Oakland University

2010 AUVSI Student UAS Competition Entry

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ABSTRACT

This year's AUVSI Student UAS Competition marks the third entry by Oakland University. Comprised of graduate and undergraduate students across several majors including Mechatronics, Embedded Systems, Electrical Engineering, Mechanical Engineering, and Computer Engineering, the Aerial Systems Club at Oakland University has built its own aircraft that is capable of intelligence, surveillance, and reconnaissance on many types of terrains. The aircraft, dubbed Microraptor is a complete low-cost autonomous quadrotor system designed for surveillance and reconnaissance applications. The Microraptor ground station is custom-made and features a graphical user interface that presents and allows the manipulation of various flight parameters. The aerial vehicle is a 4-rotor vertical takeoff and landing (VTOL) vehicle that features the advantages of traditional helicopters with significant reduction in mechanical complexity. The vehicle frame is a handmade with aluminum rods. The onboard avionics system is a custom dual processor design capable of autonomous path navigation and data exchange with the ground station. The vehicle is outfitted with a video and still-photo system that provides real-time images to the system operator through a GUI. The system has been tested, and showed very good results. Its low-cost, payload capabilities, safety features and performance are promising.

1 INTRODUCTION

This paper describes the design, implementation, and performance of our UAS (Unmanned Aerial System), which is comprised of a four-rotor aerial vehicle and a ground station. This UAS is capable of remote control operation, as well as autonomous operation in every phase of flight. It is capable of autonomous vertical take-offs and landings, as well as predefined path navigation and image acquisition. The ground station analyzes imagry and sends navigation commands to the UAS. The team analyzed the competition requirements and from our previous experiences at this competition and experimenting with various body designs, we were able to improve our overall performance of the UAS.

1.1 MISSION REQUIREMENT ANALYSIS

After careful consideration of AUVSI UAS Competition requirements, the UAS was designed to carry out those specific requirements. The resulting UAS was able to autonomously takeoff, land, hold altitude, navigate between waypoints, recognize targets, and has multiple safety features.

1.2 SYSTEMS ENGINEERING APPROACH

Taking the requirements, and the last two years results, the team was able to identify three major flaws to improve the UAS. Through rigorous testing and simulations, corrective actions are implemented to the design. The first was the poor quality of images captured. This was improved by using a higher resolution video camera. The second problem was in high wind conditions, where the UAS was under performing. This was corrected by lengthening the rotor arms and using a more flexible and lightweight material. The third improvement made was increasing the execution speed of the PID controllers. This made the UAS more responsive during flight and more stable during landing.

1.2.1 DESIGN AND DEVELOPMENT

The first thing made clear to the team was that weekly meetings are critical to insure progress on the subsystems. The overall system is comprised of the following subsystems: Stability Control, Navigation Control, Imagery System, and Target Recognition System. Each subsystem was designed and tested separately with two team members working on each. This method was thought to be practical and efficient for our case. During the weekly meetings, updates to each subsystem were given and ideas exchanged. The help from faculty and other team members enabled progression to the goal: The System. In addition, safety measures in every aspect were always priority number one.

1.2.2 TESTING AND TROUBLESHOOTING

Full-scale simulations were conducted to test the performance of modules, as they were finished. The first tests were just a proof of flight. The proof of flight tests were manual tests using a radio controller with no autonomy. Once basic flight was achieved, other control systems, such as altitude hold, GPS navigation, target recognition and finally all three were tested and tuned for best performance.

2 AIRBORNE SYSTEM

A quadrotor aerial vehicle was chosen because of its many benefits over fixed wing aircraft and conventional helicopters. The benefits range from vertical take-off and landings to reduced mechanical complexity. Moreover, in case of accidents or malfunctions, the kinetic energy stored in four smaller motors is safer than that stored in a single large motor.

2.1 PRINCIPLE OF OPERATION

Before discussing the principle of operation, we will need to introduce the terminology used to describe the vehicle's angular motions. In aerial vehicle, Euler angles (roll, pitch and yaw) are used to define the relative orientation of a vehicle with respect to a reference frame. In general, the aerial vehicle's front and back are aligned along the x axis, and the right and left are aligned along the y axis. The z axis is orthogonal to the x and y axis. Rotational motions around x-axis, y-axis and z-axis are called roll, pitch and yaw respectively. The Euler angles of a quadrotor are illustrated in Figure 1.

A quadrotor is a rotary wing aerial vehicle, and it has the capability of vertical take-off and landing (VTOL). The X shaped skeleton is the main body structure, and four rotors are mounted at the four ends of this main structure (front, back, left and right). The rotors consist of two sets of counter-rotating propellers and motors. The front and back propellers rotate counter clockwise, while the left and right propellers rotate in the opposite direction. During the rotation of the rotors, a reaction force (gyroscopic effect) is created from four rotors. From Figure 2, rotors A and C generate reaction force 1. Rotors B and C generate reaction force 2. Therefore, the yaw motion of the vehicle is controlled by varying the relative speed of the two set of rotors, while keeping the collective lift of the vehicle constant. The roll of the vehicle is controlled by varying the relative speed between rotors B and D. Similarly, the pitch of the vehicle is controlled by varying the relative speed between rotors A and C. Finally, the altitude of the vehicle is controlled by varying the collective speed of the four rotors.

