UARC

Jeremy Brooks, Edwin Giraldo, and
Clint Mansfield

School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, Florida, 32816-2450

***Abstract* — This paper will discuss the design and realization of the Unmanned Aerial Reconnaissance Copter (UARC). With the assistance of digital feedback sensors, the vehicle can achieve steady flight without user interaction. There are commercially made helicopters that can perform the same routines. However, what they do not provide is affordability, as commercial systems on the market today cost thousands of dollars. The goal was then to create such a device that mimics much of the Draganflyer's features at a more affordable cost. This paper aims to document the design methodology and ultimate construction decisions made in constructing such an apparatus.**

***Index Terms* — Draganflyer, four-prop helicopter, 6-degrees of freedom, autonomous vehicle, UAV, feedback control system.**

I. Introduction

When air flight took place, many different solutions were created. Transporting of goods and materials, vacations and business negotiations, and protecting civil liberties by military personnel. The reliability of electronics has made its way into applications used every day. Common items such as micro-controlled toothbrushes that monitor timed sessions, motor vehicles that can sense danger ahead and distribute power to the brakes in an event of a crash, and sophisticated robots that can mow your lawn without control are some to name a few.

Much of the focus of this project was to highlight those applications as used by the military. Currently, there are 223 UAV's used by the United States Air Force whose sole purpose is to attack and scout unfamiliar ground. The design would call for a four-prop helicopter in which the frame is constructed of carbon fiber. To provide efficiency in power, brushless motors have been implemented to achieve longer flight time. Ideally, this vehicle would be mounted with a wireless camera to transmit video back to a portable device. To maintain stability, 7 sensors will monitor the orientation of the vehicle and update the microprocessor with feedback of its current status.

Fig. 1. The Draganflyer is a remote-controlled helicopter equipped with gyros, accelerometers, and a magnetometer. The vehicle, which can be customized, can be purchased for around \$800.00 - \$16,000.00.

The design will consist of four major components: Data interpretation, feedback control system, flight dynamics, and signal filtering. Individually, any of these components has sufficient complexity and a multitude of options to make of an interesting project. However, integrating all these components together allow our group to exercise ideas not learned in the classroom setting.

II. Data Interpretation

A. Sensors

To assist in hovering, a multitude of sensors are needed to let us know when the contraption is tilting, accelerating angularly, collision detection, obstacle avoidance, and falling. During takeoff, the accelerometer will allow the monitoring of whether or not the motors are working in sync in a manner that the helicopter ascends vertically. Secondly, this will allow crash avoidance into the ground while landing. Because the blades will be spinning as descending occurs, it is important to monitor tilting such that the blades do not interact with and objects in the ground. The next sensor will be utilized to measure how much distance there is between the UARC and the ground. A second sensor will also be aimed upwards to detect a ceiling, branches or other obstacles that could interfere with the UARC's flight path. The downward facing sensor will take constant measurements to sense how far off the ground the UARC is hovering. The purpose of the gyros is to update UARC on its rotational state. As the vehicle experiences forces that disturb stable hover, it is needed to know how fast it is falling and whether it's the yaw, pitch, or roll cardinal system. A remote keychain device will be used as an emergency kill switch in the event the UARC experiences possible crash or undetermined response. The code will sense for a particular high bit value on a port to listen in and see when the keychain has been activated. Once it has been activated, the software will communicate with the UARC for a safe landing.

B. Sub-microcontroller

To minimize the potential risk of damaging the pricey microcontroller, the group decided to enable a chip that would handle all the sensor inputs and communicate with the main microcontroller via I^2C. This powerful device can be accessible via address lines during programming and only takes two lines on the main microcontroller. Although one address can be accessed at one point in time, the switching speed can allow multiple readings per second. The device can also be daisy-chained to allow more inputs if needed. Should the chip be damaged for some unforeseen reason, it will be relatively cheap to replace. Once our board was fabricated, this was the toughest surface mount component we had to solder due to the spacing of pins being 0.65 mm.

