Autonomous Micro-Aerial Vehicle Navigation Using a Custom Optic Flow Sensor Ring

Master Project: Final Presentation

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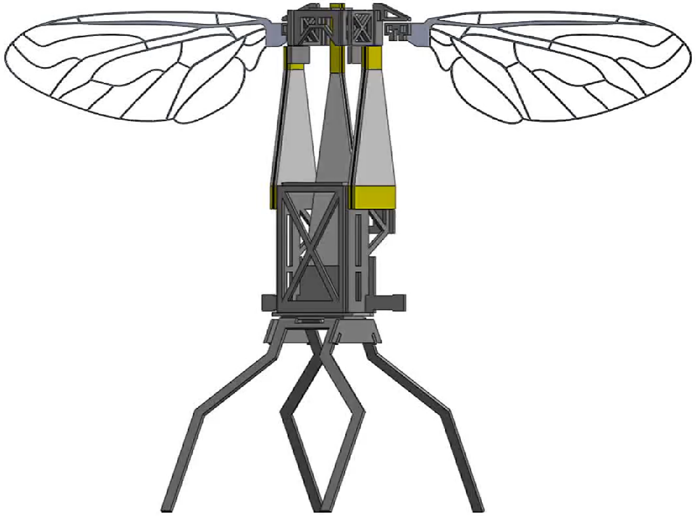
ROBOBEES

- Researchers at Harvard University are working to create a swarm of robotic honey-bees
- Such a distributed robotic system can be used for tasks such as:
  - Search and rescue
  - Hazardous environment exploration
  - Military surveillance
  - Weather and climate mapping
  - Crop pollination
  - Traffic monitoring

Image: Popular Science

ROBOBEES

- Half-gram flapping-wing autonomous micro-aerial vehicle
- The RoboBees are an extremely resource-scarce platform
  - Limited power
  - Limited computation
  - Limited sensing



ROBOBEES

- The project is divided into three parts:

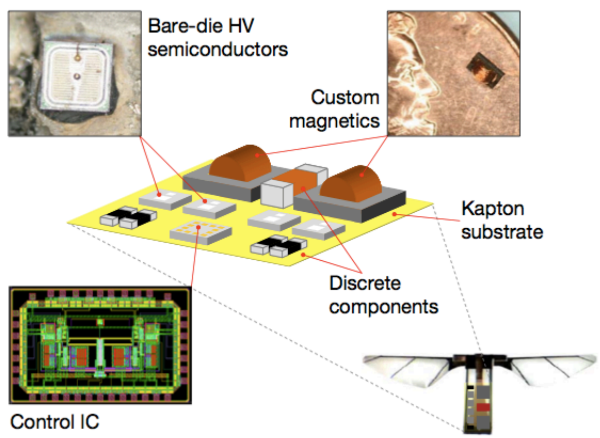
Body

- Designing an insect-sized, autonomous flapping-wing micro-aerial vehicle (MAV)

Image: Eliza Grinnel

Brain

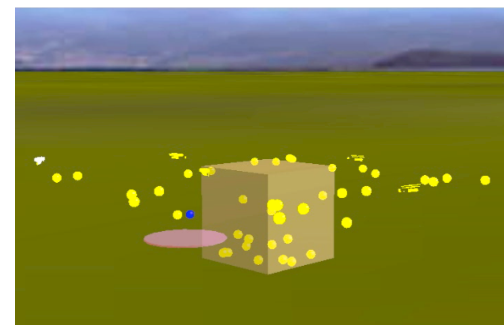
- Development of sensors, control, and circuitry to direct flight

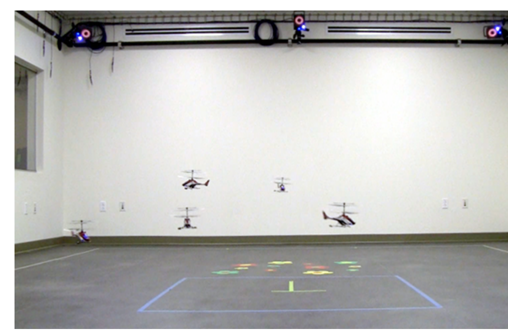


Karpelson et al., 2010

Colony

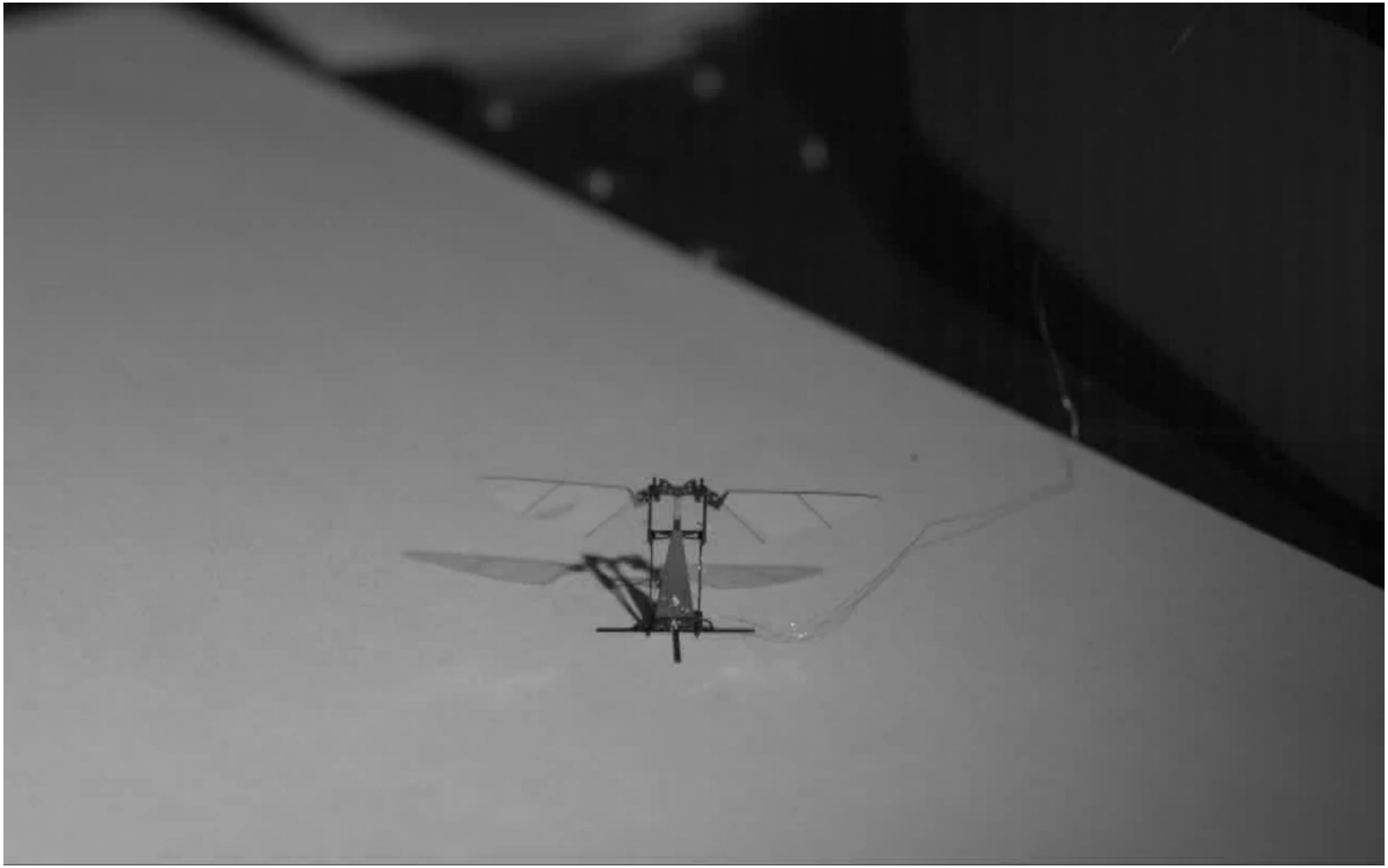
- Coordinate a hive of miniature robots to accomplish tasks





Kate et al., 2012

ROBOBEES

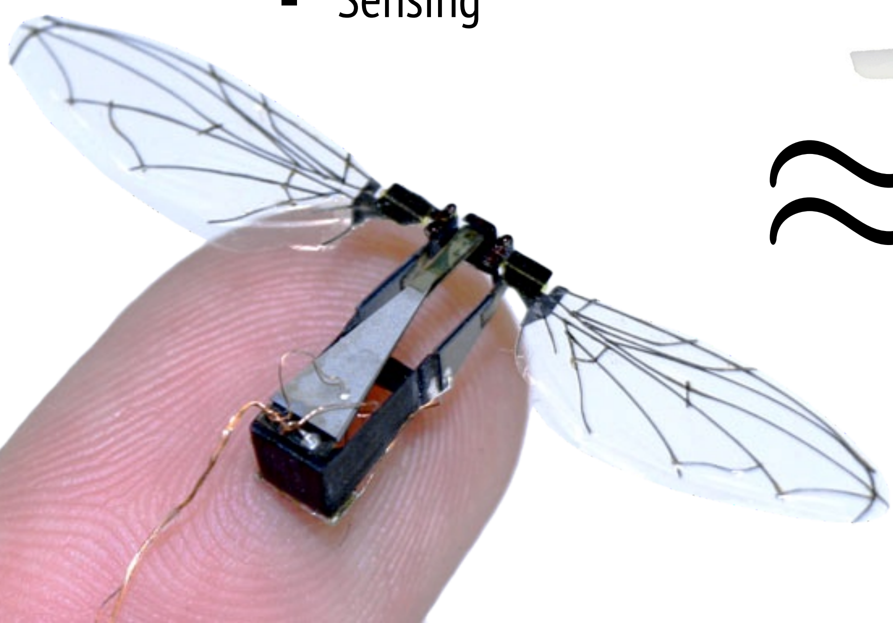


Progress…but not there yet.

