MAV Flight Stability and Control

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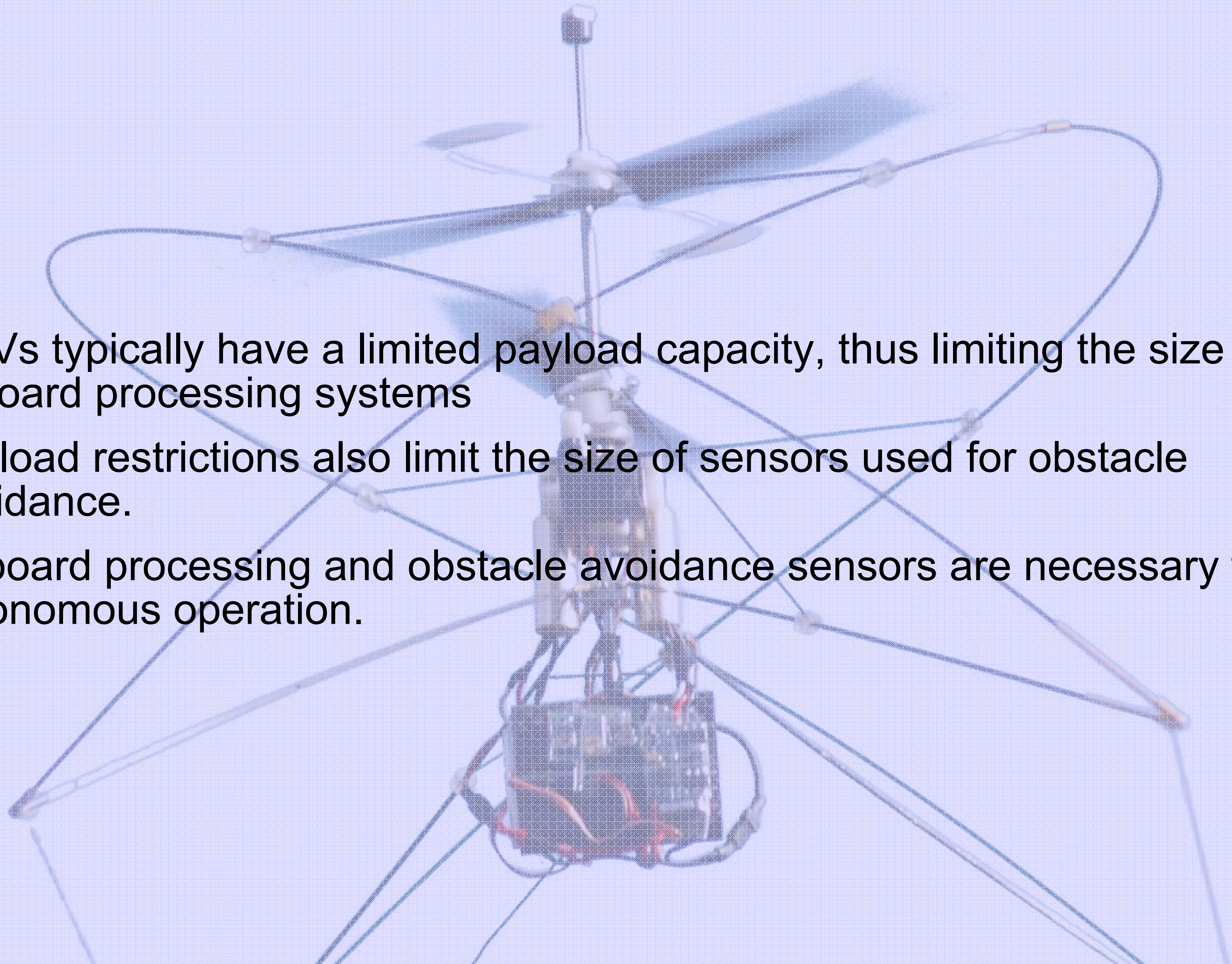
Motivation

- Many projected missions for a capable MAV require autonomous or semi-autonomous control of the vehicle.
- Accurate knowledge of the dynamic characteristics of the vehicle aids in the development of controllers and control strategies.
- Standard methods for determining the dynamics of full size rotorcraft are not currently feasible for MAV’s
- The ability to easily determine the dynamics of a MAV experimentally will allow optimization studies of vehicle components that affect stability characteristics.

Motivation



- MAVs typically have a limited payload capacity, thus limiting the size of onboard processing systems
- Payload restrictions also limit the size of sensors used for obstacle avoidance.
- Onboard processing and obstacle avoidance sensors are necessary for autonomous operation.

Objectives

Develop the ability to determine the stability derivatives of a MAV using experimental techniques in ground test facilities.

Create a system that provides the necessary sensing, processing and communication capabilities to provide control and navigation on an MAV.

Outline

1. Evaluate the use of a forced oscillation testing and flight testing for determining the dynamics a rotary-wing MAV, i.e system identification.
2. Development and construction of hardware system for sensor interfacing, control calculation, actuation and communications.
3. Creation of a simple algorithm for attitude estimation given inertial and magnetic information, as first step toward autonomous control.
4. Evaluate optic flow as a technique for obstacle avoidance.

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Possible MAV System ID Techniques

Flight Testing

- System parameters are calculated from flight test data
- Control inputs are used to perturb the vehicle about a trimmed flight condition

Forced Oscillation Testing

- Vehicle is perturbed using an oscillatory mechanism
- Force response and vehicle position data are measured
- System parameters are calculated from the force response to the known perturbation

Flight Testing

Description

- Human pilot perturbs the vehicle with frequency sweeps or doublets of specified control inputs
- Control states and vehicle flight parameters are recorded
- Control inputs and vehicle response data are reduced to the frequency response of the vehicle
- Transfer functions are approximated from the frequency response

Flight Testing

U N I V E R S I T Y O F M A R Y L A N D

Advantages

- Many parameters determined at once
- Results obtained over a large frequency range
- No assumptions made about trim state or rotor response

Disadvantages

- Can only test capable flight worthy vehicles
- Experienced pilot needed to perform tests
- Small payload limits available quality and quantity of sensors
- Advanced software needed to reduce test data

Forced Oscillation Testing

Description

- The vehicle is perturbed by a forced sinusoidal oscillation
- Synchronized position and force response data are recorded
- Inertia forces are subtracted
- Vehicle force response is determined from the first order harmonic representation of the data
- Transfer functions are approximated from the frequency response

Forced Oscillation Testing

Advantages

- Ability to test partial vehicles or simplified rotors
- No need for experienced RC pilot
- Vehicle parameters can be easily changed and retested

Disadvantages

- Only a few system parameters can be determined from each test
- Different test stands are needed for each type of perturbation
- Control states not tested
- Aerodynamic forces are difficult to separate from inertia forces

Hardware Requirements

Flight Testing

- High quality miniature sensors capable of obtaining necessary flight data
- Acquisition of necessary data reduction software (e.g. CIFER)

Forced Oscillation Testing

- Forced oscillation stand with force balance to measure responses to prescribed motion
- Different forcing mechanisms to perturb vehicle about various degrees of freedom

Forced Oscillation Testing

- Forced oscillation techniques have been widely used to determine aerodynamic stability derivatives for fixed wing vehicles in wind tunnel test facilities.
- Initial Study: Develop a forced oscillation test stand to find the response of the vehicle to perturbations in forward velocity and evaluate the effectiveness of the technique for MAVs

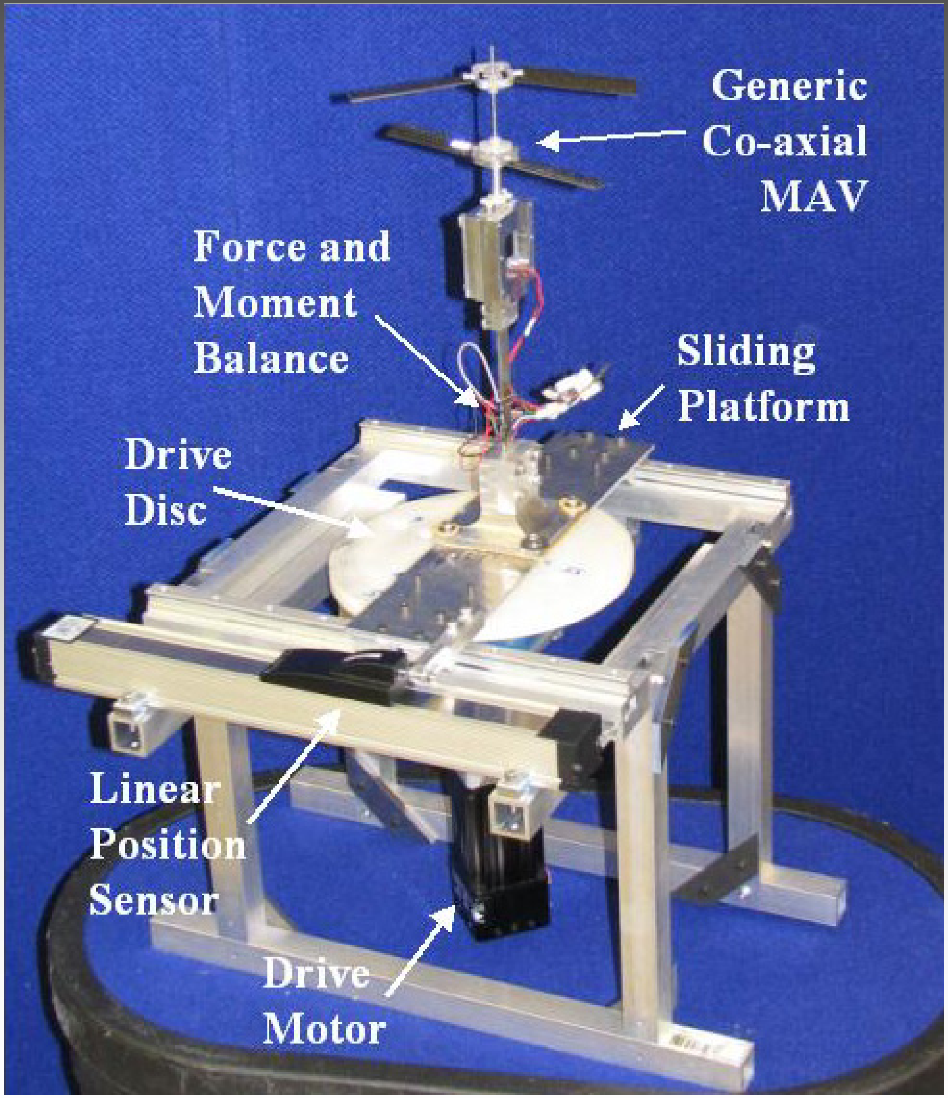
Forced Oscillation Test Stand

Requirements

- Linear sinusoidal velocity perturbation along the vehicle's X-body axis
- Variable oscillation frequency and amplitude
- Measurement of X-force and pitching moment
- Measurement of vehicle position
- Synchronized data acquisition of force and position data