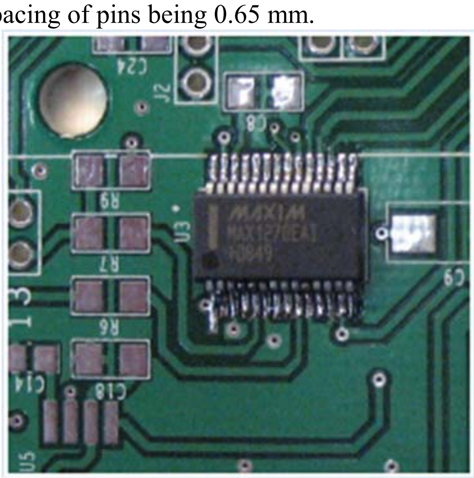

Fig. 2. The Max127 surface mount component proved to be the toughest part to solder in the circuit board. All of the sensors are linked up to this chip and only two lines are routed to the main microcontroller.

C. Main microcontroller

The Coridium ARMmite microcontroller runs at 60 MHz and has many features. It is easily programmed through the USB interface and has plenty of I/O ports. There are also 8 10-bit A/D channels, 8 hardware PWM channels, and 32K of flash memory. The board is a little big because it contains a small breadboard, but still maintains a light weight as the design calls for. Because the chip cannot be detached from the development board, the entire board will be implemented into the final design.

III. Feedback Control System

In order to achieve flight stabilization a number of key factors are involved in making this a success. Correctly configuring the feedback controls is necessary for stable flight. Some sensors will have to be ignored during certain criteria. For example, if a coordinate is issued that demands the UARC in making a turn, a signal is sent to the motors to carry out the role. During this time, power is increased to the motor for the appropriate turn and less power sent to the other motor to create an arc. The accelerometer and gyros should be programmed well to allow the apparatus to carry out the sequence of turning. Should the sensors be allowed to remain on, the microcontroller will be sending a signal to turn all while the sensors are informing the microcontroller to correct itself due to tilting. Each sensor had to undergo different scenarios to determine whether they should be on or off to carry out a request from the microcontroller. During programming, careful consideration was given to this area to make sure no errors are made because it could pose a unplanned crash. Because constant feedback is being sent to the microcontroller, any instruction that interferes with the sensors or the UARC can have disasters. During designing, special methods were made to make sure high current traces, radio frequency, analog and digital lines were all separated to avoid noise.

A. Sensor interaction

During testing the sensors were calibrated each time to get a proper DC voltage. This is done to rule out any discrepancies that might occur from one test to the other. Some of the sensors used are ratio metric with voltage. To assure a time-invariant system is used each time, a voltage regulator was used straight from the battery source. However, we quickly realized other factors affect output such as temperature, and orientation. To counteract this, we devised software filtering to assist in getting accurate readings. As the UARC is powered on, the ultrasonic sensor provides a distance of the ceiling to assure it can hover in the amount of space. The program will then begin the lift procedure if the previous sensors pass initialization. Table 1describes the duty cycle generated from the microcontroller passed on to the speed controllers.

The beginning of the loop function for flight has now been initiated. Within this function, the microcontroller communicates with the MAX127 and gets readings from the gyros, accelerometer, and ultrasonic.

STATE	DUTYCYCLE (uS)
IDLE	0
LIFT	550
HOVER	500
LAND	450

Table 1. The state diagram for the proper duty cycle applied to maneuver the UARC. The value is compared to the total period of 20,000 µs.

B. *Program interaction*

Some checks and balances have been placed to make sure we are in control of a disaster- should it occur. Because our group used a lipo battery for operation, the batteries are very sensitive and should not be drained completely to avoid damaging the component. For this reason the program is set to light up a greed led when operation is normal. Once the lipo battery has reached the threshold for recharge, the program turns off the green led and powers a red led as a visual indicator. The kill switch will serve as the on and off operation of the UARC. An led has been placed underneath the vehicle for visual inspection of when data has been received by the wireless kill switch. The placement of the sensor was placed here in case the UARC is in flight and we can see it from the ground. Finally, a dual color led has been placed on the PCB to determine when the UARC is in calibration mode. This will provide a visual inspection when the program is busy and the vehicle should not be tinkered with.