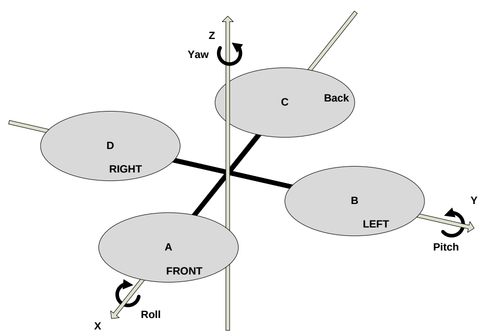

Figure 1. Rotational Motion of Quadrotor

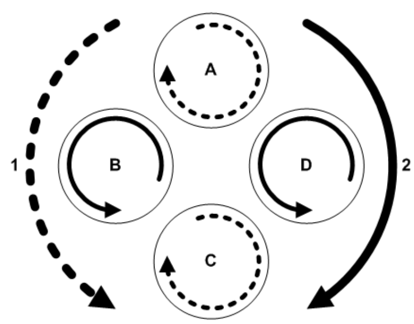

Figure 2. Quadrotor Reaction-Torque Schematic

2.2 VEHICLE STRUCTURE

To select the material for the airframe, one has to be aware of the weight and strength factors as well as the manufacturing cost. The limitations of lifting forces and flying times require the vehicle to be lightweight. In addition, the airframe should be strong enough in case of accidents and rough landings. As a result, aluminum is used to construct the airframe. The frame consists of two aluminum rods that are 36 inches long crossing each other. All the electronic devices, battery and landing gear are placed around the crossing section. The resulting airframe weighs approximately 1 kg and measures 36 × 36 inches without excluding propellers. Figure 3 shows the whole quadrotor aerial vehicle system.

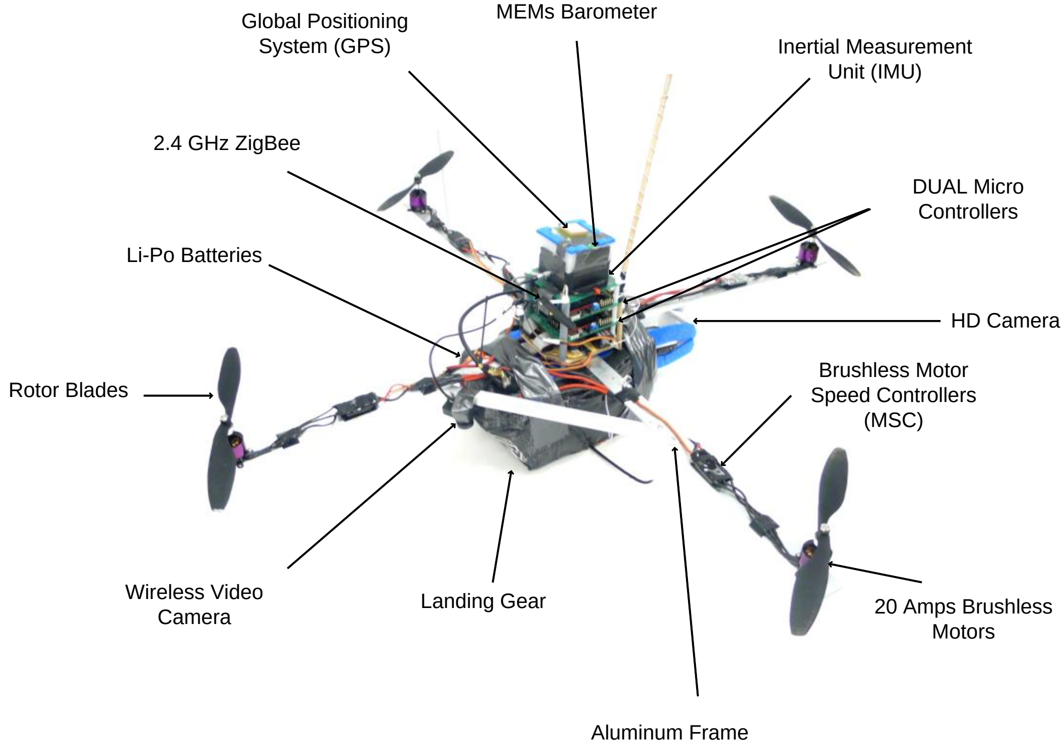

Figure 3. Quadrotor Reaction-Torque Schematic

2.3 POWER PLANT

Four Hacker A20-20L out-runner brushless motors were used to drive the system. Out-runner motors are highly efficient. Each motor weighs around 57 grams and consumes 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 slow-flying 12-18 oz Parkflyer models. This 12-pole motor creates significant torque at low speeds and can thus drive direct props without the need for a gearbox. The commercial availability of such propellers with the desired length and pitch is limited to one brand, which are the 10" x 4.5'' EPP1045 propellers from MAXX Inc. Using the selected motors and propellers, the quadrotor is capable to lift 2.2 kg. As a power supply for the motors and all other electronic devices, two lithium polymer (Li-Po) batteries were used due to their exceptional power to weight ratio. First, a 5000 mAh and 11.1 V Li-Po battery provides power to the motors. Second, a 500 mAh and 7.4 V Li-Po battery provides power to the electronics. The total battery package weighted 400 grams, which comprises around 20 % of the total weight. The package is capable of providing approximately 10 minutes of flight time in the autonomous flight mode.

2.4 AVIONICS

The avionics system (shown in Figure 4) is a dual processor design capable of autonomous path navigation and data exchange with the ground station. Figure 5 shows a general flow chart describing the different avionic components and the communications between them. The telemetry processor is responsible for data monitoring and collection from the sensors. The collected data is shared with the control processor, which is responsible for vehicle stabilization and navigation, as well as wirelessly transmitting data to the ground station. The monitoring function, which is installed on the control processor 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.