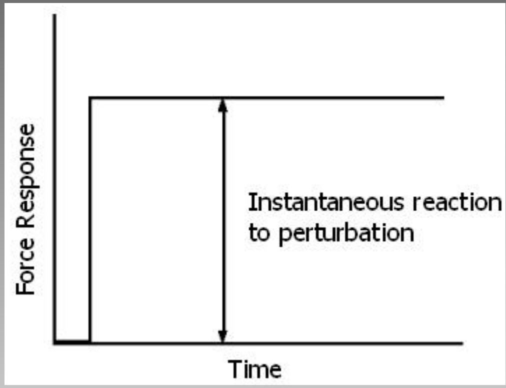
Stability: Forced Oscillation Test Stand

- Scotch yoke driven by servo motor produces a sinusoidal oscillation.
- The frequency of oscillation controlled by the servo motor (0-3 Hz).
- The amplitude of oscillation controlled by changing the pin offset (1.5-7 in).
- A strain gauge force balance is mounted to the sliding platform
- Force balance is capable of measuring X-force and pitching moment.
- The vehicle under consideration is rigidly mounted at the tip of the cantilevered beam.
- A precision linear position sensor measures the position of the sliding platform.
- Simultaneous force and position data are digitally recorded using Matlab.

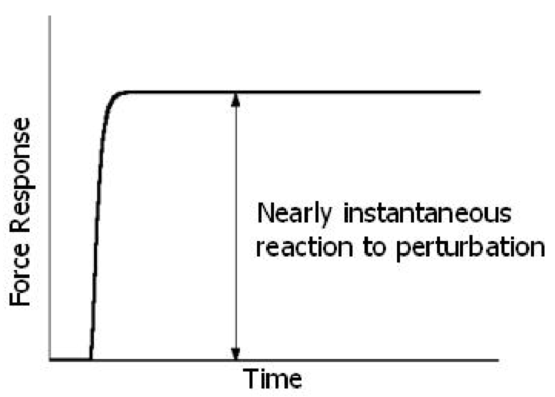


Background

- Constant coefficient stability derivative equations assume an instantaneous force or moment reaction to a perturbation in flight conditions.

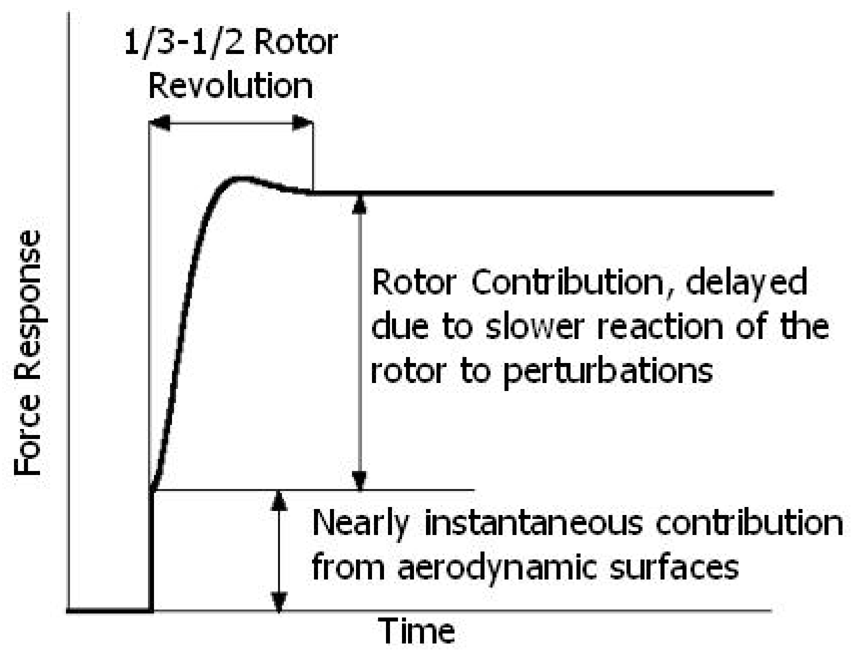


- Forces acting on aerodynamic surfaces such as those present on traditional fixed wing aircraft establish themselves very quickly.



Background

- The force reaction of the rotor is not instantaneous
- Delayed rotor response combines with the nearly instantaneous response of aerodynamic surfaces.



- Stability derivative equations can be only be considered sufficiently accurate if the motion of the vehicle is slow in comparison to the rotor response.

Background

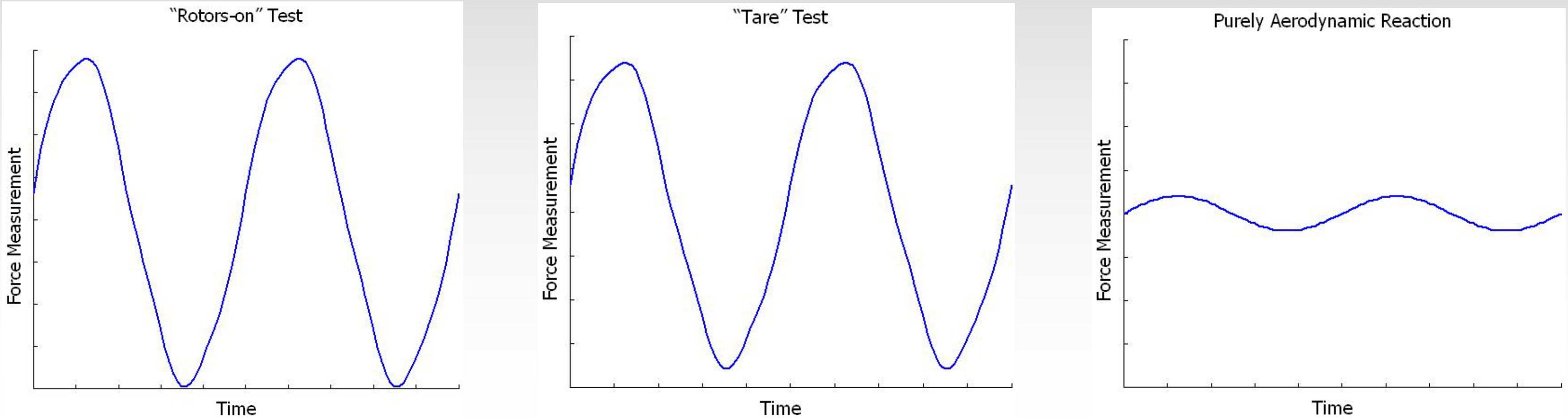
The rotor system of a rotary wing MAV does not react instantaneously to perturbations.

The forced oscillation frequency during testing must be low enough so that the oscillation motion can be considered slow with respect to the reaction time of the rotor.

Test Procedure

- A "tare" test is preformed to determine the inertia forces.
- A "rotors-on" test is then preformed to determine the combination of aerodynamic and inertia forces.
- The "tare" test is subtracted from the "rotors-on" test to obtain the purely aerodynamic response of the vehicle.
- Synchronized force and position data is reduced to meaningful stability derivatives or transfer functions.

"Rotors-on" test – "Tare" test = Purely Aerodynamic Reaction

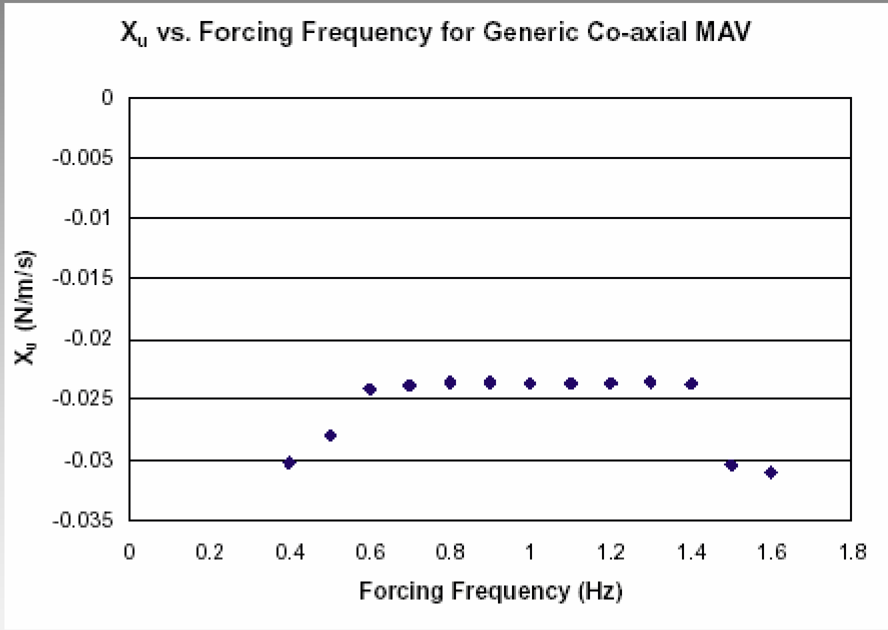


Forced Oscillation: Data Analysis

- **Goal:** Use preliminary measurements of the stability derivatives of a generic Co-axial MAV to validate the forced oscillation method.
- How?
  - Show that the frequency of the forced oscillation is slow enough for the reaction of the rotors to be considered instantaneous.
  - Show that the measured stability derivatives remain consistent over a range of valid forcing frequencies and amplitudes.
  - Show that varying a parameter of the vehicle will produce the change in stability derivative predicted by simple qualitative analysis.

Forced Oscillation: Data Analysis

- According to the theory behind the method, the measured stability derivative is independent of frequency and amplitude.



- The plot above shows that the stability derivative X_u is consistent for forcing frequencies between .6 and 1.4 Hz.