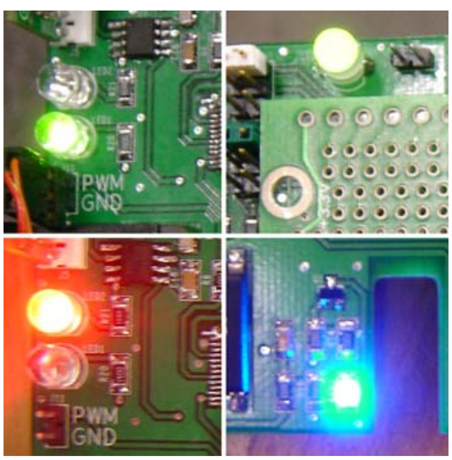

Fig. 3. The UARC provides visual feedback to avoid a disaster. From counter-clockwise direction: Green led lights up during normal operation. However, when the voltage on the lipo battery drops below a certain threshold it lights up red. A bright blue led located on the bottom of the PCB lets us know when a signal has been received by the killstart switch. An led located near the microcontroller lets us know when it is in program-mode.

IV. Flight Dynamics

The dynamics of UARC are relatively simple due to the fact that it's modeled as a symmetrical rigid body system. There is a six degree of freedom movement derived from the translational and rotational physics. The inputs to the system will consist of total thrust on the vertical axis (F) and the torques about each axis (T1, T2, T3). These dynamics will also need to be represented from an inertial frame, being its initial coordinates before flight. The translational coordinates are represented by the traditional x, y, and z notation and the Euler angles of rotation are represented by Φ, θ, and Ψ. Since the number of inputs is less than outputs, this system is considered under actuated.

Due to the special symmetrical nature of UARC the center of gravity is at the origin of the B frame along with the moments of inertia. Also UARC is modeled as a rigid body. Out of every article and document referenced this is always the case. The beauty of this is that of simplification and efficiency. This aids to create the under actuated system that was described earlier.

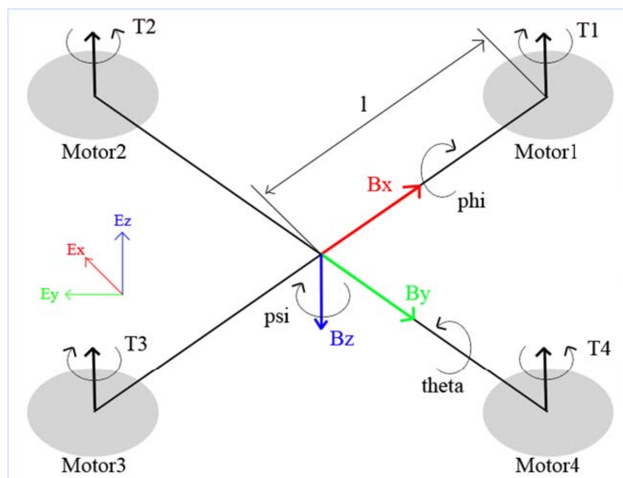

Fig. 4. The free body diagram of the UARC.

