Vision Based Landing System for a VTOL-MAV

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Introduction

Technical Aims

- Operation without legal restrictions
- Autonomous flight also in urban environments
- Teaming UAV/UAV and UAV/UGV
- Tracking and geo-localization of objects

GPS signals not always available

➡ Augmentation of navigation system with image based system

Outline

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- AirQuad
- Image based navigation estimation
- Image based height estimation
- Simulation environment
- Results
- Conclusion

AirQuad

Specifications

- Electrically powered
- Max. dimensions 92 cm
- Take-off weight 1000 g
- Payload capacity 200 g
- Operating time 25 min
- Max. altitude ~ 500 m
- Max. speed ~ 50 km/h
- Operating range > 5 km

Image based navigation estimation

Assumption

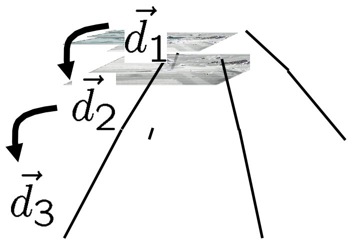
Augmentation of navigation system during hovering and landing situations

➡ Homographies suitable for motion estimation

Optical flow estimation

$$F_k(\vec{x}) \overset{!}{=} F_{k+1}(\vec{x}+\vec{d})$$

- Lucas-Kanade Algorithm



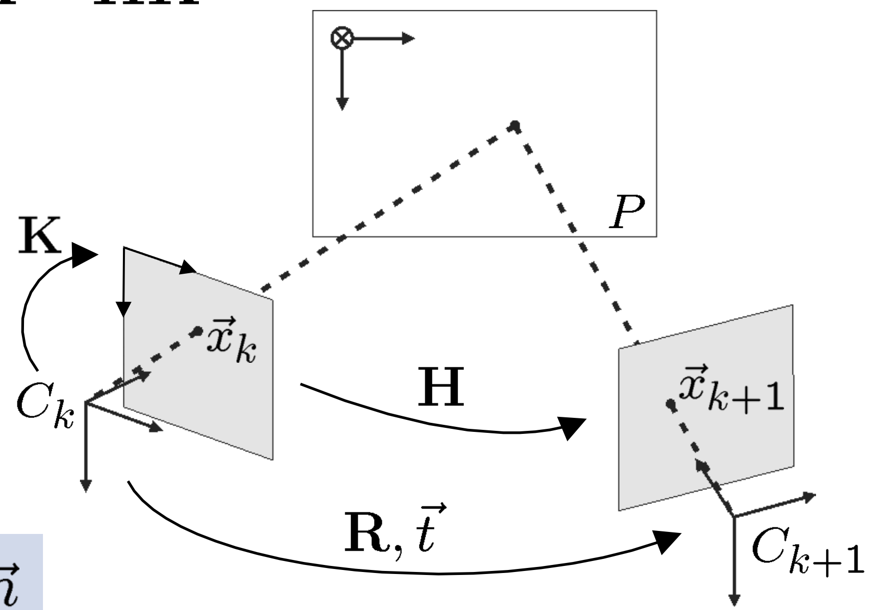
- Optical flow with census transform (based on Stein 2004, Zabih and Woodfill 1994) augmented with cross-correlation

Image based navigation estimation

Homography estimation and decomposition

- Estimation with RANSAC (RANdom SAmple Consensus)
  $\vec{x}_{k+1} \sim \mathbf{H}\vec{x}_k$
- Calibrated homography $\mathbf{H}_{cal} = \mathbf{K}^{-1}\mathbf{H}\mathbf{K}$
- Decomposition:
  $\mathbf{H}_{cal} = \pm\lambda\left(\mathbf{R} + \frac{1}{d}\vec{t}\,\vec{n}^T\right)$

  with $\mathbf{R}$ rotation matrix
  $\vec{t}$ translation
  d distance to scene plane P
  $\vec{n}$ normal vector of P in camera coordinates

