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The Problem:

- It's difficult to film extreme sports
  - Mountain biking
  - Snowboarding/skiing
  - Cross country running
  - White water rafting

Helmet mounted GoPro Camera

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Poor focus, blurriness, and distortion

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Traditional Options

- Helmet cameras get boring fast
- Cameramen along the path are no good
- A vehicle might work...

But is expensive

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Quadrotor Advantages

- A quadrotor can
  - Fly closer to the athelete
  - Operate at lower costs
  - Be more portable and available
  - Carry large payloads

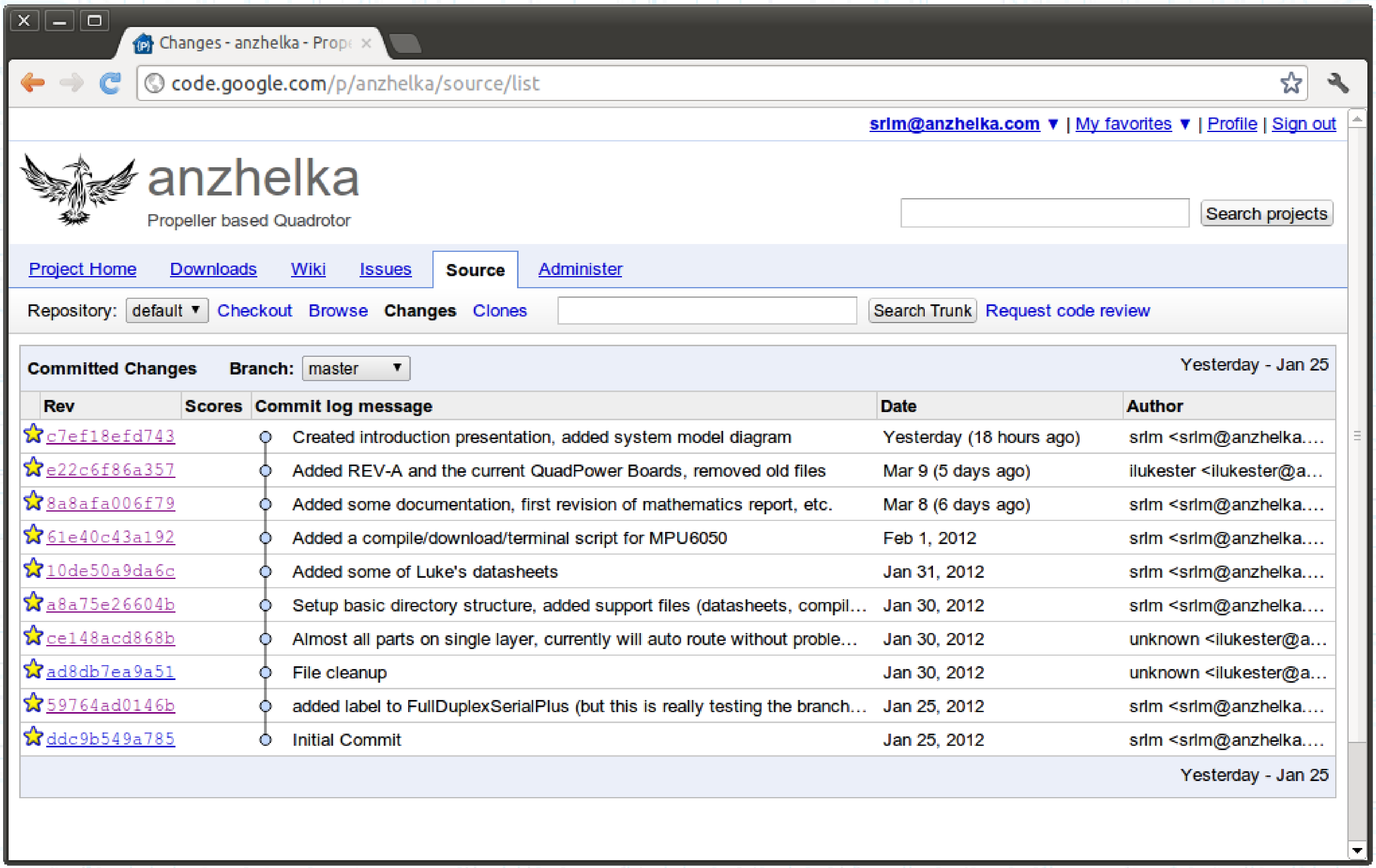
Goal

Create a fully programmable aerial quadrotor that is autonomous, stable, and controllable

Ancilliary Goals

- Create stable quadrotor platform
- Use Parallax P8X32A for low level control
- Be completely open source, from hardware to software
- Have extensive and up to date documentation on all aspects

Open Online Repository



Changes - anzhelka - Prop

code.google.com/p/anzhelka/source/list

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Propeller based Quadrotor

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Committed Changes **Branch:** master ▼ Yesterday - Jan 25

Rev	Scores	Commit log message	Date	Author
c7ef18efd743		Created introduction presentation, added system model diagram	Yesterday (18 hours ago)	srlm <srlm@anzhelka....
e22c6f86a357		Added REV-A and the current QuadPower Boards, removed old files	Mar 9 (5 days ago)	ilukester <ilukester@a...
8a8afa006f79		Added some documentation, first revision of mathematics report, etc.	Mar 8 (6 days ago)	srlm <srlm@anzhelka....
61e40c43a192		Added a compile/download/terminal script for MPU6050	Feb 1, 2012	srlm <srlm@anzhelka....
10de50a9da6c		Added some of Luke's datasheets	Jan 31, 2012	srlm <srlm@anzhelka....
a8a75e26604b		Setup basic directory structure, added support files (datasheets, compil...	Jan 30, 2012	srlm <srlm@anzhelka....
ce148acd868b		Almost all parts on single layer, currently will auto route without proble...	Jan 30, 2012	unknown <ilukester@a...
ad8db7ea9a51		File cleanup	Jan 30, 2012	unknown <ilukester@a...
59764ad0146b		added label to FullDuplexSerialPlus (but this is really testing the branch...	Jan 25, 2012	srlm <srlm@anzhelka....
ddc9b549a785		Initial Commit	Jan 25, 2012	srlm <srlm@anzhelka....