Forced Oscillation: Data Analysis

- At frequencies above 1.4 Hz. The forcing frequency is too fast for the rotor to fully respond.
  - Qualitative observations of the rotors reveal that the rotor plane does not tilt as clearly.
- At frequencies below .6 Hz. the response of the rotor is too small to be accurately measured.
  - Qualitative observations of the rotors during testing reveal that the tilt of the rotor plane is barely perceptible.

Forced Oscillation: Data Analysis

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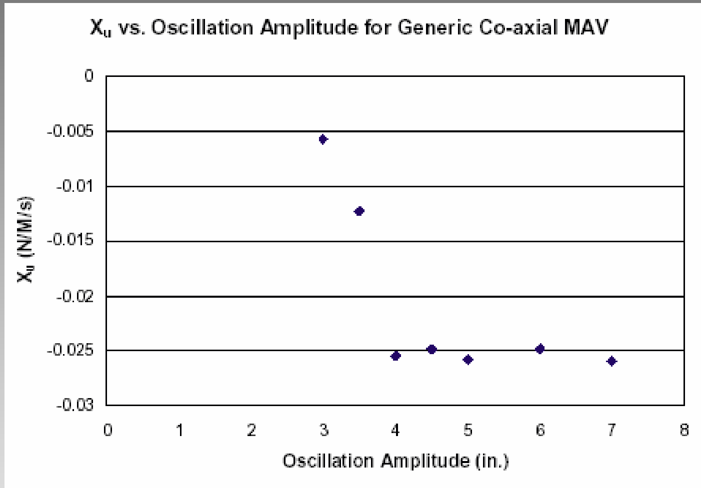
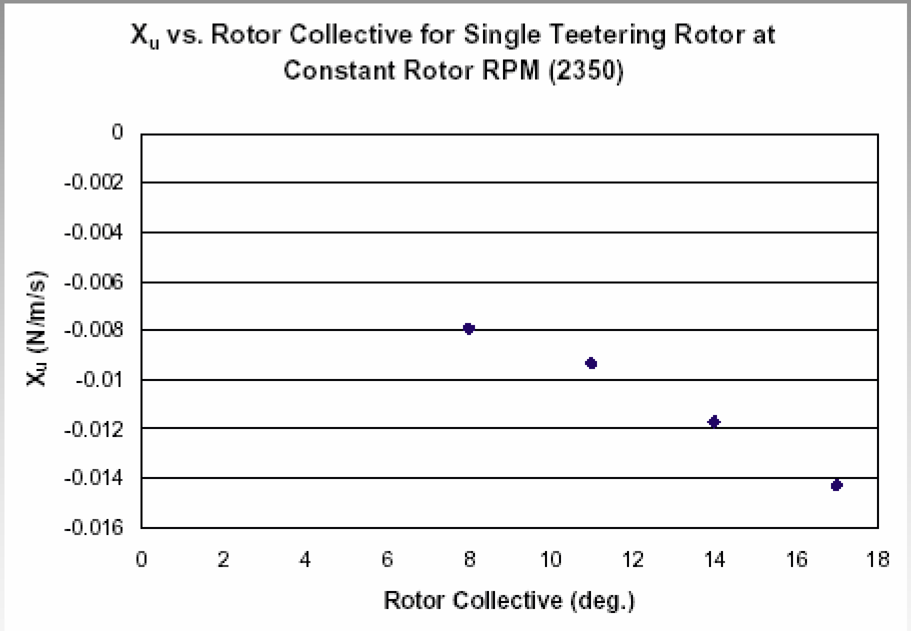
- The plot below shows that the stability derivative X_u is consistent for forcing frequencies between .6 and 1.4 Hz.



- At forcing amplitudes below 4 inches peak-to-peak the induced velocity perturbation is not large enough to produce an accurately measurable rotor reaction.
  - The response of the rotor was barely perceptible at oscillation amplitudes below 4 inches.

Forced Oscillation: Data Analysis

- For a single teetering rotor at constant RPM, qualitative analysis predicts that the stability derivative X_u will increase in magnitude as the collective pitch angle of the rotor blades is increased.



- From the plot above, it is clear that the testing process produces the expected trend in X_u for a change in rotor collective.

Theory

Position of the vehicle as forced by the motion of the sliding platform is given by:

$$x(t) = A_0 \sin(\omega t)$$

Differentiating gives the velocity:

$$\dot{x}(t) = A_0 \omega \cos(\omega t) = \Delta u$$

Because the vehicle is perturbed about a hover condition this function gives the perturbation velocity

Theory

The aerodynamic force response as measured by the force balance can be represented by a Fourier series approximation.

$$F_{A_x} = F_{IN} + F_{OUT} + HHT$$

Dropping the higher harmonic terms because the aerodynamic response will occur at the forcing frequency ω

$$F_{X_A} = \left|F_{IN}\right| \sin(\omega t) + \left|F_{OUT}\right| \cos(\omega t)$$

This can also be represented in magnitude-phase form

$$F_{X_A} = a\cos(\omega t - \psi)$$

Theory

The parameters of the magnitude-phase representation are given by

$$a = \sqrt{\left|F_{IN}\right|^2 + \left|F_{OUT}\right|^2}$$

$$\psi = \tan^{-1}\left(\frac{\left|F_{IN}\right|}{\left|F_{OUT}\right|}\right)$$

The gain of the system is given by:

$$\frac{\text{output amplitude}}{\text{input amplitude}} = \frac{a}{A_0\omega}$$

Data Reduction

- The results are converted into X-force and pitching moment using the calibration matrix of the force balance.
- Force and moment measurements are converted to a point on the bode diagram

Terms from Fourier Series Approximation → Force Balance Calibration Matrix → $\left|F_{OUT}\right|$ & $\left|F_{IN}\right|$

$$\text{gain} = \frac{\sqrt{\left|F_{IN}\right|^2 + \left|F_{OUT}\right|^2}}{A_0 \omega}$$

$$\text{phase} = \tan^{-1}\left(\frac{\left|F_{IN}\right|}{\left|F_{OUT}\right|}\right)$$

System Parameter Applications

- The result of the system identification process is approximate transfer functions between control and perturbation states and the resulting vehicle response

Transfer Function

Perturbation in forward velocity

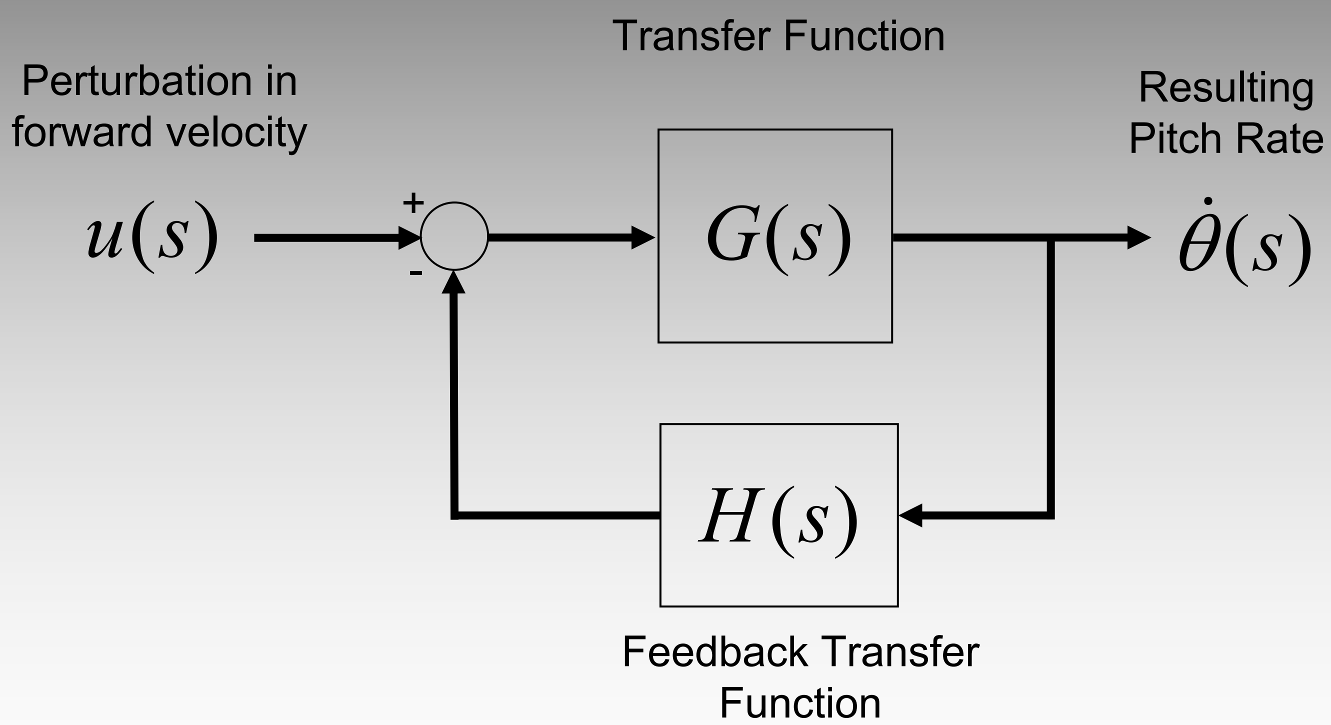
Resulting Pitch Rate

$$u(s) \longrightarrow \boxed{\frac{\dot{\theta}(s)}{u(s)}} \longrightarrow \dot{\theta}(s)$$

- Thus we can predict the response of the vehicle from the transfer function

System Parameter Applications

- If the vehicle response is not favorable, the transfer function can be used to design a control system



System Parameter Applications

- The transfer function from perturbation in forward velocity to pitch rate is now given by:

$$W(s) = \frac{G(s)}{\left[1 + G(s)H(s)\right]}$$

- Thus by designing an appropriate feedback control transfer function *H(s)* the closed loop transfer function *W(s)* can be tailored to meet specific requirements
  - Gain and phase margins
  - Pole locations

