

Stabilization and Control of a Micro-scale Helicopter

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We are developing a control system to perform electronically stabilized flight of a small electric helicopter. The Blade CX2 counter-rotating helicopter was modified by creating an inertial measurement unit (IMU) control board, while maintaining the original motor, servos and power supply. A microcontroller, magnetometer, sonar, gyroscope, 3-axis accelerometer, and a barometric pressure sensor were integrated into the board in a modular, low weight, low cost, and flexible package. The microcontroller acts as the data management and signal processor for the system. Ongoing software development is utilizing sensor data in the calculation of corrections to flight controls; with the short term goal of maintaining an optimal altitude and orientation. This is the first stage of a general purpose platform for small autonomous vehicles that have payload capabilities as a major limiting factor.

Nomenclature

| | | |
|------------|---|--|
| a_x | = | x component of the acceleration |
| a_y | = | y component of the acceleration |
| a_z | = | z component of the acceleration |
| D_x | = | drag coefficient for linear motion |
| D_θ | = | drag coefficient for angular acceleration |
| $e(t)$ | = | controller input |
| F_g | = | sum external forces acting on the helicopter |
| Θ | = | pitch |
| I | = | helicopter's total moment of inertia |
| I_{xx} | = | moment of inertia about the x-axis |
| I_{yy} | = | moment of inertia about the y-axis |
| I_{zz} | = | moment of inertia about the z-axis |
| I_{xz} | = | product of inertia in the xz-plane |
| K | = | proportional gain for continuous PID |
| K_P | = | proportional gain for discrete PID |
| L | = | moment about the x axis |
| $m(t)$ | = | controller output |
| M | = | moment about the y axis |
| M_a | = | total mass of the helicopter |
| M_g | = | total external moments of the helicopter |
| N | = | moment about the z axis |
| p | = | rotational velocity about the x-axis |
| q | = | rotational velocity about the y-axis |
| r | = | rotational velocity about the z-axis |
| T_i | = | integral time |
| T_d | = | derivative time |
| T_I | = | integral gain |
| T_D | = | derivative gain |

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| | | |
|--------|---|----------------------------|
| τ | = | sum of the angular torques |
| u | = | velocity along x-axis |
| v | = | velocity along y-axis |
| w | = | velocity along z-axis |
| Φ | = | roll |
| Ψ | = | yaw |

I. Introduction

Interest in the development of small autonomous helicopters has been increasing significantly in the aeronautics field. Some of the most notable projects have occurred at institutions such as MIT and Carnegie Mellon. These systems have been designed on larger helicopter designs, with wingspans of up to 5 feet.¹ Our current platform is the smaller, Blade CX2 counter-rotating, RC helicopter, with a wingspan of roughly 1 foot. There are several major constraints that face the development of autonomous helicopter flight, with the major three being power, payload and price.

The Blade CX is a 227 gram model helicopter with a 34.5cm main rotor diameter. It uses counter rotating main rotors instead of a tail rotor to counteract the torque from the lifting motors. It has been designed to be a stable, non-aerobatic model, with a low center of gravity, relative to the center of lift, and it lacks collective pitch control. Thrust is simply controlled by motor speed. It therefore uses a four channel radio to command pitch, roll, yaw and thrust. It has relatively slow dynamic response, is constructed of inexpensive, readily replaceable plastic components, and at \$200 is affordable. The electric motors provide quiet and hassle free indoor flight. These qualities make it an excellent platform for a small UAV. The major constraint for the control system is weight, with power consumption and cost as secondary concerns.

Power considerations have held back the development of smaller hobby helicopters, but with newer breakthroughs in battery technology, especially lithium polymer materials, power has increased and helicopter size has decreased.² Along with these power considerations, the other major concerns revolve around expenses, payload and maneuverability. Helicopters are known for their outstanding maneuverability, especially in tight spaces. When controlling these small hobby helicopters, it is often times difficult for human control, but the incorporation of an inertial measurement unit will ease any of these manned flight problems. Another issue regarding these helicopters is their low payload capabilities. With maximum allowable payload on the order of roughly 60 grams, the implementation of an inertial measurement unit needs to revolve around this obstacle. The finale task in development of this board is to create a cost effective addition to the current helicopter design. With larger scale commercial products selling for upwards of \$16,000, we have created a much more inexpensive sensor and board unit. Together, the maneuverability, payload and price all played a key role in the design aspects of this project.