ROBOBEES

- We use a micro-helicopter platform as a stand-in for the RoboBees while under development
- Similar limitations on
  - Weight
  - Power
  - Computation
  - Sensing

Vision-based sensing



$\approx$

VISION

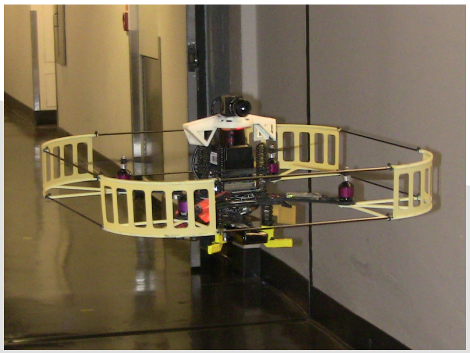
- The RoboBees will use omnidirectional vision sensors for navigation and control
  - Low power
  - Lightweight
  - High information density
  - Existing sensor technology
- We have developed an specialized vision-based sensor ring for use with our helicopter platform

Source: Czech Technical University

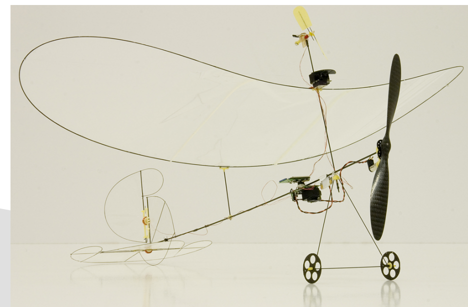
GOALS

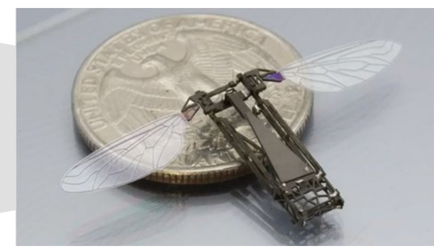
- Get the RoboBee-inspired hardware ready for testing
  - Vision-based sensing
  - Fully on-board computation
- Build a simulation for testing behaviors

STATE OF THE ART

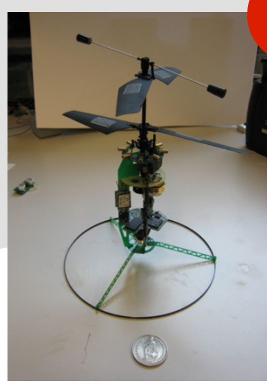

Shen et et al., 2011

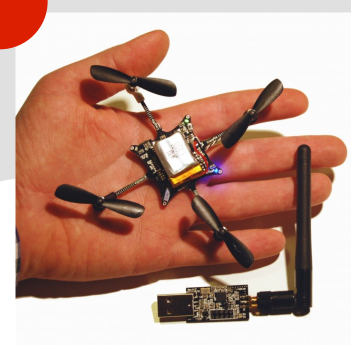

Calafell et al., 2011


Zufferey et al., 2006


Wood et al., 2012


Zingg et al., 2012


Bermes et al., 2010


Bitcraze, 2013

Larger payload
Greater computational power
Extended sensing

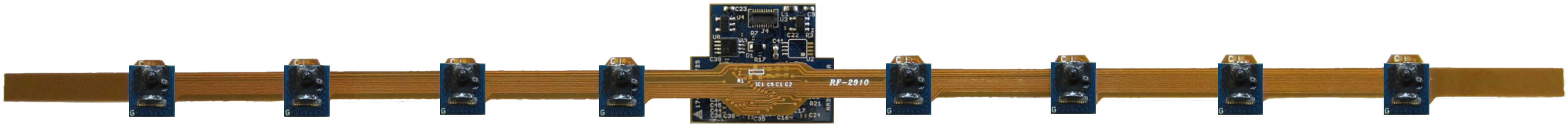
→

Small size
Little computational power
Limited sensing

PLATFORM

- Coaxial helicopter
  - based on Blade mCX2
  - 19 cm rotor diameter
  - 2 DC motors for rotors
  - 2 linear servos adjust swashplate
- Completely autonomous
  - custom control board designed by Centeye Ltd.
  - lithium-polymer battery
  - gyroscope
  - wireless radio
- Custom optic flow sensor ring
- 30 g total weight

SENSOR RING



Sensor control board

- 48 MHz 32-bit AVR microcontroller
- Readout images from vision chips
- Perform optic flow estimation and send to helicopter control board

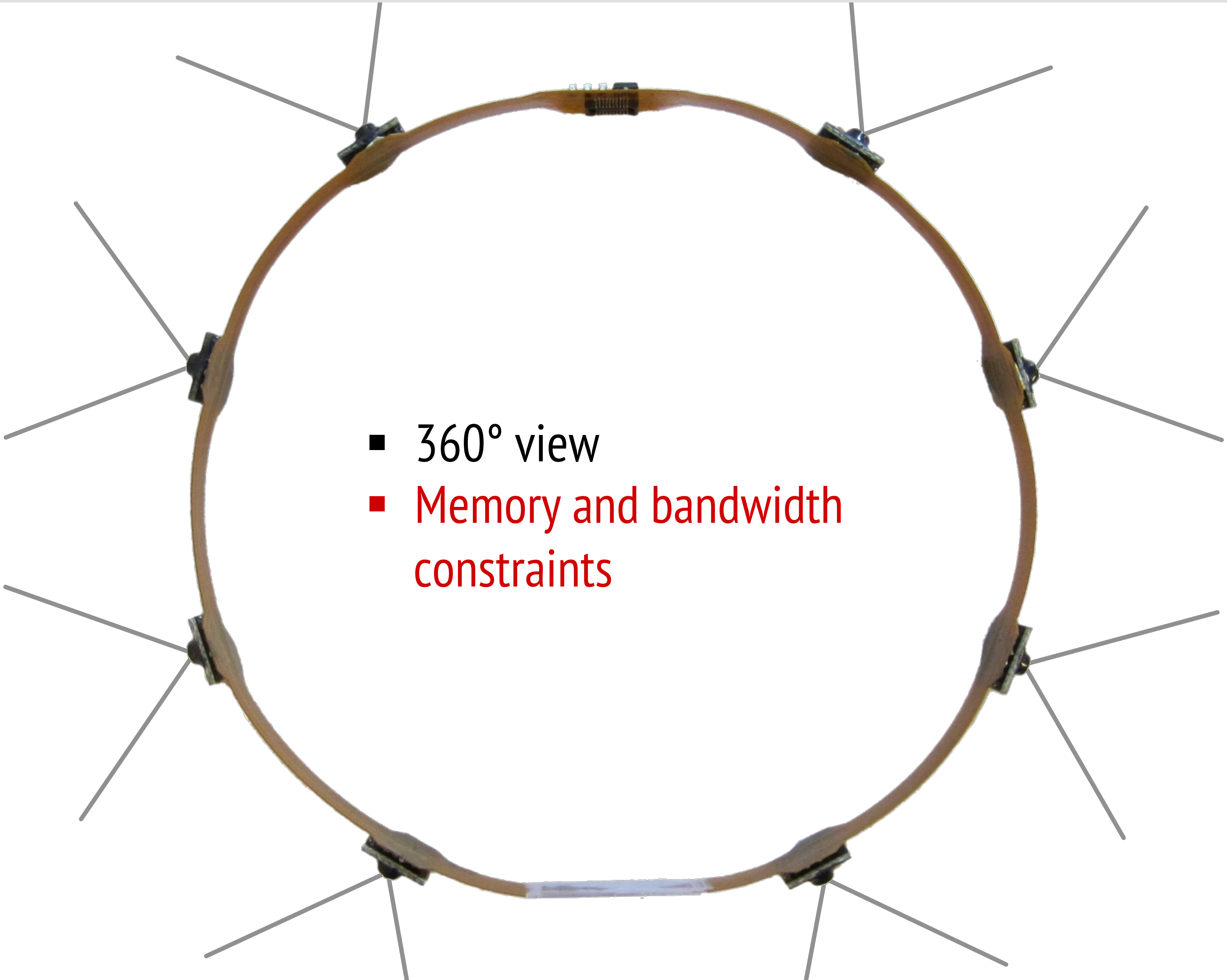
Sensor strip

- Flexible printed circuit board (PCB)
- 10 cm diameter ring

Vision chips

- 8 specialized vision chips from Centeye Ltd.
- 64 x 64 array of logarithmic pixels
- 10-bit ADC readout
- Integrated optics with ~75° field-of-view

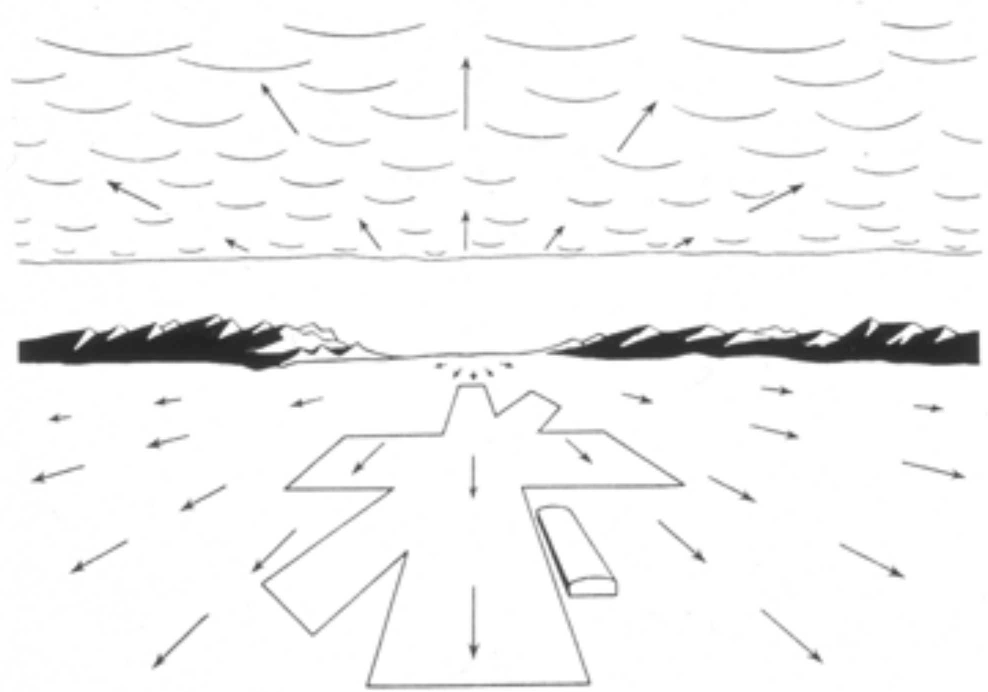
SENSOR RING



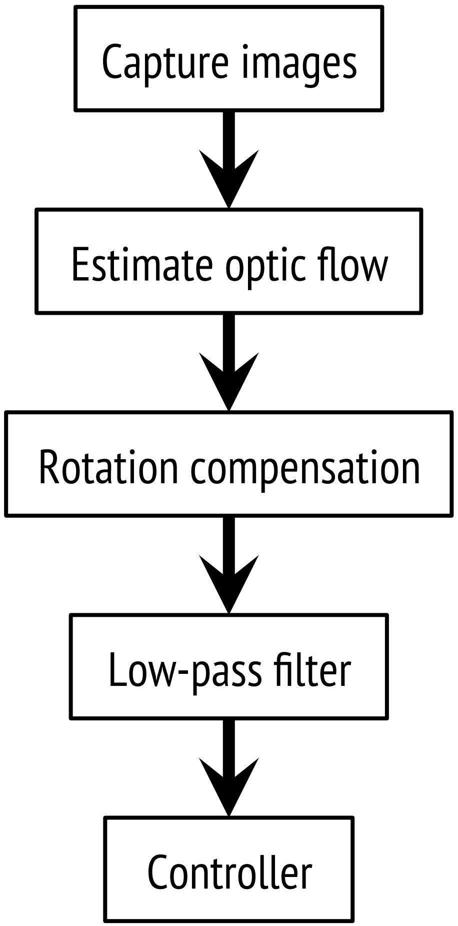
- 360° view
- Memory and bandwidth constraints