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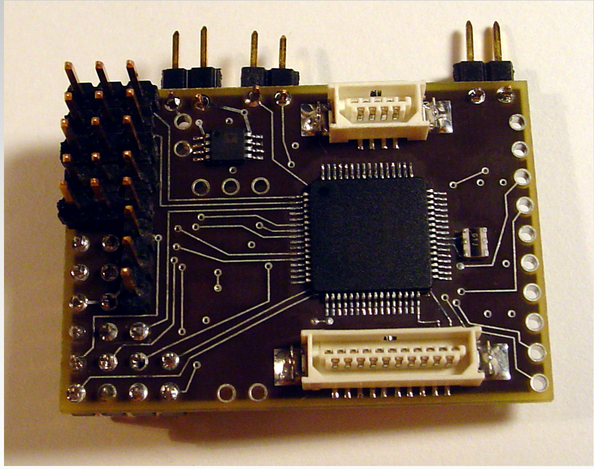
Technical Challenges

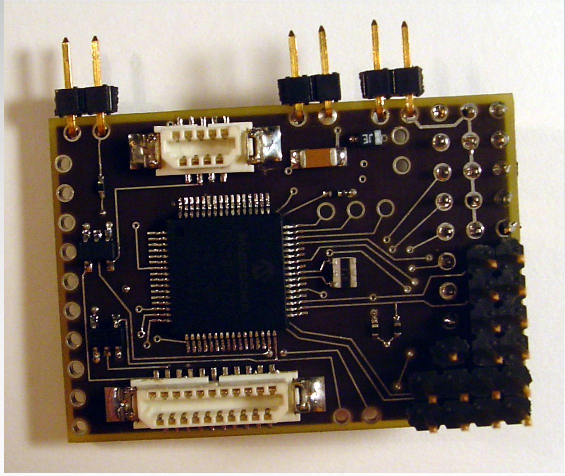
- Limited MAV payload size and weight
- State estimation using noisy MEMS-based inertial measurement signals
- Large communication range is desirable, but limited by antenna weight

Actuator Module

Actuator Module:
- **~8 grams**
- **12 V to 5 Volt power regulator**
- **8 bit PIC mcu @ 40 MHz (2X)**
- **UART buffering/ communication enabled with 5 Volt and 3 Volt devices**



Actuation Side



Sensor Interface Side

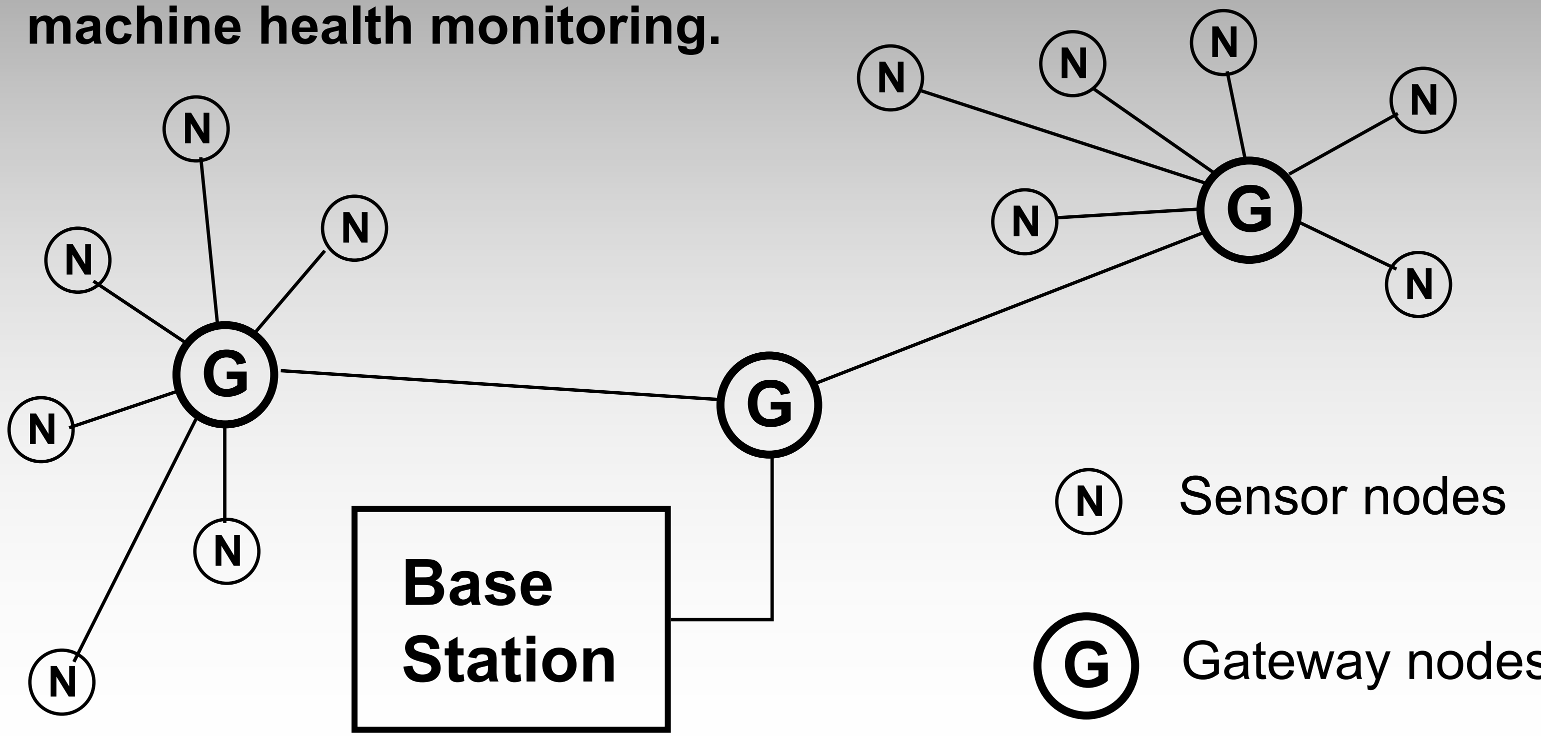
Transceiver Module

Transceiver Module:

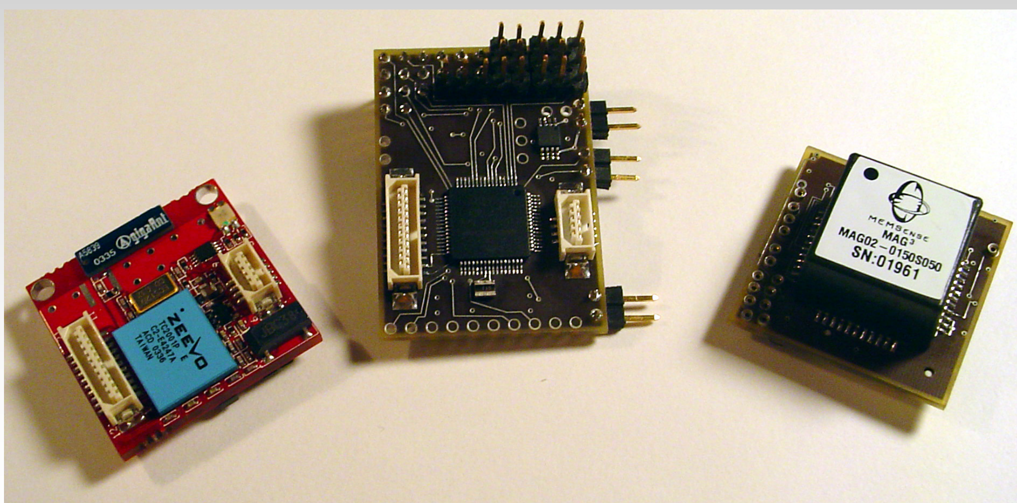
- **~8 grams**
- **12 V to 5 Volt power regulator**
- **8 bit PIC mcu @ 40 MHz (2X)**
- **UART buffering/ communication enabled with 5 Volt and 3 Volt devices**

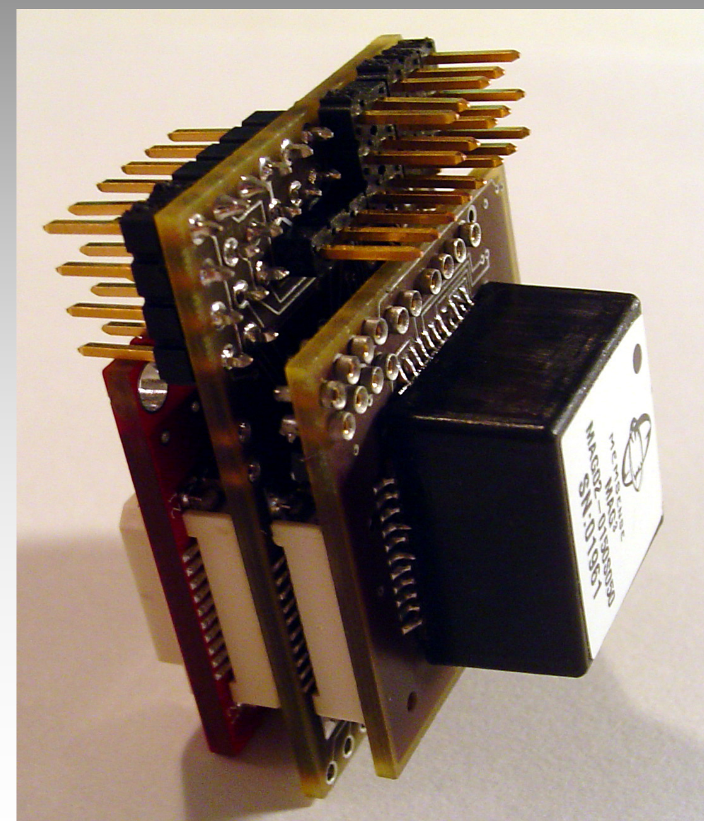
Wireless Sensor Networks

- **Hundreds or thousands of nodes wirelessly connected in a self-organizing mesh network based on signal strength.**
- **Wireless sensor networks are currently in use for habitat, (temperature/humidity), monitoring and vibration-based machine health monitoring.**



Configuration for feedback control, inertial measurement, and bi-directional wireless communications