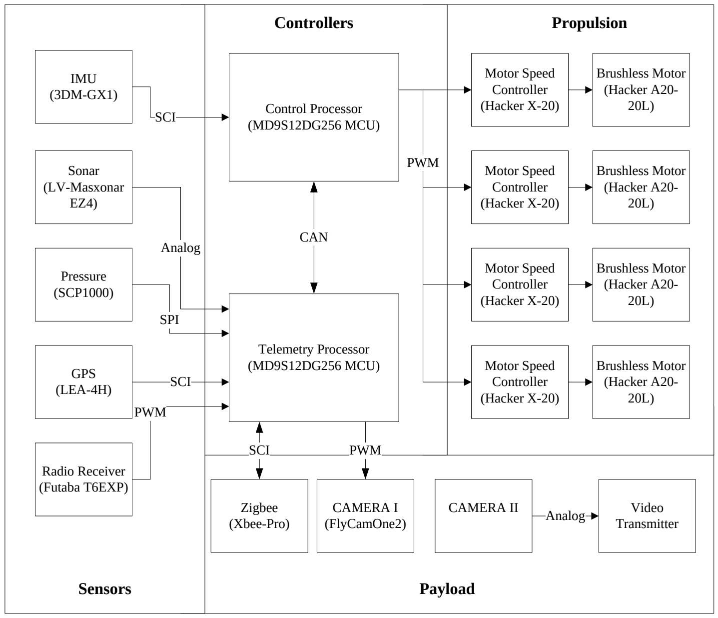

Figure 4. The Quadrotor Avionics

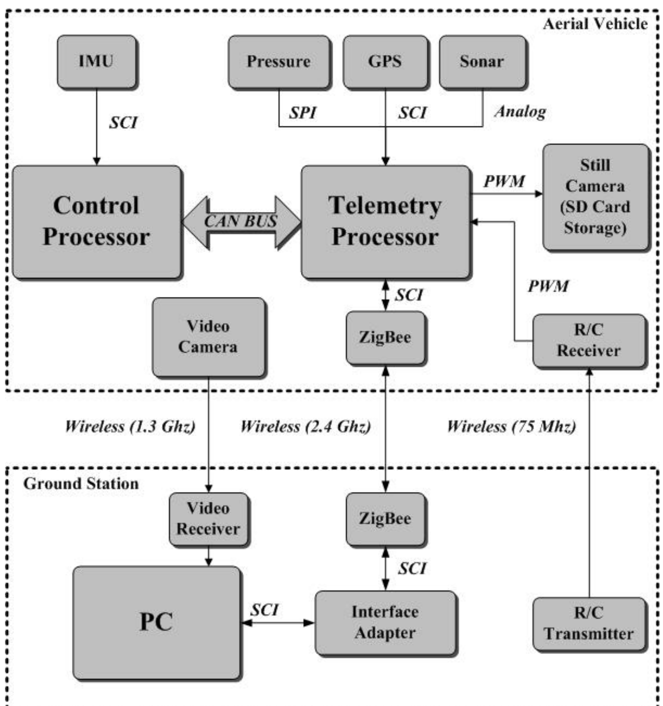

Figure 5. General System Overview

To ensure reliable communication between the two processors, a one 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 processors. A ZigBee wireless module is used to relay data between the vehicle and the ground station. The telemetry packets are 77 byte frames and contain all the vehicle flight data (i.e. GPS, altitude and status) in addition to some error and flow control data. The following sections provide more detail on each avionics component.

2.4.1 IMU

The inertial measurement unit (IMU) provides vehicle attitude estimates to the control processor. The MicroStrain's 3DM-GX1 module was selected for this task [3]. It is a very sensitive module that incorporates both accelerometers and gyroscopes to estimate attitude. 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. The IMU estimates are gyro stabilized and therefore have good vibration tolerance. The IMU sends its data on the serial bus at 38400 Baud to the control processor. 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 data flow and error control information every 13 ms. Data transmission takes ~2.5 ms, which leaves 10.5 ms as the PID control loop periods.

2.4.2 MEMS ALTIMETER

The absolute pressure sensor (SPC1000, VTI Tech.) is placed on the top layer with IMU and GPS. The SCP1000 is an absolute pressure sensor which can measure the pressure between 30 kPa to 120 kPa [1]. The altitude of the vehicle can be obtained by measuring atmospheric pressure because the pressure decreases while the altitude increases. The sensor has a high speed mode and a high resolution mode. For the high speed mode, which is selected in our case, the pressure is updated at a 9 Hz rate, while the resolution is restricted to 3 Pa. The high resolution mode has 1.5 Pa of resolution, but the sensor updates the pressure at 1.5 Hz. The serial peripheral interface (SPI) is used to obtain pressure readings.

2.4.3 GPS RECEIVER

The global position system (GPS) is a marine electronic device. It receives several satellites' signals and provides a three dimensional positioning coordinate, as well as standard time. The GPS is an essential device for outdoor navigation systems to obtain the current position of the vehicle. The U-Blox C04-4H Global GPS device is used for the test-bed [2]. The C04-4H is an evaluation board. It consists of an LEA4H GPS module and a ceramic patch antenna. The board has a serial and a USB interface, and it constantly broadcasts an updated position and time every second. The position accuracy is 2.5 m. The size of the device is 35 × 35 × 9 mm. The device is mounted on top of the aerial vehicle to obtain an optimal reception rate of satellite signals.

2.4.4 TELEMETRY PROCESSOR

The telemetry processor has multiple responsibilities. It is a Freescale HCS12 microcontroller 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 provides the control processor with IMU, compass, altitude, and data in addition to command signals from the ground station. Heading and altitude commands from the ground station are translated into desired altitude, pitch, and yaw values and passed to the control processor.

2.4.5 CONTROL PROCESSOR

The control processor is also a Freescale HCS12 that is responsible for vehicle stabilization. It reads the Euler Angles from the IMU and control signals from the telemetry processor and performs Proportional-Integral-Differential (PID) control loops. In this project, four PID control loops are used to stabilize and control the vehicle (Figure 6). 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. 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 respectively. The PID gains are found experimentally, and our system allows wireless update of the PID gains to allow in-flight tuning.