OPTIC FLOW

- We use the sensor ring to measure optic flow around the MAV
- Optic flow is the apparent visual motion of objects, surfaces, and edges in a scene caused by the relative motion between an observer and a scene

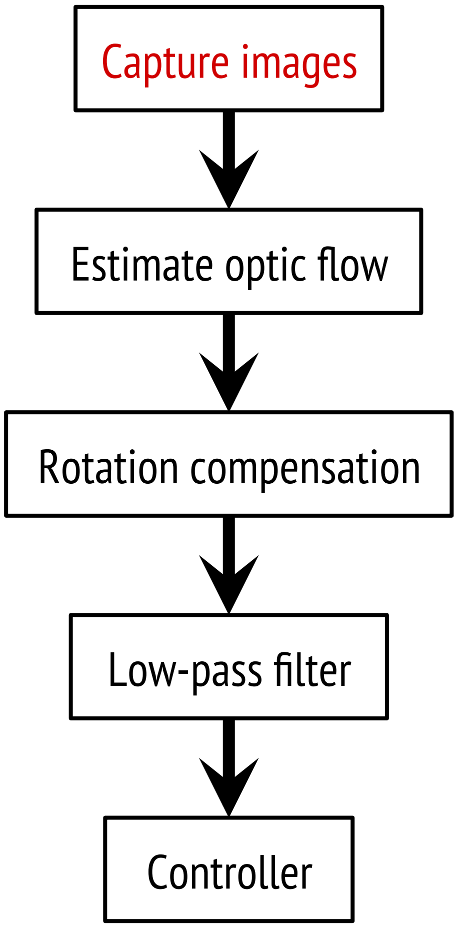


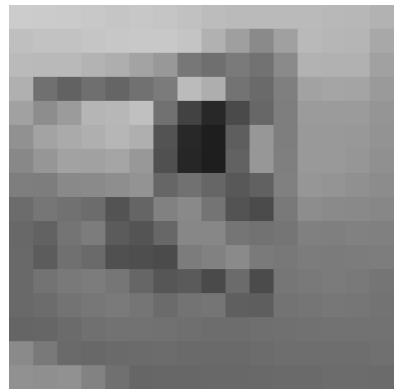
OPTIC FLOW



- We want to extract information from the environment by estimating the optic flow around the vehicle

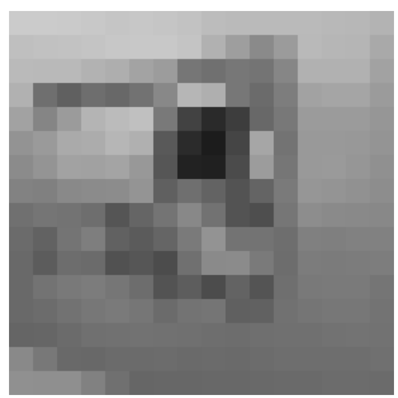
OPTIC FLOW





$f_0(x, y)$

Image at t_0



$f(x, y)$

Image at t

OPTIC FLOW

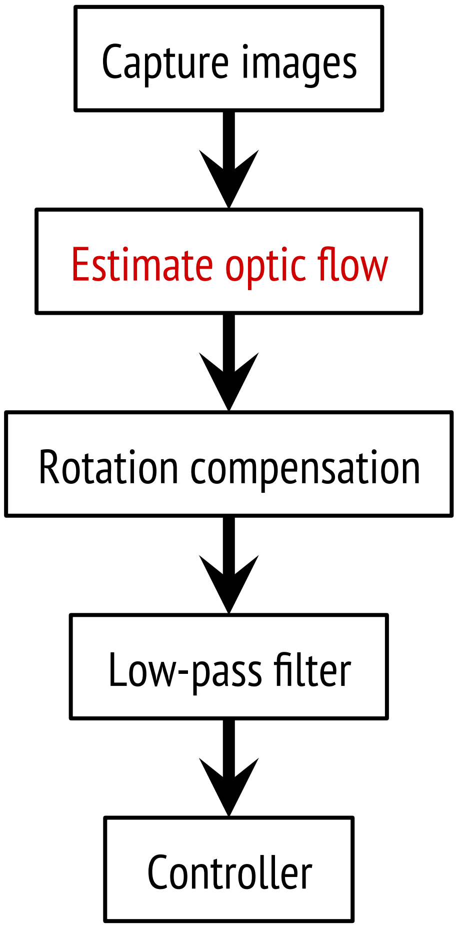
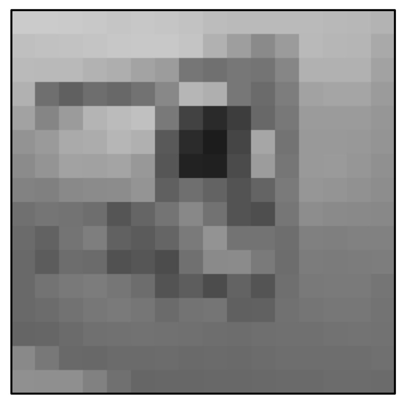


Image interpolation algorithm (I2A)

- Simple, fast, and lightweight algorithm
- Assumes the current image can be linearly interpolated from previous image and space shifted reference images



$$
\begin{aligned}
f_1(x,y) &= f_0(x+\Delta x_{ref}, y) \\
f_2(x,y) &= f_0(x-\Delta x_{ref}, y) \\
f_3(x,y) &= f_0(x, y+\Delta y_{ref}) \\
f_4(x,y) &= f_0(x, y-\Delta y_{ref})
\end{aligned}
$$

$$
\hat{f} = f_0 + 0.5\left(\frac{\Delta x}{\Delta x_{ref}}\right)(f_2 - f_1) + 0.5\left(\frac{\Delta y}{\Delta y_{ref}}\right)(f_4 - f_3)
$$

OPTIC FLOW

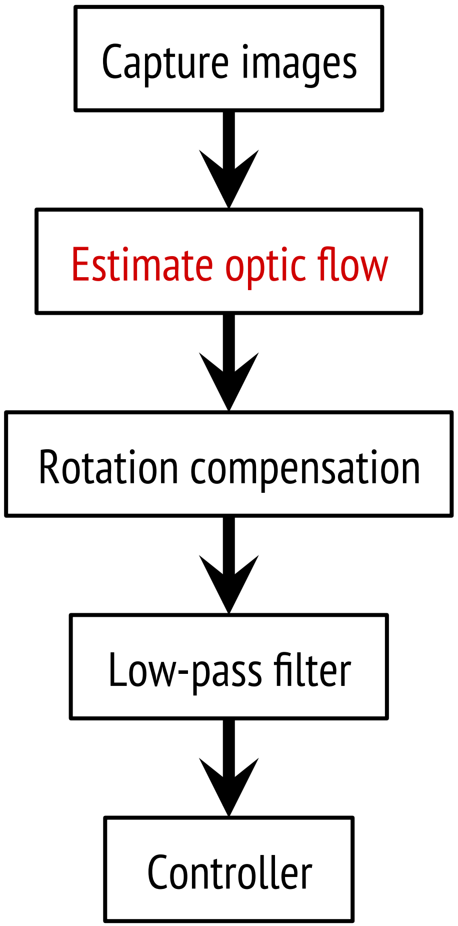
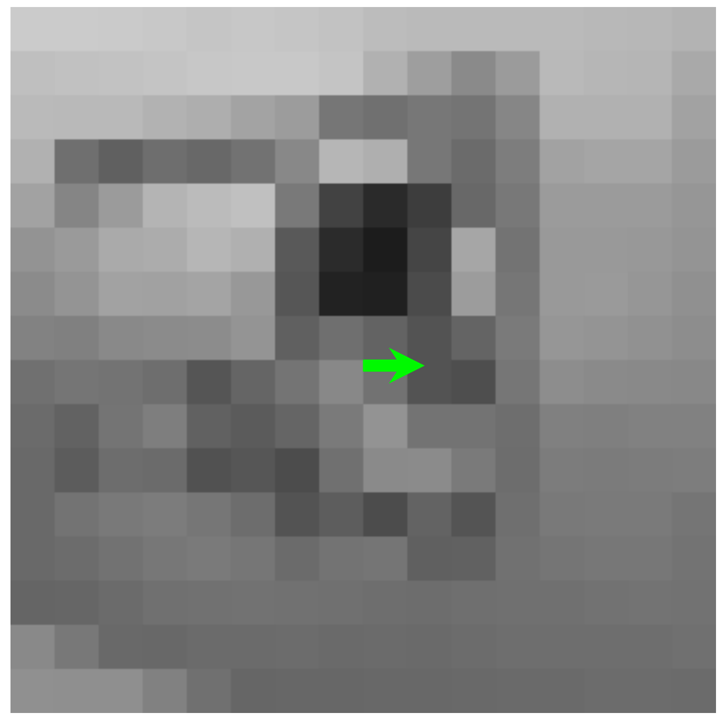
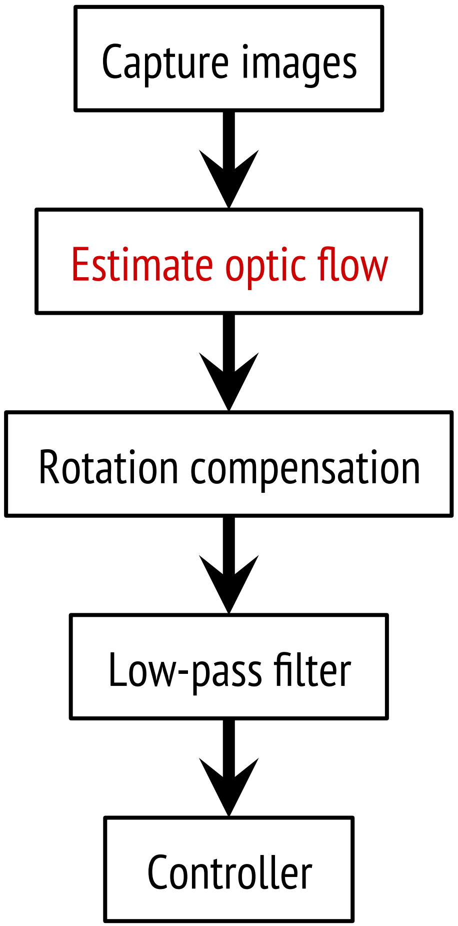


Image interpolation algorithm (I2A)

- By minimizing the error between the interpolated image and actual image, we can estimate the flow



OPTIC FLOW



What causes this optic flow?

