. Similarly, the landing procedure is initiated if the radio signal is not received by the telemetry processor for more than 30 seconds.

As an added safety feature, all data frames passing between the microcontrollers use checksum bits. The checksum will ensure perfect data transfer and optimal operation. In case any error occurs at any frame an error is reported and the frame is treated as garbage and is never used.

5. Summary and Current Status

The system described has been integrated and tested successfully with the exception of tether-less flight. Successful tests include GPS path entry, display of vehicle position and other data received through the ZigBee link, manual radio control, video reception, and waypoint navigation. At the time of preparation of this paper, control loop gains are being fine-tuned in a laboratory environment. It is anticipated that stable flight will be achieved in time for the competition.