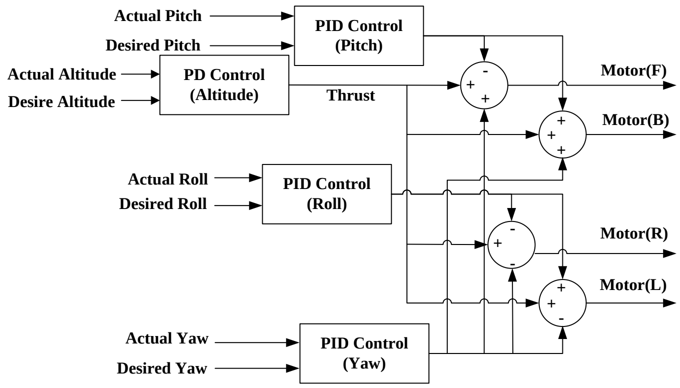

Figure 6. Control System Diagram

2.5 Payload

The payload includes two vision systems: a wireless video system and a high definition (HD) video system. The wireless video system will stream live video to the ground station during all mission time. The HD video system is store the video to the onboard SD card during the flight.
The wireless video system is composed of a CCD (Charge Coupled Device) camera, a transmitter, and a ground station receiver. This system operates at the 1.3 GHz bandwidth. The camera has a 1/3 inch Sony CCD, weighs 22 grams, and has a 420 TVL horizontal resolution. The transmitter has a 300 mW power capacity capable of transmitting video signals over one mile. The HD video system is a 1080p high definition camera from Kodak with an onboard SD card. The camera's dimensions are 11 cm x 6 cm x 2 cm and has a weight of 150 grams.

3 GROUND STATION

The ground station consists of a laptop computer, ZigBee transceiver, 72 MHz radio transmitter and an analog video to USB converter. The ground station software is composed of two main components:

1. The navigation control and monitoring software.
2. The target recognition software.

Figure 7 shows both software components. The rest of this section will describe these software components in detail.

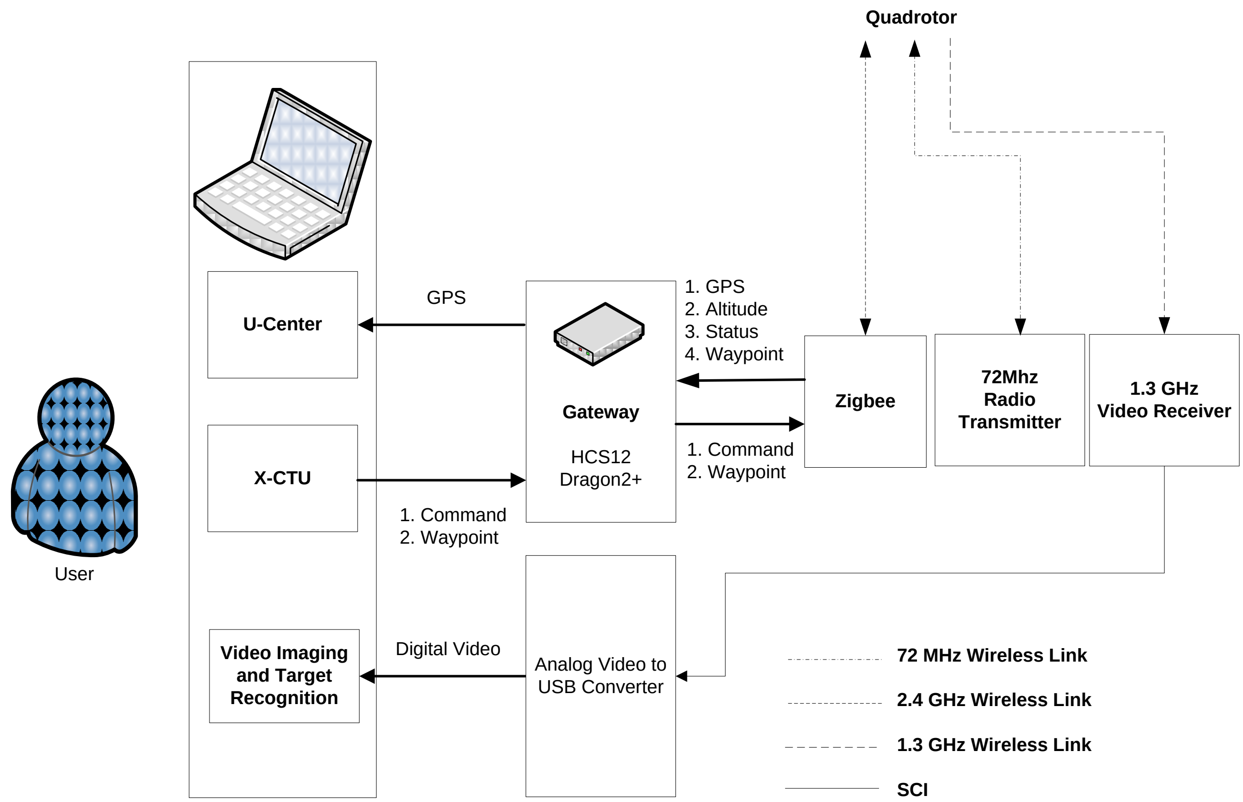

Figure 7. Ground Station Overview

3.1 THE NAVIGATION CONTROL AND MONITORING SOFTWARE

The U-Blox GPS software (U-center) (Figure 8) is used to provide a GUI for the user displaying and tracking the real time location of the aircraft as well as a means for updating GPS waypoints. During manual flight, the user can control the vehicle's angle of attack and thrust.