OPTIC FLOW

Capture images

↓

Estimate optic flow

↓

Rotation compensation

↓

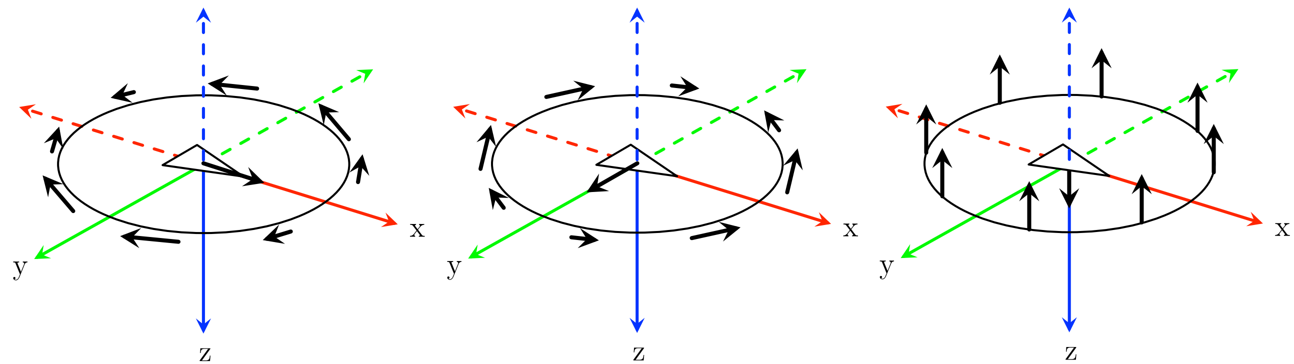
Low-pass filter

↓

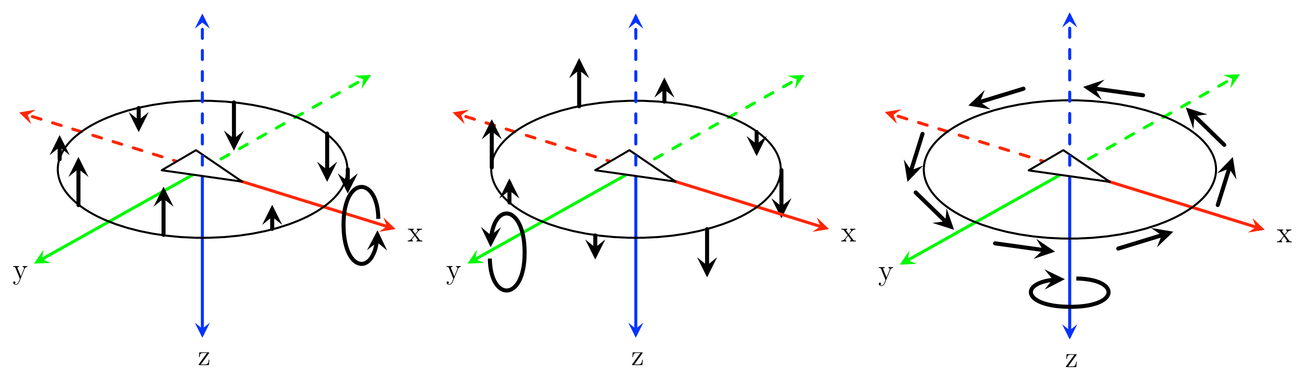
Controller

- There are two, additive components to optic flow:

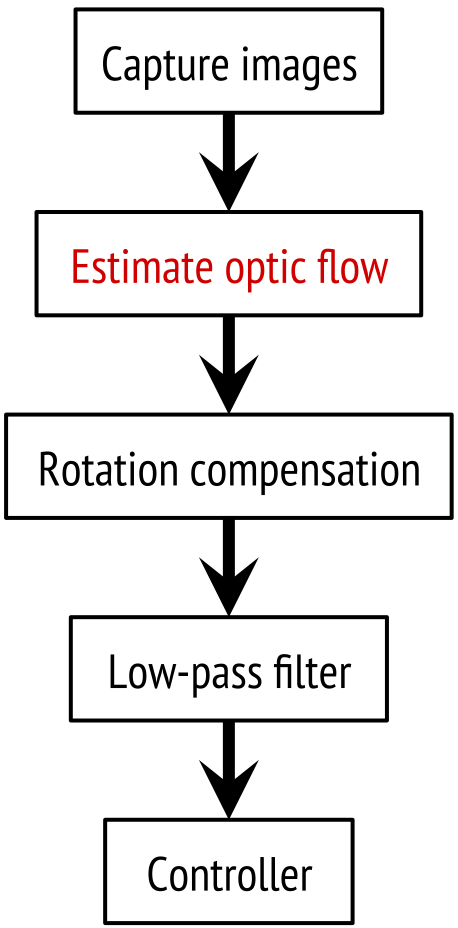
Translation



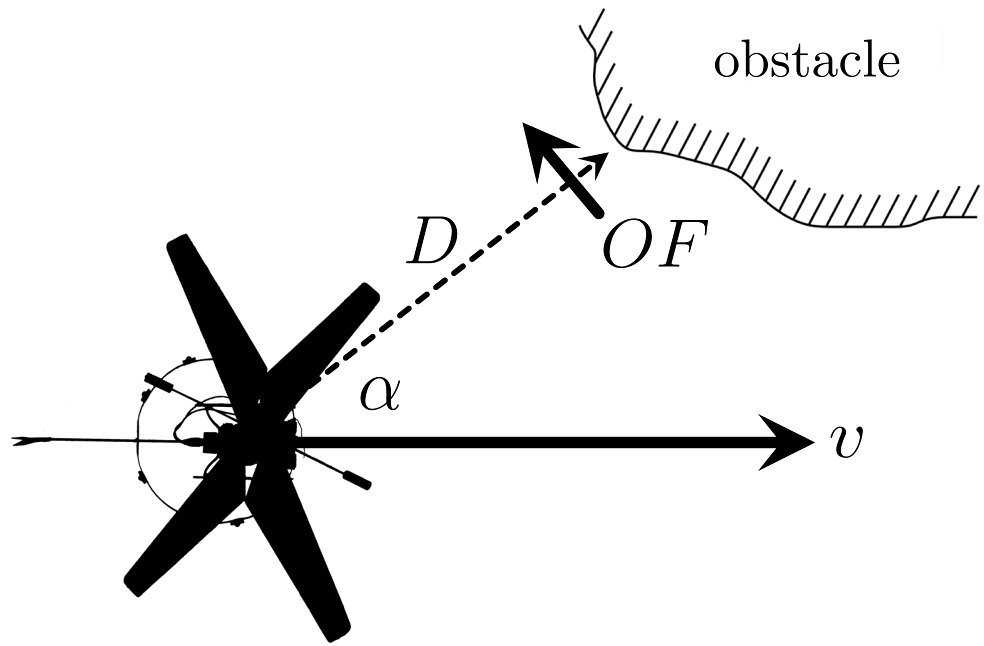
Rotation



OPTIC FLOW

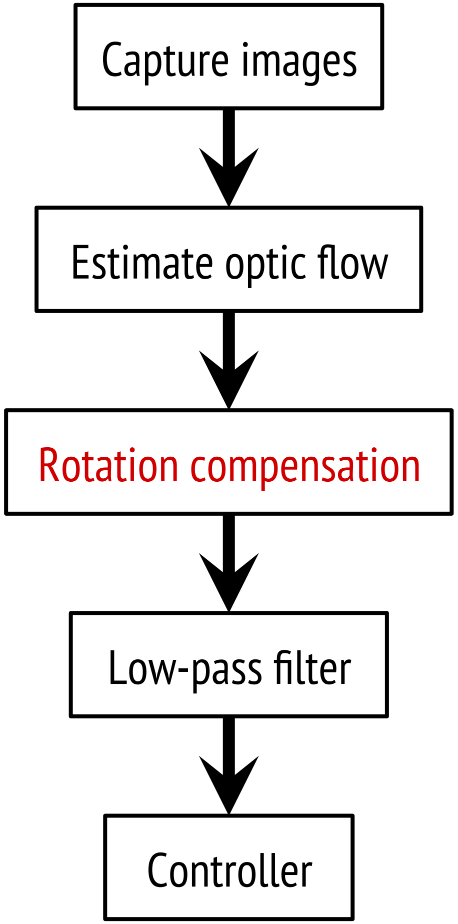


- Translational optic flow gives us information about the environment
- Rotational optic flow does not

