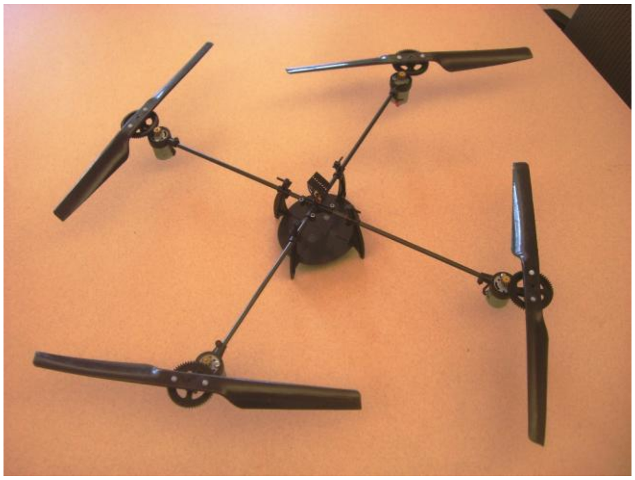
Testing Autonomous Hover Algorithms Using a Quad rotor Helicopter Test Bed

In conjunction with

University of Washington Distributed Space Systems Lab

Justin Palm
Andy Bradford
Andrew Nelson



Milestone One Report

9 April 2010

Under the instruction of Professor Eric Klavins

Introduction

What is a quad rotor? A quad rotor is a type of helicopter that has four independently controlled motors each connected to separate airfoil blades. The quad rotor system is a very stable platform achieved by opposing motor direction that allows for easy hovering capabilities. This quality makes it an ideal candidate for testing autonomous flight algorithms. This paper will discuss to whom the project is intended and define the functional requirements that they demand. In addition, we will describe the performance criteria to meet those demands by identifying the system plant, actuators, sensors, and control resources. Also included is the project schedule and costs associated with the proposed system.

The Customer

Professor Mesbahi is our customer who also heads up the Distributed Space Systems Lab (DSSL) which focuses on numerous areas of controls in engineering such as: guidance, navigation and control of both single and multi-platform aerial (and space) systems. The Lab has one Quad Rotor that has only flown under direct remote control. The customer desired to autonomously fly a Quad Rotor helicopter to a specified waypoint in 3D space using first an overhead Vicon positioning system. It is the customers desire to have this quad rotor A later goal included replacing the Vicon system with an onboard IMU, GPS and ultrasonic range finder for outdoor flights. This control system is much different than the original Gumstix and Robostix control system in order to simplify and expedite the project with known programming software and language.

Performance Criteria

As mentioned above, the first part of our project will employ the indoor Vicon system. Once we have achieved our initial goals using this system, we will scale the system to allow for outdoor flight. Because of this, we have split the performance criteria into indoor and outdoor sections as they will differ substantially.

After researching specifications from the internet regarding the quad rotor helicopters, we averaged and estimated flight performance. Flight durations on average last about fifteen minutes and response times [from commanded input to final position] of fifteen seconds or less were noted. Vertical climb and horizontal velocities of twenty feet per second were approximated, which will be limited due to the size of the during the hover operations, we expect almost no steady state error. Empty weight also has an effect on the performance so it will be another goal of ours to maintain it at a minimum, allowing for longer flights. The microcontroller’s clock is 20MHz and other system latencies are unknown, however, they are estimated to be less than the requirement for autonomous hover control. The functional and performance requirements for the quad rotor system are listed below.

Indoor Performance Criteria

Functional Requirements

1. Fully autonomous control with a given position
2. Automated sustained hover at a location in 3D space
3. Controlled take offs and landings
4. Payload capability
5. 30 minute flight time
6. Low battery return home feature

Performance Requirements

1. Positional accuracy of better than 1 inch in each direction (x,y,z).
2. Capable of handling system latency of up to 50 ms.
3. Less than 10 seconds to complete any position change within the Vicon system (approximately 360 cubic feet).
4. Capable of carrying a 4 oz. payload on top of the base system weight.
5. Battery monitoring input to microcontroller 1Hz resolution.

Outdoor Performance Criteria

Functional Requirements

1. On board position tracking and feedback
2. Interface with GPS
3. Be able to reject outdoor disturbances (i.e. wind).
4. React to changes in the ground

Performance Requirements

1. Lateral velocity of more 15ft/s.
2. Vertical velocity of more than 10ft/s
3. Positional accuracy within 1 meters (GPS limited)
4. Scale the Electrical Engineering building in 20 seconds

Plant and System Modeling

In order to develop a control loop, we must first describe the forces involved in the system. Figure 1 below shows a free body diagram of the system. The actuators of the plant are DC motors. Each motor spins an airfoil blade that generates a thrust. The entire system has a center of mass that (ideally) is located at the geometric center of the quad rotor. In this basic configuration, each of the motors respective thrust equal one quarter of the total weight to achieve hover. By controlling the speed of each motor relative to each other allows control of the pitch (θ), roll (ϕ), and yaw (ψ).