Keeping these design constraints in mind a control board was created, where all additional sensors and electronic parts cost roughly \$200 and weigh only 20 grams. The system revolves around the use of the MSP430, which is a low power, and low cost microcontroller from Texas Instruments. A magnetometer is used on the board to set up an orientation of the helicopter with respect to a relative magnetic field of the room the flight is occurring. A 3-axis gyroscope determines any pitch, yaw or roll of the helicopter. Forcing measurements in three axes are measured using an accelerometer. A barometric pressure sensor has been implemented to determine the height of the helicopter, and sonar sensors are placed on the board to distinguish any walls or other obstacles in the near vicinity. The microcontroller control code will time the information influx from all of these sources, and use various feedback loops for autonomous flight control.

The initial goal for our system is to wrap a simple closed loop control around the servo controller in order to make the system easy to fly. While the Blade CX is already easier to fly than many other model helicopters, it still requires practice to master. The system exhibits noticeable coupling between yaw and thrust. It will lose altitude when the pilot commands a yaw change. Additionally, while the Blade CX comes with gyro stabilization for the yaw axis, the helicopter still exhibits significant drift in yaw control, with rotation rates of up to 360 degrees per second observed. This effect cannot be trimmed out, as it appears to be coupled to thrust. We would like to enable hands off hover with active altitude and yaw stabilization

The future goals of this project are the complete implementation of all sensors on the control board, as well as additional sonar units and a low weight camera system. This will result in a completely autonomous aerial vehicle. Another capability of the helicopter will be the use of the sensors as an overriding feature to human controlled flight. Control code could be employed that will continuously run, and act as obstacle avoidance even with a human flying the helicopter. This system is also the prototype for a general purpose inertial measurement unit that can be added

onto other hobby aerial vehicles. Its low cost and low weight aspects are ideal for inexpensive RC planes and helicopters.

II. Helicopter Flight Characteristics and Specifications

One of the most obvious hardware differences between a conventional helicopter, and one with counter-rotating main rotors, is the lack of a tail rotor. This has several performance advantages especially in small R/C versions including the overall reduction in weight, reduced mechanical complexity, and a smaller moment of inertia about the rotor axis. When maintaining a constant orientation in flight, the rotors' angular momentum vectors are equal in magnitude and opposite in direction resulting in zero net torque in the yaw direction. Positive or negative yaw is induced by the increase or decrease of one rotor's speed in relation to the other. This upsets the angular momentum balance and causes a moment about the yaw axis. Changes in direction are accomplished in the same manner as regular helicopters by the deflection of the thrust vector in relation to the center of gravity of the body. The swash plate is articulated by servos to tilt the rotational plane of the blades, thereby altering the direction of the thrust vector which is assumed to be perpendicular to the plane of rotation. The upper flybar and associated link to the pitch of the upper rotor blades act to dampen sudden changes in overall rotor position by temporarily maintaining the previous angle of attack of the upper rotor. This is critical for the prevention of undesirable high frequency phugoid excitations as well as the reduction of coupled responses to control inputs. It should also be noted that only the lower set of rotor blades have their pitch and role controlled by the servos, while the upper set is left free to act as the damper, its pitch controlled by its own inertia and that of the flybar assembly.

The short term goal of constant height and orientation lends itself to several simplifications from a flight control standpoint. The characteristics of the properly tuned helicopter are such that it naturally settles into a stable position in roll and pitch, leaving only yaw left to be actively stabilized. Because we are not attempting any precise maneuvers, the complex equations governing the motions of the helicopter body in flight can largely be put aside. We will be utilizing a simple PID control over the speeds of the motors to control both the height and yaw. Gains will be determined roughly through knowledge of the maximum angular acceleration of the motors and the moment of inertia about the rotor axis. Fine tuning will proceed experimentally, resulting in a system that can quickly respond to perturbations in height and yaw. We assume that the roll and pitch encountered in the slight perturbations will not affect magnetometer accuracy to a significant degree and that if such extreme motions are induced, they will be quickly damped by the system's inherent stability in those axes.