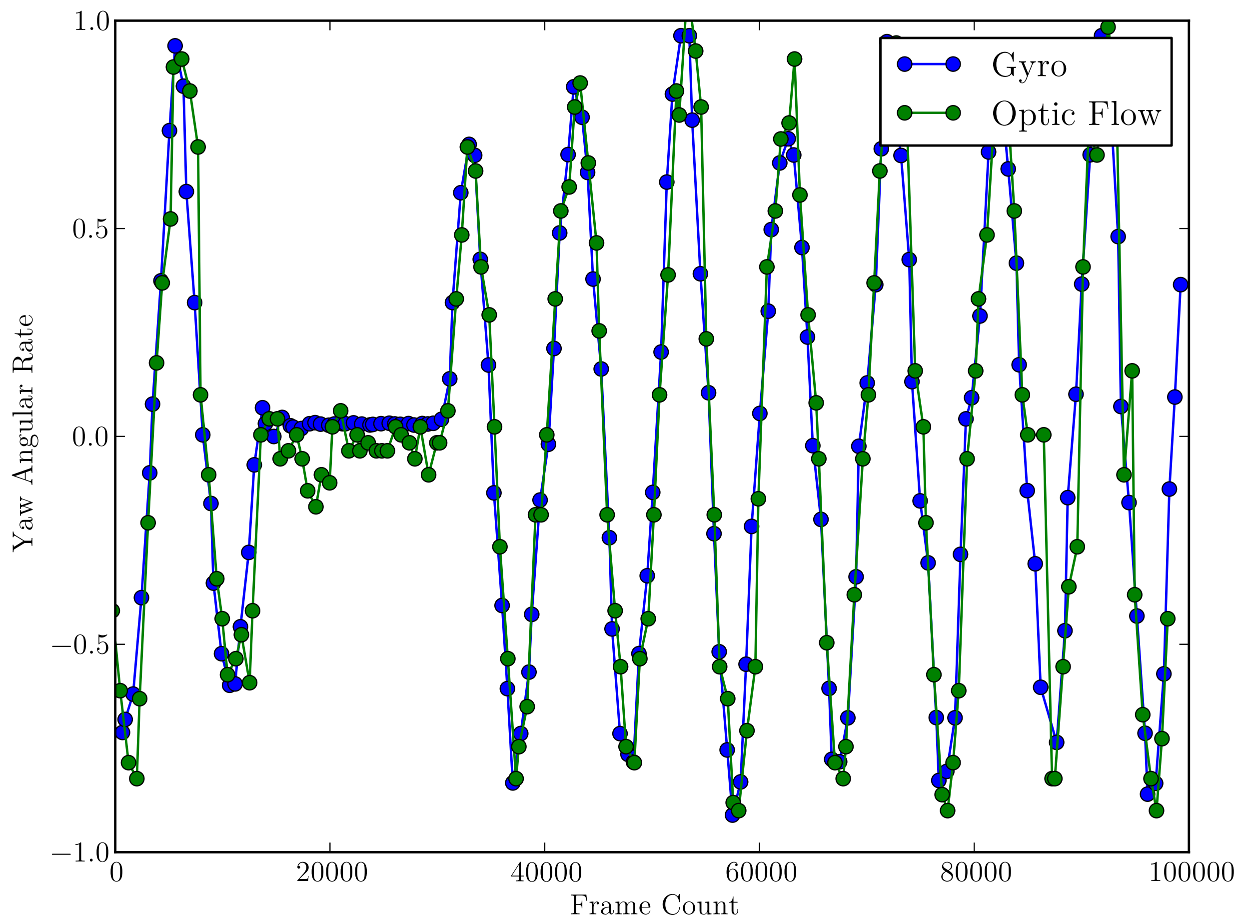


$$OF = \frac{v}{D} \cdot \sin \alpha$$

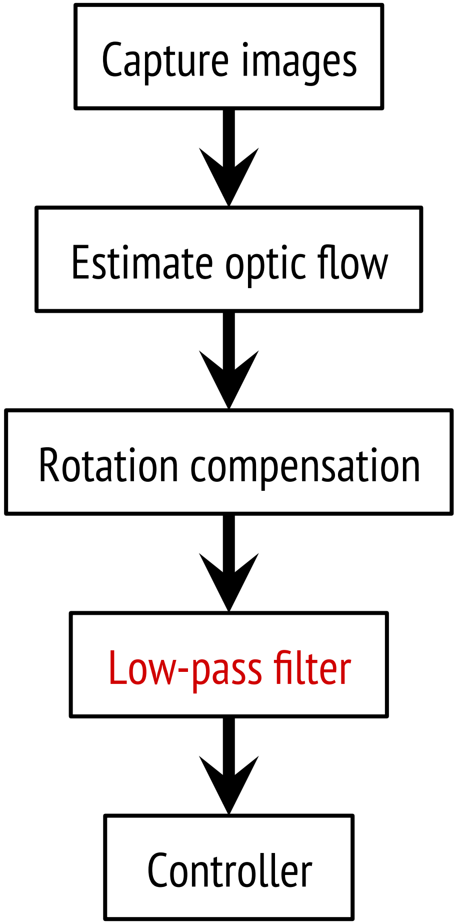
OPTIC FLOW

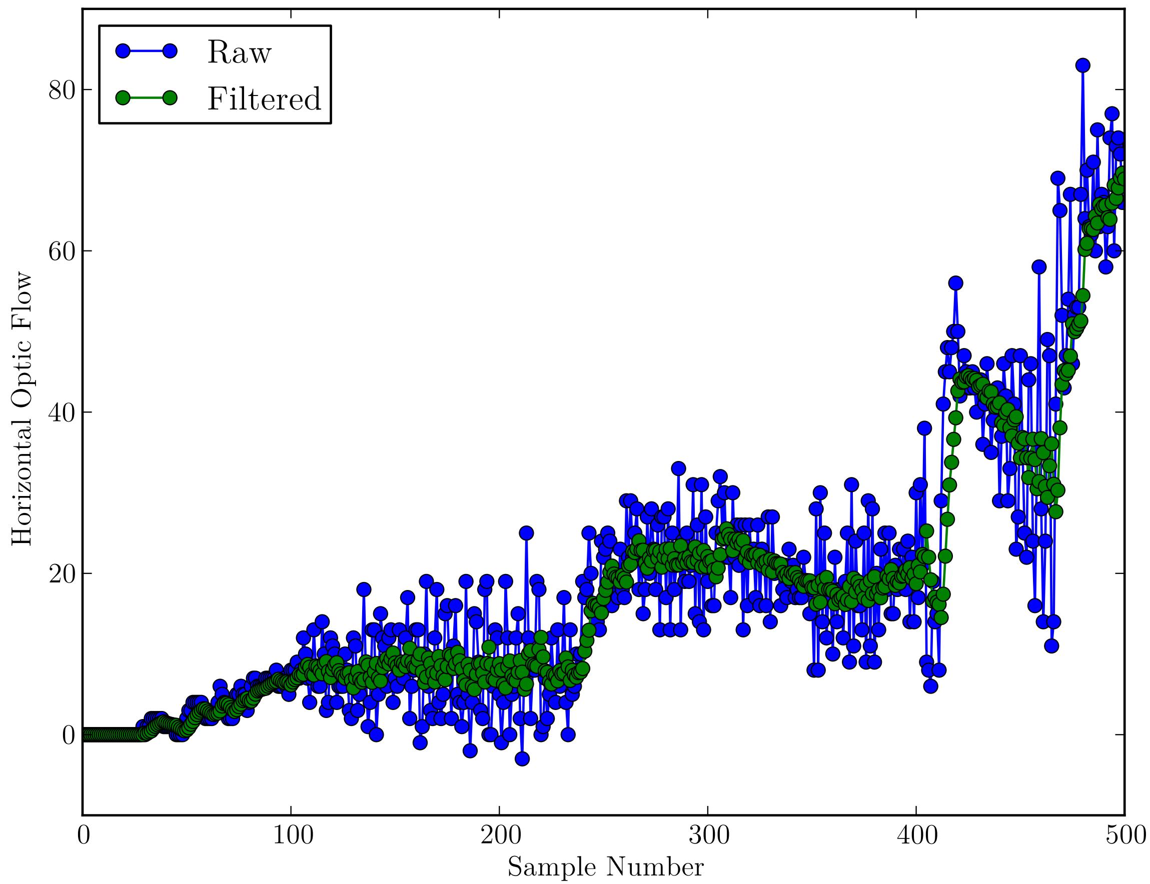


- Subtract rotational optic flow component based on inertial sensors



OPTIC FLOW


Capture images
Estimate optic flow
Rotation compensation
Low-pass filter
Controller

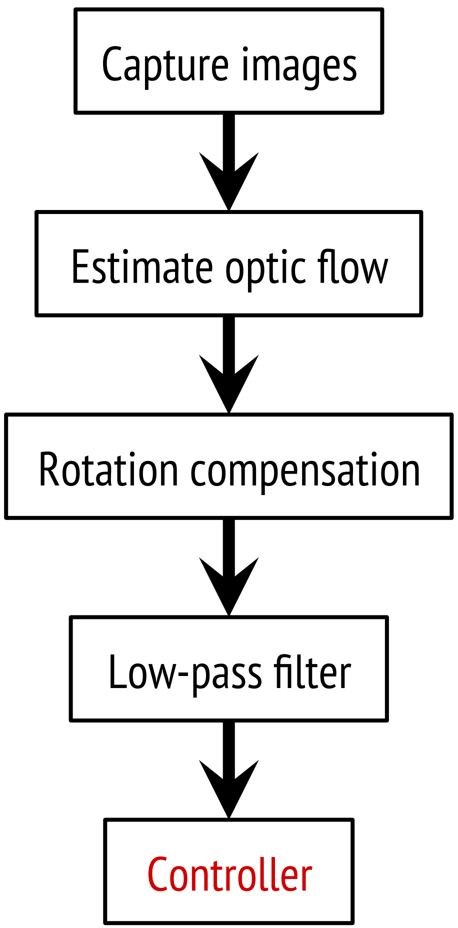

Raw
Filtered
Horizontal Optic Flow
Sample Number
0
20
40
60
80
100
200
300
400
500

OPTIC FLOW

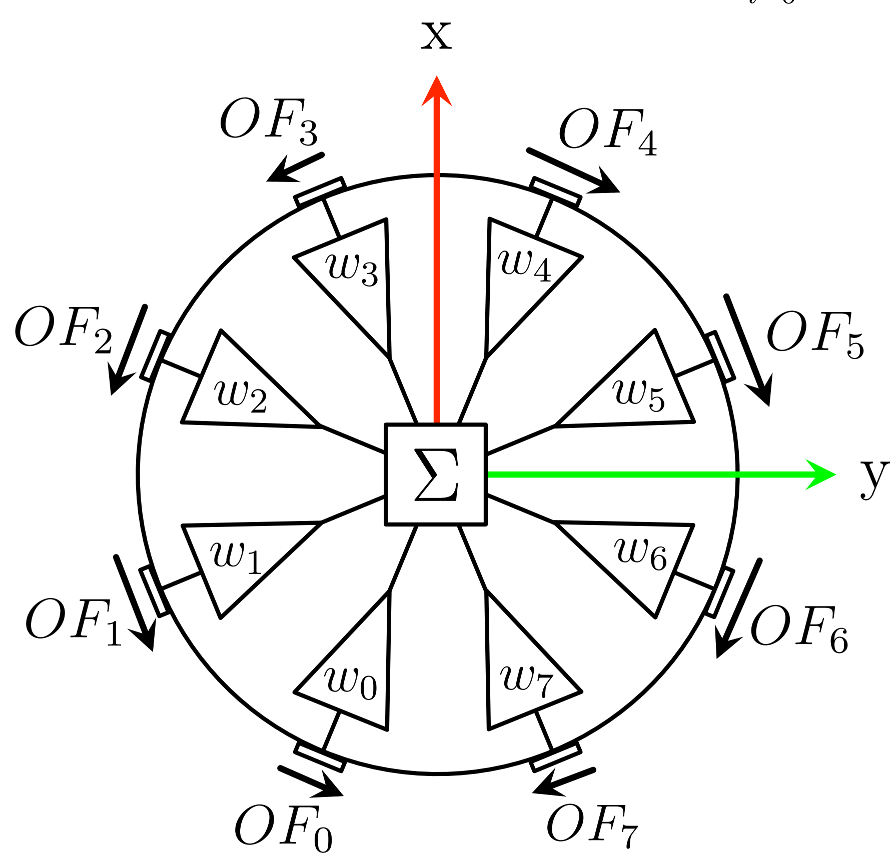
Capture images
↓
Estimate optic flow
↓
Rotation compensation
↓
Low-pass filter
↓
Controller