Yesterday - Jan 25

Open Hardware

Parallax Elev-8

Open Costs

Supplier	Name	Unit	Qty	Total
Parallax	Altimeter	$29.99	1	$29.99
Parallax	Protoboard USB	$29.99	1	$29.99
Parallax	Propeller Chip QFP	$7.99	1	$7.99
Parallax	64KB EEPROM	$1.99	1	$1.99
Parallax	5 MHz Crystal	$1.10	1	$1.10
Sparkfun	Radio Modem UM96	$44.95	2	$89.90
Hobby King	450 Outrunner Motor - Trinigy	$14.04	4	$56.16
Hobby King	30A ESC	$5.99	4	$23.96
Hobby King	3S 30C 1000mAh Battery	$8.99	1	$8.99
Hobby King	3S 30C 8000mAh Battery	$44.11	1	$44.11
Hobby King	Deans XT Plugs (10 pairs)	$3.08	2	$6.16
Hobby King	12 AWG 1 meter wire BLACK	$2.49	3	$7.47
Hobby King	12 AWG 1 meter wire RED	$2.49	3	$7.47
!McMaster-Carr	5/8" Aluminum Tubing 6'	$16.38	1	$16.38
!McMaster-Carr	3/32" Delrin 24"x48"	$70.67	1	$70.67
!McMaster-Carr	1/4" Delrin 12"x12"	$27.87	1	$27.87
!McMaster-Carr	4-40 5/8" Standoff	$0.46	12	$5.52
Amazon	Optima 7 RC Receiver	$58.04	1	$58.04
DIY Drones	Propellers 10x4.5 1 push 1 pull	$6.00	2	$12.00
Pololu	CHR-UM6-LT IMU Sensor	$149.99	1	$149.99

$655.75 per quadrotor

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Specific Technical Goals

- Maintain pitch/roll/yaw to desired angle
- Traverse to desired position
- Carry a payload of small video camera
- Be able to yaw/tilt payload

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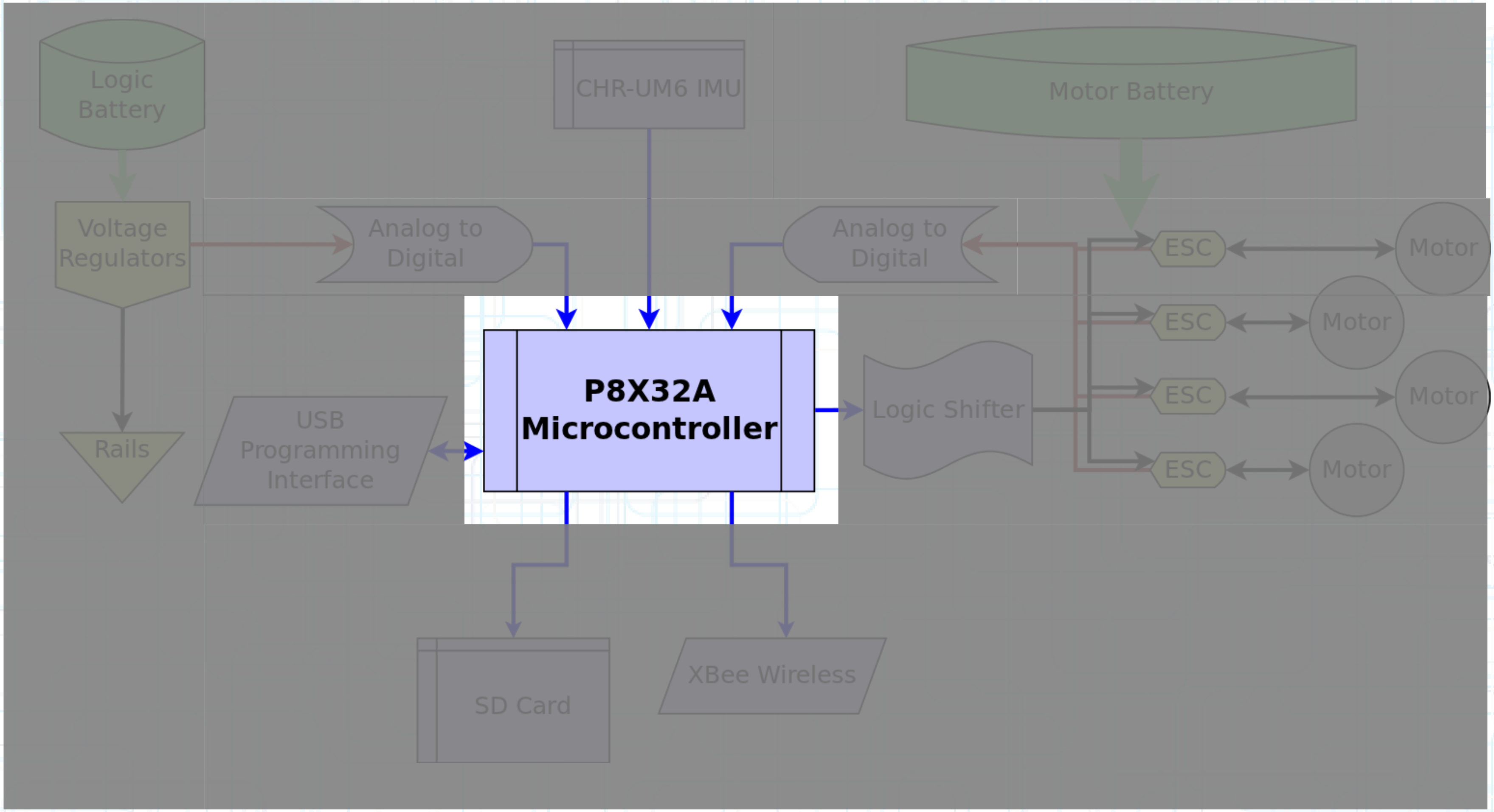
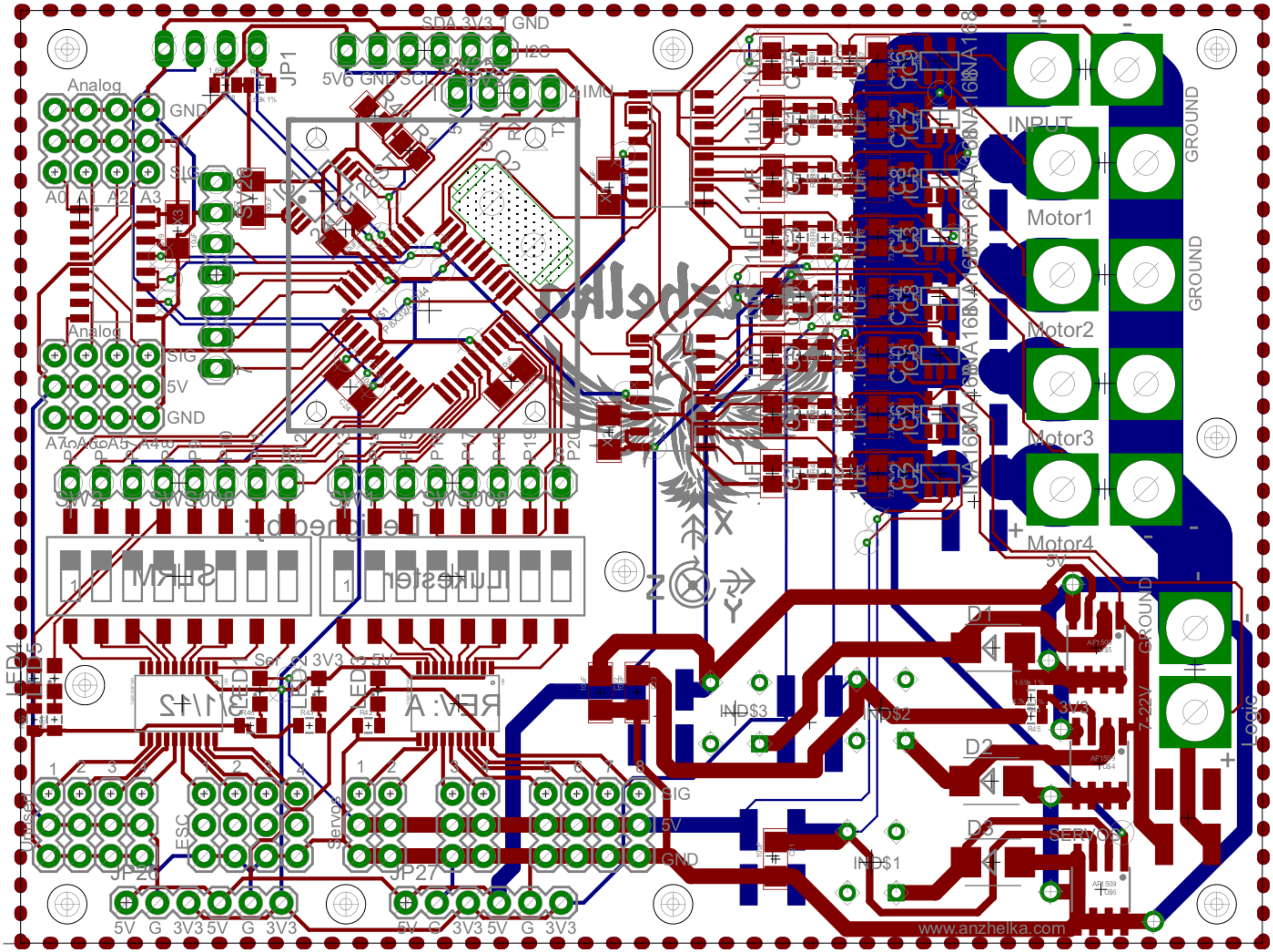
System Architecture