A. *Equations*

In helicopters there is just one main rotor producing vertical lift and a smaller tail rotor to counteract the Coriolis Effect. Thanks to the symmetrical nature and even number of rotors the Coriolis Effect can be counter acted in UARC by having the moments created from opposing motors cancel out. This is accomplished by setting one motor in a clockwise motion with the other in a counter clockwise motion. By varying individual thrust of two motors on the same axis the rotational angles will be controlled leading to translation. Now when in motion there are a few things to take into account. For starters, the drag created by the rotors that are opposing motion. There is also a net moment along each axis of rotation created by the change in thrust. These forces and moments can all be related to the square of angular velocity of the blade, Ω, through aerodynamic coefficients C_t, C_q. Let A be blade area, ρ density of air and r be radius of the blade then,

$$T = C_T \rho A r^2 \Omega^2 \tag{1}$$

and

$$Q = C_Q \rho A r^2 \Omega^2 r \tag{2}$$

Where T is thrust and Q is torque on the rotor shaft. The equations can be further reduced when hovering occurs. This is possible because Ct, Cq, and ρ are constants where i represents each individual motor (i = 1, 2, 3, 4). Ultimately blade angular velocity Ω will be represented by applied voltage. The translational dynamics are,

$$\boldsymbol{f}^b = \omega^b \times m v^b + \boldsymbol{f}_{tot} \tag{3}$$

f_{tot} is defined as,

$$f_{tot} = -C_{x,y,z}\left(\left(v^b\right)^2\right) + mgZ + \sum_{i=1}^{4}\left[-T_i z - D_i (x \;\; y)\right] \tag{4}$$

$C_{x,\,y,\,z}$ represents the drag coefficients, Z defines the vertical axis in the inertial frame, while the (x, y) defines velocity direction, g is the force of gravity, and D_i is the drag force on rotor opposing the direction of travel. The Rotational dynamics are,

$$\tau^b = \omega^b \times J\omega^b + \tau_{total} \tag{5}$$

τ_{total} is defined as,

$$\tau_{total} = \left[\left(\sum_{i=1}^{4}\left[Q_i z + R_i (x \;\; y) + D_i h(-y \;\; x)\right] + l\left(-T_2 + T_4\right)x + l\left(T_1 - T_3\right)y\right]\tag{6}$$

B. Hardware

Since weight is of concern, we had to choose a frame that would use lightweight material while being durable in the event of a crash. Draganflyer sells a bare bones kit available at their website for applications such as ours. The carbon fiber design has motor mounts, and battery compartment. The kit also came with nylon blades for the propellers and all the nuts and bolts to hold it together. The UARC will use four DC powered motors to spin the propellers, steer and create lift. The motors will have to be able to rotate either clockwise or counter-clockwise. One pair of opposite motors will need to rotate clockwise, while the other opposite pair will need to rotate counter-clockwise to keep the angular acceleration about the yaw axis at zero – or essentially offset the torques normally handled by the tail rotor in a typical helicopter. To accomplish this, the kit was designed to have counter rotating blades already incorporated. The motors used are powerful enough to allow the UARC to fly up to 10 feet in height for 15 minutes without draining the battery. There are two types of connections between a propeller and motor. The first connection is called direct drive or inrunner in RC terms. The second is called indirect drive or outrunner. A outrunner is basically just putting the propeller directly on the motor shaft. Alternatively, inrunner incorporates a gearbox with a given gear ratio to translate the motor rotation to the propeller.

Fig. 5. The bare bones kit sold by Draganflyer for helicopter projects. The frame is made of carbon fiber material, the blades of nylon, and the interconnections of plastic.

The UARC utilizes four motors to get off the ground and there were a wide variety of motors to choose from. In the end the brushless Dc motors were chosen for our design. With brushless motors, the armature stays stationary while the permanent magnets rotate preventing the need for brushes. This means there are no brushes or commutator to clean or replace. Also there's no friction to slow the motor down therefore the battery life is extended and the power to weight ratio is increased. The noise and the EMI are reduced as well. However brushless motors are more expensive and need a speed controller to control the speed.

An electronic speed controller does what its name implies - it controls the speed of a motor. The UARC's onboard sensors will gather information and send it to the microcontroller. The microcontroller processes it, and then creates 4 separate voltages or PWM signals that represent the speed of each individual motor. Some speed controllers work by using a varying voltage input instead of a PWM signal. Each speed controller takes that signal and controls its respective motor speed accordingly.