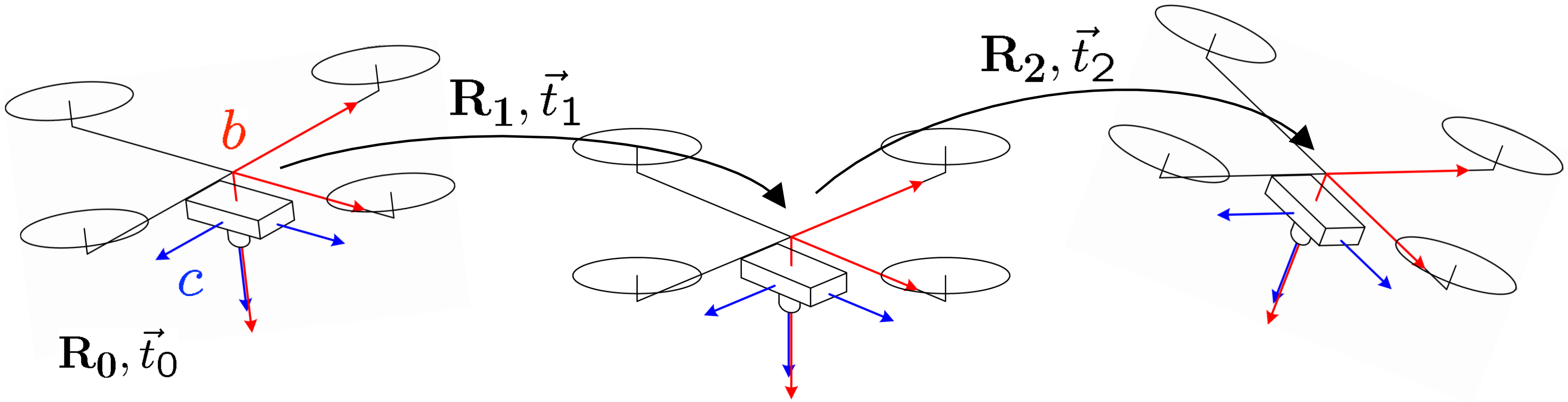


➡ Decomposition into $\mathbf{R},\ \frac{1}{d}\vec{t},\ \vec{n}$

Image based navigation estimation

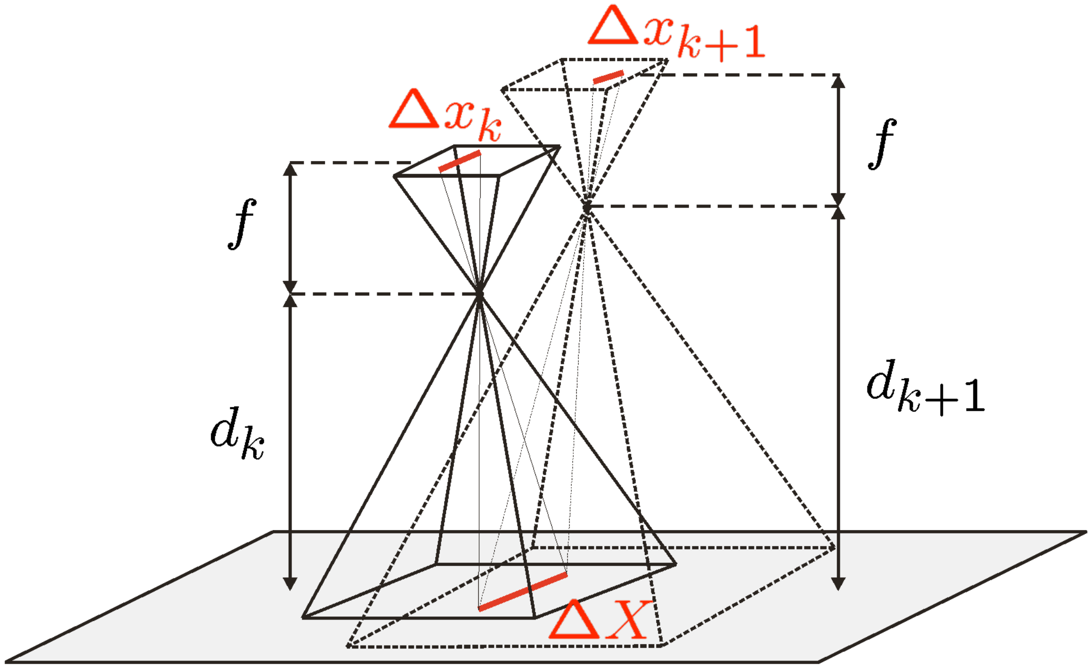
Propagation of attitude and position

- To be known
  - Initial position and attitude
  - Attitude $\mathbf{C}_{b,c}$ between Camera and MAV
  - Distance to scene d, in this case height above ground



➡ Estimation of distance to scene necessary

Image based height above ground estimation



- With theorem of intersecting lines $\frac{d_k}{\Delta X} = \frac{f}{\Delta x_k}$
- From two different positions

$$\left.\begin{aligned} d_k &= f\,\Delta X\,\frac{1}{\Delta x_k} \\ d_{k+1} &= f\,\Delta X\,\frac{1}{\Delta x_{k+1}} \end{aligned}\right\} \xrightarrow[d_{k+1} - d_k]{\Delta d_{k,k+1} =} \boxed{d_{k+1} = \frac{\Delta d_{k,k+1}}{1 - \frac{\Delta x_{k+1}}{\Delta x_k}}}$$

Image based height above ground estimation

Estimation

$$d_{k+1} = \frac{\Delta d_{k,k+1}}{1 - \frac{\Delta x_{k+1}}{\Delta x_k}}$$

- $\Delta d_{k,k+1}$ from barometric pressure sensor
- Δx_k, Δx_{k+1} from optical flow

Conditions

- Orientation of MAV and camera compensated
- Equation numerically well-conditioned

$$\left(1 - \frac{\Delta x_{k+1}}{\Delta x_k}\right) \neq 0 \quad \Rightarrow \quad \left|1 - \frac{\Delta x_{k+1}}{\Delta x_k}\right| > t$$

- Equivalent is motion in vertical direction:

$$\left(1 - \frac{\Delta x_{k+1}}{\Delta x_k}\right) \approx \left(\frac{\Delta d_{k,k+1}}{d_k}\right) \quad \Rightarrow \quad \left|\frac{\Delta d_{k,k+1}}{d_k}\right| > t_1$$

Image based height above ground estimation

Conditions

- Motion in vertical direction: $\left|\frac{\Delta d_{k,k+1}}{d_k}\right| > t_1$

  e. g. $t_1 \in [0.1 \ldots 0.2]$
- Displacement not from noise: $\left|\Delta d_{k,k+1}\right| > t_2$