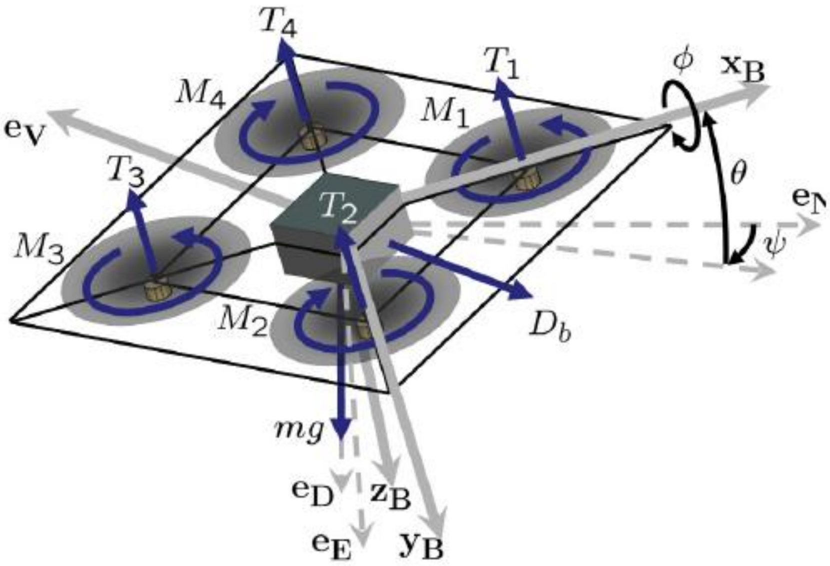


Figure 1: Free body diagram of the quad rotor system. [1]

One of the benefits of the quad rotor design is its inherent yaw stability. This is achieved by counter rotation of adjacent motors. Referring to figure 1 above, motors M1 and M3 spin in the same direction whereas motors M2 and M4 are spinning in the direction opposite M1 and M3. This feature makes the quad rotor an ideal platform for autonomous position tracking.

The free body diagram above has been used by the distributed space system lab to create a system model. That model will be used in our control implementation and effectively replaces the Plant block shown in figure 2 below.

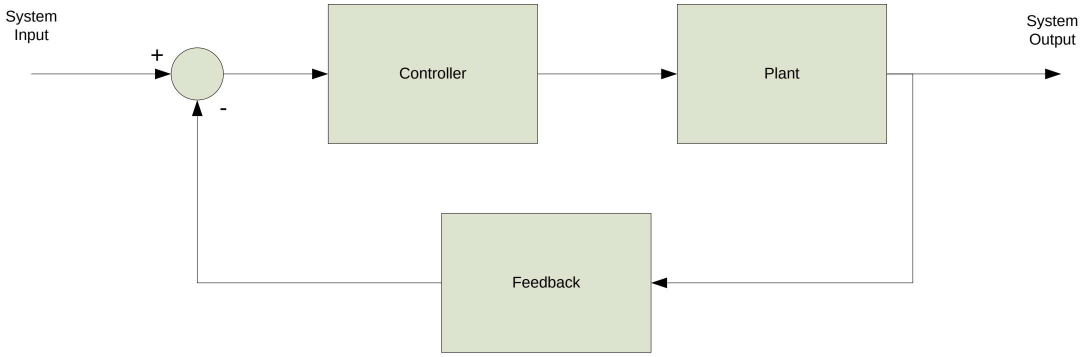


Figure 2: Top level feedback loop

In order to achieve automation, a feedback control loop will be employed. As our initial goal is to achieve automation by using the Vicon system in the DSS Lab. This system consists of 6 six infrared cameras that are able to track reflective balls/nodes to within 0.1mm accuracy. The system includes the software interface that outputs precise position data that we will then use in the control loop. A picture of the Vicon camera system and computer is shown below.