- The optic flow data give information about the environment that can be used for control
- Use a set of base autonomous behaviors
  - Corridor following
  - Wall following
  - Obstacle avoidance
  - Hover in place

OPTIC FLOW



- Simple, reactive controller: $\delta_j = \sum_{i=0}^{7} w_{i,j} \cdot OF_i$



HARDWARE

HARDWARE

- We worked to get the platform ready for testing
  - Communication with sensor ring
  - Image acquisition
  - Optic flow calculation
  - Collection of sample datasets
  - Reading from gyroscope
  - De-rotating flow
  - Wireless communication
  - Vicon motion tracking

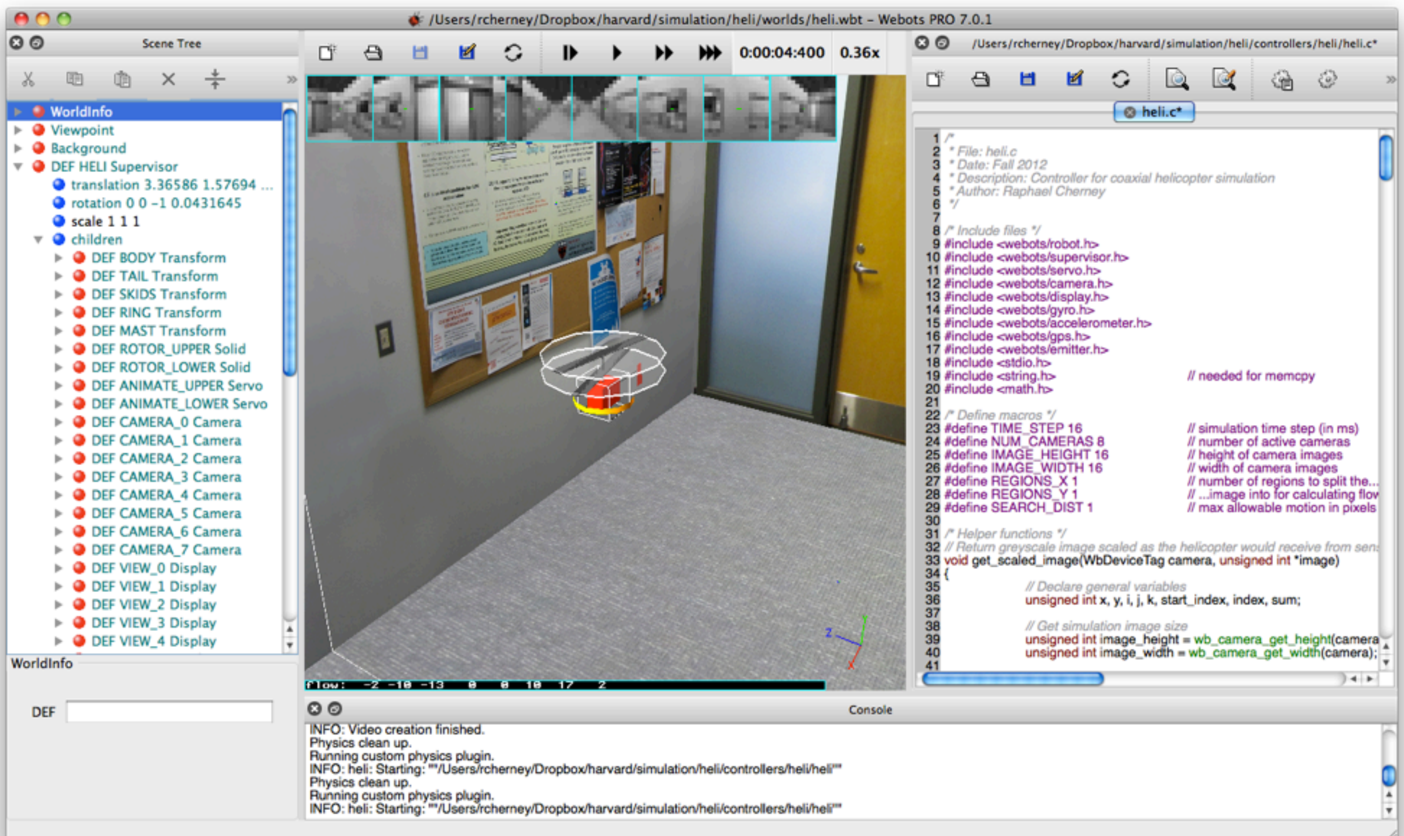
HARDWARE

- When working with MAVs, there are a variety of difficulties associated with using actual hardware
  - Limited testing environments
  - Limited flight time
  - Harder to program devices (longer iteration time)
  - Difficulty tracking motion
  - Difficulty logging data
  - Hardware malfunctions

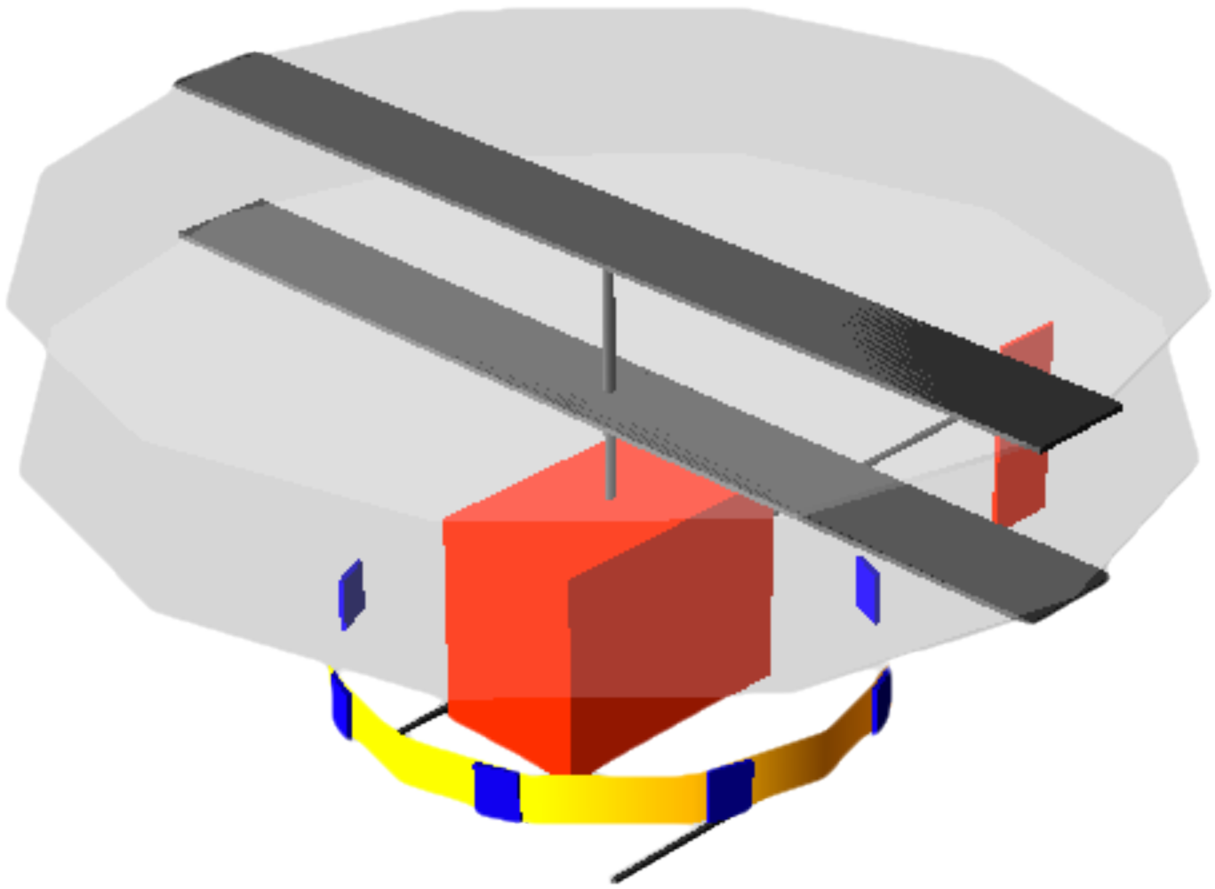
SIMULATION

SIMULATION

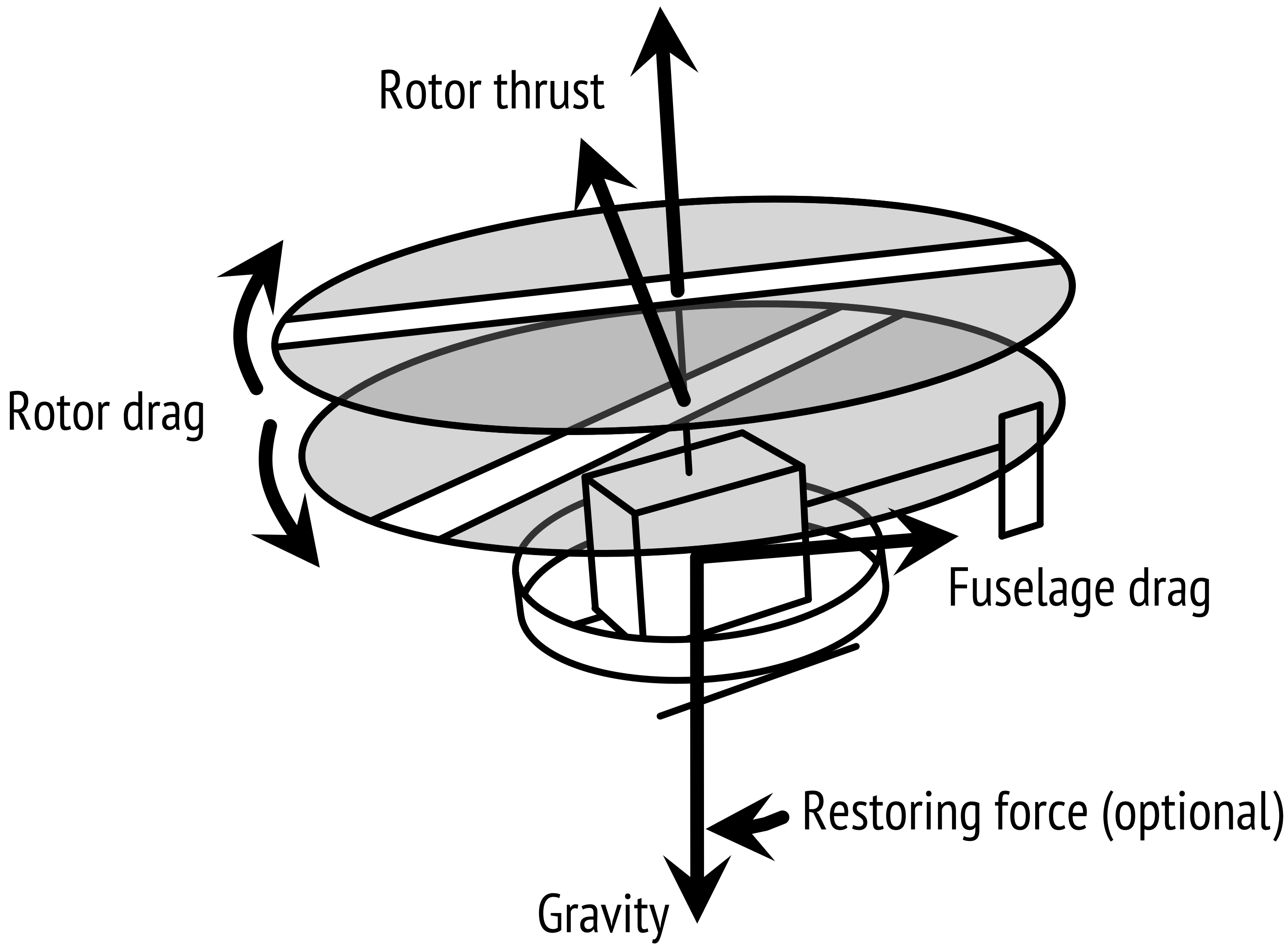
- Developed a model of the MAV and indoor environment for testing