  e. g. $t_2 = 3\sqrt{2}\,\sigma_{\text{baro}}$

Continuous estimation of height above ground

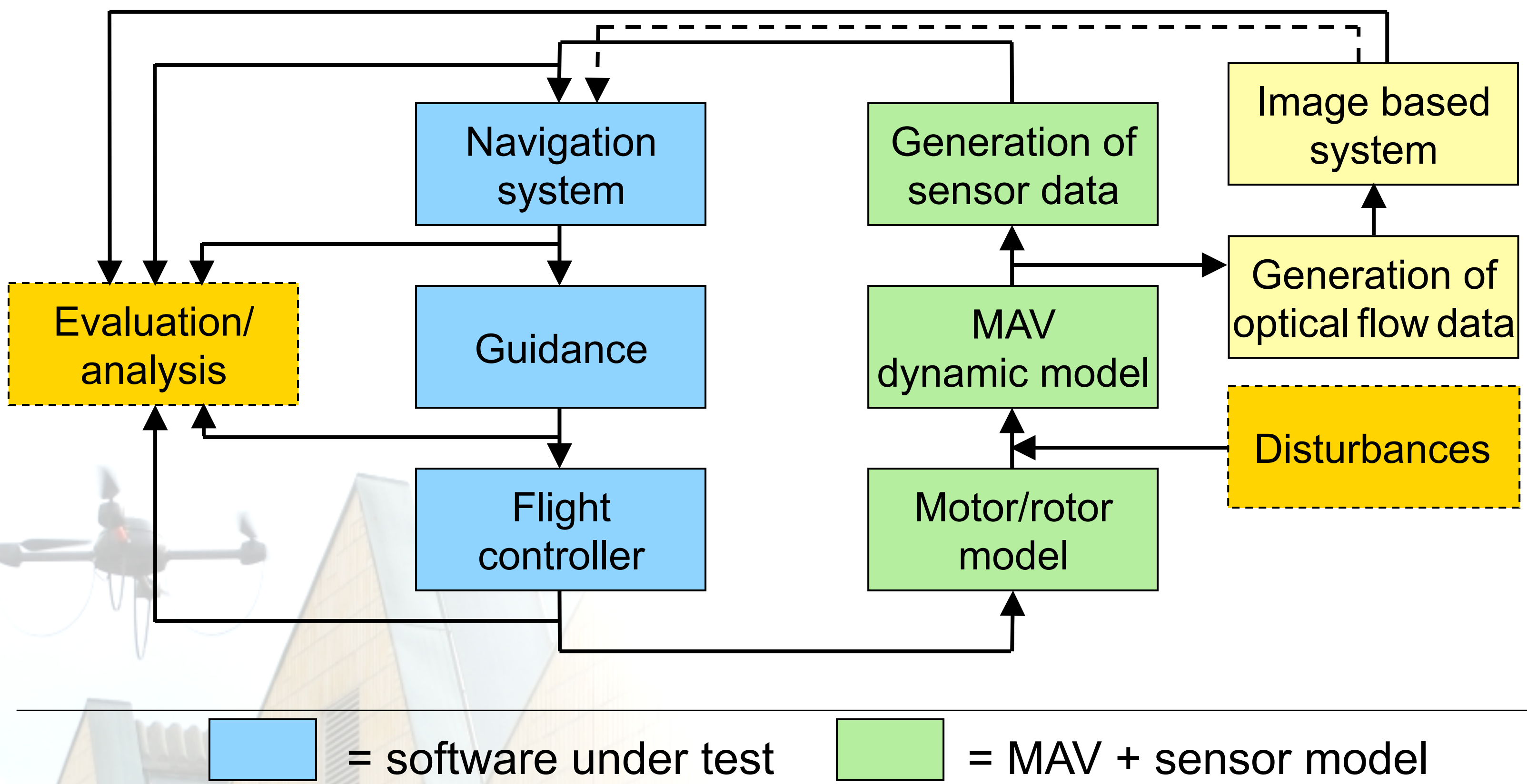
- with Kalman filter:
  $\Delta d_{k,k+1}$: known inputs, d_{k+1} :easurements
- with optical flow: $d_{k+1} = d_k \frac{\Delta x_k}{\Delta x_{k+1}}$

Outline

- AirQuad
- Image based navigation estimation
- Image based height estimation
- **Simulation environment**
- Results
- Conclusion