IMU/Intel Mote Configuration

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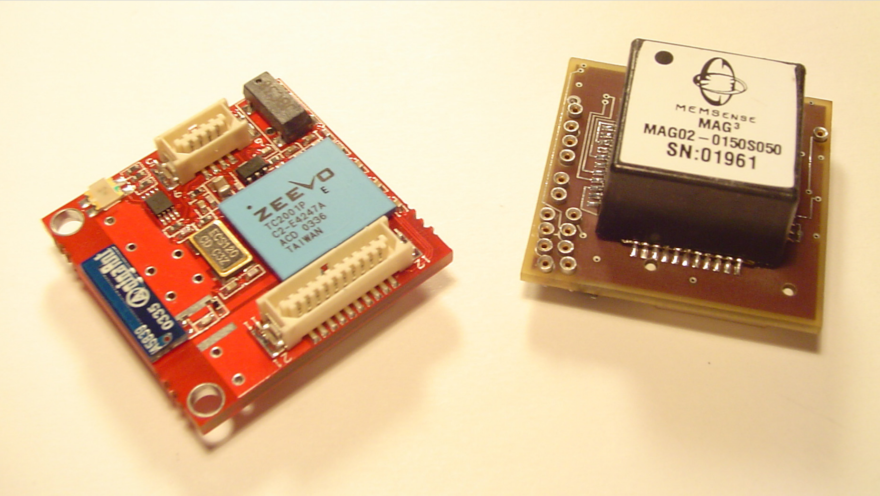
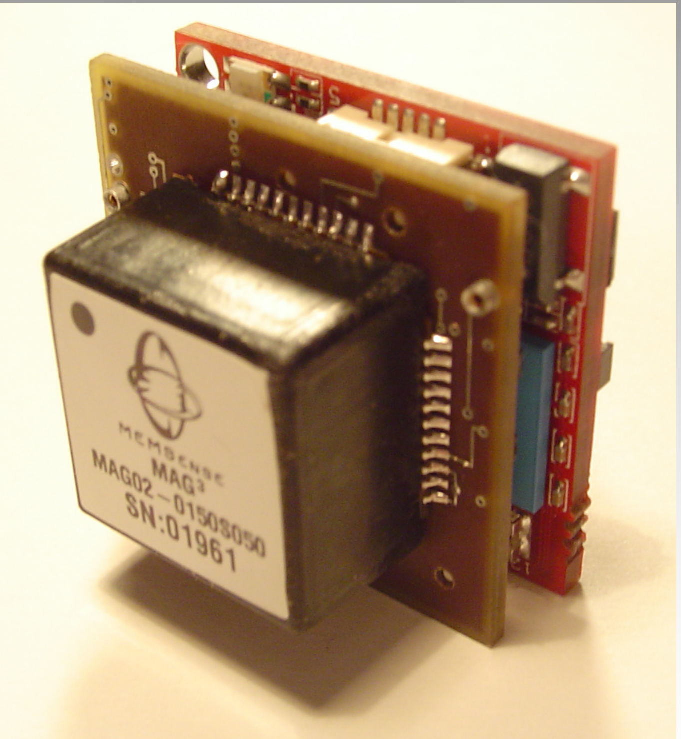
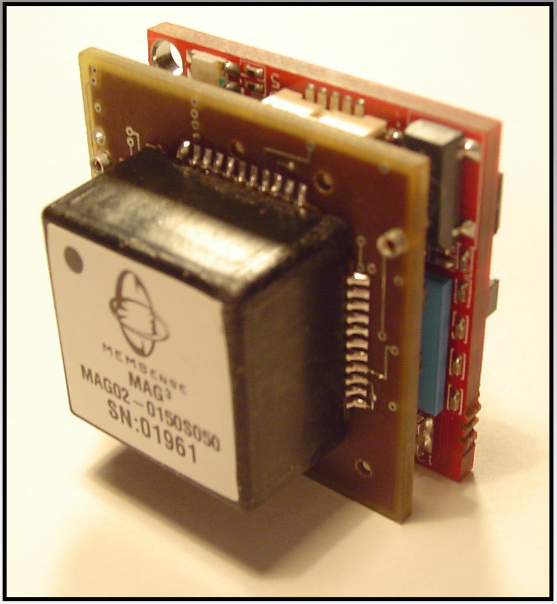
Configuration for minimal complexity inertial and magnetic telemetry



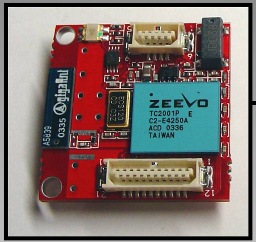


IMU/Intel Mote Configuration

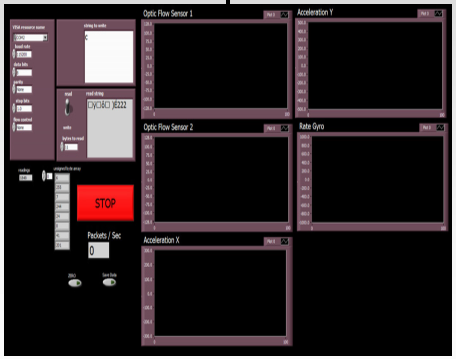
Intel Mote can be used as a simple telemetry module, sending back data at a max rate of ~172 Hz



Telemetry Data

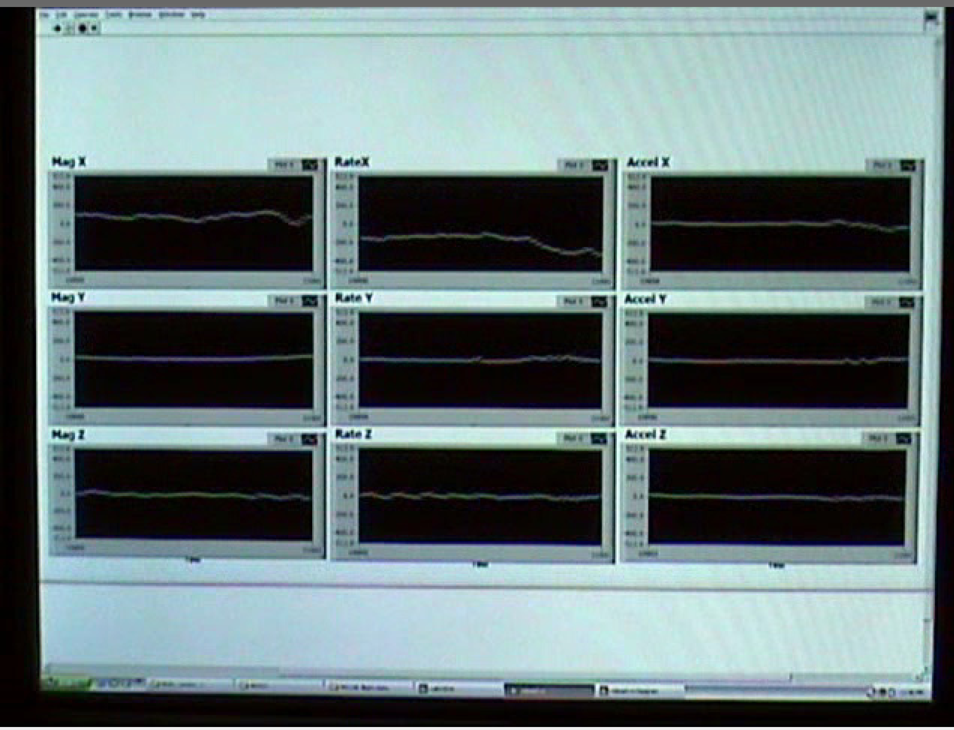


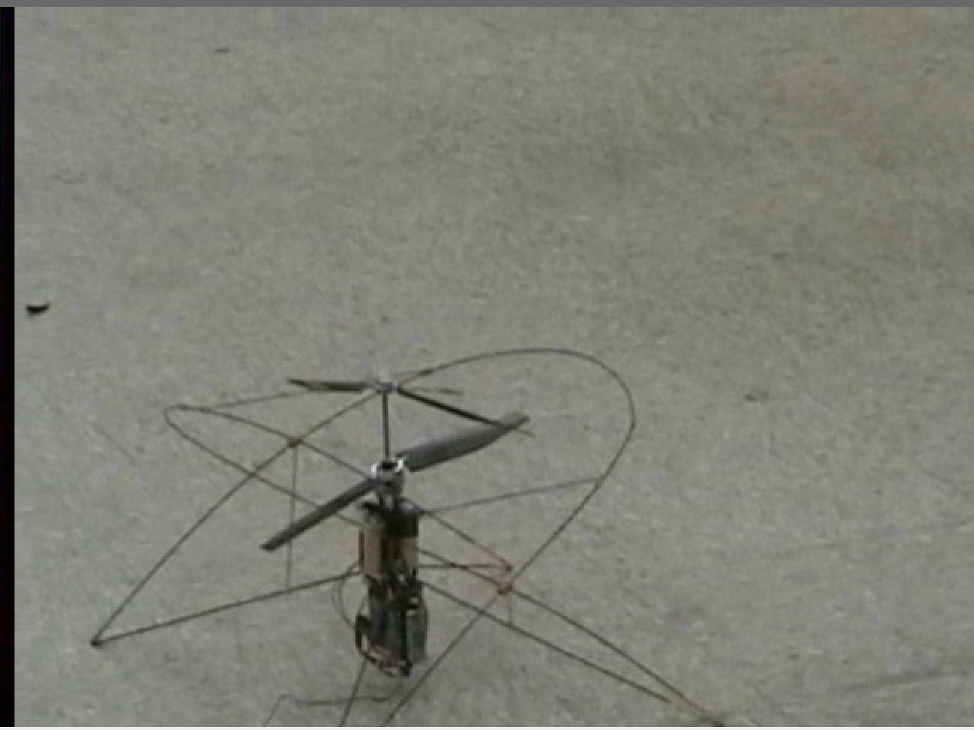
Base station node



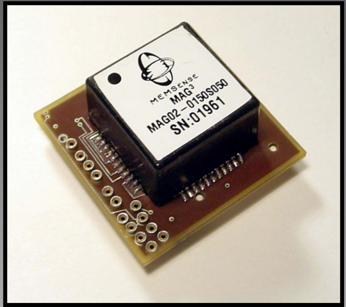
LabVIEW Interface

Data Collection Demo





Various Configurations Possible

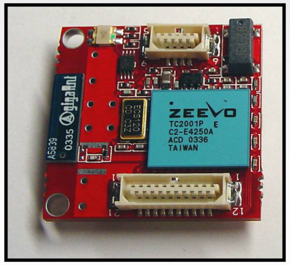


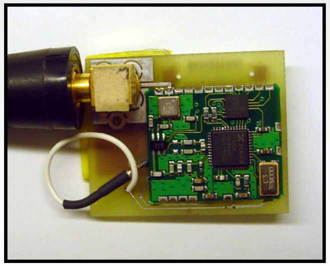
IMU module (8 gm.)