The U-Center, an evaluation software designed for the U-Blox GPS device, provides a graphical user interface. The user can load any map and provide three reference GPS positions. The program automatically calibrates the GPS coordinates of the map. From Figure 8, for instance, a satellite image is imported from Google Earth and assign three reference points to calibrate the GPS coordinates of the image.

A second program that the computer runs is the Digi's X-CTU (Figure 9). This software is designed for XBee 2.4 GHz wireless devices. The software provides a text base user interface. While the U-center displays the vehicle's position, time and quality of satellite signal, etc., the user can actually send messages to the aerial vehicle by typing a sentence with X-CTU software. The sentence is written in a predefined protocol. The user can update and change the waypoints and send commands such as the landing and holding position.

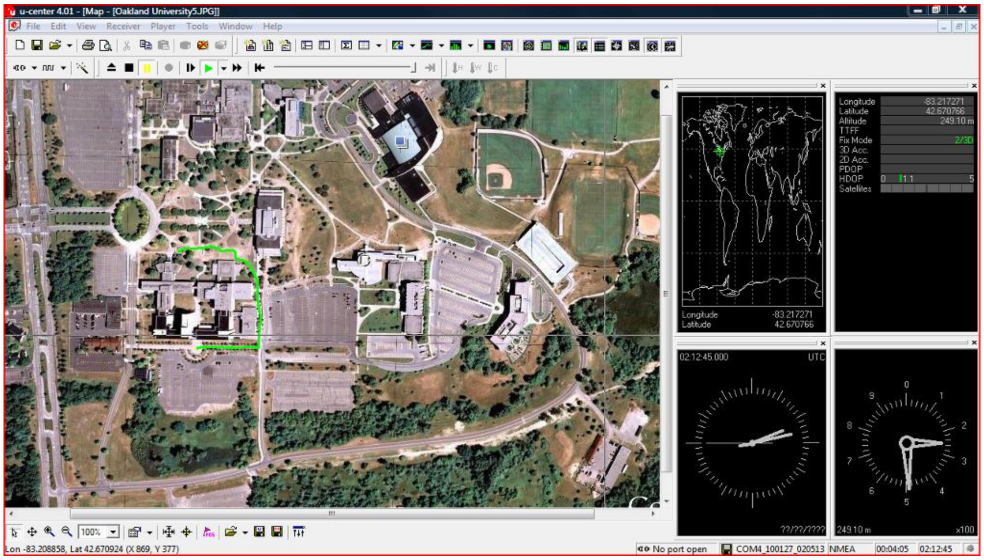

Figure 8. Ground Station Overview

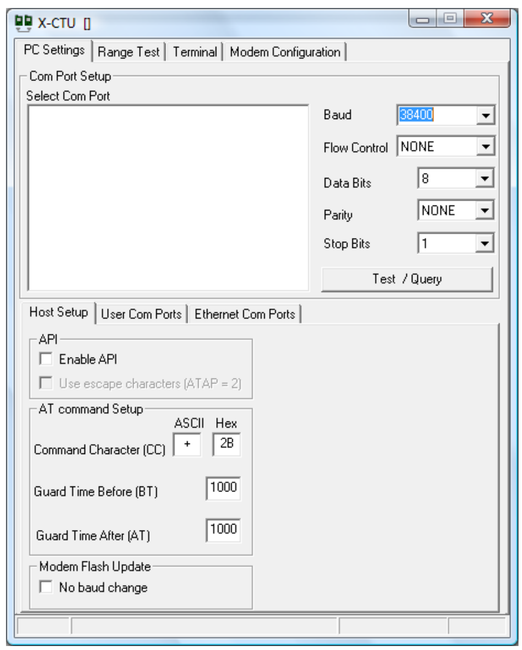

Figure 9. Ground Station Overview

The program receives NMEA sentences from the vehicle. According to the sentence, the software displays the vehicle's position on the customized map which is described above. The program has a capability to zoom in and out the map. Also, the previous position will be displayed with different colors; therefore, the user can easily observe and analyze the vehicle's path during the flight. The time, altitude and quality of satellite signals are also displayed in sub windows.

The received data are passed on by the onboard telemetry processor to the control processor. Translation of data frames received from the ground station is performed by the telemetry processor and results in only three setpoints that are passed to the control processor. These setpoints are: desired altitude, desired pitch, and desired yaw. The quadrotor vehicle is capable of precise altitude control, so the desired altitude data is passed as received from the ground station. Based on the actual lateral position as determined by the telemetry processor and the desired lateral position received from the ground station, a new heading is computed and passed to the control processor in form of a desired yaw value. The quadrotor is designed to either hold position or move forward by pitching down by 10° from the horizontal (i.e. always traveling at a fixed airspeed) and to hold roll at 0° at all times. The vehicle therefore moves towards waypoints by periodically adjusting vehicle yaw while traveling at a constant speed.

3.2 THE TARGET RECOGNITION SOFTWARE

Two parallel approaches have been adopted for target recognition. The first approach uses the frames captured by the video camera system. Figure 10 shows a sample frame of the video captured at 200 ft. Matlab™ scripts were implemented to compute the coordinates for each frame based on available altitude, attitude, and GPS data from the ground station.

Figure 10. Sample Video Frame

The second approach for target recognition is based on the images captured by the still photo camera system. Upon landing, the captured images, which are stored on a SD memory card, are removed from the quadrotor.
These images are inspected to determine possible targets. The selected pictures are loaded onto Macromedia Flash. A JavaScript was written to trace the x-y coordinates of the mouse over a picture of the field the quadrotor flew over. The pictures are made 50% transparent and then placed over the field. The pictures are then resized and rotated as necessary. Once all of the pictures are placed, the Macromedia Flash program is then started to determine the targets locations. Once the program runs, the mouse x-y coordinates are given in degree decimals. When the mouse is placed over the targets, the x-y coordinate is recorded and then converted from degree decimals to latitude and longitude. Figure 11 shows a screenshot of the still image processing GUI.