C. Building a test prototype

The purpose of building the 2D test assembly is for that of gaining experience in the dynamics and controls that need to be implemented for the final design of UARC. This assembly will simplify the project significantly yet still define the process and methods to be accomplished. First of all the number of actuators is reduced to two, being the two motors that originally came with the Draganflyer frame. Secondly the number of output variables is reduced to two. These variables are Z and θ which represent the height and the pitch angle about the y axis respectively. Figure 6 below shows the schematic of what the contraption will look like and its free body diagram.

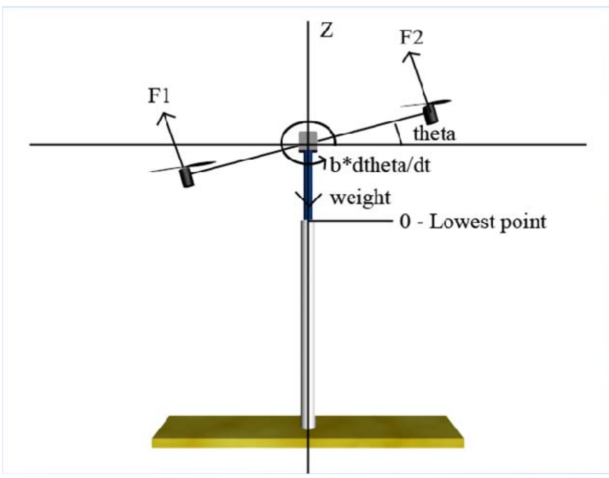

Fig. 6. Free body diagram for the 2D design setup.

Another attribute that this will simplify is the sensor readings. The 2D test assembly will not use sensors. This means it will be cheaper to make, lighter, and less code and hardware intensive. The rotational signal will not have to be filtered or calibrated for noise and drift. It will instead retrieve the angle through the voltage drop of a potentiometer. The pot will create a nice linear voltage that can be input into the computer and interpreted accordingly. Since the signal is given so nice there is no need for any system in between to filter it and create unnecessary delay.

V. Simulation

Simulation is crucial to any aspect of engineering. UARC is no different. By using the power of Matlab and Simulink, UARC can be realized before it is actually physically developed. Through trial and error a good starting point can be established for the physical realization of UARC. The first simulations ran were that of the 2D prototype. Using the dynamic equations derived they can be formed into a simulink model. Equation (7) along with figure 7 below shows the equations for translation along the z axis and the corresponding model with step response. Equation (8) alone with Figure 8 shows the rotational equations, model, and step response.

$$m\ddot{Z} = \left(F_1 + F_2\right)\cos(\theta) - c\dot{Z} - mg \qquad (7)$$

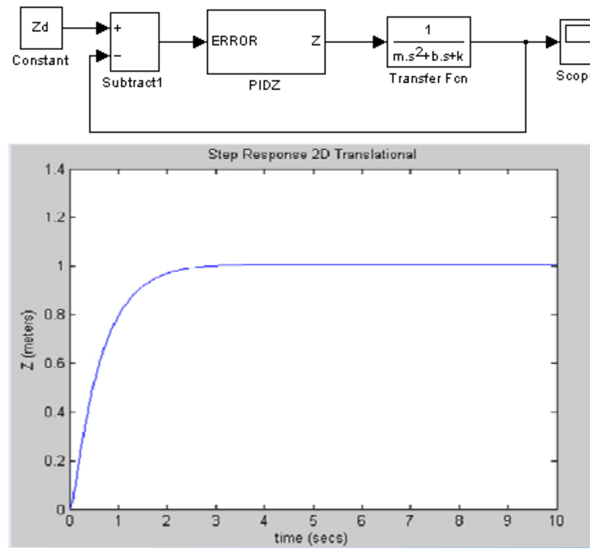

Fig. 7. Translational model 2D and step response.