RC receiver
(~2gm.)

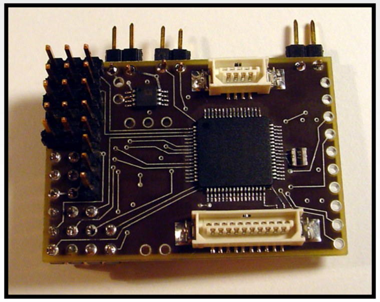
RC
receiver

Intel Mote or Transceiver Module (6.4 gm. ea)





Actuator Module (~8 gram)



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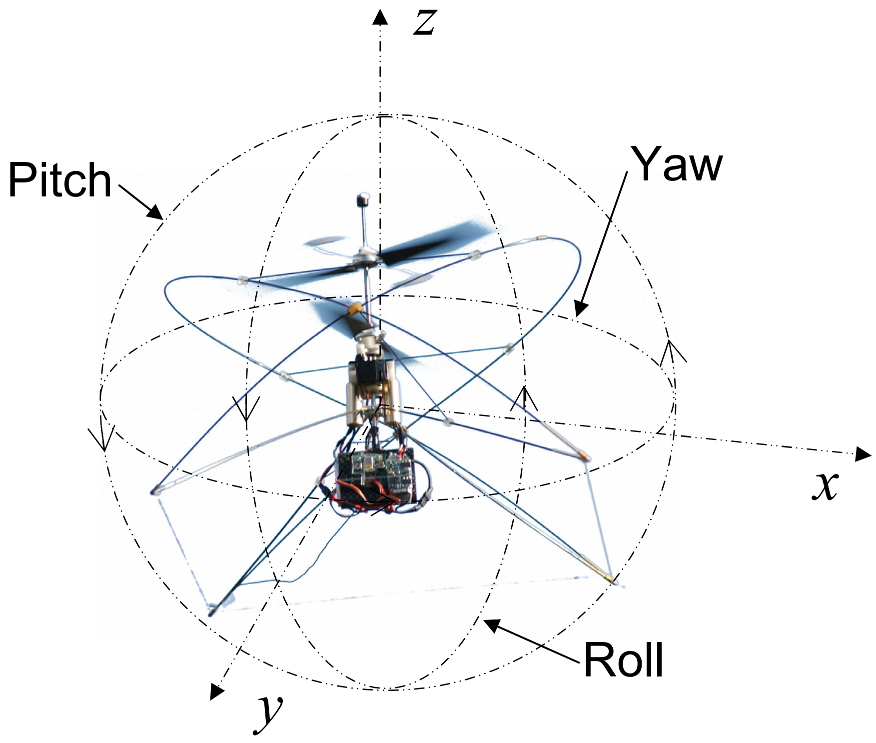
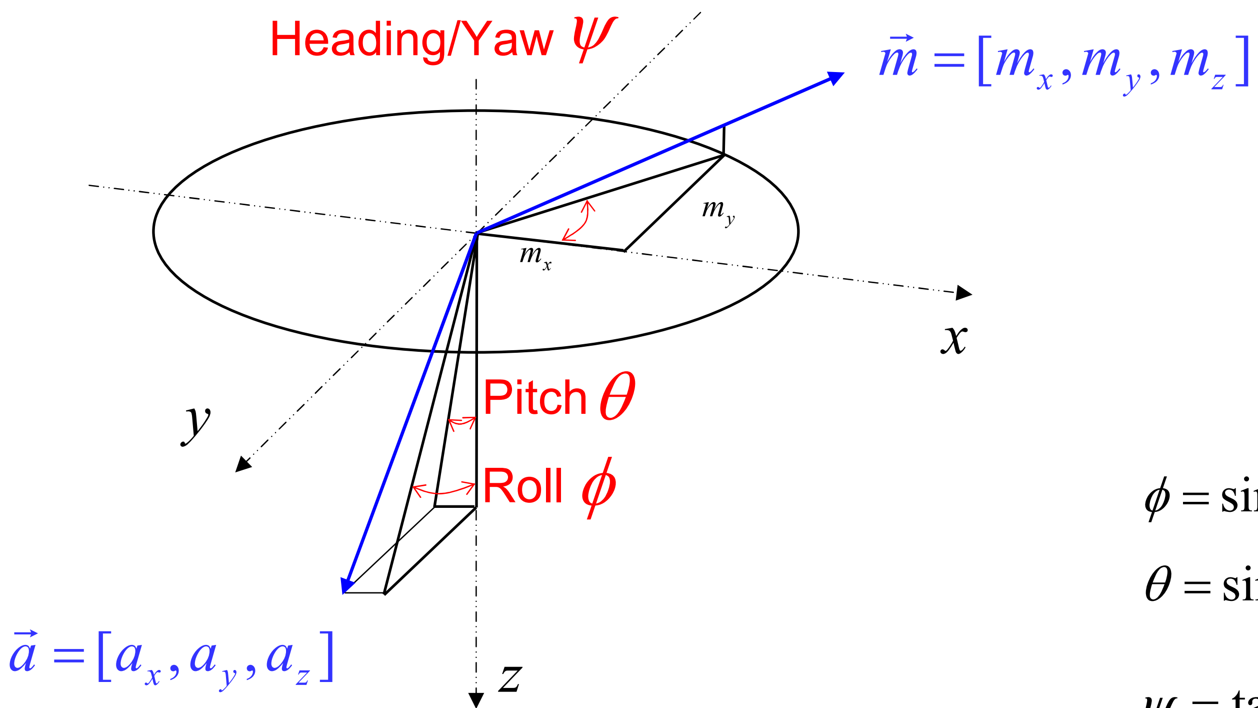
Attitude Representation



Euler Angles

Attitude Determination



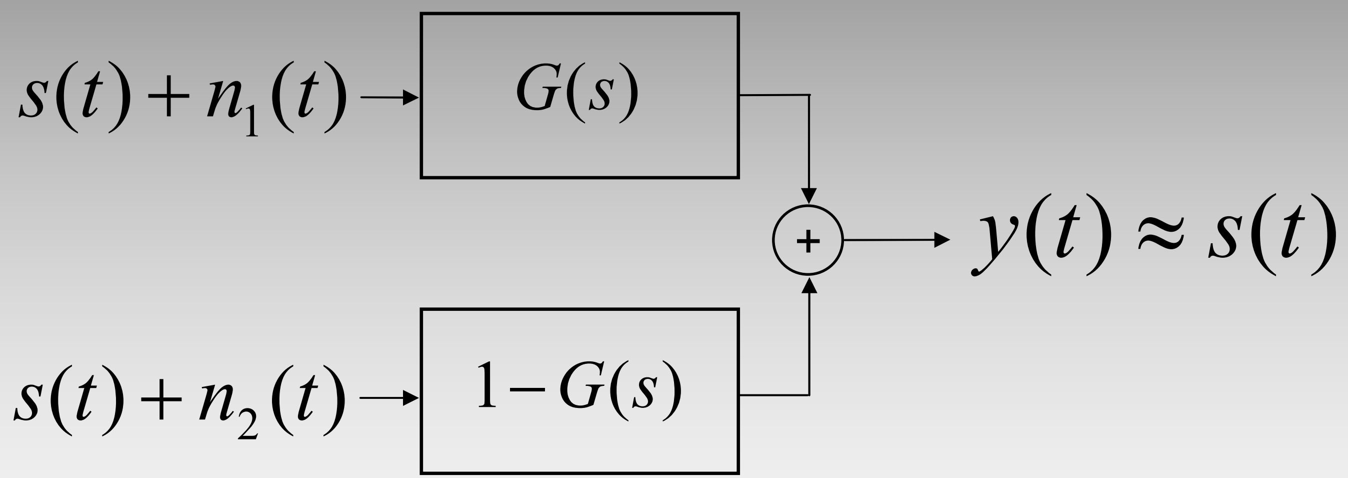
$$\phi = \sin^{-1}(a_y)$$

$$\theta = \sin^{-1}(a_x)$$

$$\psi = \tan^{-1}\left(\frac{m_y}{m_x}\right)$$

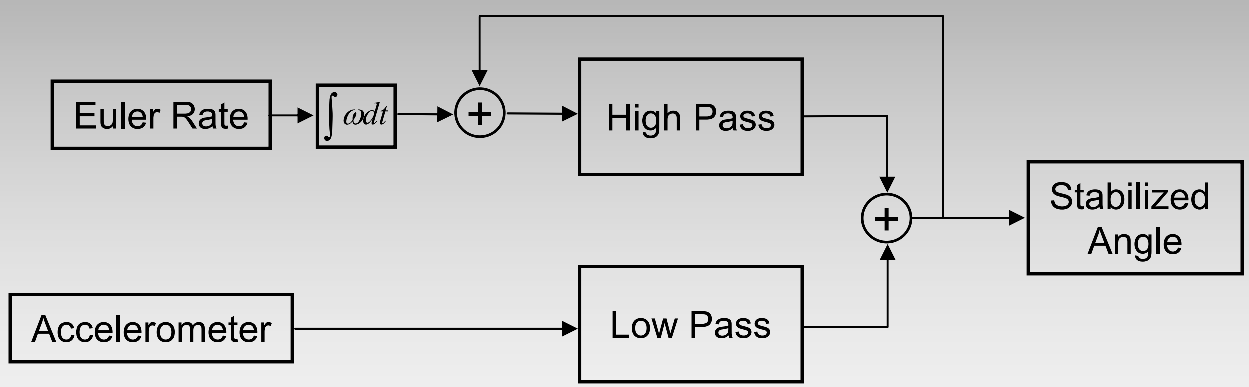
Complementary Filter

In general, for two sources of the same measurement with complementary noise characteristics:



Complementary Filter

For this particular application:



Implemented on Giant MAV

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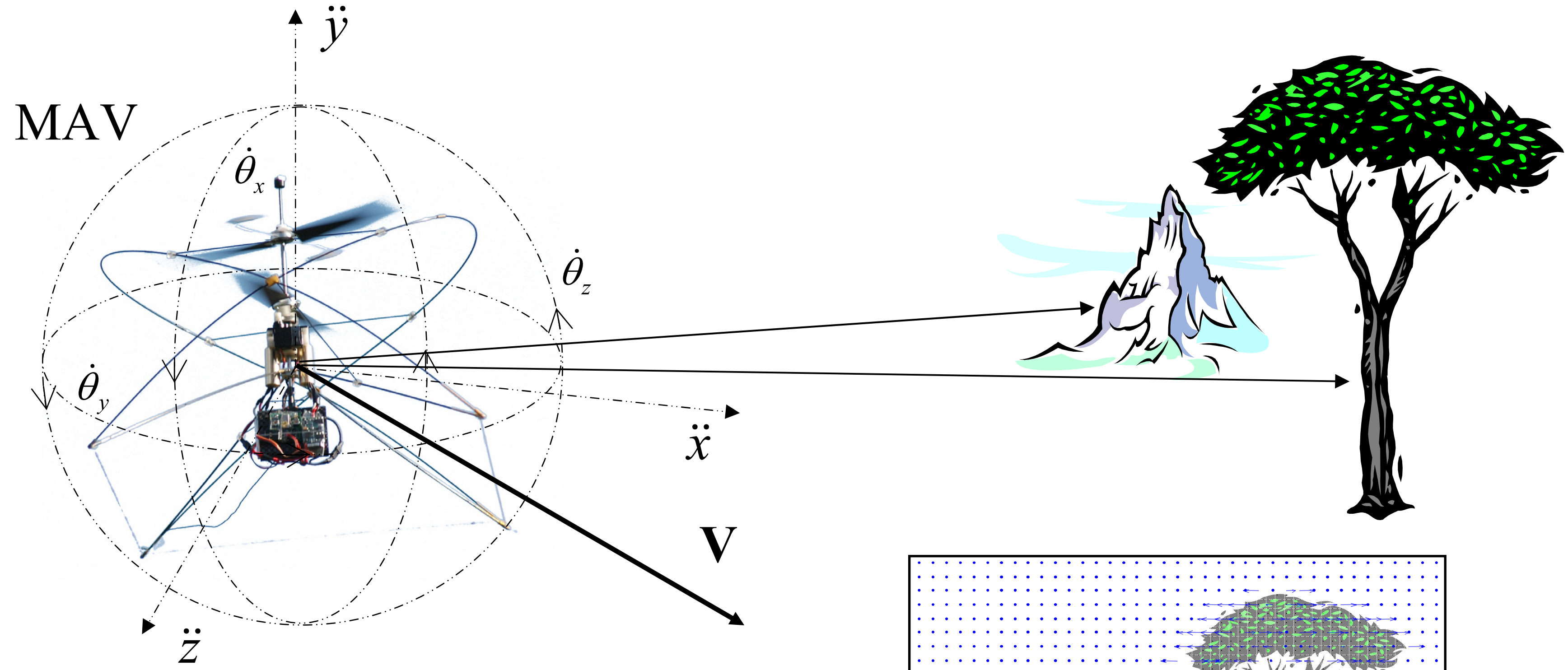
Motivation to use Optic Flow

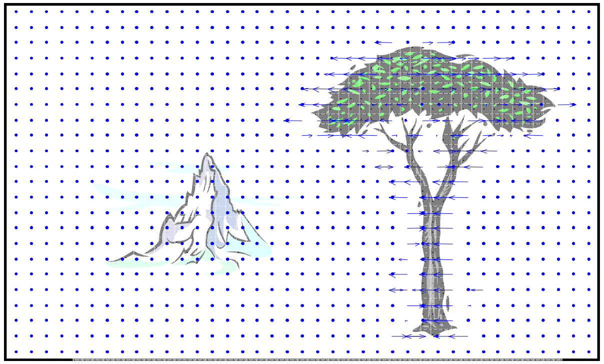
Insects use optic flow as their primary method of navigation

Insects are very good at flying!

A relatively simple and lightweight solution to MAV navigation may be found by attempting to mimic the method of navigation utilized by insects.

Vision-Based Navigation





Problem: Visual processing too complex in general for current vehicles

One Solution: Mimic insects

Perceived Motion of Obstacles due to V

Optic Flow

Optic Flow

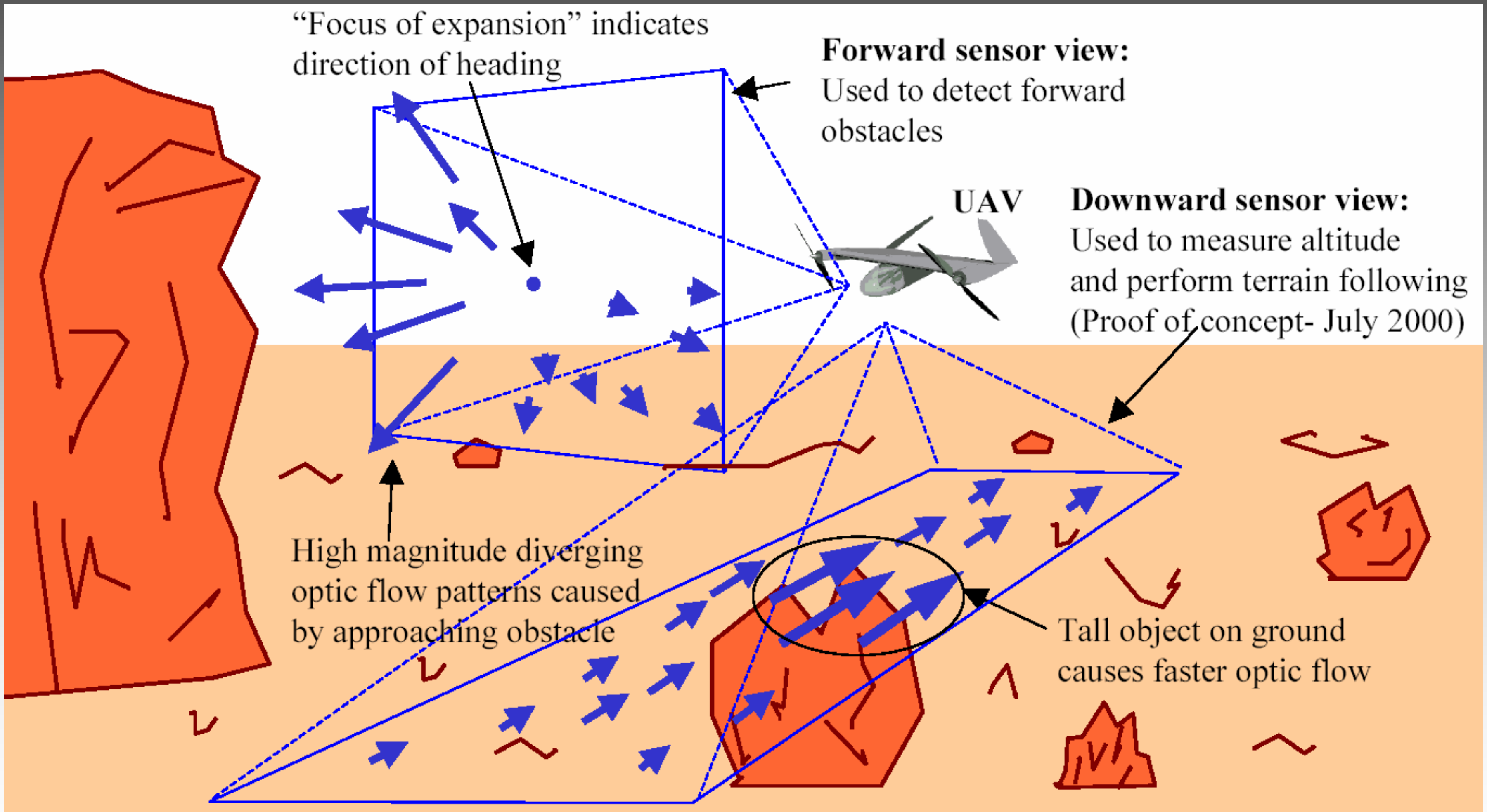


Photo courtesy: Centeye

Optic Flow

The apparent motion of the visual field perceived by an observer that results from rotational and translational motion through the imaged environment.