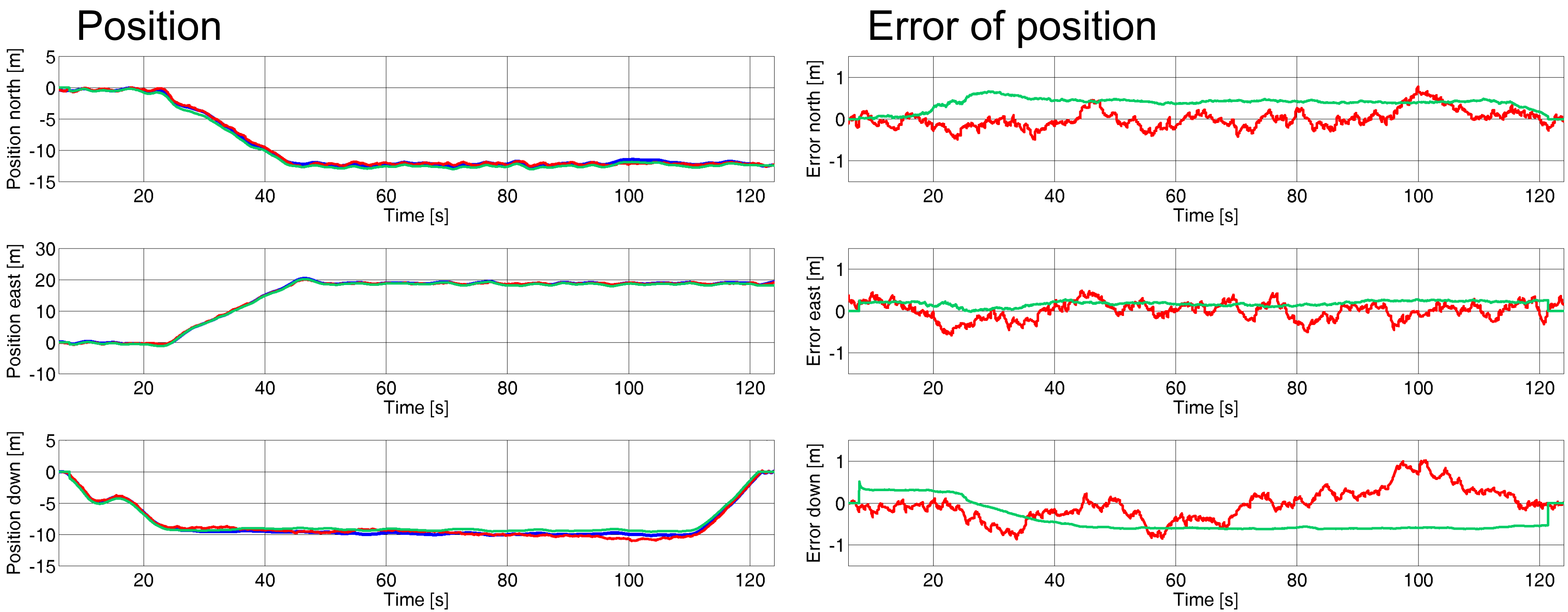
Simulation environment

- Essential for algorithm development and testing
- MAV model included
- Test of operational C-code



