# Autonomous Navigation for Flying Robots

# Lecture 7.2: Visual Odometry

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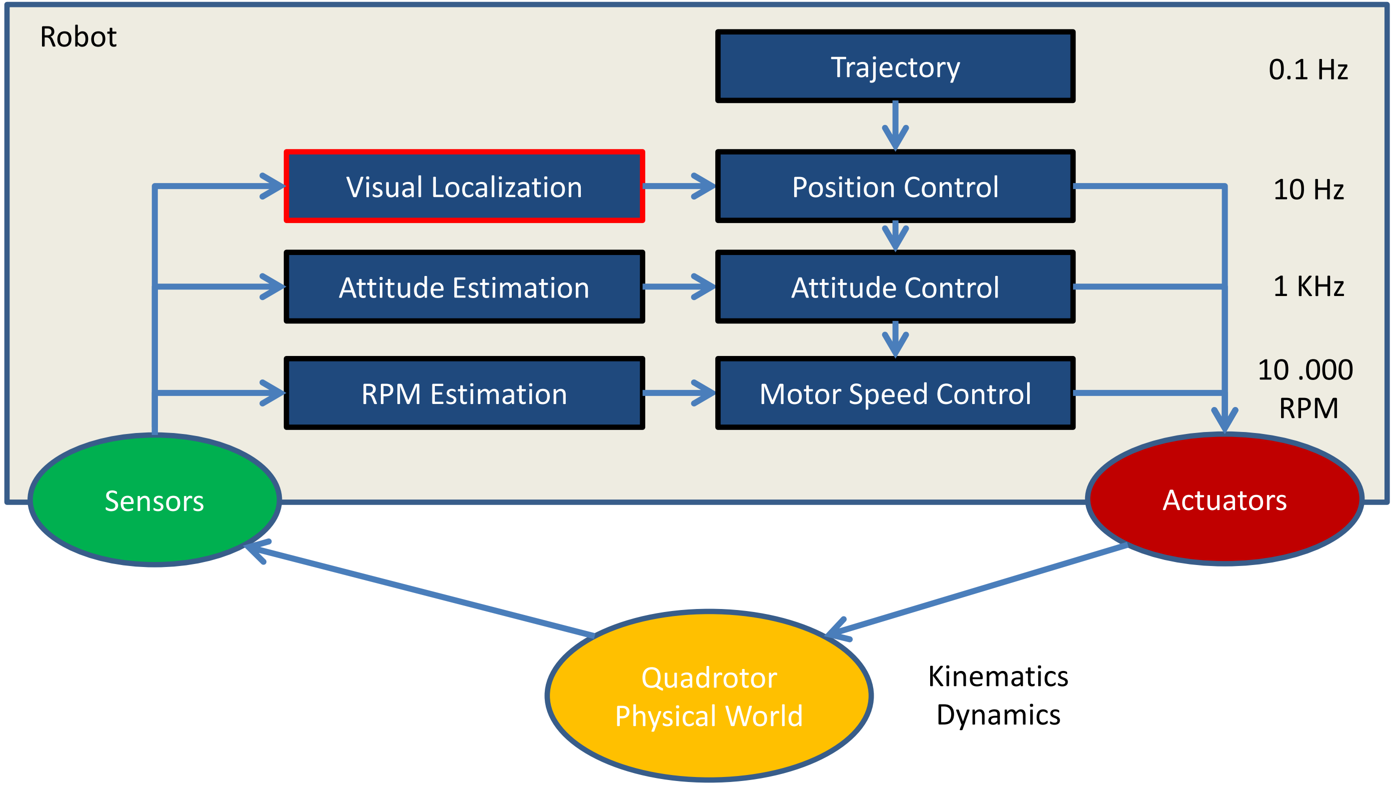
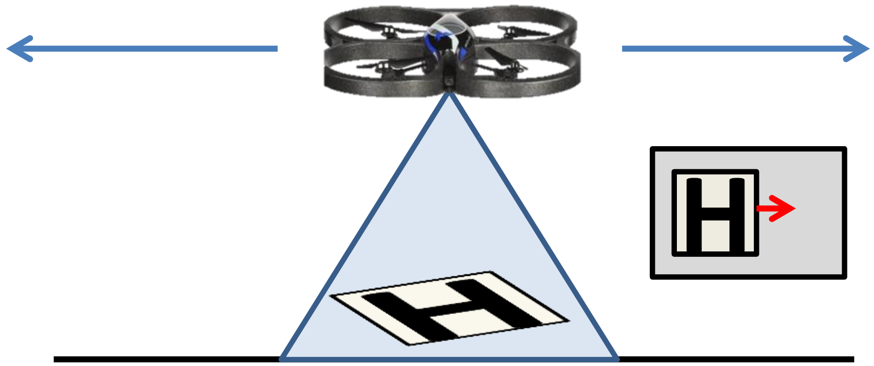
# Cascaded Control