The stock figures for the Blade CX2 are shown in Table 1 as given in the user manual.

| | |
|----------------------|-------------------|
| Length | 400mm |
| Height | 182mm |
| Main Rotor Diameter | 345mm |
| Weight RTF w/Battery | 227 g |
| Battery | 7.4V 800mAh Li-Po |
| Motor | 180 (2 installed) |

Table 1. Blade CX2 Physical Specifications.

III. Flight Control

Flight control of a helicopter is dependent on three characteristics: trim, stability, and response. Trim refers to the ability to maintain equilibrium with the flight controls fixed. Hover is a trim condition. Stability refers to the response of the aircraft when it is disturbed from a trim state. This will be a major concern when trying to achieve hover – will the helicopter return to equilibrium when it is disturbed or depart from it? The third characteristic, response, refers to the helicopter's response to pilot inputs and external disturbances. This is a major source of complexity since a helicopter typically responds to single-axis inputs or disturbances with a multi-axis response – cross-coupling is unavoidable. However, in the case of hover in a controlled environment in which the controls have been fixed and only small outside disturbances are anticipated, response is not a major concern and therefore cross-coupling will be ignored.

In order to perform control on the BladeCX, we need to have an understanding of the governing equations of motion. This requires an in-depth look at both the aerodynamics acting on the blades and fuselage body and the dynamics of the blades. However, for our system we are able to make simplifying assumptions.

As mentioned previously, for hover in a controlled environment we can ignore cross-coupling effects. Another simplification we will make is to ignore blade flap. In hover, a helicopter's rotor blades experience the same velocity at all points in their rotation. However, in, for example, forward flight, the rotor blades move faster going around the front of the aircraft than they do coming around the backside and the flow can actually become reversed at the inboard edge of this retreating blade. If nothing is done to prevent this, lift will become greater on the advancing blade and lesser on the retreating blade. If this is not prevented, the lift imbalance will lead to torque,

which leads to an unstable flight vehicle. Blade flap is the method by which this torque imbalance is prevented. Blades are hinged at the hub so that the higher-speed advancing blade rises, reducing the angle of attack, and the lower-speed retreating blade drops, increasing the angle of attack. This increase and decrease of angle of attack result in lift coefficient changes, eliminating the imbalance of lift forces.

In our case, blade flap can be neglected for two reasons. First and foremost, the blades on the BladeCX are rigid, not hinged, thus blade flap is not possible. This makes the blade system mechanically simpler, and reduces lag in the control response. Secondly, even if our blades were hinged, in hover, blade flap does not occur since the velocity of all blades is the same at all points in their rotation.

Another consideration that we will neglect is the aerodynamic coupling that occurs as a result of the interactions between the two counter-rotating rotors. Experimental data shows qualitatively that the inner part of the lower rotor experiences a downwash from the upper rotor and the outer part of the lower rotor experiences an upwash from the upper rotor.³ However, lift considerations of each rotor separately is beyond the scope of this project - we will be considering the two rotors as a system acting together to apply a single total lift force, therefore aerodynamic interactions between the two rotors can be neglected.

Based on these simplifications, the rotational and translational equations of motion are fairly straight-forward. By choosing a material point P and calculating its acceleration relative to the center of gravity G , then summing that with the acceleration of G relative to fixed earth and assuming that the sum of the external forces on the aircraft center of mass can be written as:⁴