Results

1. Simulation: Hovering at defined position and landing

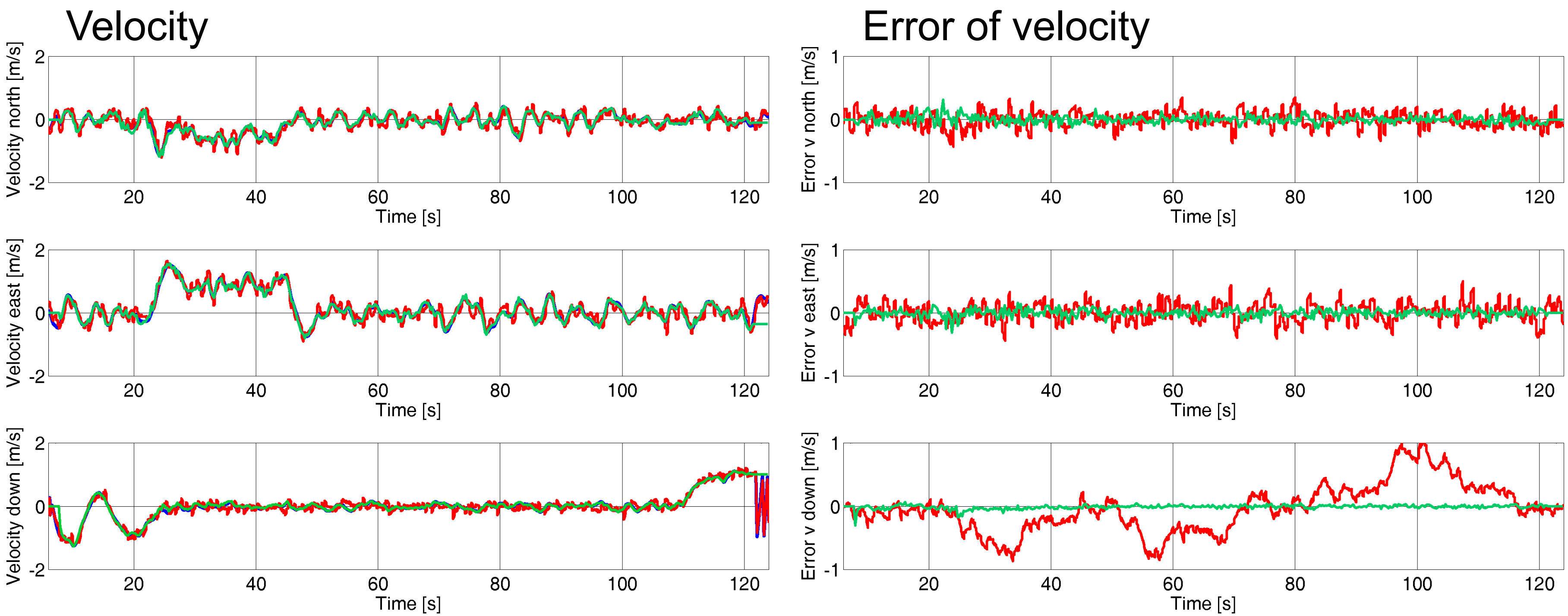


Frame rate 25 fps, image size 640x480, 200 features, feature noise $\sigma = \frac{1}{3}$ pix.

Ground truth GPS/INS/Mag/Baro Vision

Results

Hovering at defined position and landing



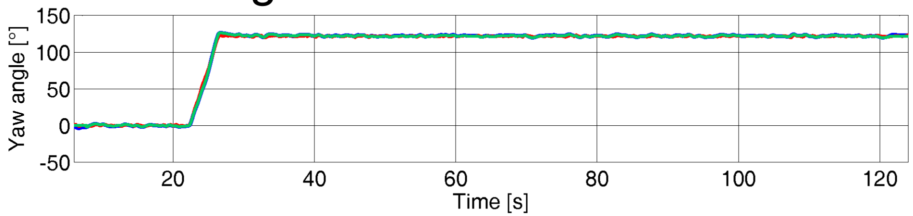
Positions divided by 1/25fps,
Averaging with n = 6, data rate 4.16Hz