# Visual Odometry

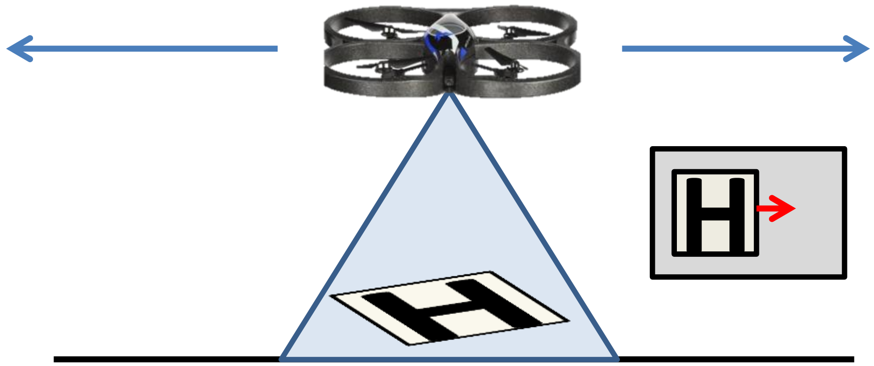
- Velocity estimates from IMU are very inaccurate
- (How) can we get more accurate velocity estimates?
- Real-time and minimal delay



# Visual Odometry

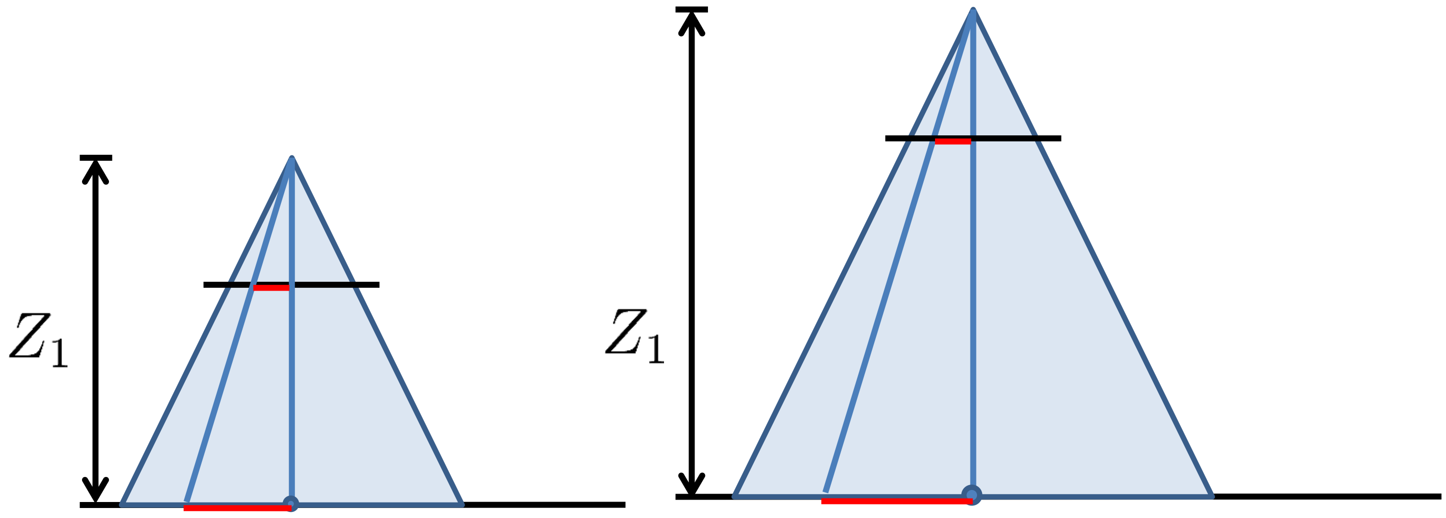
Idea:

- Track the motion of one or more points in the camera image
- Estimate 3D motion from this



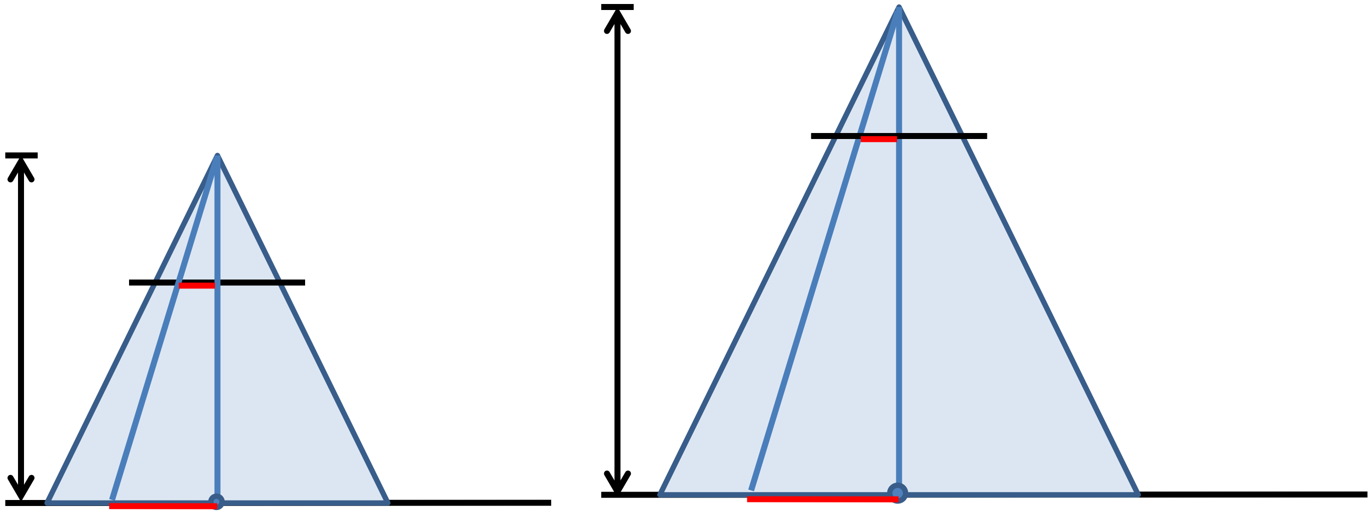
# Scale Ambiguity

- Purely from monocular vision, it is not possible to determine the absolute speed



# Scale Ambiguity

- Purely from monocular vision, it is not possible to determine the absolute speed
- Insight: We need additional sensors



# Visual Odometry

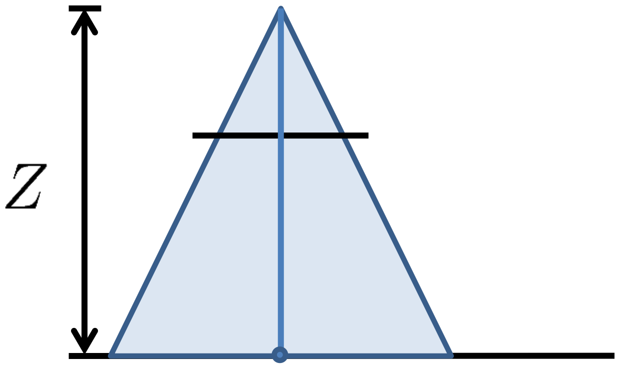
Typical sensor combination for visual odometry on UAVs:

- IMU (provides absolute orientation)
- Height sensor (ultrasound)
- Downlooking camera

Furthermore, we assume a planar floor.