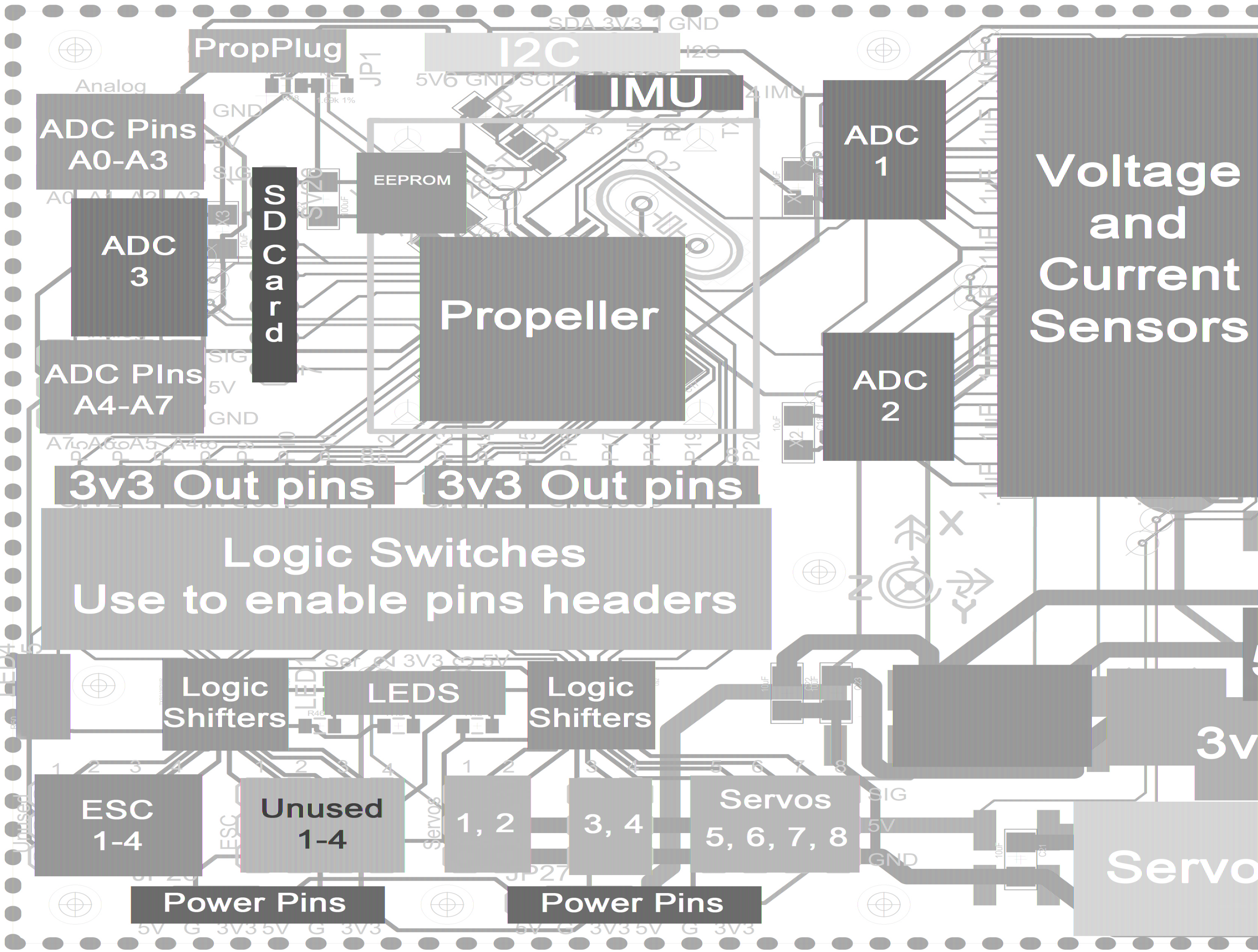


Rev A PCB



SDA 3V3 1 GND
I2C
5V6 GND SCL
JP1
IMU
Analog
GND
5V
SIG
A0 A1 A2 A3
Analog
SIG
5V
GND
A7 A6 A5 A4
INPUT
GROUND
Motor1
GROUND
Motor2
Motor3
Motor4
5V
D1
D2
D3
3V3
7-22V
Logic
IND$1
IND$2
IND$3
SIG
5V
GND
ESC
Servo
SERVOS
JP26
JP27
5V G 3V3 5V G 3V3
5V G 3V3 5V G 3V3
REV: A
www.anzhelka.com

