Flight Testing Small UAVs for Aerodynamic Parameter Estimation

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Motivation

- Lack of small UAV lift/drag regression models
- Small UAVs do not fly “steady-level”
- Designers need data to conduct quantitative trades
- Off the shelf systems not sufficient
  - No air data system
  - Closed source, lack of error propagation

Goals

1. Integrate air data acquisition system into flight vehicle
2. Measure drag polar and lift curve slope from flight test
3. Quantify changes in vehicle performance from configuration changes

Equations of Motion

Newton's 2nd Law, in body axes:

$$\Sigma F = \frac{d}{dt}(mV)$$

Fixed mass assumption (electric aircraft):

$$\Sigma F = ma$$

Applied forces:

$$\Sigma F = F_{AERO} + F_G + F_T$$

Assume no thrust:

$$\Sigma F = F_{AERO} + F_G$$

Assumptions

- Re-arrange terms:

$$\Sigma \mathrm{F} = \mathrm{ma}$$

$$F_{AERO} + F_G = ma$$

$$F_{AERO} + mg = ma$$

$$F_{AERO} = m(a - g)$$

$$F_{AERO} = -m\boxed{r}$$

- Rotate from body to wind axes:

$$F_{AERO}^{w} = R_b^w F_{AERO}^{b}$$

where

$$R_b^w = f\boxed{(\alpha, \beta)}$$

Only an accelerometer and an air data system are required to get lift/drag forces in gliding flight

Sensor Selection

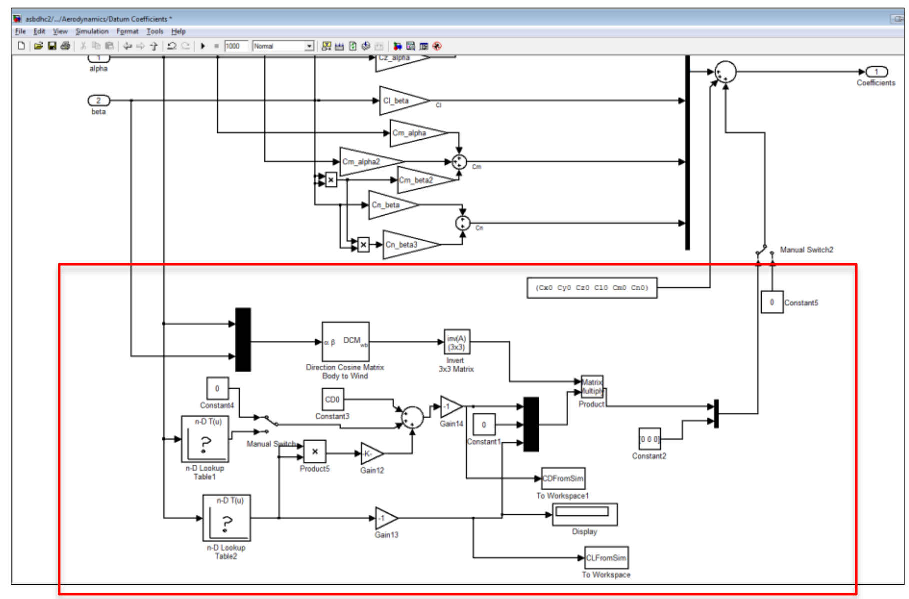
- Analog Devices ADXL-362
  - +/- 8G range
  - SPI interface
  - Ultra-low noise (175 µG/$\sqrt{Hz}$)
  - Available as SMD and breakout board
- Air Data System
  - Five-hole probe from Aeroprobe
    - 6” x 1/8” OD tube
    - Calibrated angles to pressures at 70 ft/s
  - All Sensors’ 5-INCH-D-DO differential pressure transducer
    - +/- 5” H_20 range
    - Digital serial interface
    - 0.5% FSO noise

Additional Sensors

- ITG-3200 gyroscope
  - Euler angles
- U-Blox LEA-6T GPS receiver
  - Euler angle correction, flight visualization
- HMR-2300 magnetometer
  - High accuracy, used for slow or vertical flight
- HMC-5883L magnetometer
  - Small, inexpensive
- Barometric pressure transducer
  - Barometric pressure/altitude
- DS18B20 temperature sensor
  - Allows density/air speed calculation
- Servo PWM signal
  - Isolates flight without throttle