$$I\dot{\omega} = \left(F_2 - F_1\right) l - b\omega \qquad (8)$$

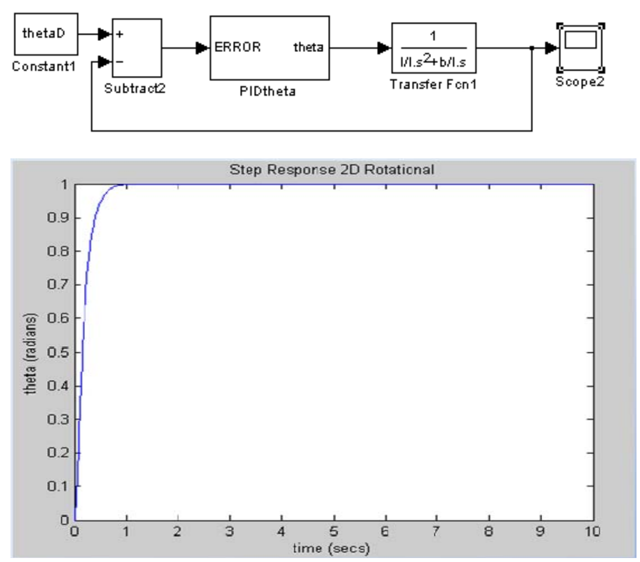

Fig. 8. Rotational model 2D and step response.

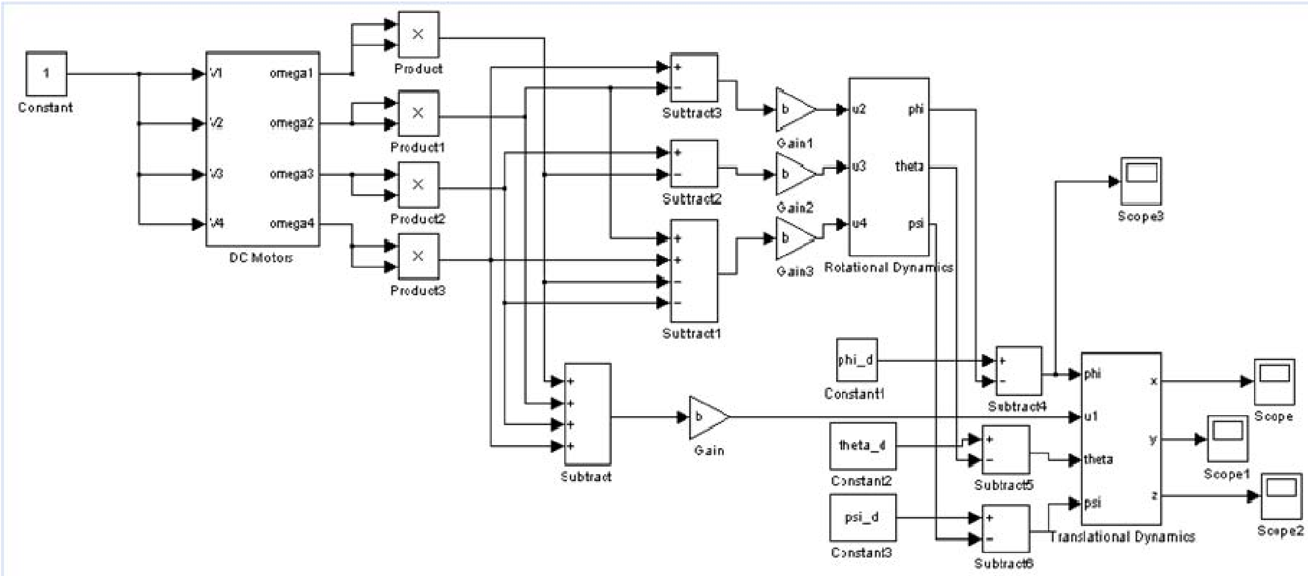

Fig. 9. Open loop model of dynamics interaction with motors thrust

VI. Signal Filtering

The design created had multiple signals what would add noise interference. The start and emergency kill switch use radio frequency to communicate wirelessly. The chip will then send a high bit value to the microcontroller. All of the sensors send a signal to the MAX127 in analog format to be converted into digital logic to be interpreted by the microcontroller. Because the development board had to be implemented into the design, the traces have to travel far to be received by the microcontroller. All of these signals introduce noise. If the PCB layout is not carefully designed, it could introduce errors and noise that cannot be suppressed. For this reason, signal filtering had to be introduced.