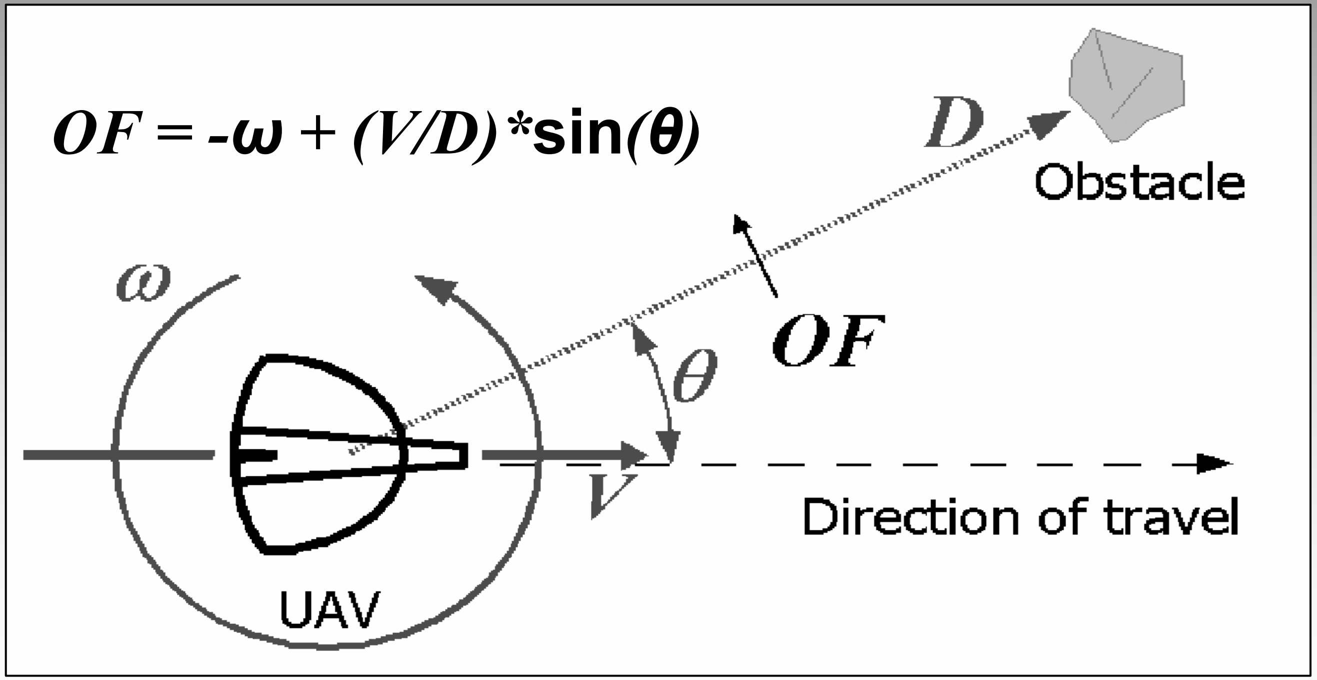
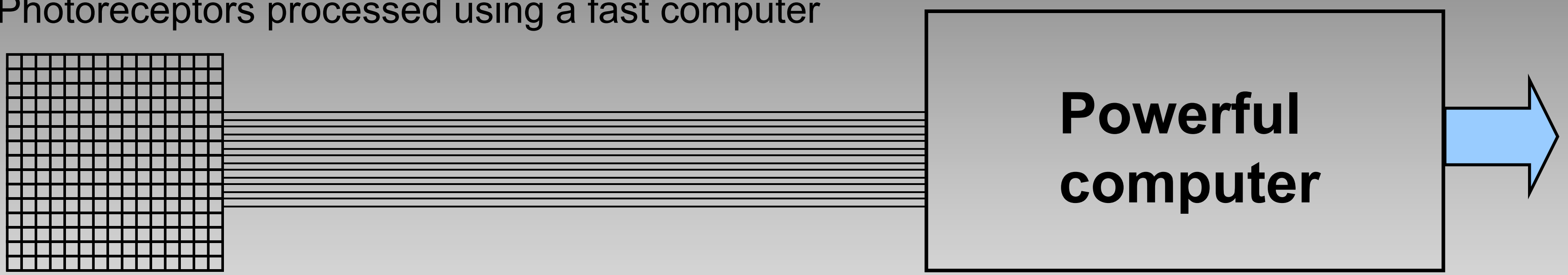


Photo courtesy: Centeye

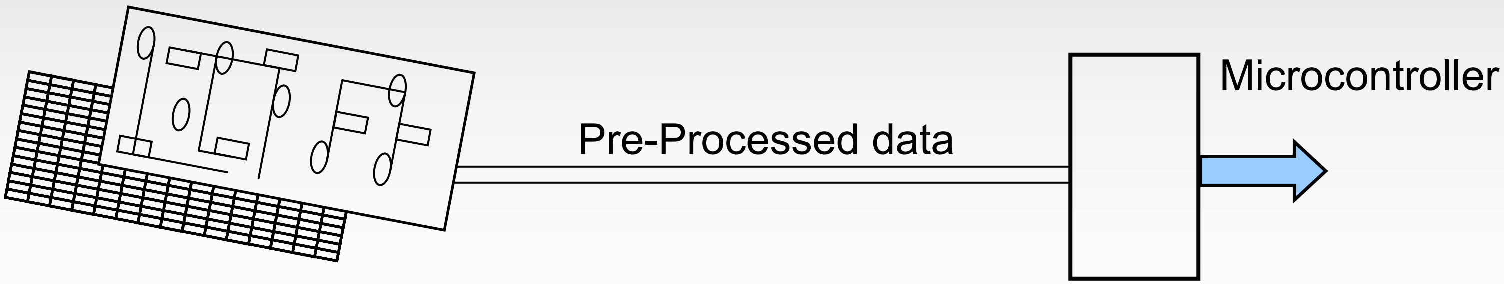
Consideration 1:

Machine Vision Image Processing

Photoreceptors processed using a fast computer



Hybrid Based – Photoreceptor data with analog pre-processing fed to microcontroller



Centeye Optic Flow Sensors

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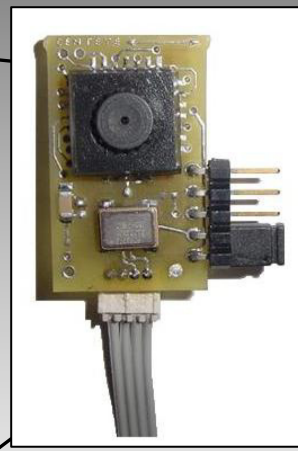
Performs complex optic flow calculations using hard-coded VLSI algorithms

Estimates a single valued average of optic flow over visual field



~4 grams

Interfaces with a microcontroller

Dr. Geof Barrows, Centeye

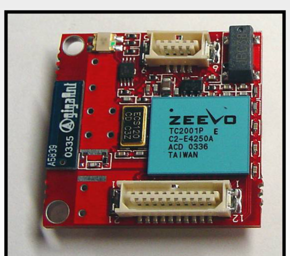
Various Configurations Possible

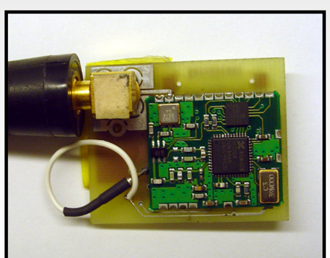
IMU module (8 gm.)

RC receiver (~2gm.)

RC receiver

Intel Mote or Transceiver Module (6.4 gm. ea)





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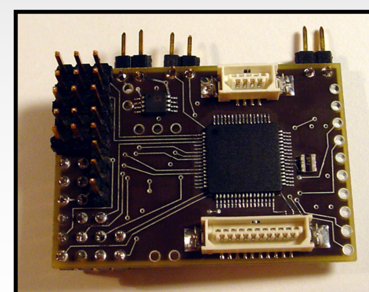
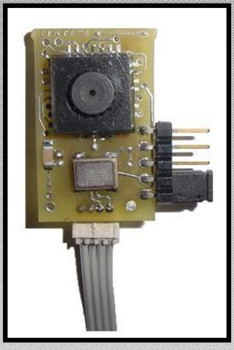
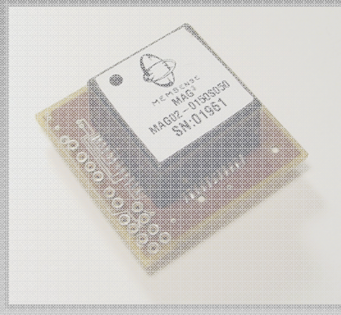


Various Configurations Possible

Optic Flow Sensor



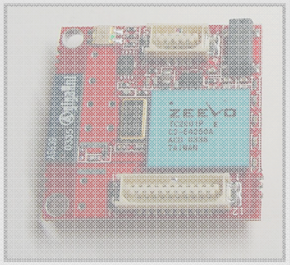


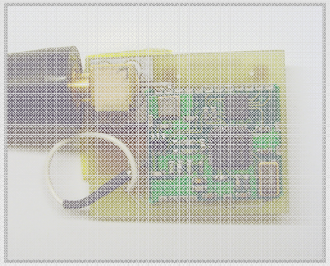
IMU module (8 gm.)

RC receiver (~2gm.)

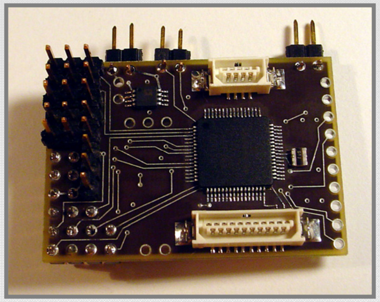
RC receiver

Intel Mote or Transceiver Module (6.4 gm. ea)

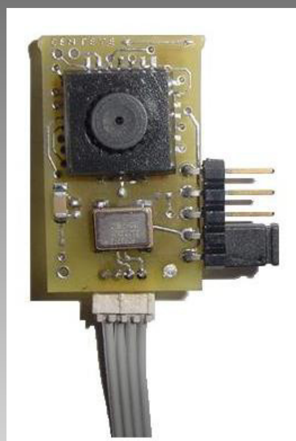




Actuator Module (~8 gram)



Full System



Optic Flow is a function of rotational rate, translational velocity, and distance from imaged objects

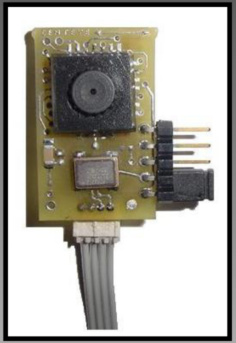
Rate gyro provides a measure of rotation rate

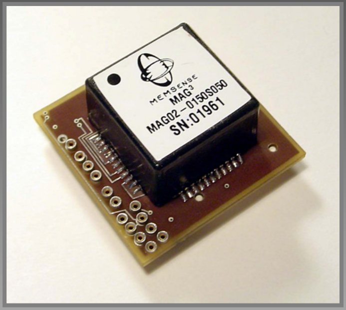
Accelerometers give translational acceleration

Fuse Information

Full System

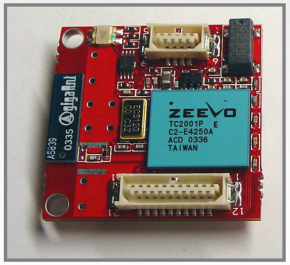
Optic Flow Sensor

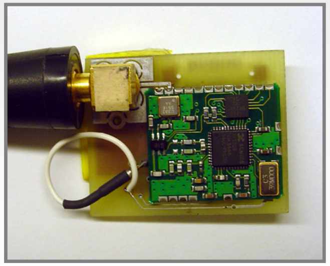




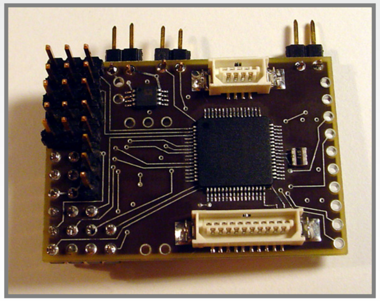
IMU module (8 gm.)

Intel Mote or Transceiver Module (6.4 gm. ea)





Actuator Module (~8 gram)



Agile MAV