Rev A Overlay



Features

- Propeller Multicore Processor
- Buck regulators for 5v (x2) and 3.3v
- Level shifting for up to 24 I/O lines
- Voltage and current sensing for
    - Motors, 5v and 3.3v rails
- 8 free analog channels
- Mounting accommodations for
    - SD card, IMU, Quickstart, BoE formfactor
- Servo and I/O 3 wire headers (WRB)

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Tasks

http://www.jasondavies.com/wordcloud/#

Test~Motors
Test~Motors
Design~PCB
Design~PCB
Populate~PCB
Populate~PCB
Select~Frame
Select~Frame
Build~Frame
Build~Frame
Research~Control~Algorithms
Select~Hardware
Select~Hardware
Write~Drivers
Write~Drivers
Code~Algorithm
Develop~Motor~Test~Stand
Create~Project~Management
Document~Project
Document~Project

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Tasks

Joint effort on all tasks

No arbitrary division of labor

Design Considerations

- Realistic constraints
- Industry Standards
- Time/Skills
- Cost effectiveness
- Resources

Testing

- Motor thrust/torque
- Attitude Measurement
- Attitude Error
- Roll/Pitch
- Yaw
- Altitude

Technical Challenges

- Quadrotors have a hard realtime computational requirement
- High current motors require special precautions
- System-wide part compatibility and interfacing
- Barebones code to keep the platform stable

Summary of progress

- Analyzed most needed control algorithms
- Designed main control board (Rev A)
- Developed motor test stand
- Designed and implemented project management

Quadrotor Mathematics

$$\begin{aligned}
\tilde{\boldsymbol{q}} &= \boldsymbol{q}_d \otimes \boldsymbol{q}^* \\
\alpha &= 2\arccos\left(\tilde{q}_0\right) \\
t_1 &= \sin \alpha/2 \\
\boldsymbol{r}_{e_1} &= \frac{\tilde{q}_1}{t_1} \\
\boldsymbol{r}_{e_2} &= \frac{\tilde{q}_2}{t_1} \\
\boldsymbol{r}_{e_3} &= \frac{\tilde{q}_3}{t_1} \\
\boldsymbol{r}_b &= \boldsymbol{q}^* \otimes \boldsymbol{r}_e \otimes \boldsymbol{q} \\
\tilde{\boldsymbol{q}}_b &= \begin{bmatrix} \cos\left(\alpha/2\right) \\ \sin\left(\alpha/2\right) \cdot \boldsymbol{r}_b \end{bmatrix} \\
\alpha_H &= \arccos\left[1 - 2\left(q_1^2 + q_2^2\right)\right] \\
\psi &= 2\,\mathrm{arctan}_2\left(q_3, q_0\right) \\
t_1 &= \cos\left(\psi/2\right) \\
t_2 &= \sin\left(\psi/2\right) \\
t_3 &= \sin\left(\alpha_H/2\right) \\
r_x &= \frac{t_1 q_1 - t_2 q_2}{t_3} \\
r_y &= \frac{t_2 q_1 - t_1 q_2}{t_3} \\
\beta_H &= \mathrm{arctan}_2\left(r_y, r_x\right) \\
M_x &= K_{PH}\alpha_H \cos\beta_H - K_{DH}\omega_x \\
M_y &= K_{PH}\alpha_H \sin\beta_H - K_{DH}\omega_y
\end{aligned}$$

$$\begin{aligned}
K_{tilt} &= \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \cdot \left(q \otimes \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \otimes q^* \right) \\
\tilde{\boldsymbol{R}}_{e_z} &= \boldsymbol{R}_{e_z} - desired\left(\boldsymbol{R}_{e_z}\right) \\
F_{PIDz} &= K_{Pz}\tilde{\boldsymbol{R}}_{e_z} + K_{Iz}\Sigma\tilde{\boldsymbol{R}}_{e_z} + K_{Dz}\dot{\tilde{\boldsymbol{R}}}_{e_z} \\
F_z &= \frac{mg + F_{PIDz}}{K_{tilt}}
\end{aligned}$$

$$\begin{aligned}
t_1 &= \frac{M_z}{4c} \\
t_2 &= \frac{M_y}{2d} \\
t_3 &= \frac{M_x}{2d} \\
t_4 &= \frac{F_z}{4} \\
F_1 &= +t_1 - t_2 + t_4 \\
F_2 &= -t_1 - t_3 + t_4 \\
F_3 &= +t_1 + t_2 + t_4 \\
F_4 &= -t_1 + t_3 + t_4 \\
t_1 &= \frac{2\pi}{D^2} \\
t_2 &= \rho K_T \\
\Omega_{d1} &= t_1\sqrt{F_1/t_2} \\
\Omega_{d2} &= t_1\sqrt{F_2/t_2} \\
\Omega_{d3} &= t_1\sqrt{F_3/t_2} \\
\Omega_{d4} &= t_1\sqrt{F_4/t_2} \\
\Omega\left(t\right)_{Ierror1} &= \Omega\left(t-1\right)_{Ierror1} + \left(\Omega_{d1} - \Omega_{i1}\right) \\
\Omega\left(t\right)_{Ierror2} &= \Omega\left(t-1\right)_{Ierror2} + \left(\Omega_{d2} - \Omega_{i2}\right) \\
\Omega\left(t\right)_{Ierror3} &= \Omega\left(t-1\right)_{Ierror3} + \left(\Omega_{d3} - \Omega_{i3}\right) \\
\Omega\left(t\right)_{Ierror4} &= \Omega\left(t-1\right)_{Ierror4} + \left(\Omega_{d4} - \Omega_{i4}\right) \\
u_1 &= K_{P1}\left(\Omega_{d1} - \Omega_{i1}\right) + K_{I1}\Omega\left(t\right)_{Ierror1} \\
u_2 &= K_{P2}\left(\Omega_{d2} - \Omega_{i2}\right) + K_{I2}\Omega\left(t\right)_{Ierror2} \\
u_3 &= K_{P3}\left(\Omega_{d3} - \Omega_{i3}\right) + K_{I3}\Omega\left(t\right)_{Ierror3} \\
u_4 &= K_{P4}\left(\Omega_{d4} - \Omega_{i4}\right) + K_{I4}\Omega\left(t\right)_{Ierror4}
\end{aligned}$$