# 2D Translation

- Assume that we look perpendicular onto the planar ground
- Assume that we know the height Z (from ultrasound)
- Assume that we observe a 2D motion of $\mathbf{x} = \begin{pmatrix} u & v \end{pmatrix}^\top$
- What is the corresponding motion in 3D?



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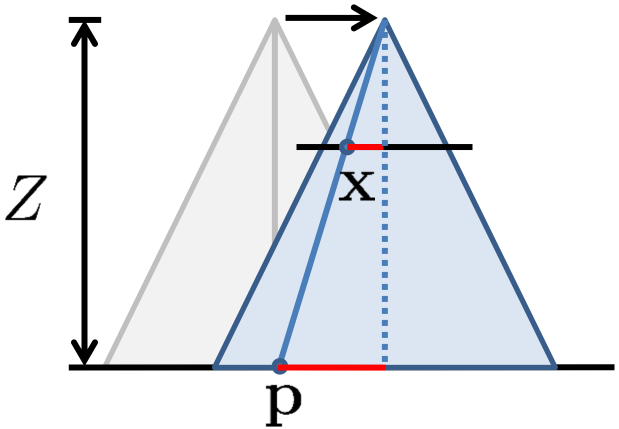



$$\mathbf{x} = \begin{pmatrix} u & v \end{pmatrix}^\top$$

$$\tilde{\mathbf{x}} = \mathbf{K}\mathbf{p}$$

$$\mathbf{p} = \begin{pmatrix} X & Y & Z \end{pmatrix}^\top$$

# 2D Translation

- 3D to 2D perspective projection

$$\tilde{\mathbf{x}} = \mathbf{K}\mathbf{p}$$

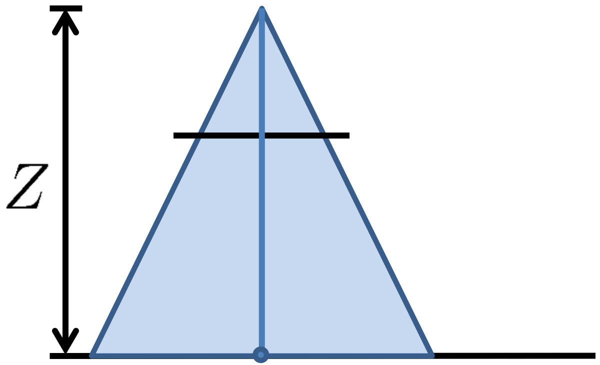
$$\lambda \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad \Rightarrow \lambda = Z$$

- Now let's solve for p (in particular, X and Y):

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \mathbf{K}^{-1} Z \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

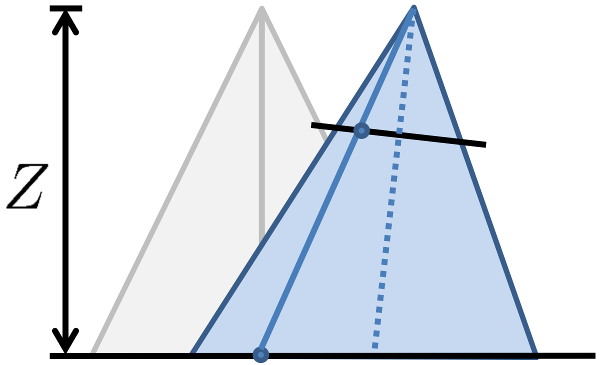
# Rotation + 2D Translation

- What if the quadrotor tilts during flight?
- Assume that we have an IMU that gives us the (relative) rotation R