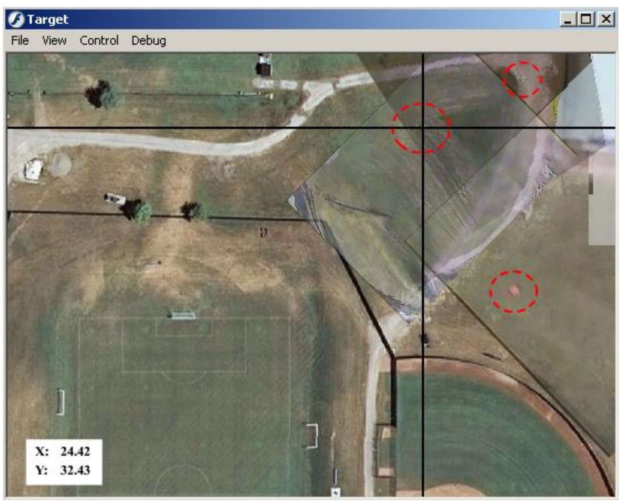

Figure 11. Macromedia Flash Program Still Image Processing GUI Showing 3 Targets

4 DATA LINK

The two UAS subsystems (i.e. Airborne and Ground station) are connected by three wireless links. Figure 12 shows these three wireless channels. The wireless links are:

1. A 2.4 GHz ZigBee wireless data link.
2. A 1.3 GHz channel for video recording and processing.
3. A 75 MHz Safety Link.

The 2.4 GHz ZigBee link is used for data exchange communication between the airvehicle and the ground station. The data sent from the airvehicle to the ground station includes the current GPS position and altitude, as well as several functionality health indicators for safety purposes. On the other hand, the ground station can send the user assigned GPS waypoints.

The 1.3 GHz channel is used for streaming video in real-time. Also, the 75MHz safety link allows the pilot to manually override the autonomous flight system for safety purposes.

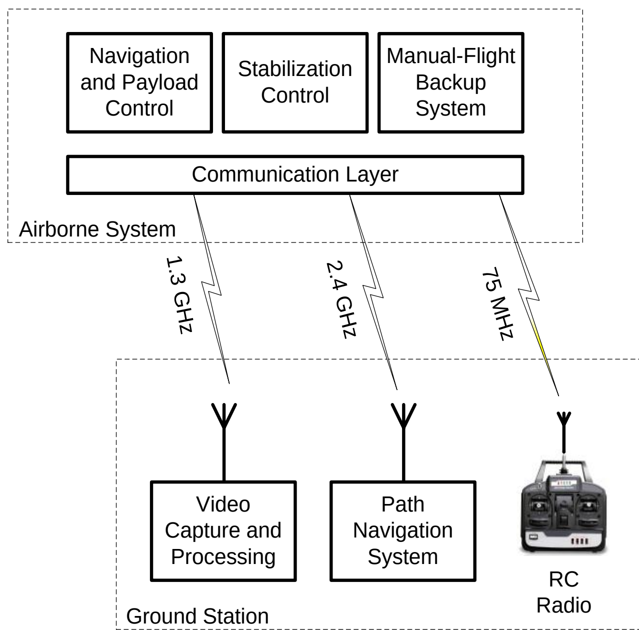

Figure 12. A High-Level View of Microraptor

5 SAFETY

During every phase of the deign process, the team had safety as the number one priority. A checklist is in possession of every team member, which are the guidelines followed from beginning to shutdown (Figure 13). After takeoff, a major concern is loss of control resulting in a crash, which could hurt persons or property on ground. In the event of such an emergency, whether during autonomous or manual flight, a switch on the radio control will stop the motors immediately. 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 telemetry processor does not receive the radio signal for more than 30 seconds. However, due to the teams focus on safety two subsystems are mounted on-board.

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Microraptor CHECKLIST

VISUAL CHECK:

1.) Propellers………………...Check for cracks, warping, and check nut is secure
2.) Antennas…………………………………………...Verify all 3 are connected
3.) Ribbon Cable/Zip ties…………………………….Verify Secure
4.) Motor Power Plug……………………………….Verify Secure
5.) Motor Controllers………………………………..Verify Secure
6.) Center of Gravity………………………………..Manually Check
7.) Parachute System………………………………..Verify Secure and Functional
8.) LED tower (simulated self destruct)……………Verify secure

PRE FLIGHT:

- Ground Station…………………………..Power On
- Emergency and Autopilot Switches……OFF
- Thrust Control…………………………..Zero
- Remote Control………………………….ON
- Avionics Switch………………………….ON
- Video Battery Unit……………………….ON
- -------SELF DIAGNOSIS
- IMU Light……………………………….Verify Functional
- RC Light…………………………………Verify Functional
- ZigBee……………………………………Verify Functional
- Video Light………………………………Verify Functional
- GPS Light………………………………..Verify Functional
- Safety Glasses……………………………ON
- Motor Battery…………………………….ON
- Camera……………………………………ON

Figure 13. Safety Checklist

Also, prevention of theft of sensitive technology was implemented. The quadrotor is equipped with a self-destruct feature that, if necessary, would prevent any enemy from steeling the technology used if acquired. If the UAS is over enemy territory and is either wounded or malfunctioning the possibility of losing some of the technology to any hostile is a real security concern. The best solution to prevent this in the real world would be to self-destruct. For this situation, the QUADROTOR will have a 5inch tower of LEDs on top to SIMULATE a self destruct. The "self-destruct" sequence is initiated when or if needed by sending a signal to the Control Processor Board on the UAS from the ground station via ZigBee.