A. Hardware

The AXDL330 chip outputs analog voltages that are proportional to acceleration. It can measure the static acceleration of gravity as well as dynamic acceleration as a result from motion, shock, or vibration. The board already incorporates the decoupling capacitor of 0.1µF to filter noise out. The bandwidth has already been set by adding a capacitor of 0.1µF which sets it to 50 Hz on the x, y, and z component pins. Furthermore, because the resolution is dependent on bandwidth capacitance chosen, there is little that can be done to change this since the manufacturer has designed this package already. As testing was done on this chip, it had little noise presented in the value. The little that was noticed could be dampened with software programming. Hence, a first pass filter was used to isolate common V_{CC} noise. The ultrasonic sensors breakout board had relatively low noise comparatively to those other sensors. Because it will be used to monitor obstacles, it is not as important for flight as the other sensors. Furthermore, it was not needed to use passive components to clean the signal produced by the component. The ADXRS613 gyro outputs a voltage relative to the rotation angle, but it's ratiometric with respect to the provided reference supply, which in this case was +5VDC at 5mA. The bandwidth can be set using an external capacitor. Because it was purchased as a breakout board it is set at –3dB frequency response to 402 Hz, although it can range between 1Hz to 3 kHz. This could be changed by if required by replacing this capacitor, or adding a resistor between 2 of the pins. This component had a lot of noise in all the testing we performed. In the end, we purchased an 8^{th} order butterworth filter to suppress as much noise as possible. At first we were concerned with timing delays this would present. But in digital logic, it was a miniscule amount of time it took to propagate the signal and made no difference in the programming. The linx RF receiver/decoder will have a ground plane underneath the component as the datasheet instructs to completely isolate noise. Lastly, bypass caps were added to all sensor input voltage traces.

B. Software

When each sensor was placed on the oscilloscope, spikes in values were seen. It was never predicted and we understood the noise would be present even if the breakout board had capacitors added to dampen them. To work around this issue we calibrated each sensor at the start of the program sequence. The UARC had to sit still to capture DC offset values. About 200 samples of each sensor were taken and averaged out to gain this DC value. The value calculated out would then be saved as a variable. After calibration, the program was designed to listen in on values being sent from the MAX127 that had slight spikes and ignored. It is noted that proper coding was done to assure the value passed on didn't mean that the UARC was falling. This idea proved to be more efficient than to develop a Kalman filter which most projects suggest. This is due to the as the design calls for matrix algebra calculations and slows down the program from continuing.