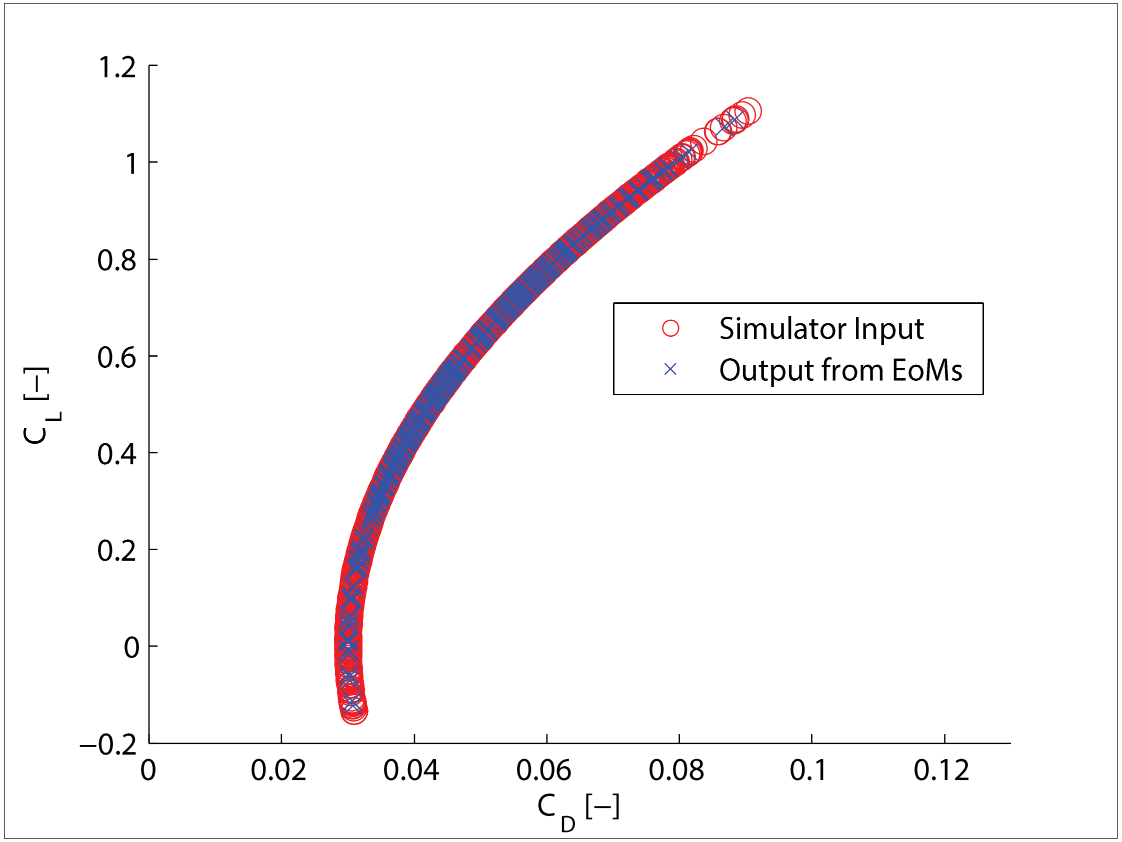
Simulator Development

- Modified de Havilland Beaver 6-DOF simulator from Simulink
  - Scaled mass and moments of inertia to R/C aircraft
  - Replaced aero forces with drag polar
  - Removed engine forces and moments
  - Output required state to workspace for comparison to estimate