MODEL

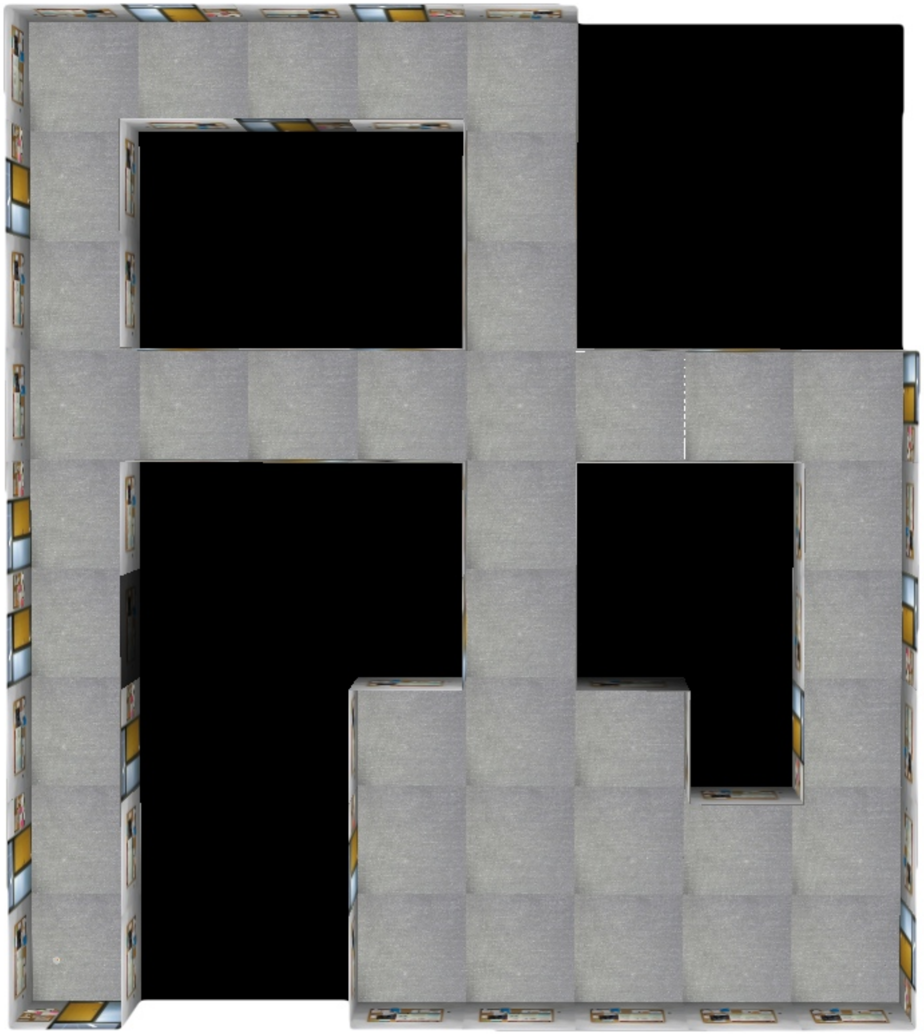


PHYSICS


Rotor thrust
Rotor drag
Fuselage drag
Restoring force (optional)
Gravity

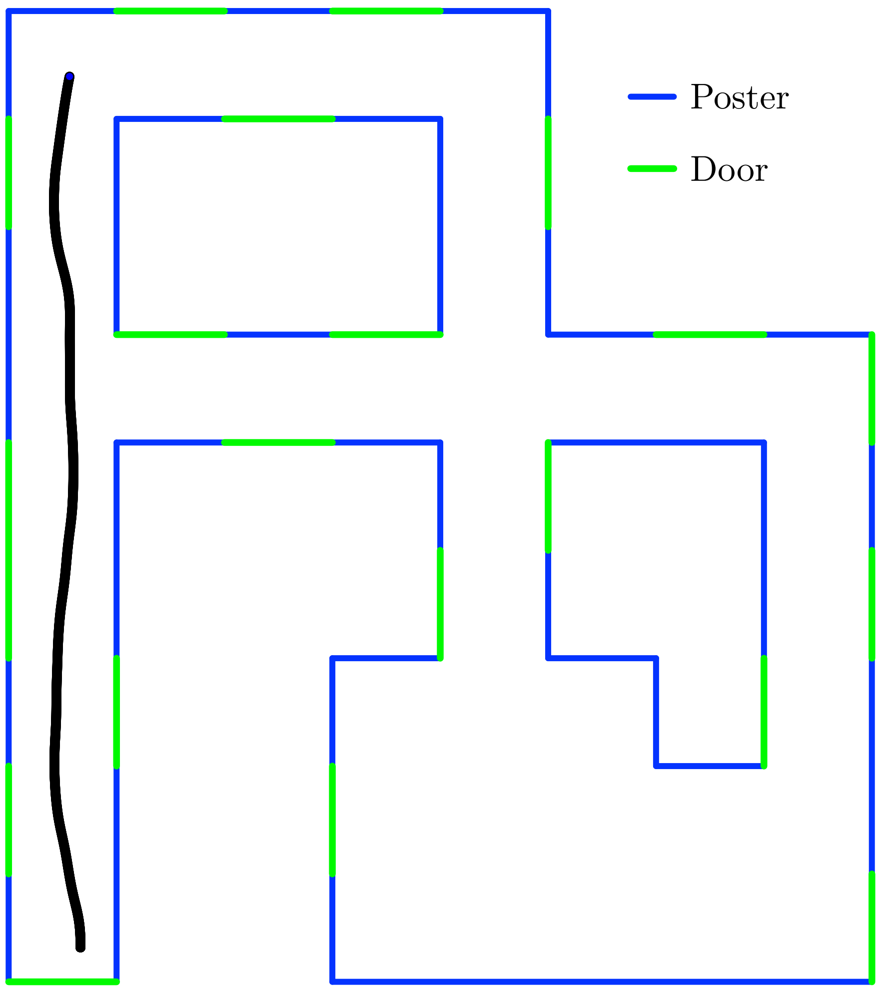
ENVIRONMENT

- Realistic, indoor simulation environment for testing
- Textures from actual test environment