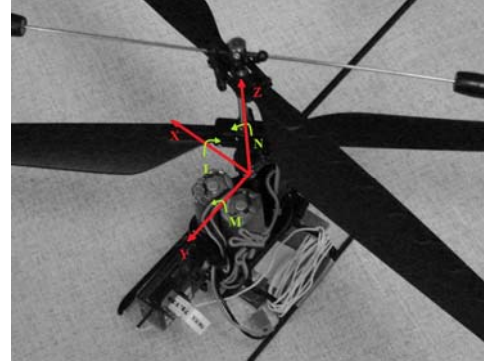


Figure 1. Coordinate System of the Helicopter

$$\vec{F}_g = X\hat{i} + Y\hat{j} + Z\hat{k} \quad (1)$$

Here, X , Y and Z are the forces in the x -, y - and z -directions respectively, Fig. 1 shows the coordinate system overlaid on the actual helicopter. We can calculate each component of force, by integrating the accelerations along each axis, a_x , a_y , and a_z , with respect to the mass, m :

$$X = \int a_x dm \quad (2)$$

$$Y = \int a_y dm \quad (3)$$

$$Z = \int a_z dm \quad (4)$$

Given that the mass of the helicopter, M_a , is:

$$M_a = \int dm \quad (5)$$

then the translational equations of motion can be written as:

$$X = M_a(\dot{u} - rv + qw) \quad (6)$$

$$Y = M_a(\dot{v} - pw + ru) \quad (7)$$

$$Z = M_a(\dot{w} - qu + pv) \quad (8)$$

where \dot{u} , \dot{v} , \dot{w} are accelerations along the x -, y -, and z -axes, respectively, u , v , and w are velocities along the x , y , and z axes respectively, and p , q , and r are rotational velocities about the x , y , and z axes, respectively.

In a similar way, the components of the rotational equations of motion are found to be:

$$L = I_{xx}\dot{p} - (I_{yy} - I_{zz})qr - I_{xz}(pq + \dot{r}) \quad (9)$$

$$M = I_{yy}\dot{q} - (I_{zz} - I_{xx})pr + I_{xz}(p^2 - r^2) \quad (10)$$

$$N = I_{zz}\dot{r} - (I_{xx} - I_{yy})pq - I_{xz}(\dot{p} - rq) \quad (11)$$

where I_{xx} , I_{yy} , and I_{zz} are the moments of inertia about the x , y , and z axes, and I_{xz} is the product of inertia in the xz plane, and the total external moment about the center of mass can be written as:

$$\vec{M}_g = Li + Mj + Nk \quad (12)$$

To account for changes in the coordinate system, rotations about the roll, pitch, and yaw need to be considered. These can be accounted by performing coordinate rotations about the yaw (ψ), pitch (θ), and roll (ϕ) axes, giving the rotation matrix:

$$\Gamma = \begin{bmatrix} \cos \theta \cos \psi & \cos \theta \sin \psi & -\sin \theta \\ \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \sin \phi \cos \theta \\ \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi & \cos \phi \cos \theta \end{bmatrix} \quad (13)$$

While precise equations of motion are useful for determining the gains of the feedback loop, they are not essential to the initial goal of this project. As we will initially be concerned only with controlling yaw and height (z -position) using only ultrasonic sensors and a magnetometer, we will not in fact be concerned with the equations of motion at all in the control loop because the only data we will be able to obtain is absolute position in the z -direction and relative position in the x and y -directions. Thus, initial gains will be estimated using the helicopter's equations of motion as a guideline, but the control will take place by directly observing the position error and providing corrections.

The feedback control system being implemented is the PID controller. Using sensor input and the previous input, the microcontroller will be able to track the gain of the system, using these control loops. The typical PID controller output formula for analog systems follows:

$$m(t) = K \left[e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \right] \quad (14)$$

Here, $m(t)$ is the output of the controller, K is the proportional gain, $e(t)$ is the input to the controller, T_i is the integral time, and T_d is the derivative time. Since this is a continuous time domain form of the PID controller, it is not relevant to computational digital control systems. A discrete time PID algorithm is needed for our purposes. To do so, the integral and derivative terms are approximated using basic calculus principles⁵:

$$\frac{de(t)}{dt} \approx \frac{e(t) - e(t-1)}{T} \quad (15)$$

$$\int_0^t e(t) dt \approx T \sum_0^t e(t) \quad (16)$$

Imputing these approximations into the above equation, and by taking the z transform of the equation, we get the digital PID transfer function.

$$\frac{M(z)}{E(z)} = \left[K_p + \frac{K_I}{1-z^{-1}} + K_D(1-z^{-1}) \right] \quad (17)$$

Where,

$$K_p = K - \frac{K_I}{2} \quad (18)$$

$$K_I = \frac{KT}{T_i} \quad (19)$$

$$K_D = \frac{KT_d}{T} \quad (20)$$

Here, K_p is the proportional gain, K_I is the integral gain, and K_D is the derivative gain.