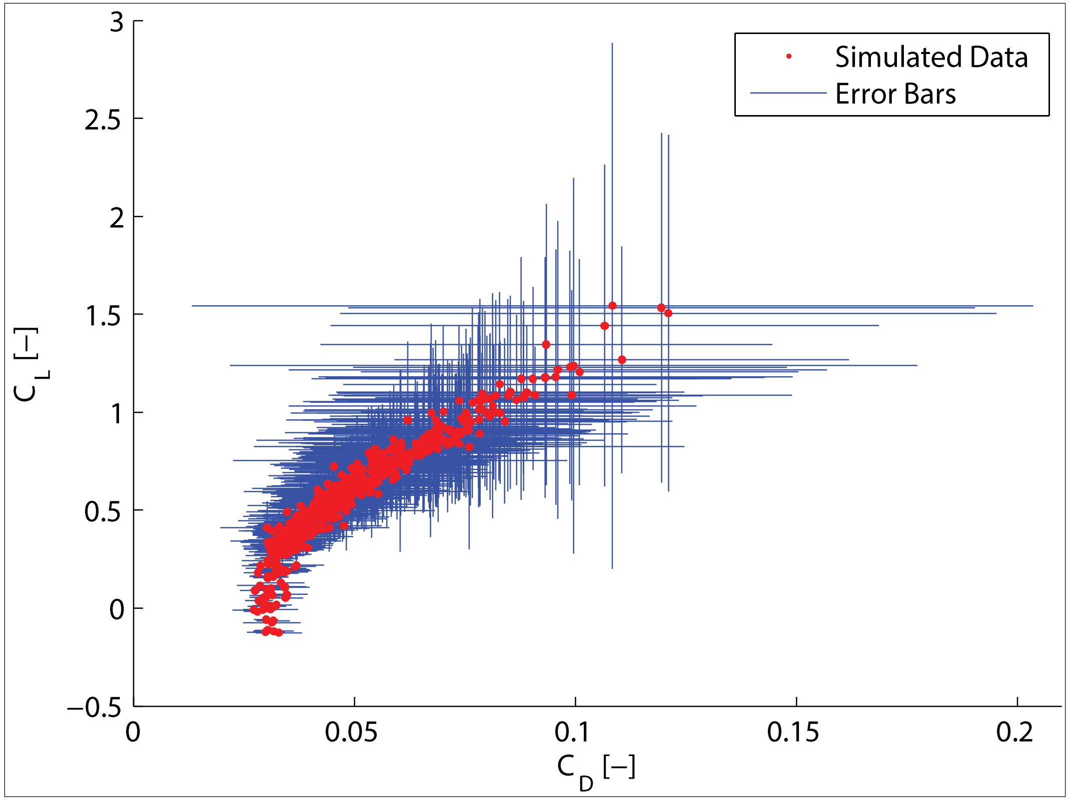
Simulation Output – No Noise

- Verified drag polar estimation method
- Helped develop data analysis routines
- Aided flight test planning



Random Error

$$\sigma_{C_i} = ||J_{ij} * \sigma_j|| = \sqrt{\left(\frac{\partial C_i}{\partial \alpha} * \sigma_\alpha\right)^2 + \left(\frac{\partial C_i}{\partial \beta} * \sigma_\beta\right)^2 + \left(\frac{\partial C_i}{\partial \vec{a}} * \sigma_{\vec{a}}\right)^2}$$



Regression Error

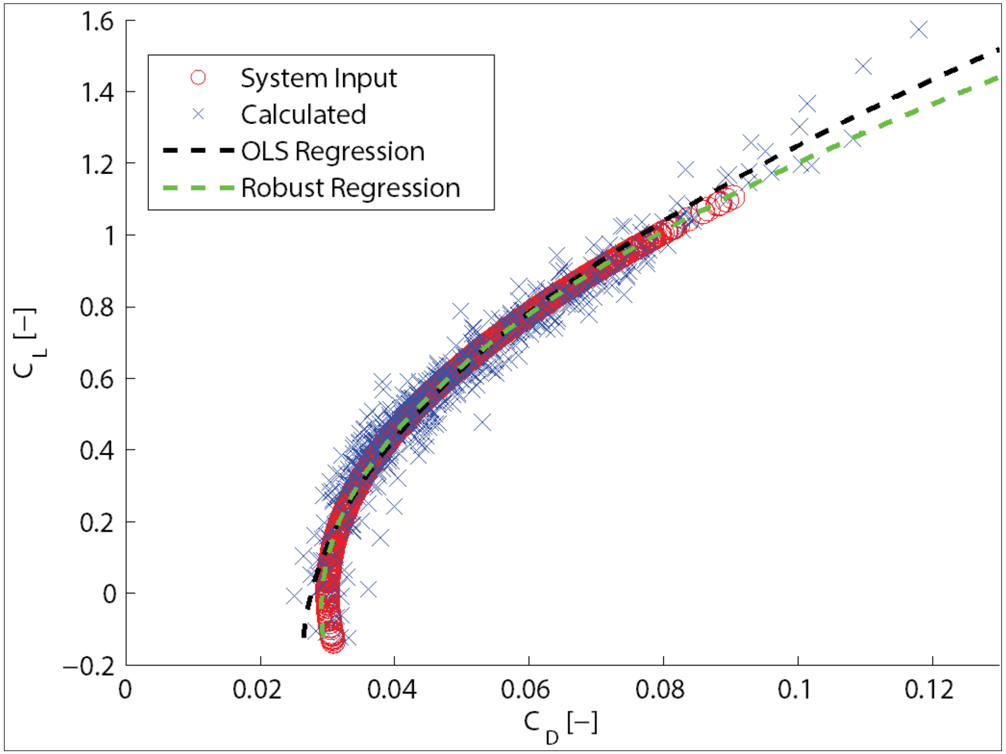
- Error of regression driven by confidence intervals
  - If the experiment is repeated, the regression coefficients will lie in this interval n% of the time

$$\beta_i = \hat{\beta}_i \pm \frac{t\ \sigma}{\sqrt{n}}$$

t = 1.96 for 95% CI

- Error in forces for random error is heteroskedastic
- Matlab's `robustfit` returns robust standard error estimates
  - De-weights heteroskedastic outliers using iteratively weighted least squares