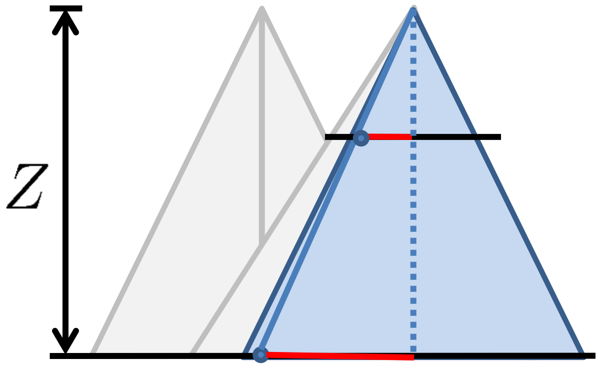
# Rotation + 2D Translation

- What if the quadrotor tilts during flight?
- Assume that we have an IMU that gives us the (relative) rotation R



# Rotation + 2D Translation

- Let's de-rotate the camera image first

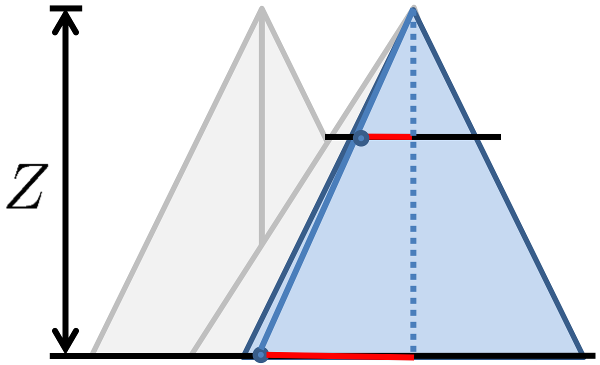


# Rotation + 2D Translation

- Point p appears in the de-rotated image at

$$\mathbf{p}' = \mathbf{R}\mathbf{p}$$

- Now only pure translation remains, same procedure as before

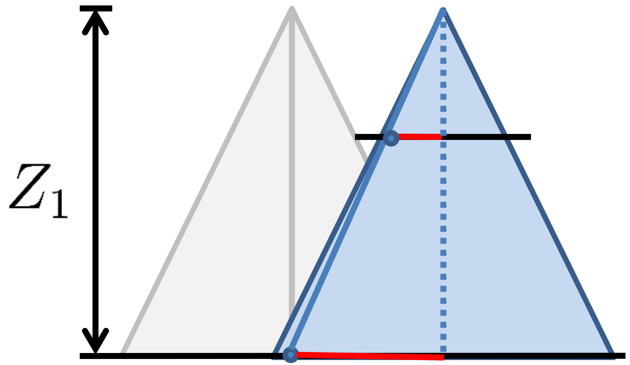



$$\tilde{\mathbf{x}} = \mathbf{K}\mathbf{p}' = \mathbf{K}\mathbf{R}\mathbf{p}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \mathbf{R}^{-1}\mathbf{K}^{-1} Z \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

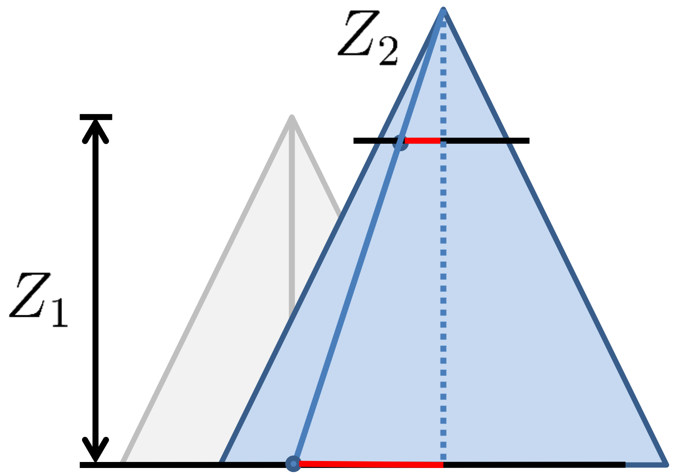
# Height Change

- What if the quadrotor changes its flying height?