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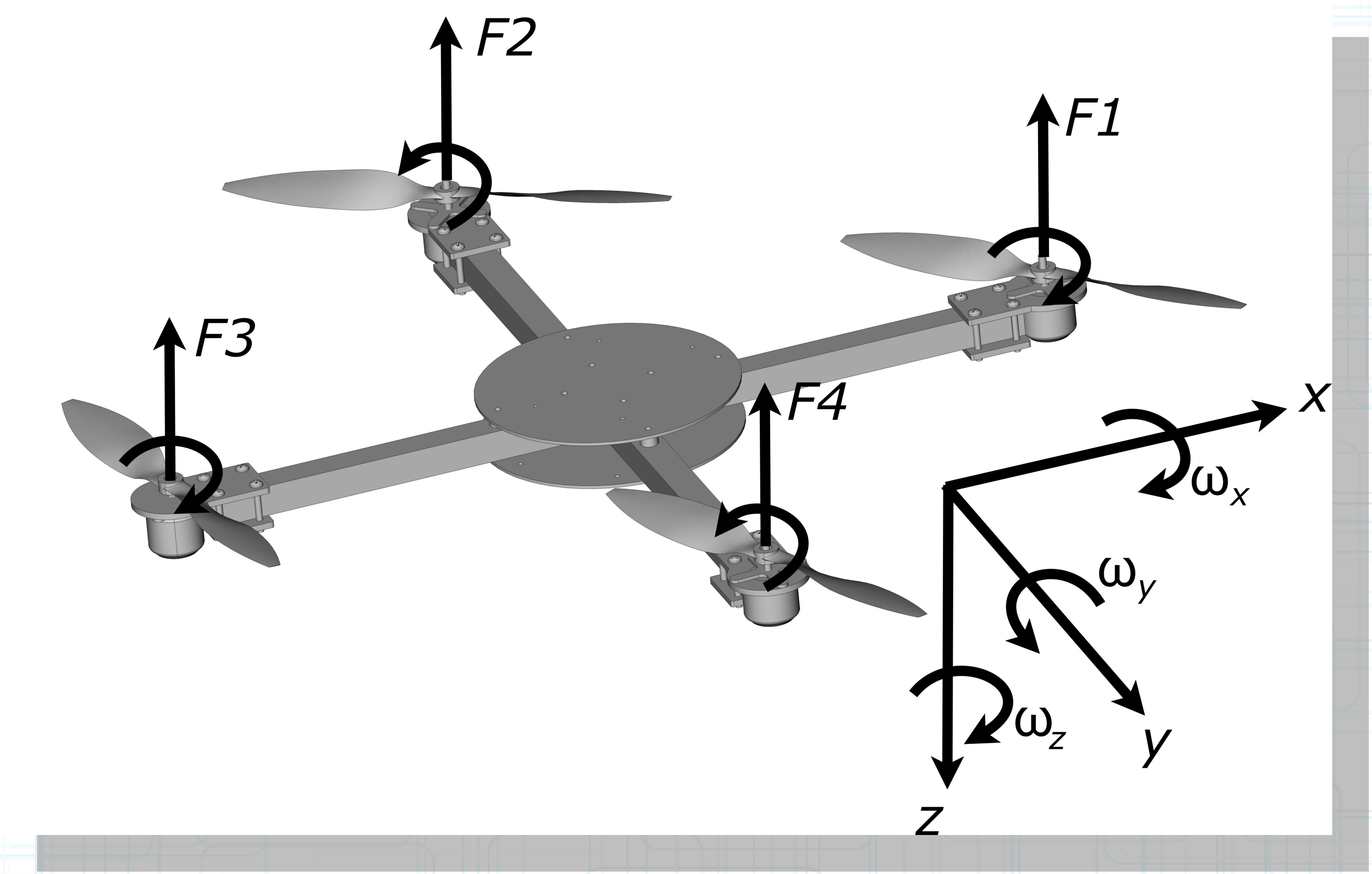
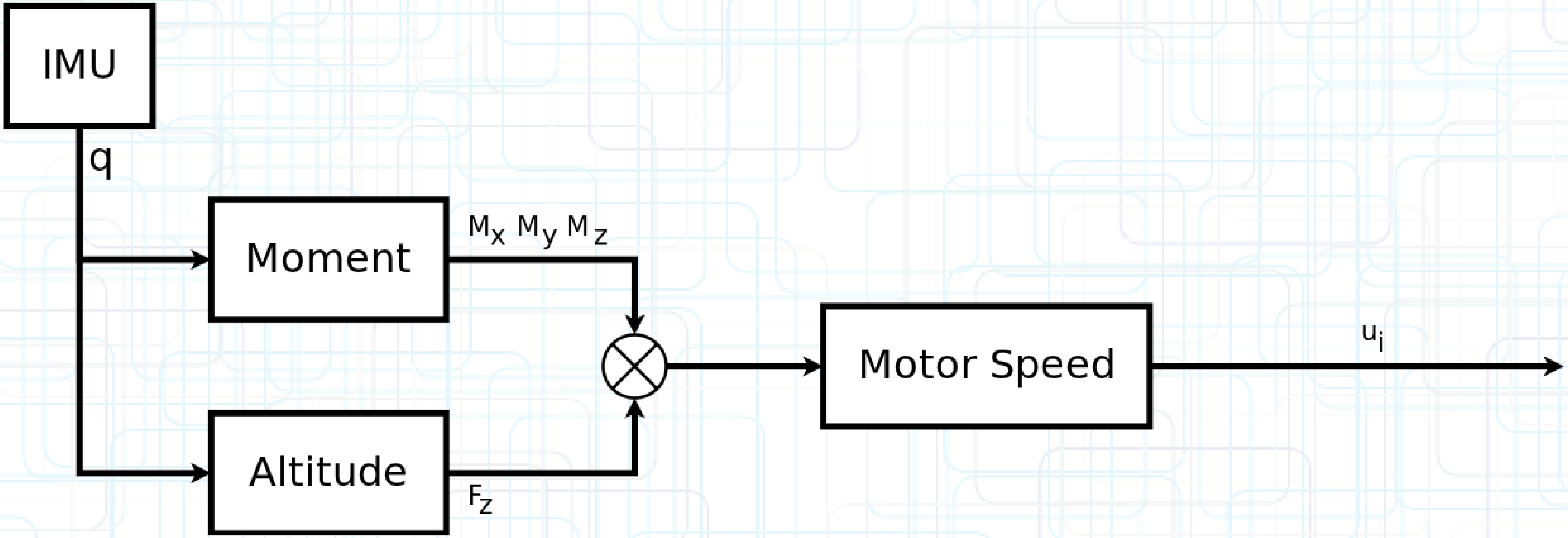
Body Reference