Tuning the gains of the system will primarily be done manually. The reasons for this are twofold: first, the instability of flight of the helicopter makes it difficult to correctly tune without trial and error, and second, our gains

can only be approximated due the fact that the simplifications made in deriving the equations of motion render it inexact.

IV. Control System

The goal of hands off hover requires, at a minimum, a means to observe yaw and altitude. There are multiple means to achieve these measurements, but no single sensor exists that will make the measurement directly. We require accurate high frequency response, in order to adequately sample the dynamics of the system, but also zero drift in the sensor outputs, so that we can maintain the desired position. This requirement for Ac and Dc response necessitates combining the signals from multiple sensors in order to achieve the desired measurements. For example, inexpensive MEMS-based gyros for sensing angular rate are widely available and have high frequency response extending to a few kilo Hertz. However, these devices tradeoff higher Dc drift for low mass and low power consumption, relative to higher performance gyros. Typical drift rates for low-cost MEMS gyros are 40 degrees/minute (with temperature calibration) to 150 degrees/second (without temperature calibration). Even the best low cost gyros exhibit drift at rates that would be noticeable to the human controlling the helicopter and would be problematic for an automated control system. This can be addressed by using a magnetometer to supply the Dc component of the sensor data for yaw. Small, multi-axis magnetometers are available from several companies, including PNI^{*}, Honeywell[†], and AKM[‡].

A similar issue with Dc performance exists for sensing altitude. While very small MEMS-based accelerometers are available, sensor noise, when integrated twice to compute displacement, rapidly overwhelms the actual signal. The presence of a Dc signal due to gravity adds additional complexity. Ideally this signal, which can be measured as a three dimensional vector, could be subtracted from the signal and the actual acceleration of the helicopter would be attained. Unfortunately, any small rotation in the helicopter's body frame will cause the direction of the gravity vector to change. This requires that an additional angular sensor be used to allow the system to discriminate between an actual acceleration, due to thrust from the rotor and a change in pitch or roll. The gyroscopes might enable this measurement, except that the aforementioned drift will quickly invalidate the measurements. For this reason, while the higher frequency components of the helicopter's acceleration are easily measured with an accelerometer, other sensors are required for estimating altitude. A barometric pressure sensor can be exploited for coarse estimates of altitude and an ultrasonic range finder yields more accurate short range measurements of height above ground.

We are certainly not the first team to require a small IMU, which incorporates multiple sensors. Numerous IMU systems that integrate accelerometers, gyroscopes and magnetometers are available. Examples include the IMU300 from Crossbow[§], the ADIS16354 from Analog Devices^{**}, and the nIMU from MemSense^{††}. These systems integrate accelerometers and gyroscopes and use on-board processing to perform sensor acquisition, data fusion and compensation. Unfortunately none met the stringent requirements for low mass, low volume and low cost that our system's design imposes. This required us to build our own system from individual sensor components. While adding an additional layer of complexity to our task, this also affords great flexibility in optimizing mass, cost and functionality.

Inertial sensors are available with myriad sensitivities and frequency responses. In order to select sensors that are appropriate for our platform we need to know more about its dynamics. Sensors with full-scale sensitivities too far inside the performance envelope of the system would likely be quickly overloaded, while sensors with large full-scale sensitivities would not yield sufficient accuracy. Additionally, the frequency response of the sensors must be large enough to adequately sample the dynamics of the system. The Nyquist criterion states that to properly sample a system the sampling rate must be at least twice the highest frequency present in the system. This requires that we place a practical bound on the likely linear and angular accelerations in the system. In order to do this we model the helicopter as a rigid body, with a mass M_o and moment of inertia I . The helicopter is subject to drag and for the sake of simplicity, we will model this as a function of velocity only, with no higher order terms. The drag coefficient for linear motion will be D_x , and the drag coefficient for angular acceleration is D_θ . The equations of motion are shown below, where F_g is the sum of the linear forces acting on the helicopter, and τ is the sum of the angular torques acting on the helicopter.