# Height Change

- What if the quadrotor changes its flying height?
- Point $\mathbf{p}$ remains at the same location
- Pixel coordinate $\mathbf{x}$ gets scaled by $\frac{Z_1}{Z_2}$



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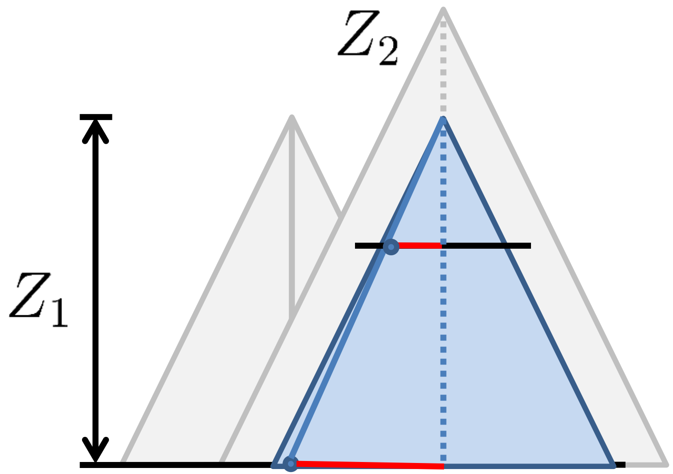



$$\tilde{\mathbf{x}}' = \begin{pmatrix} u\frac{Z_1}{Z_2} \\ v\frac{Z_1}{Z_2} \\ 1 \end{pmatrix} = \mathbf{KRp}$$

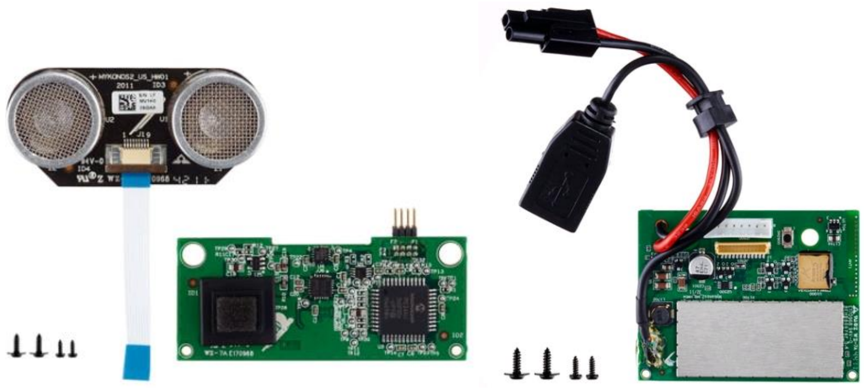
$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \mathbf{R}^{-1}\mathbf{K}^{-1} Z_1 \begin{pmatrix} u\frac{Z_1}{Z_2} \\ v\frac{Z_1}{Z_2} \\ 1 \end{pmatrix}$$

# Increasing Robustness

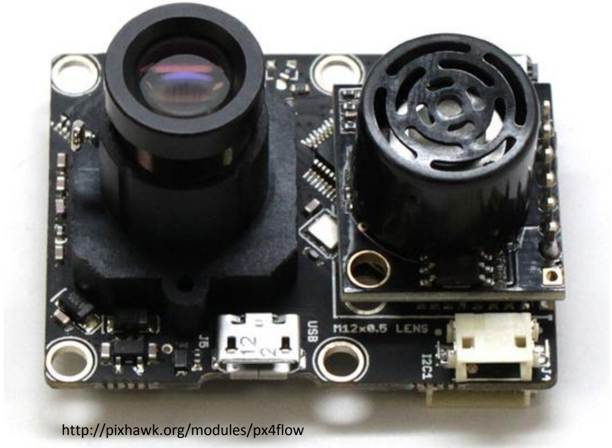
- So far, we tracked only a single point in the image
- Motion estimate is noisy and potentially an outlier
- Solution:
  - Track multiple points (e.g., 16)
  - Majority vote (RANSAC algorithm)