Quaternion Mathematics

- Avoid gimbal lock
- Smaller memory requirements (4 floats)
- More efficient mathematical operations
- Smooth interpolation between orientations.
- No trigonometric functions for orientation updates

Control Loop Flow



- To be executed at ~100Hz +
- Parallelization possible

Block: Moment

Input variables:	$\boldsymbol{\omega}_b$	angular velocity in the body frame (rad/s)
	$\mathbf{q}$	attitude quaternion
	$\mathbf{q}_d$	desired quaternion

Input constants:	K_{PH}	tilt moment proportional constant
	K_{DH}	tilt moment derivative constant
	K_{Pz}	yaw moment proportional constant
	K_{Dz}	yaw moment derivative constant

Output: $M_x - M_z$ total rotor moments along each axis $(N \cdot m)$

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Moment PID

$$M_x = K_{PH}\alpha_H \cos\beta_H - K_{DH}\omega_x$$
$$M_y = K_{PH}\alpha_H \sin\beta_H - K_{DH}\omega_y$$
$$M_z = K_{Pz}\psi - K_{Dz}\omega_z$$

Block Altitude

Input variables:

$\mathbf{q}$	attitude quaternion
$\boldsymbol{R}_{e_z}$	position in the inertial frame (m)
F_z	total force of the rotors on the z axis (N)
$desired(\boldsymbol{R}_{e_z})$	Desired z position (altitude) (m)

Input Constants:

m	quadrotor mass $(kg\ ?)$
g	local gravity (m/s^2)
K_{P_z}	Proportional PID gain for F_z
K_{I_z}	Integral PID gain for F_z
K_{I_z}	Derivative PID gain for F_z

Output Variables: F_z total force of the rotors on the z axis (N)

Motor PID

$$F_z = \frac{mg + F_{PIDz}}{K_{tilt}}$$

- Maps to the total thrust required
- Adjusts for mass of vehicle
- Adjusts for the tilt of the system

Block: Motor

Input variables:	F_z	total force of the rotors on the z axis (N)
	M_x, M_y, M_z	total rotor moments along each axis $(N \cdot m)$
	n_{imeas}	rotation frequency of the rotors (Hz)

Input Constants:	D	rotor diameter (m)
	d	offset of each rotor from the center of mass (m)
	ρ	air density (kg/m^3)
	K_t	thrust coefficient
	K_q	torque coefficient
	K_{P_i}	Motor Proportional PID gain (for $1 \leq i \leq 4$)
	K_{I_i}	Motor Integral PID gain (for $1 \leq i \leq 4$)
	π	pi

Output Variables:	u_i	motor command

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Control Matrix

$$\begin{bmatrix} F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & -d & 0 & d \\ -d & 0 & d & 0 \\ c & -c & c & -c \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & -d & 0 & d \\ -d & 0 & d & 0 \\ c & -c & c & -c \end{bmatrix}^{-1} \cdot \begin{bmatrix} F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$$

- Rewritten twice to solve for two variables
- Main control equation of quadrotor attitude

Control Matrix Simplified

$$F_1 = +\frac{M_z}{4c} - \frac{M_y}{2d} + \frac{F_z}{4}$$
$$F_2 = -\frac{M_z}{4c} - \frac{M_x}{2d} + \frac{F_z}{4}$$
$$F_3 = +\frac{M_z}{4c} + \frac{M_y}{2d} + \frac{F_z}{4}$$
$$F_4 = -\frac{M_z}{4c} + \frac{M_x}{2d} + \frac{F_z}{4}$$

- Previous matrix multiplied out
- Relation between signs and motor rotation direction

Force to Rotational Speed

$$\Omega_{di} = \frac{2\pi}{D^2}\sqrt{\frac{T}{\rho K_T}}$$

- Converts desired thrust T to motor speed
- Note the effect of the square root

Quadrotor Dynamics

- Dynamics – Study of cause of motion
- Kinematics – Study of motion, ignoring cause

Body Translation

$$\dot{\boldsymbol{V}}_b = \frac{1}{m}\begin{bmatrix} 0 \\ 0 \\ F_z \end{bmatrix} + \boldsymbol{q}^* \otimes \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \otimes \boldsymbol{q} - \boldsymbol{\omega}_b \times \boldsymbol{V}_b$$

- High school physics: F = ma
- Acceleration due to
  - Thrust
  - Gravity (rotated)
  - Fictitious forces