* <http://www.pnicorp.com/>

† <http://www.honeywell.com/>

‡ <http://www.akm.com>

§ <http://www.xbow.com>

** <http://www.analog.com>

†† <http://www.memsense.com>

$$M_a \ddot{x} + D_x \dot{x} = F(t) \quad (21)$$

$$I \ddot{\theta} + D_\theta \dot{\theta} = \tau(t) \quad (22)$$

It would be useful to know the frequency response of this system, in order to know the required frequency response of our sensors. By taking the Laplace transforms of the equations of motion, the transfer functions for linear and angular motion are:

$$G(s) = \frac{1}{s^2 M_a + s D_x} \quad (23)$$

$$G(s) = \frac{1}{s^2 I + s D_\theta} \quad (24)$$

By substituting $j\omega$ for s we obtain the magnitude of the frequency response:

$$|G(\omega_x)| = \frac{1}{\sqrt{\omega^2 D_x^2 + \omega^4 M_a^2}} \quad (25)$$

$$|G(\omega_\theta)| = \frac{1}{\sqrt{\omega^2 D_\theta^2 + \omega^4 I^2}} \quad (26)$$

These two equations demonstrate that the system exhibits a low pass response, so if the parameters D_x , D_θ , M , and I can be determined, an upper bound on ω can be set. This upper bound is the effective frequency response of the system, and the sensors that we use should be able to respond at this frequency. As a first approximation, the D_x and D_θ terms can be ignored in estimating the cutoff frequency. If a 40db cutoff, relative to $\omega=1$ is arbitrarily established then ω_x , ω_θ can be bounded to less than 10 rad/sec. This is not to say that the angular rotation will never exceed this value, this is mean as a bound on the frequency response of the system to broadband excitation.

A six axis load cell allowed us to estimate the maximum thrust and maximum torque that the helicopter is capable of producing. The maximum thrust measurement, T_{max} was made with both sets of rotors spinning at their maximum rate, and the maximum torque, τ_{max} was measured with one motor completely off. See appendix for experimental results which found the maximum torque and lift force of the helicopter. We also estimated the moment of inertia, I by measuring the mass of individual components and their distance from the center of rotation.

$$\tau_{max} = .045 \text{ Nm} \quad I = .42 \times 10^{-3} \text{ kgm}^2 \quad M_a = .220 \text{ kg} \quad T_{max} = 2.8 \text{ N}$$

It should be noted that the value for τ_{max} is larger than it will ever be during the actual operation of the helicopter, as it is unlikely that completely stopping a blade will ever be a controllable point about which we would like to operate. Likely torques will probably start at ten percent of τ_{max} and diminish. The high frequency portion of the linear position estimate will come from accelerometers, while the high frequency component of the rotation will come from a gyro. The maximum plausible signals from each, neglecting the damping terms due to aerodynamic loading, are:

$$\ddot{x}_{max} = \frac{T_{max}}{M} = 12.7 \text{ m/s}^2 \quad \ddot{\theta}_{max} = \frac{\tau_{max}}{I} = 10.7 \text{ rad/s}^2$$

The aerodynamic loading coefficients are difficult to estimate, and will tend to reduce the maximum value, so they can be omitted for the purposes of determining an upper bound. As the gyros are actually measuring $\dot{\theta}$, rather than the angular acceleration, $\ddot{\theta}_{max}$ must be integrated. If the helicopter were allowed to accelerate unchecked for one

second at $\ddot{\theta}_{\max}$, the angular rate would be 613 degrees/second. In reality, the control loop will respond faster than one second, so sensors with a lower maximum rate could be used.

V. The Sensors

The goal of low weight is analogous to small size, so we chose components that were in very small, surface mount packages.