# Two Examples

- Parrot Mainboard + Navigation board [Bristeau, IFAC WC 2011]
  Camera + IMU + ultrasound + pressure, 180 USD
- Pix4flow sensor from ETH [Honegger et al., ICRA 2013]
  Camera + IMU + ultrasound, 120 EUR



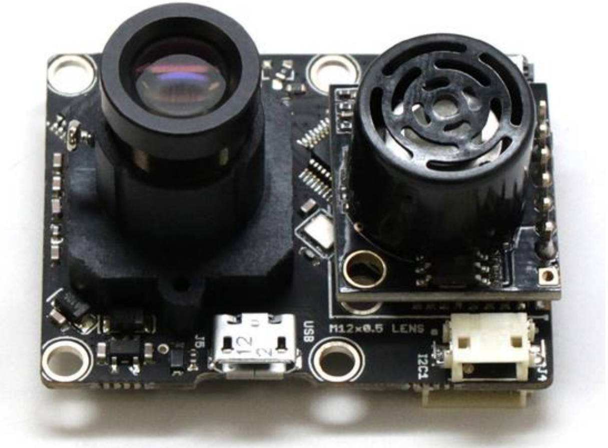
http://www.parrotshopping.com/us/p_parrot_product.aspx?i=230895



http://pixhawk.org/modules/px4flow

# Pix4Flow Sensor
## [Honegger et al, ICRA 2013]

- Smart camera module
- 752Hx480V (60fps), 188Hx120V (250fps), 16mm lens
- ARM Cortex M4 (168 MHz, 192 KB RAM, single precision floating point operations)
- MEMS gyroscope (L3GD20)
- Ultrasound sensor
- Outputs speed over serial link
- Open-source



# Demo Video
## [Honegger et al, ICRA 2013]


Dominik Honegger, Lorenz Meier, Petri Tanskanen and Marc Pollefeys. **An Open Source and Open Hardware Embedded Metric Optical Flow CMOS Camera for Indoor and Outdoor Applications, ICRA2013**.

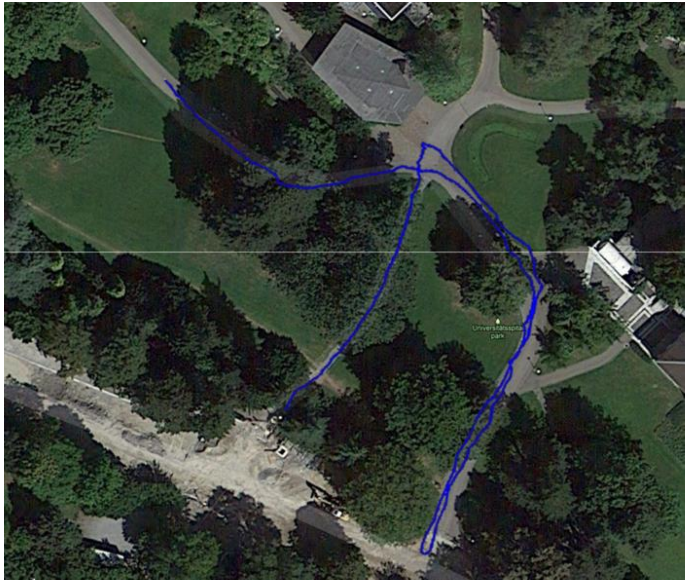
# Pix4flow on a Modified Ardrone
## [Honegger et al, ICRA 2013]

Dominik Honegger, Lorenz Meier, Petri Tanskanen and Marc Pollefeys. **An Open Source and Open Hardware Embedded Metric Optical Flow CMOS Camera for Indoor and Outdoor Applications, ICRA2013**.