Body Rotational Motion

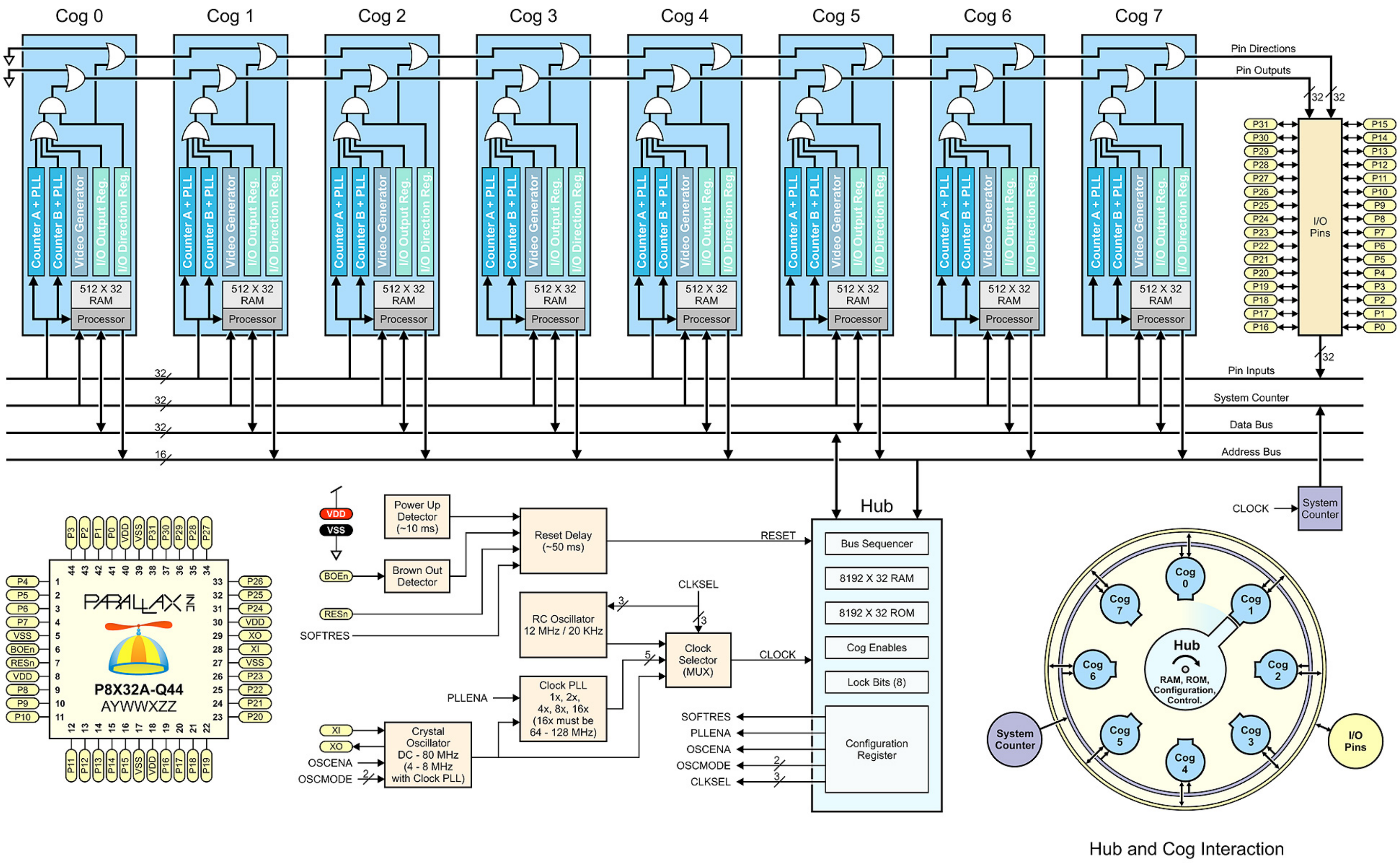
$$\dot{\boldsymbol{\omega}}_b = \boldsymbol{I}_{nb}^{-1} \left(\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} - \boldsymbol{\omega_b} \times (\boldsymbol{I}_{nb} \boldsymbol{\omega}_b) \right)$$

- Similar to translation equation
- Rotation due to
  - Moments
  - Fictitious forces

Specific Hardware

- Propeller
- Brushless Motors
- Eagle Tree Sensors
- IMU

Propeller Microcontroller



Hub and Cog Interaction

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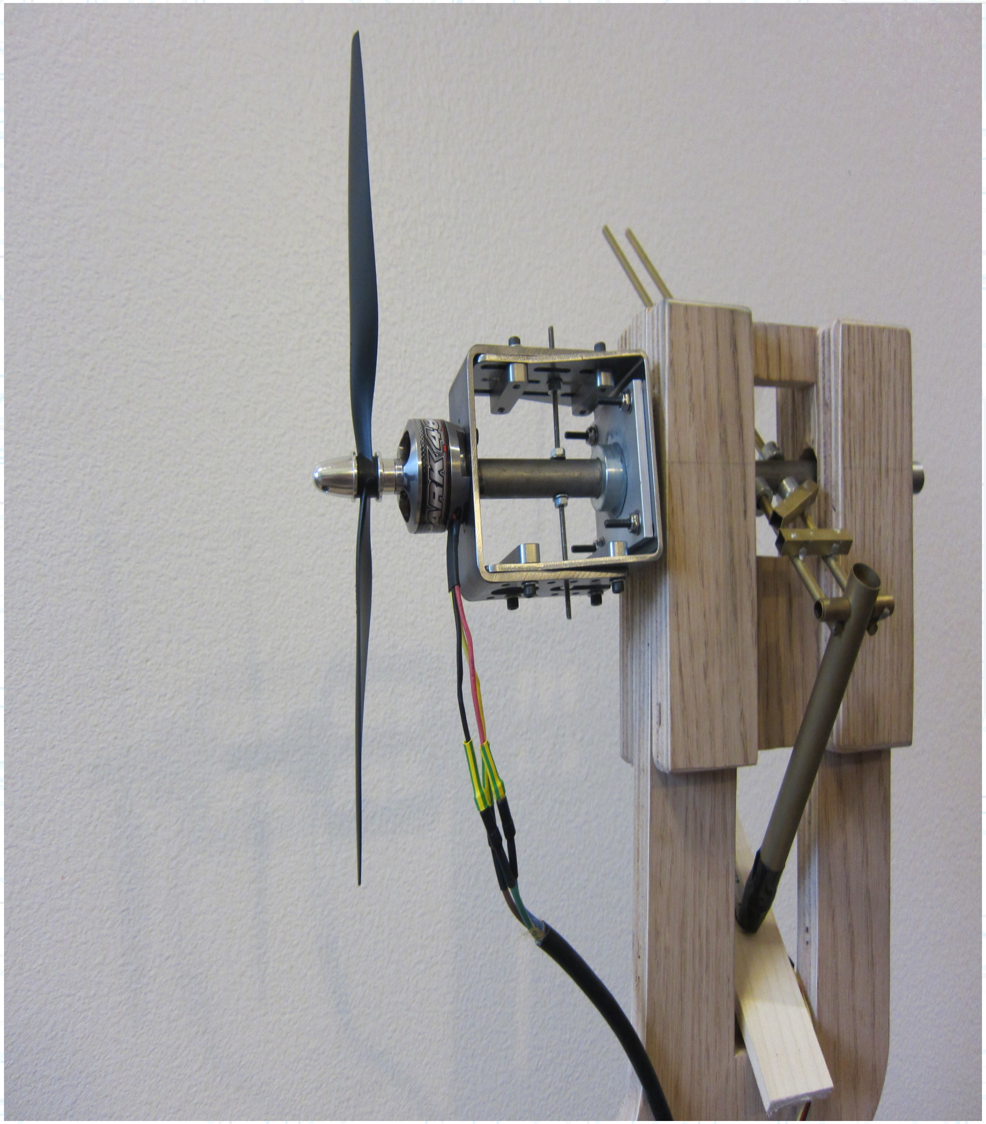
Brushless Motors