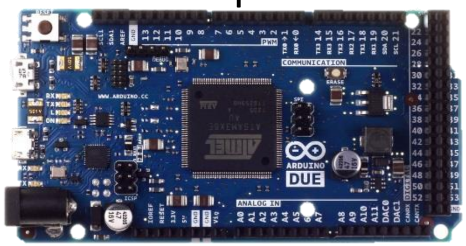
Heteroskedasticity



	C_{D0}	K_1	K_2
System Inputs	0.0493	0	0.03
OLS Estimate	0.0355	-0.0136	0.0275
Robust LS Estimate	0.0460	-0.0037	0.0292

System Architecture

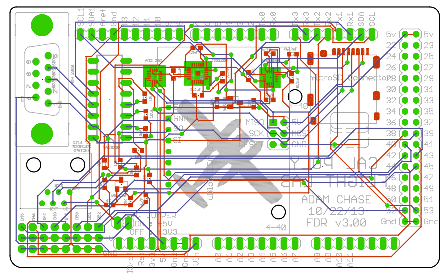
Arduino Due Flight Computer



- 84 MHz clock
- 32-bit processor
- 4 UART channels

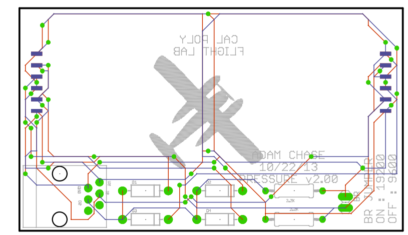
+

Data Acquisition Shield



- Custom PCB
- Integrates external mag, pressure sensors
- Customizable to fit packaging needs

External Air Data System



- Custom PCB
- Pressure, temperature, and alignment accel
- RJ-25 interface

Aeroprobe Five-Hole Probe

- Calibrated angles to pressures at 70 ft/s

Calibration – Accel/Gyro

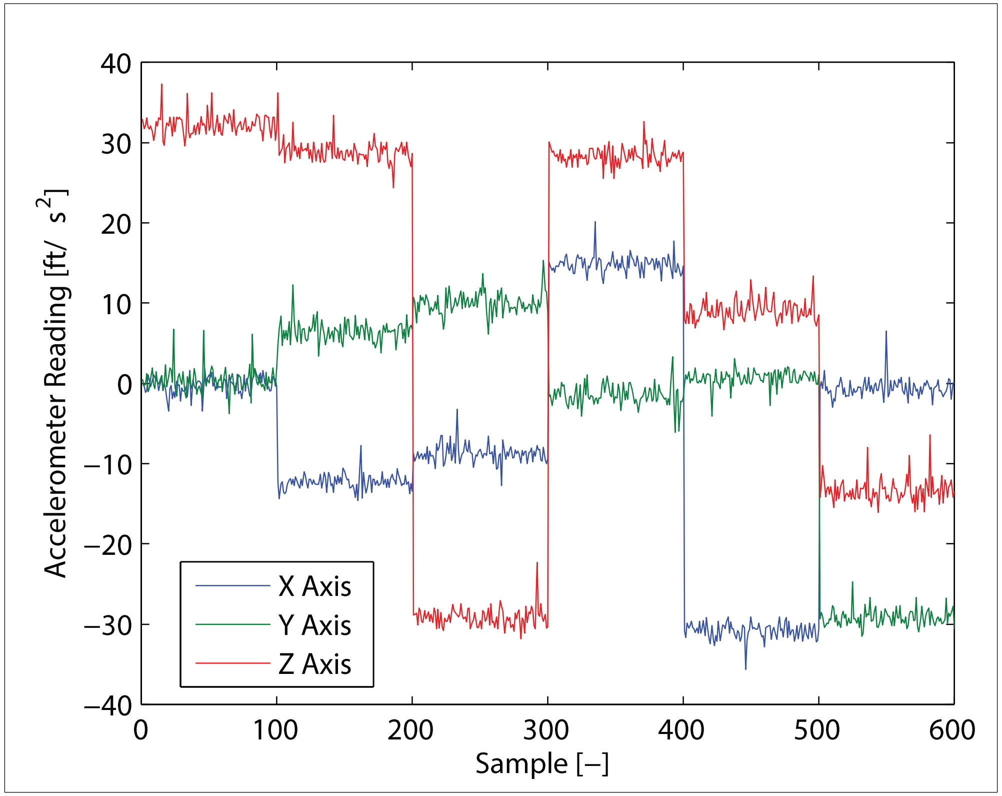
- Data collected with a known magnitude
  - 1G for accelerometer, 33 1/3 RPM for gyro (turntable)
- Nonlinear least squares:

$$minimize\ f(x) = (mag(\vec{a}) - 1G)^2$$

where

$$x = [m_x\ m_y\ m_z\ b_x\ b_y\ b_z]$$

$$a = [a_x\ a_y\ a_z]$$

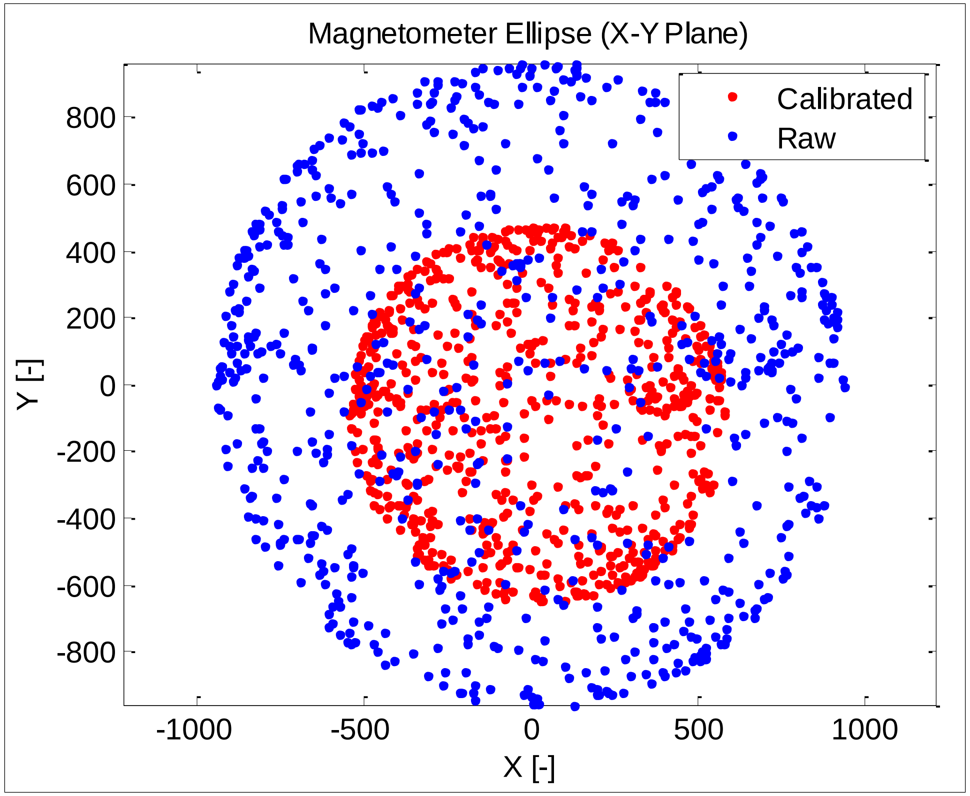


Calibration - Magnetometers

- Soft- and Hard-iron effects removed with least squares
  - Centers ellipse around zero
  - Scales each axis to turn ellipse into a sphere