Ground truth GPS/INS/Mag/Baro Vision

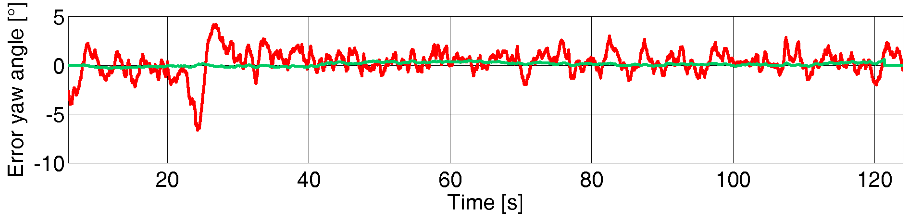
Results

Hovering at defined position and landing

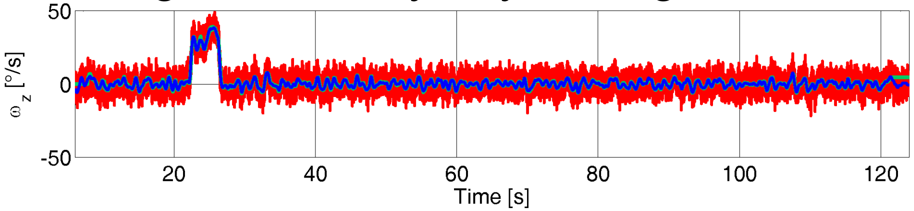
Yaw angle



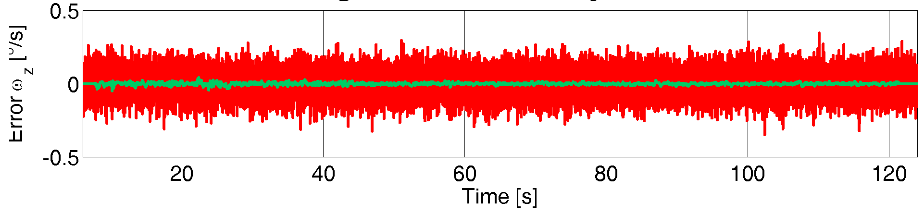
Error of attitude



Angular velocity of yaw angle



Error of angular velocity



Yaw angle is divided by 1/25fps

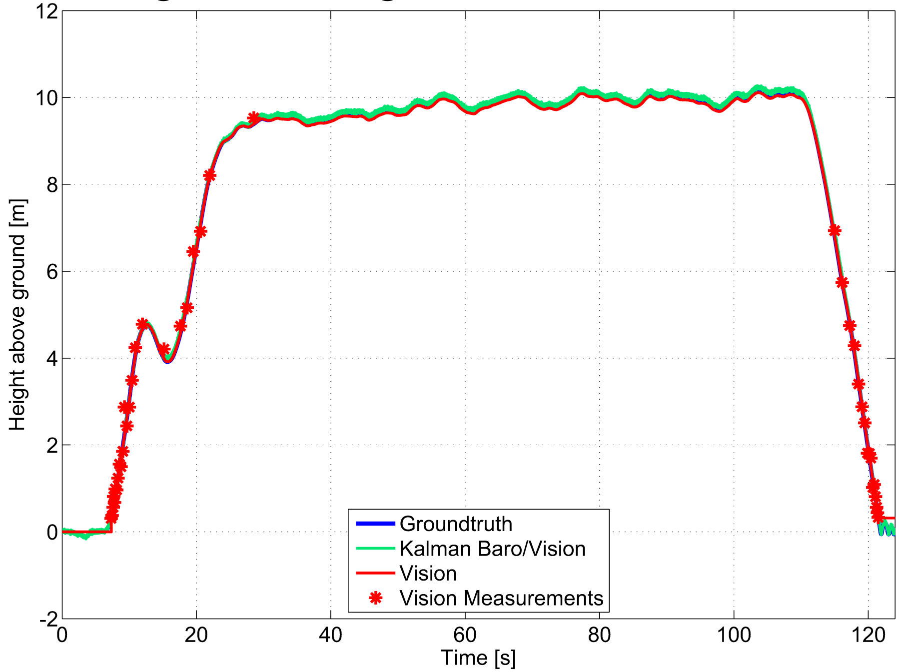
Magnetometer measurement can be corrupted by metallic surfaces. → Improvement by vision system