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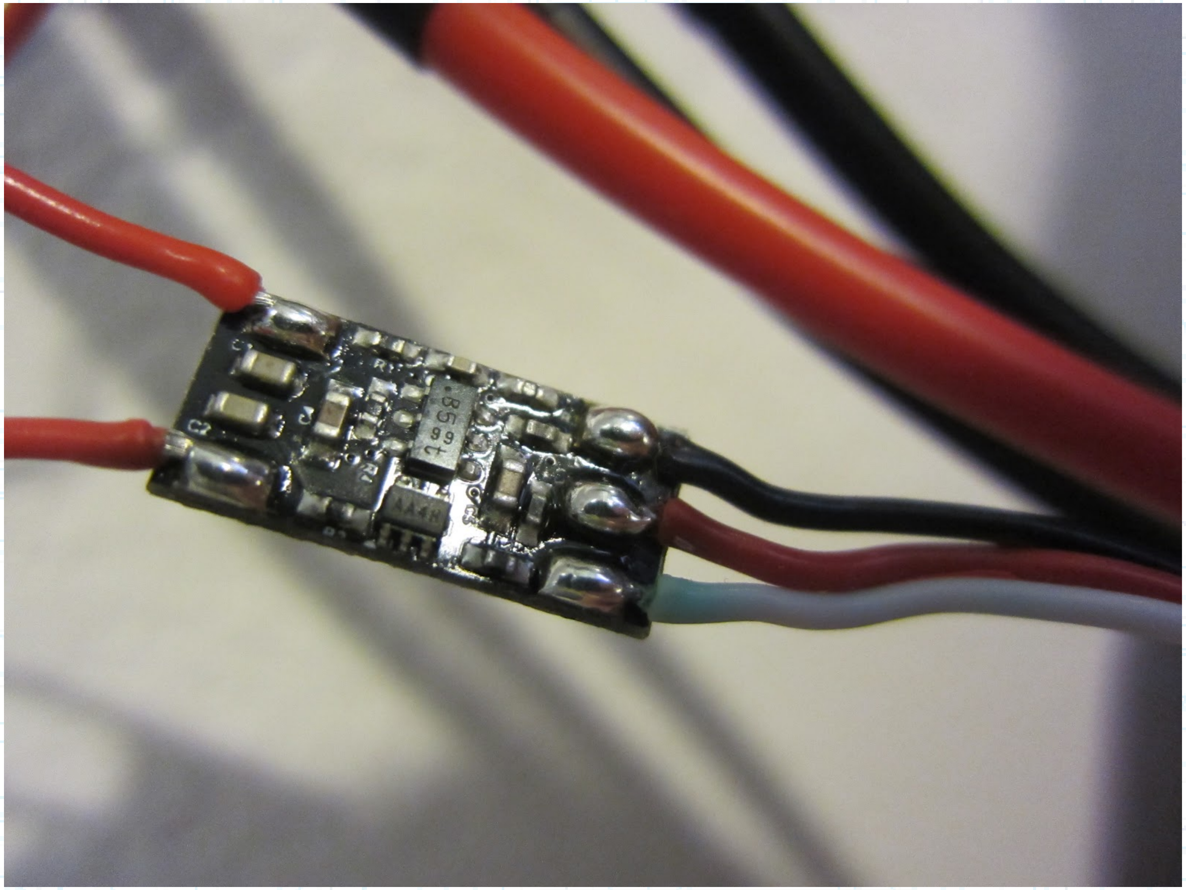
Eagle Tree



- Measures BLDC control pulses

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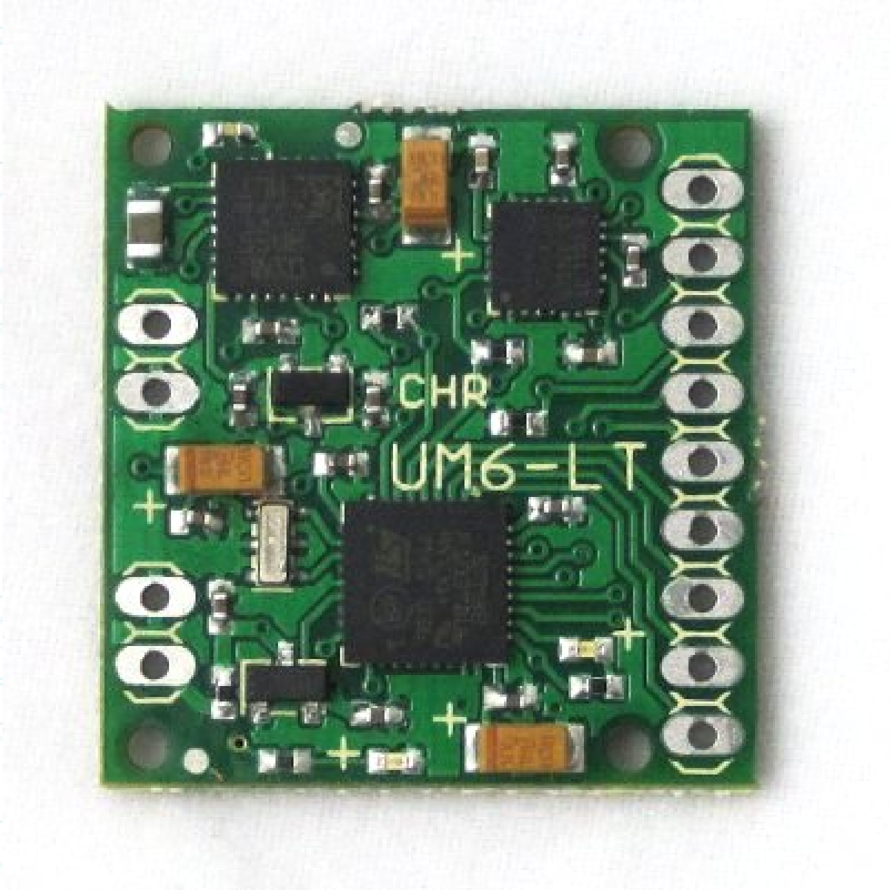
Inertial Measurement Unit

- 9 axis of measurement
    - 3 Gyro
    - 3 Accelerometer
    - 3 Magnetometer
- Onboard Extended Kalman Filter



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Next Steps

- Implement Control Loop
- Test Flying Code
- Achieve Stable Hover

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Acknowledgement

- Laser Cutting: Rich Harman(W9GFO)
- Machining: Dale Holtkamp and Gene Sherman
- Algorithms: Frank Lewis and Emanuel Stingu
- Design: Dr. Brisk, Dr. Liang, Dr. Kastner, Tom Wypych, Dr. Chomko
- Workshop: Elmar Palma
- Components: TI, Microchip
- Other: Mr. McBroom (Luke)

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Conclusion

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Questions?

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