- Alignment through rotation matrix

$$\vec{N}^2 = \overline{R_1^2}\,\vec{N}^1$$



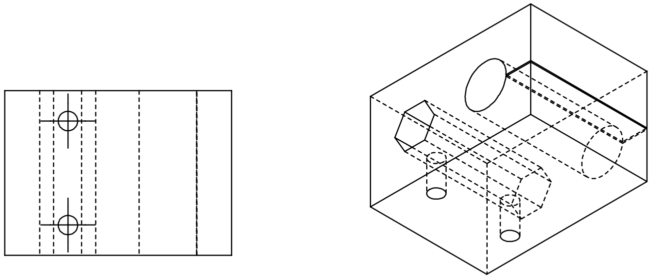
Calibration – Air Data System

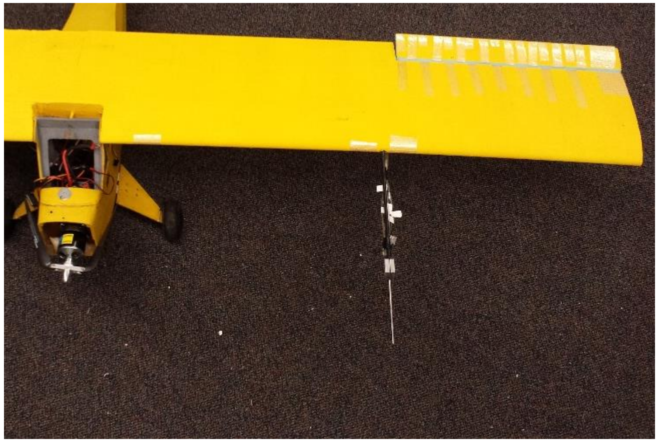
- Alignment calibration:
  - Known alignment between adapter and probe
  - Calibrate accelerometer on adapter
  - Measure rotation between probe accelerometer and body accelerometer

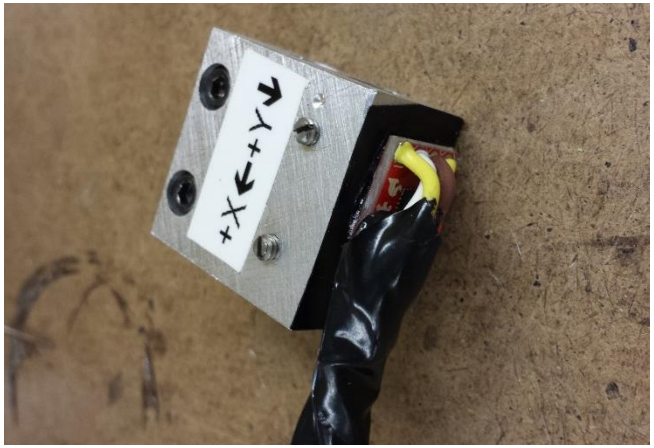
$$\vec{G}^2 = \overline{R_1^2}\,\vec{G}^1$$

- Zero-offset removed pre-flight
- Slope calibrated with nVision's Reference Pressure Recorder
- Angles calibrated to pressures from the manufacturer

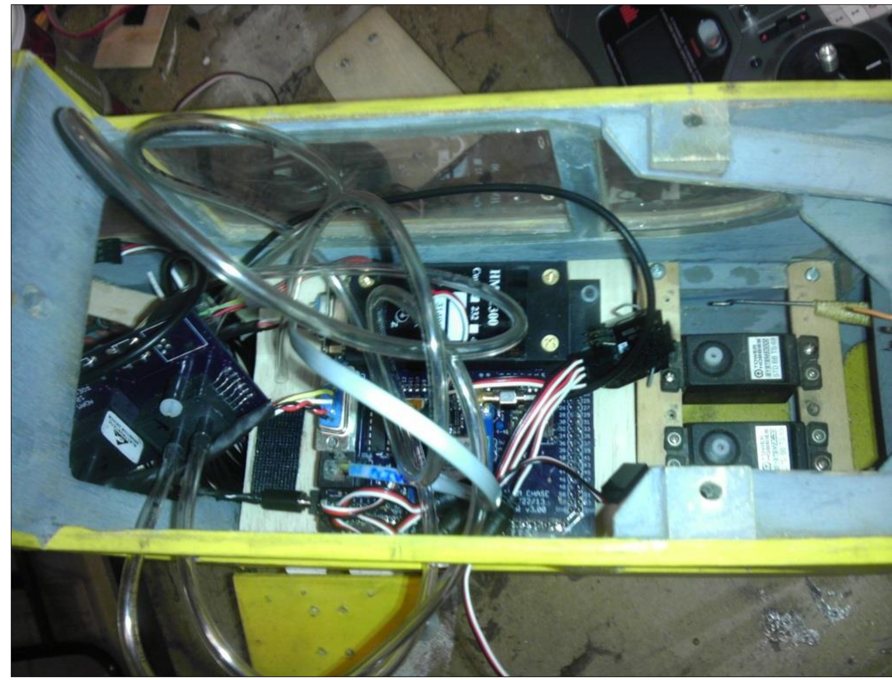
Air Data System Integration







Flight Test



Flight Crash

Future Work

- Verify system accuracy
- Integrate sensors into an INS solution
- Instrument for in-flight thrust measurement
- Stability/control derivative estimation