A. Gyros

While accelerometers are widely available in 3 axis products, we were unable to obtain any gyroscopes with this level of integration. Many IMU designs exploit three identical Gyro packages, and orient them normal to each other in order to achieve three axis sensitivity. This seems straightforward, but it imposes the requirement to mount one of the sensors normal to the circuit board, which presents manufacturing and alignment challenges. We chose instead to use two different gyro packages. One, the two axis IDG300 from Invensense^{††}, allows integrated pitch and roll sensing. The other gyro, an ADIS 16100 from Analog Devices^{§§}, enables yaw axis sensing, in a package that mounts flat on the board, obviating the need for a perpendicular mounting scheme. The ADIS 16100 uses a digital SPI interface and has a full scale sensitivity of +/- 300 degrees/second. The IDG300 provides an analog output and a full scale sensitivity of +/- 500 degrees/second. Both devices allow user selectable low pass filtering, and we have limited the bandwidth of each device to 40 Hz, and each device is sampled at 100Hz.

B. Accelerometer

There are many integrated 3 axis accelerometers available, as these devices are finding applications in a multitude of consumer devices. The three axis KXR94-2353 from Kionix^{***} provides full axis sensitivity of +/-5g and uses a digital SPI interface. It allows user selectable low pass filtering, which we have set to 40Hz and the device is sampled at a 100 Hz rate.

C. Magnetometer

Like the Gyro, there are few completely integrated 3 axis magnetometers available. Most of the available parts either a too large, or include only 2 axis sensitivity. In this case, we were forced to choose a solution that requires a physical mount normal to the main board. The MicroMag3 from PNI^{†††} integrates a very low power, and fairly broad band magnetometer with an ASIC for signal conditioning. The device provides 3 axis sensitivity, and a digital SPI interface. The part is sampled at 100Hz.

D. Pressure Sensor

The SCP1000 from VTI^{†††} is an absolute barometric pressure sensor with a digital output option. It has an onboard temperature sensor that allows calibration and has an advertised minimum resolution of 10cm altitude in the low sample rate, high sensitivity mode. At 1.8Hz, this device has a low update rate, but can be used to provide the low frequency component of the altitude signal. It is internally band limited, and sampled at 1.8 Hz.

E. Range Sensor

The intended operating environment for the helicopter is indoors, where GPS reception is poor. The challenges of dead reckoning with noisy, inexpensive sensors make this option unfeasible for this application. We have selected ultrasonic range sensors to provide absolute position inputs. There are four LV-MaxSonar-EZ0 modules from Maxbotix^{§§§} that provide range from .15 to 6.4 meters. Each sensor weighs 2 grams. The four sensors are sampled at a 20Hz rate and one of each is oriented down, back, 45 degrees left of forward and 45 degrees right of forward.

F. Servo Control and Operator Radio command link

As sold, the Blade CX provides a 72MHz transmitter, and integrated receiver, gyro and motor control unit. This module has been replaced by our new control system, and we have chosen the 1.2 gram Micro9-S-4CH 900MHz

†† <http://www.Invensense.com>

§§ <http://www.analog.com>

*** <http://www.kionix.com/>

††† <http://www.pnicorp.com>

††† <http://www.vti.fi/en/index.html>

§§§ <http://www.maxbotix.com>

receiver from Plantraco^{****}. The PWM signals from this receiver are passed to our new control board where they are captured by a dedicated timer module. These control inputs are then used as the input point of the PID control loop that generates the actual signals which are then sent to another PWM generator in order to command servos. The motor control is identical to the servo control, except that the motor control uses an additional low-side MOSFET switch to affect speed control by modulating the current to the motor.

G. Sensor Fusion and Data Processing

While each of the sensors provides a subset of the signals required by the control loops, no one sensor is capable of supplying the entire signal. The sensor signals must be acquired, integrated, filtered and calibrated in order to be useful to the control system. This system also has the obvious requirement of real-time operation, so we decided to partition the processing load across multiple processors. The low level data acquisition, sensor fusion, filtration and servo I/O is handled by an MSP430F2618 from Texas Instruments^{†††}. The MSP430 is a family of small, low power flash based microcontrollers that integrate a broad line of peripherals on-chip. It includes several timer modules for PWM I/O as well as multiple serial ports. The MSP430 in this system is integrated into an 18 gram board with all of the sensors and is responsible for setting the sample rates, performing FIR filtering of the input data streams, receiving R/C input from the operator and commanding the motors and servos. It is also capable of implementing very simple control loops, and our first attempts at closed loop control use this device alone. The MSP430 does not have sufficient capability to handle multiple matrix inversions or implement the Kalman filtering that we believe will be required for future progress. For this reason, the MSP430 and sensor board is designed to mate with a small Linux based computer from Gumstix^{‡‡‡}. This 8 gram board provides a 400MHz processor, with 128MB RAM and a 32MB flash memory for code. The two processors communicate via an RS232 link, with the MSP430 providing sensor data, and the Gumstix module providing command outputs for the motors and servos. The entire system, including all sensors, R/C control and data processing weighs 34 grams, or roughly 70% of the Blade's 50 gram payload capability.