Figure 3: Vicon computer system

Figure 4: Vicon infrared camera

System inputs and interfaces

The proposed solution to the project was to use the Gumstix Virtex Pro microcontroller platform on the quad rotor interfacing to their Vicon motion capture setup using Wi-Fi. There were several shortcomings to this system. The major drawback was using the motion capture setup limits the usage of the quad rotor to inside the room. The second is that using the motion tracking over wifi would produce serious latency in the control loop. While this should not pose much of an issue, it could limit the speed of movement of the quad rotor due to it becoming unstable with fast position changes. The third issue is the Gumstix are pretty bloated and overly complex for our purpose. Running a full blown Linux kernel means that there will be significant overhead in all operations. Since we would be programming the system in user mode, the Linux kernel has the ability to preempt our feedback control at any time and the system will offer very little in real-time constraints. This could be alleviated by using something like Xenomai, but we are not sure how well the system is supported under the Gumstix platform. Another difficulty comes where only one in three people in the group is experienced with Linux and had systems actively running Linux. Since the tool chain is only supported under Linux, this limits our ability to do development for the system. Solving these issues is what made us decide to consider a different approach to the electronics.

In order to simplify the design, we are building the system in two parts. The first will be to build a simplified system where the position is detected using the Vicon system and Matlab and Real-Time Workshop. The feedback loop will be implemented directly on the computer running Matlab. Matlab will then feed out the raw duty cycles for the PWM control on the motors over a 900MHz wireless link to the quad rotor. This will allow rapid prototyping and help us create a solid control model for the quad rotor in just a few weeks. Since we are using a dedicated 900MHz wireless link instead of wifi of the Gumstix, latency with the system should be much less.

The electronics system that we will be using is shown in Figure 5. Since the entire feedback system is running on a computer, the microcontroller that needs to be on the quad rotor has very low requirements. The ATMega328 is chosen mostly due to being easy to program and able to be expandable for the second phase. We will be connecting the wireless link directly into the ATMega over the UART interface on the microcontroller. We chose to use the Digi XBee Pro 900 radios due to the 1.8 Mile line of sight transmission distance they offer with 156 Kbps data rate. We chose to stick with 900 MHz over 2.4 GHz due to less congestion on the 900 MHz band and lower path loss. This radio link will be both used for sending commands and debugging flight characteristics. The motor drive will connect to four PWM outputs on the ATMega, one for each motor on the quad rotor. The entire system will run off a TDK Lambda 3.3v switching regulator powered by a 2100mAh 3-cell lithium polymer battery. This will be the same battery used for powering the motor drive system. The computer acting as the feedback loop will connect to the 900MHz radio over USB and will get its input from the Vicon setup over Ethernet.

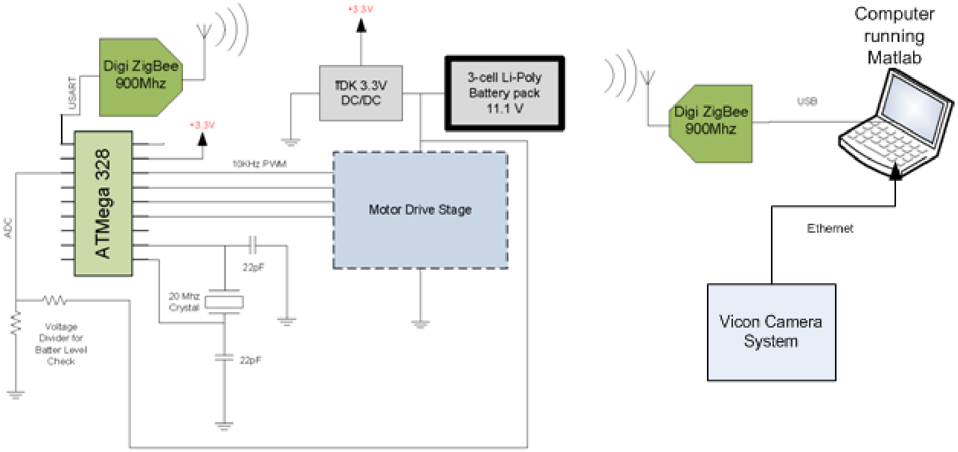


Figure 5: System diagram showing the Indoor Vicon System

Once the system is working in Matlab, we will be working on removing the reliance on the Vicon system. In order to do this we will need to move sensing of position to the quad rotor. Due to the drop in price of MEMs sensors, we will be able to use a full inertial measurement unit (IMU) on the quad rotor with a small budge and with low weight. This (IMU) will provide 3-axis accelerometers, gyroscopes, and magnetomometers for position sensing. We will be supplementing this with GPS in order to get more accurate sensing of position and account for drift in the other sensors. In order to minimize collisions with the ground, we plan on also adding an ultrasonic range finder. Communication with the quad rotor will be using the same 900MHz radio modules we used in the first part.