However, if the UAS is recoverable without the need for personnel to enter enemy territory, the quadrotor has a single parachute system that can be deployed on command. The Parachute housing will be spring loaded and pointed straight up. When the power is received to the system, also by the avionics battery, two micro servos will retract on opposite sides of housing causing the weak strings to break. When this occurs, the pressure from the spring will instantly eject the chute out. The reason we designed this with two micro servos was to insure the parachute will shoot straight out and not get stuck inside housing.

As an added safety feature, all data frames communicating between the microcontrollers use checksum bits. The checksum will ensure perfect data transfer and optimal operation. In case any error occurs at any frame, the error shall be reported and the frame will be discarded.

During autonomous flight, the dual processors continuously monitor the system's sensors to determine failure and when to land or shut down the motors.

- IMU data link failure
    - If the IMU fails resulting in the craft not knowing its orientation in the air, the watchdog counter never resets so the quadrotor initiates a grounding algorithm.
- GPS data link failure
- If the GPS link fails, the program sends an alert to the ground station and enters manual flight mode.
- Radio link failure

- Control processor determines PWM values from the radio out of range or old and quadrotor returns to initial waypoint

A status byte (Figure 14) is sent between the processors during all communications to reflect system failure.

0: Success 1: Fail	IMU	R/C	Sonar	GPS	n/a	n/a	n/a	Ready
	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1	0 / 1

Figure 14. Status Byte packet format

6 TESTING AND EVALUATION

This section shows the testing performance results for all of the quadrotor UAS components. The performance of the vehicle's attitude, altitude and position control are presented next.

6.1 ATTITUDE AND ALTITUDE

The vehicle's attitude PID controllers were perfectly tuned. The vehicle's larger frame size helped to make it even more stable in presens of wind. Figure 15 shows the roll, pitch, and yaw PID controllers response in the presence of around 10 mile/hour wind. The figures reflect how the vehicle is stable.
Figure 16 shows the performance of the altitude hold PID controller at 100 ft hight above ground.

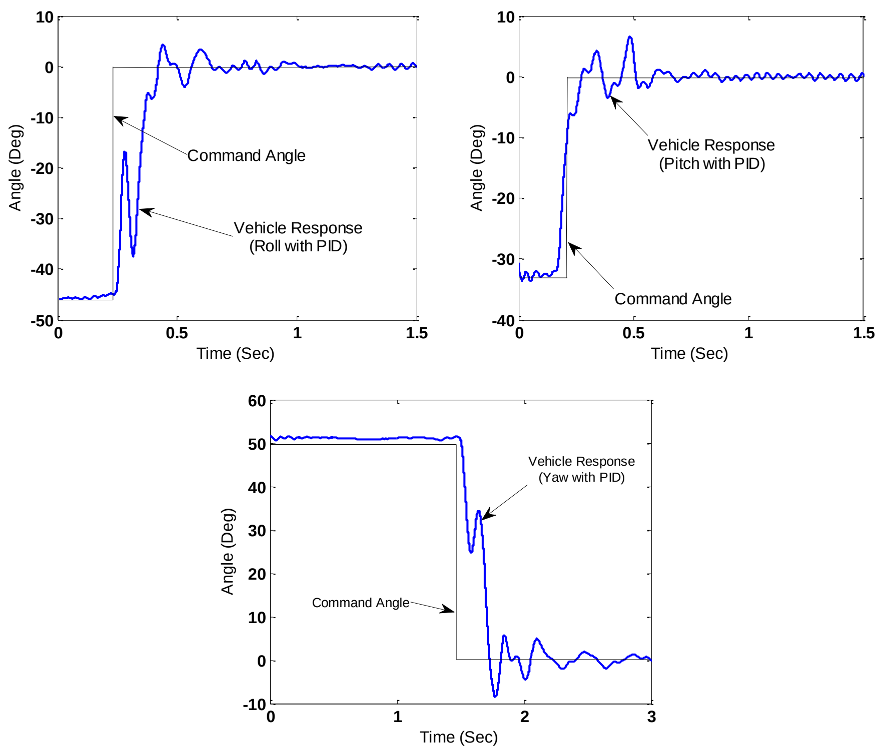

Figure 15. PID Control System Responses (roll, pitch and yaw)

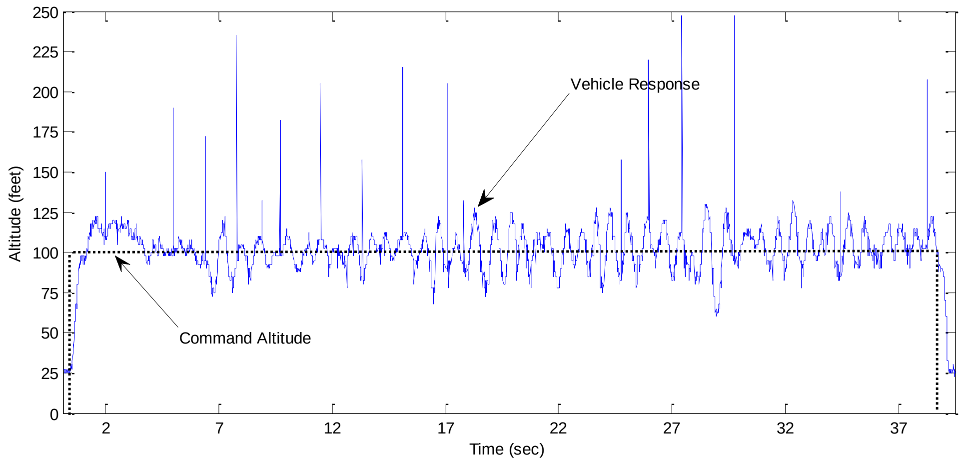

Figure 16. Altitude Response (Wind: 6 miles/hr)

6.2 GPS HOLD AND WAYPOINT NAVIGATION

Figure 17 shows the vehicle's GPS hold performance; while Figure 18 is a picture of the actual vehicle holding the desired GPS position.