VI. Conclusion

Our first benchmark in this project is achieving stable hover without pilot controls using only the magnetometer and the ultrasonic range sensors. From here we will continue to integrate the rest of the sensors on the IMU along with additional range sensors and a low weight camera system with the final goal of achieving completely autonomous flight. We also hope to generalize the IMU board to enable it to be used in a variety of applications.

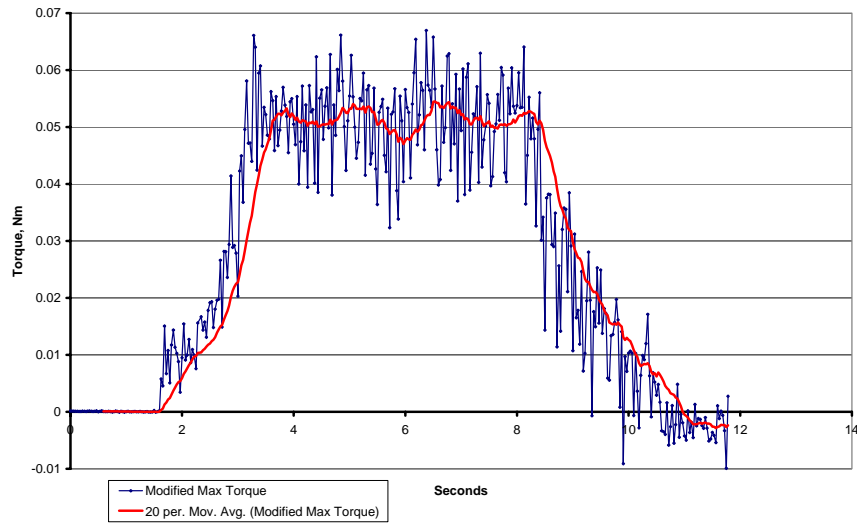
**** <http://www.plantraco.com>

††† <http://www.ti.com/>

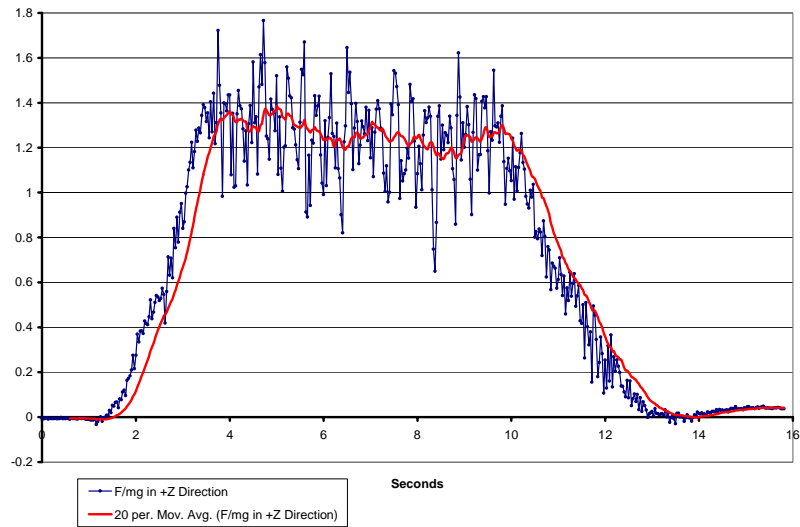
‡‡‡ <http://www.gumstix.com/>

Appendix

Maximum Yaw Torque with 900mAh Battery



Non Dimensional Lift Force with 900mAh Battery



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