This improved advanced package is shown in Figure 6 below. We will keep all the electronics hardware from the original setup except for the Vicon system and add to it. It is now become possible to do full inertial sensing on the quad rotor without sacrificing weight and cost. Within the past month, STMicro has released the first development board in their iNEMO line. The STEVAL-MKI062V1 offers 3-axis accelerometers, 3-axis gyroscope, and 3-axis magnetomometer sensing. These sensors are all tied together into a 72Mhz Arm Cortex M3 microprocessor with the entire unit only taking up 4.5cm x 5cm. We plan to use this for the basis of the second phase of our system. This will be where we will implement our feedback loop. Attached to the USART port on the IMU will be a 900MHz ZigBee radio module, which will be moved from the ATMega's UART port from the previous system. Since the STMicro development board only has one free UART port, we will use the UART on the ATMega to interface with the GPS. To sense the ground and make sure we don't crash into it, we will be using an ultrasonic rangefinder. This will interface with the ATMega due to it having extra ADC ports free. The ATMega and the STMicro will communicate with each other over the SDI port. This port was chosen due to the fast speed and that it is the one interface that both microcontrollers have free. Agian, the main purpose of the ATMega in this system will be to get commands for the motors and setup the PWM outputs. It will also be relaying the auxiliary sensors to the STMicro board. We will also be using the same motor drive system from the first part and the same battery and 3.3v regulator since all added sensors also run off of 3.3v power.

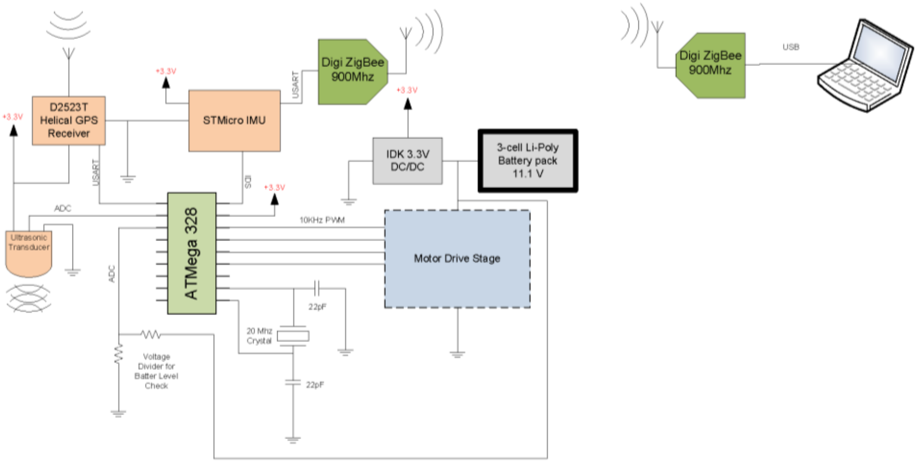


Figure 6: system diagram showing the Vicon system replaced by an IMU (Inertial Measurement Unit) and ultra sonic transducer

Cost and Schedule constraints

The Distributed Space Systems lab has granted the money to build two quad rotor systems. The parts required for the two systems are outlined below. This proposal has been approved and the parts are currently en route.

Name	part number	distributor	cost	qty.	ext.
Draganflyer Airframe	DF-COMPLETE-AIRFRAME	rctoys.com	$119.95	1	$119.95
Draganflyer Frame Bracing	DF-FRAMEBRACING	rctoys.com	$14.95	2	$29.90
2100mAh 11.1v LiPo	TP-2100-3SPL2	rctoys.com	$47.99	2	$95.98
Deans Battery Connector Pair	DE-ULTRA	rctoys.com	$3.55	2	$7.10
900MHz Dipole Antenna	WRL-09143	Sparkfun	$7.95	4	$31.80
Digi XBee Pro 900	WRL-08768	Sparkfun	$44.95	4	$179.80
XBee Explorer USB	WRL-08687	Sparkfun	$24.95	2	$49.90
Ultrasonic Range Finder	SEN-08502	Sparkfun	$27.95	1	$27.95
GPS Reciever	GPS-09566	Sparkfun	$79.95	1	$79.95
GPS Interface Cable	GPS-09123	Sparkfun	$2.95	1	$2.95
Atmel ATMega328P	COM-09061	Sparkfun	$4.30	2	$8.60
STMicro iNEMO IMU	497-10048-ND	Digikey	$250.00	1	$250.00
3W 3.3v DC-DC Regulator	445-2474-ND	Digikey	$11.37	2	$22.74
20.000 MHz Crystal	300-8507-ND	Digikey	$0.63	2	$1.26
22pF Ceramic Cap	BC1005CT-ND	Digikey	$0.08	10	$0.76
6-pin header	609-3218-ND	Digikey	$0.37	2	$0.74
Optioisolator	160-1370-5-ND	Digikey	$0.75	10	$7.50
PTC Fuse	F3189-ND	Digikey	$0.84	4	$3.36
Motor Drive Stage	Many Parts	EE Store	$10.00	2	$20.00
				Total	$940.24