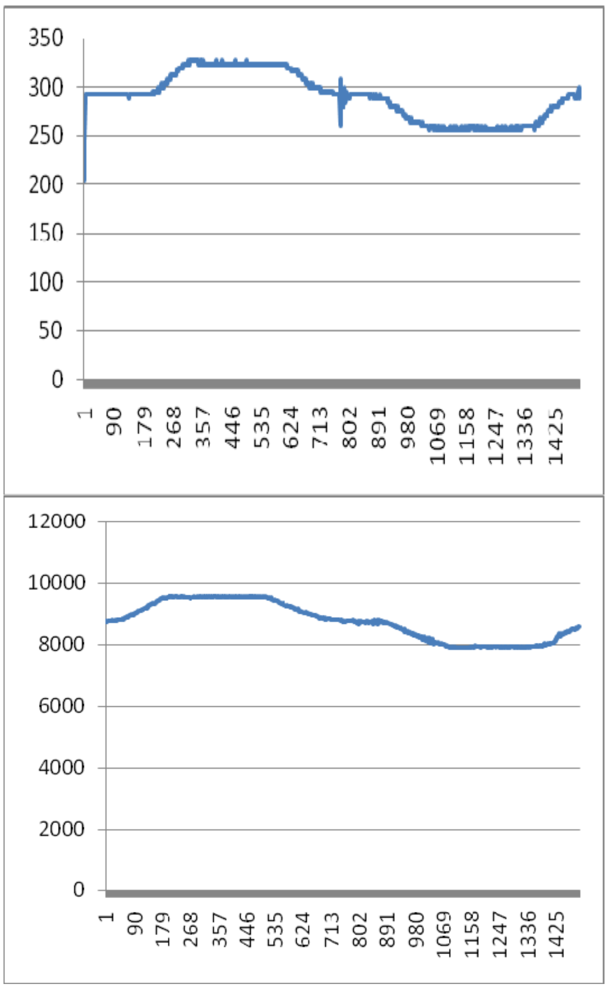

Fig. 10. An example of spiked values acquired from the accelerometer during testing. This slight variance in value could potentially crash the UARC. With the code we developed, the spikes are normalized to avoid crashes.

VII. First Flight

After we studied the 2D assembly and gained confidence that it could stabilize on its own, I was time to add the extra axis. One might think you that you would have to recode the programming to handle the 3D design, but nothing is further from the truth. The code is just duplicated and that axis is independently trying to balance, much like the other axis previously discussed. The fear of crashing and damaging components was one thing that was to be prevented to further the concept of the project. For this reason, a latching system was used to have a controlled experiment without disaster. With the use of nylon strings, the UARC was tethered to a platform to restrict it from flying past 1 ft. from the platform.

VIII. Conclusion

When the idea of designing UARC first arose, the task seemed somewhat trivial. Just throw some motors on rods and apply some voltage to them. That concept soon proved to be more challenging than expected. There are many engineering applications that were tackled and it can be overwhelming. Through research and peer counseling, UARC began to take form.

With all the hard work and labor put into this project, the UARC has accomplished everything the objectives we set forth. It was able to achieve stable hovering, obstacle avoidance, and land autonomously. The final value put into this project was estimated at $1,300. The same design specs sells for over 10K online.

Acknowledgement

The group would like to acknowledge those who assisted in the development of this project and research. As having the group made up of strictly electrical engineers and having little involvement in programming made it rather difficult to construct this project. While the challenge existed, the determination to proceed overpowered the challenges that lied within. Don Harper, a system administrator of the college of Electrical Engineering at UCF, served not only as a reference point but as a mentor as well. Don has been involved as a lead engineer for the DARPA grand challenge project. He has more than 20 years of experience in different areas of subject such as simulation, embedded computing, wireless networking, robotics and controls. The green Subaru seen driving autonomously around UCF campus was his wife's car he donated to participate in the DARPA challenge. He laid the ground work in setting up the 2D design to understand the physics.

Gary Stein helped us implement the 3D design set forth in the objectives. He is involved with the robotics club and mentors his group in competitions taken on. As previously constructed a four-prop helicopter himself, he was able to give us great wisdom in helping us through our project. He offered his own personal time to make sure our project came to a realization.

GROUP MEMBERS

Clinton Mansfield is a 27 year old graduating Electrical Engineering Student. He is a passionate musician and artist whose area of interest include control systems, dynamics, and design. He hopes one day to apply his knowledge to the advancement of the space program.

Jeremy Brooks is an senior Electrical Engineering student at the University of Central Florida. He will receive his BSEE degree in August of 2009, and presently works as a PCB designer for an electronics contract manufacturing company in NJ. Upon graduation he plans to pursue a career in the engineering profession.

Edwin Giraldo is a 27 year old senior Electrical Engineering student at the University of Central Florida. After receiving his bachelor's degree, he plans on pursuing a Masters Degree in Fabrication of Semiconductor Devices.

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