# Evaluation

## [Honegger et al, ICRA 2013]

- 1.6m altitude, manual flight
- Pure integration of position from velocities (no GPS)



Honegger et al, ICRA 2013

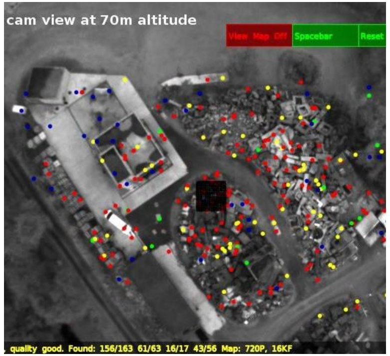
# Alternative Methods

- Stereo camera or depth sensor → next week
- Wide-angle camera + IMU (no ultrasound)

# Visual Odometry using PTAM

## [Weiss et al., ICRA 2012]

- Build sparse 3D map from visual features
- Based on PTAM library [Klein and Murray, ISMAR 2007]
- Drop old keyframes to keep computation time constant
- Use IMU to estimate scale





Stephan Weiss, Markus W. Achtelik, Simon Lynen, Margarita Chli and Roland Siegwart. Real-time Onboard Visual-Inertial State Estimation and Self-Calibration of MAVs in Unknown Environments. In IEEE International Conference on Robotics and Automation (ICRA), 2012.
http://wiki.ros.org/ethzasl_ptam

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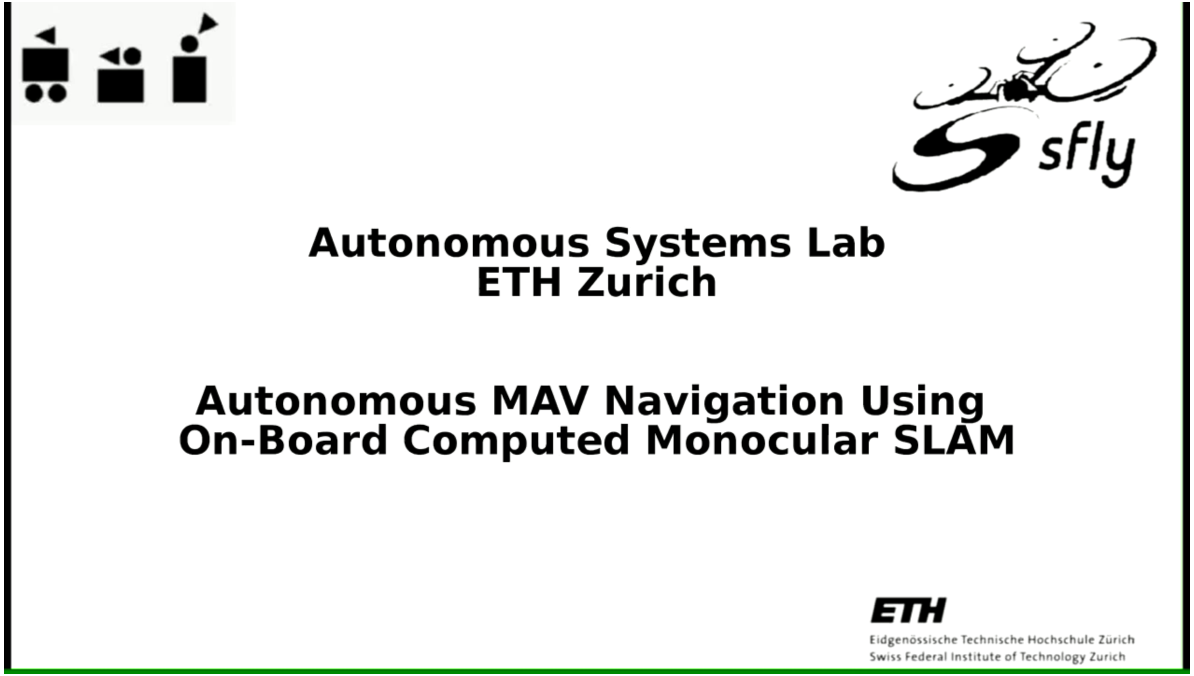


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# Lessons Learned

- Visual odometry for UAVs
- Typical sensor setup and basic algorithm
- Alternative methods

- Next week:
  Cutting-edge research
  results from our group