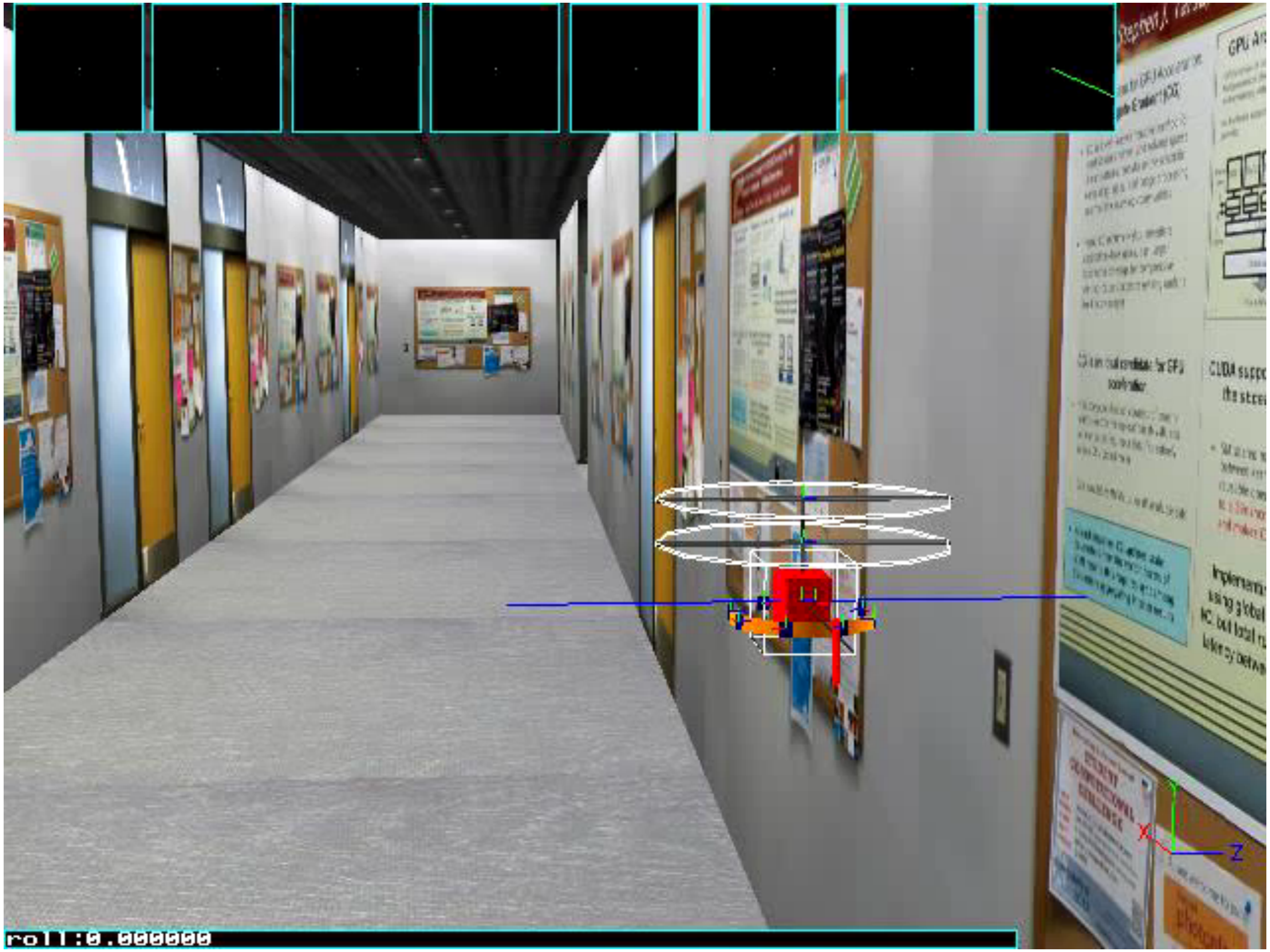


SIMULATION

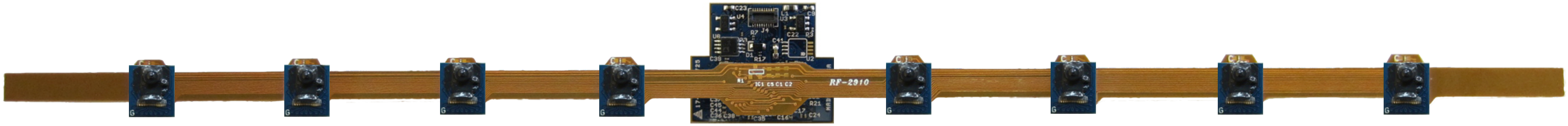
- We can test behaviors in simulation and then port controllers to our hardware
- As an example, we implemented a simple corridor centering algorithm
  - Balance optic flow



SIMULATION



SENSOR CONFIGURATIONS



- The optic flow sensor ring has a memory and bandwidth limitations
- What is the best configuration for reading out sensor data?

SENSOR CONFIGURATIONS

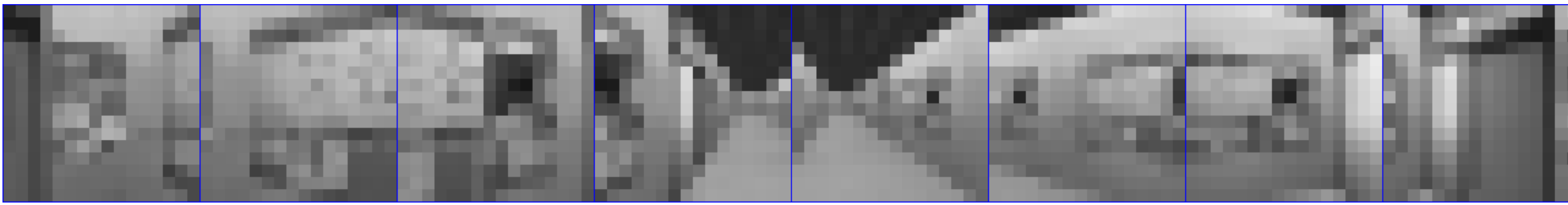
Camera Angle:	$\frac{-7\pi}{8}$	$\frac{-5\pi}{8}$	$\frac{-3\pi}{8}$	$\frac{-\pi}{8}$	$\frac{\pi}{8}$	$\frac{3\pi}{8}$	$\frac{5\pi}{8}$	$\frac{7\pi}{8}$
Configuration A:	16×16	16×16	16×16	16×16	16×16	16×16	16×16	16×16
Configuration B:			32×32	32×32	32×32	32×32		
Configuration C:	64×8	64×8	64×8	64×8	64×8	64×8	64×8	64×8

(Constant pixel size)

SENSOR CONFIGURATIONS

Configuration A

16×16 (×8)



Advantages

- Evenly distributes images around MAV
- Efficient binning of pixels for improved signal
- Can easily condense data into logical vectors
- Easy to implement

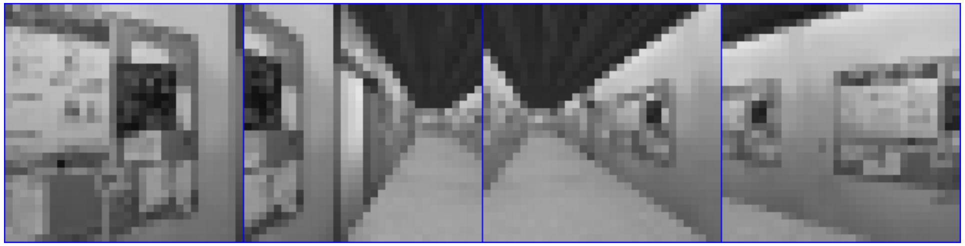
Disadvantages

- Low pixel count limits number of flow vectors that can be found with a given camera

SENSOR CONFIGURATIONS

Configuration B

32×32 (×4)



Advantages

- Better resolution when traveling “forward”
- Increased sensitivity in the optic flow estimate (due to higher resolution)
- Can support larger number of optic flow vectors per image
- Image overlap provides redundancy

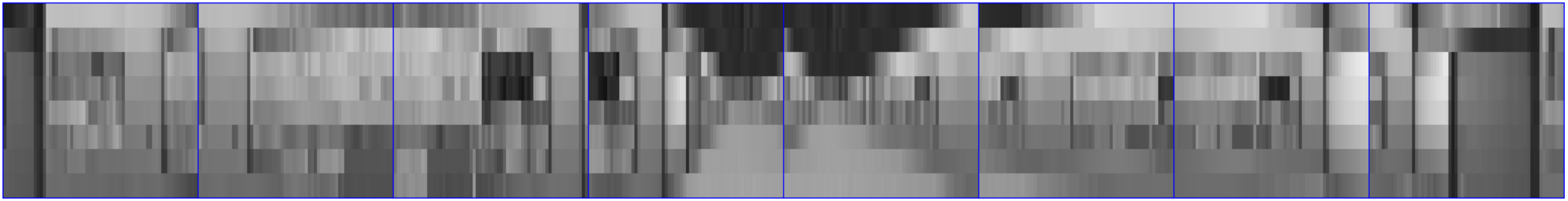
Disadvantages

- No data from behind (cannot track obstacles you have passed)
- Overlapping images means we are not maximizing our total field of view (redundancy may be unnecessary)

SENSOR CONFIGURATIONS

Configuration C

64×8 (×8)



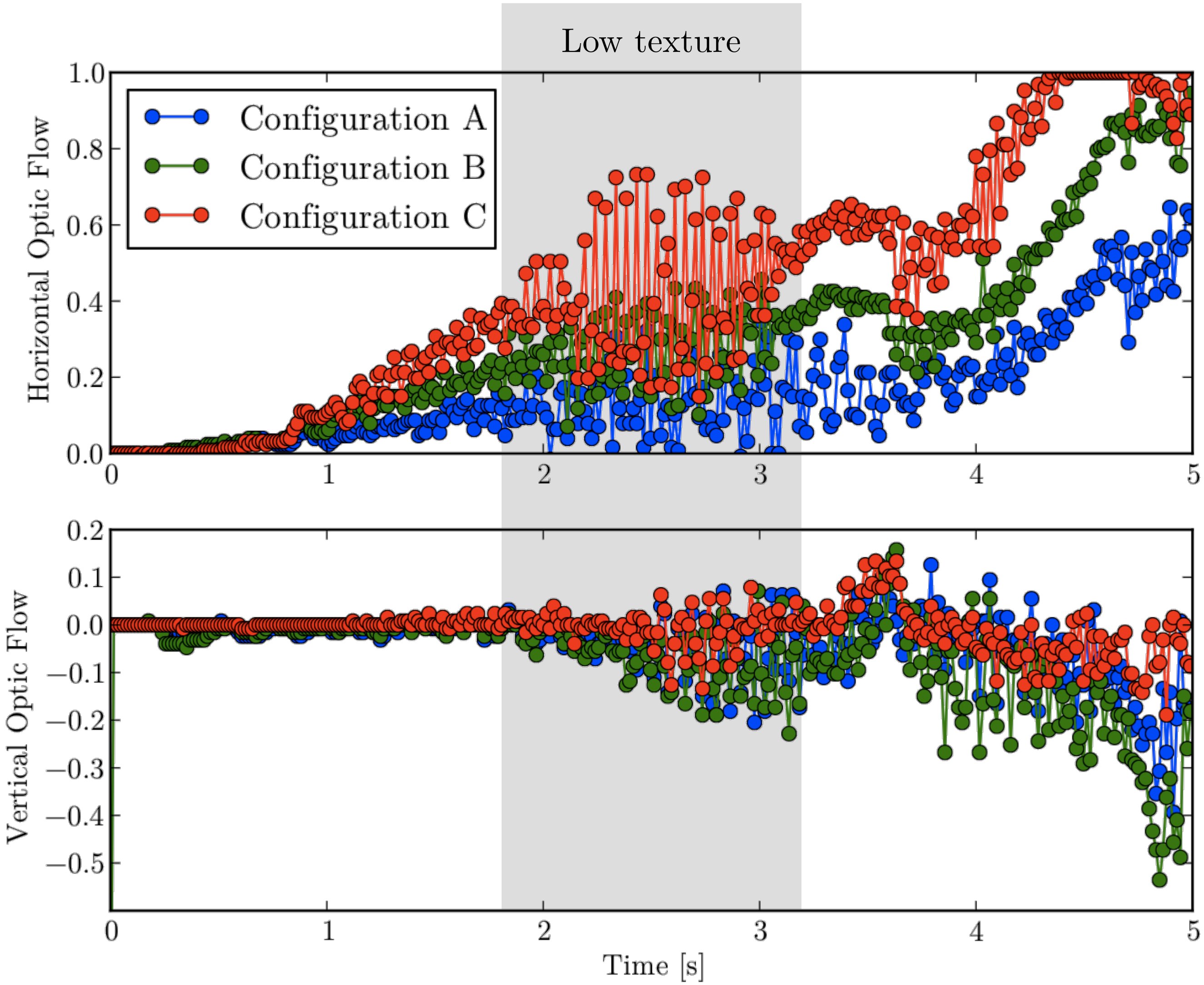
Advantages

- Maximizes sensitivity for horizontal flow
- Evenly distributes sensing around MAV (bilaterally symmetric)
- Uses full sensor area

Disadvantages

- Reduced vertical flow data
- More difficult to implement in hardware

SENSOR CONFIGURATIONS



FUTURE WORK

- Test with hardware (in progress)
- Implement additional base behaviors (in progress)
- Egomotion estimation
- Combine base behaviors into advanced control and planning algorithms
- Coordinate action with multiple agents

ACKNOWLEDGEMENTS

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- Richard Moore
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- Laboratory of Intelligent Systems (LIS)

QUESTIONS