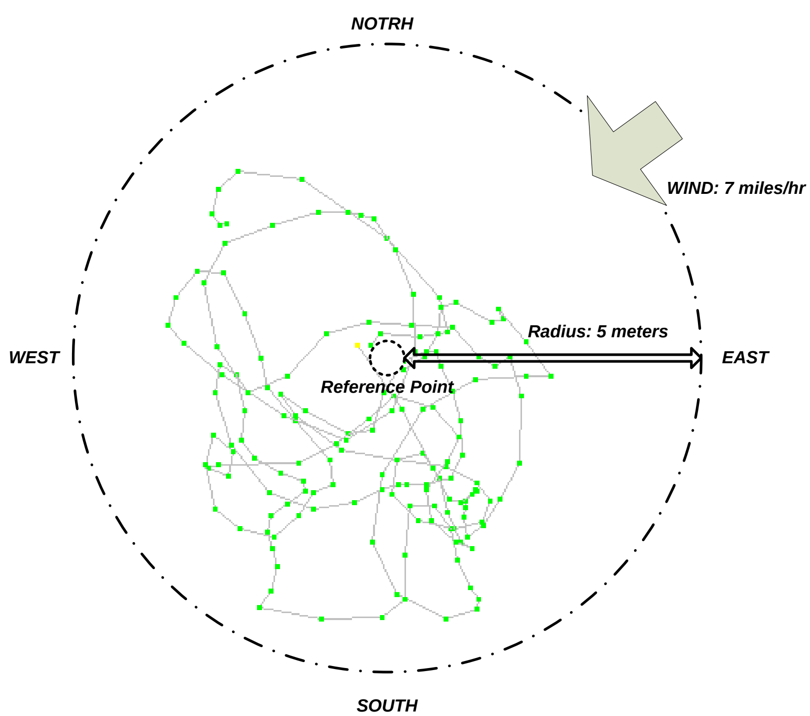

Figure 17. GPS Hold (Wind: 7Mph NE, Flight Time: 3 min, Altitude: 1.5 meters)

Figure 18. Quadrotor Flight during the GPS hold test

For the waypoint navigation, we assign multiple waypoints to an onboard MCU (the telemetry controller). During the experiment, the three waypoints (Home, Way 1 and Way 2) are assigned to make the vehicle loop through the three way points. As shown in Figure 19, the vehicle successfully flew through the waypoints. For the duration of 90 seconds, the vehicle made a complete loop (home – way 1 – way 2 – home). The distance of flight is approximately 100 meters.

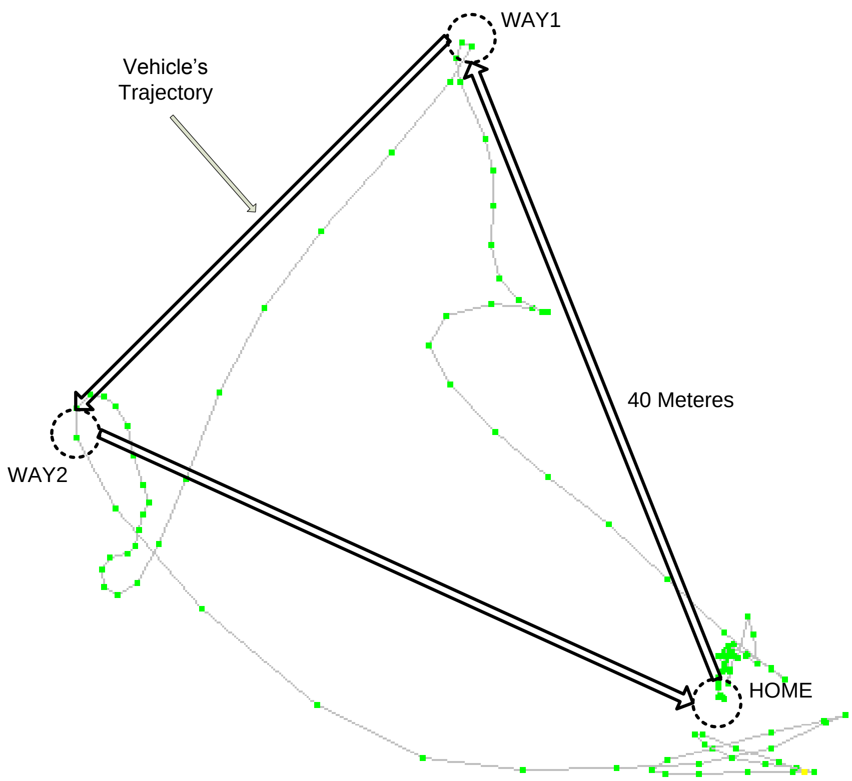

Figure 19. Position of Vehicle during the Waypoint Navigation

6.3 TARGET RECOGNITION

Figure 20 is an aerial image captured by the imagery system while flying 500 ft above ground. The figure shows two detected targets, the targets can be clearly identified. Target #1 is a square shape (4'x4'), while Target #2 is a triangle that is half size of Target #1.

Figure 20: Aerial Image at 500 ft

7 Conclusion

Advances in microcontrollers and energy storage technologies have revived the concept of quadrotors for UAS applications in recent years. This paper described the design, implementation and performance of Microraptor: a low-cost quadrotor system that is designed for surveillance and reconnaissance applications. The system's performance is promising as newer technologies pave the road for more power storage batteries, more efficient motors and less weight materials.

ACKNOWLEDGMENTS

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