Figure 7: Parts list and total reflecting 2 complete quad rotor systems

Estimated Project Timeline

Tasks	Week of...									
	5-Apr	12-Apr	19-Apr	26-Apr	3-May	10-May	17-May	24-May	31-May	7-Jun
Preliminary Design Complete and Order Parts	■									
Build/Test Motor Drive, Setup wireless comm. & Microcontroller		■								
MS2: Build Simulink Models, Complete Remainder Hardware/Assembly/Testing			■	■						
First Flight(Open Loop), System Model Validation, Technical Documentation				■	■					
MS3: Controller Design, Control System validation, Automation Algorithms					■	■	■			
Autonomy Achieved, Autohover and Waypoint Tracking							■			
MS4: Controller Implentation							■	■	■	
Advanced Maneuver Algorithms (Fly In Circles, Spin in place...)								■	■	
LAB Visit by Mr. Klavins and Technical Documentation									■	
Final Reports Due										■

Technical Obstacles

Most of the difficulties with the quad rotor will be getting the thing to have stable flight. Even though the quad rotor is the most stable helicopter known, the stability just gives us the ability to hover without needing feedback. The actual models for flight are still quite complex. While we have one quarter to work on this project, the grad students in the Distributes Space Systems Lab have spent the past year working with the quad rotor, all the farther they have gotten is to create model parameters and some simulations. We have not had a chance to study this work yet much, so we don't know how good the models are. If there are issues in the model and it doesn't end up matching the quad rotor very well, we could have a very hard time tweaking the model to work.

A side issue with the model could be its ability to reject disturbances. While inside, there are very few disturbances that could affect the quad rotor, outside the wind can cause significant issues. Once outside we will need to verify that the system is still capable of remaining stable when the wind starts blowing. Also outside there are many objects we could collide into. Due to limited time, we probably won't be able to implement full collision avoidance because this would require many more sensors and algorithms for what should happen when something looks like it will collide. This alone could be a huge and expensive project to implement. For this reason, we will pick the routes we give the quad rotor and make sure there is nothing in the way to hit.

Once we start working outside we will be losing quite a bit of precision due to the lack of resolution of GPS. While modern GPS units are rated to within 2.5 meters, we could like to be more accurate than that. In order to do this, we will need to test the area and see what type of reception we get. This may also require implementing something like Kalman Filters for the IMU data to improve accuracy.

Another issue we could have with the system is getting is getting the Vicon system to interface well with Matlab. Being a system made primarily for post processing work and not one made for real time data acquisition, the Vicon system's interfaces are poorly documented. While there are some scripts that the DSSL lab has to get the data out to Microsoft C\#, they have not used the interface to Matlab. This shouldn't be too much of a problem implementing, but since none of us have worked with the system it is hard to say.

The final issue we will have is the due to the shortness of the quarter. This is a large project to try and tackle in 10 weeks. The quad rotor is a project that was started over a year ago, so being able to finish in 10 weeks may be pushing it. While we have most of the experience needed in the team to implement the system, there is still going to be a lot of work to do. If we run into any major problems, it could extend the time to finish well past the end of the quarter.

Team Management

We have an excellent mix of skills with the group we have selected. In addition, we all have experience working with each other. These qualities will allow for smooth transitions through the milestones we have set as described in the project timeline above.

Justin Palm: Project Manger and Hardware Engineer
    Major: Electrical Engineering
    Concentrations: Analog Systems, Power Electronics, Controls Systems
Andrew Nelson: Lead Software Engineer
    Major: Electrical Engineering/Computer Science Engineering
    Concentrations: Analog Systems, Controls Systems, Rockets and Instrumentation
Andy Bradford: Lead Systems Engineer
    Major: Aeronautical Engineering
    Concentrations: Aeronautics, Controls, Composites

References

1. Hoffman, G. M., Huang, H., Waslander, S. L., Tomlin, C. J., "Quad rotor Helicopter Flight Dynamics And Control: Theory and Experiment," AIAA 2007-6461, August 2007