Ground truth — GPS/INS/Mag/Baro — Vision

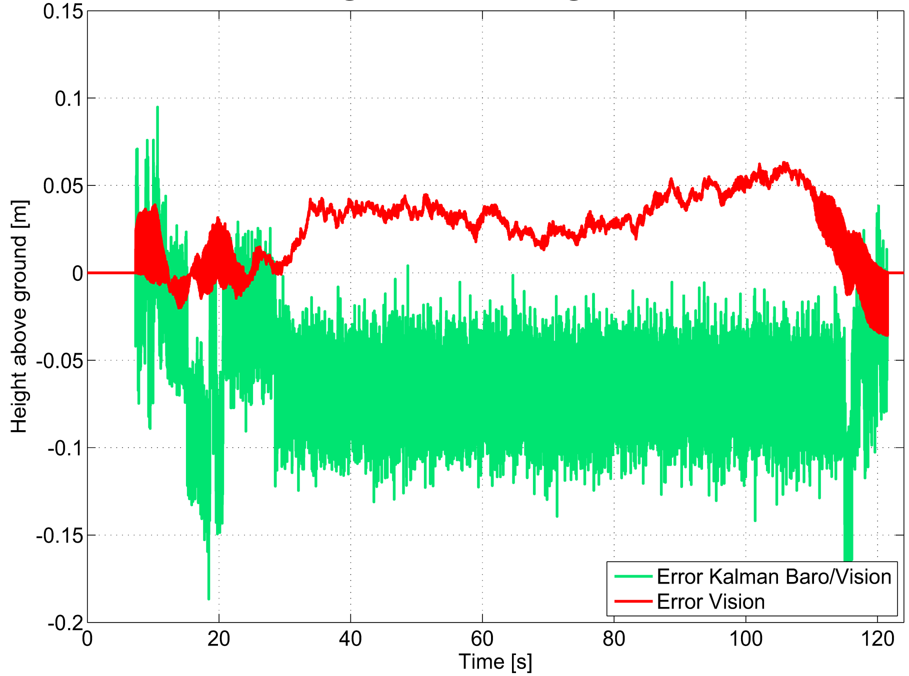
Results

Hovering at defined position and landing

Height above ground estimation



Error of height above ground



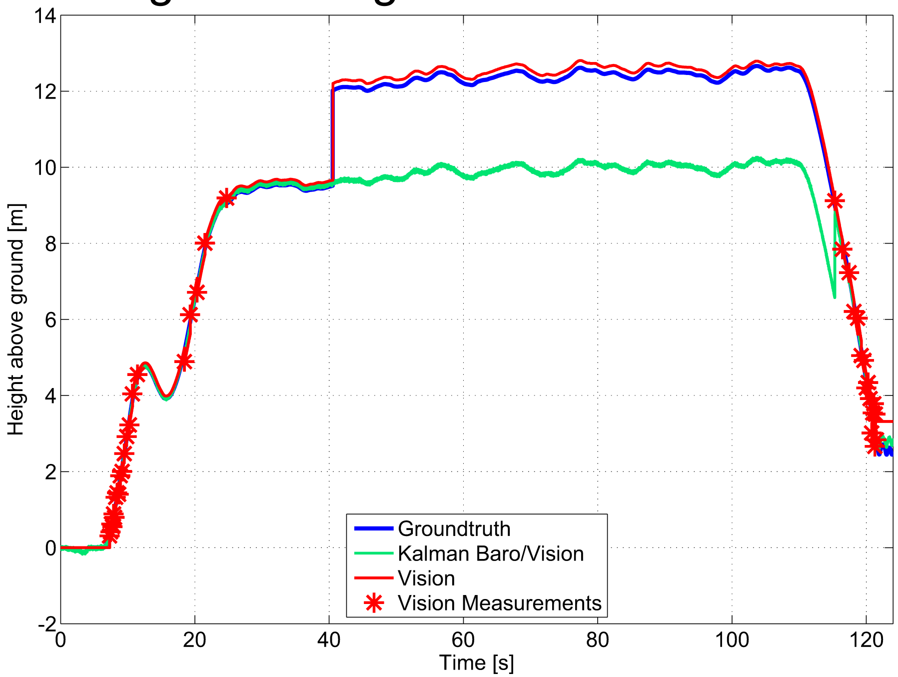
Baro rate 25Hz, baro offset -5m, baro noise $\sigma = 0.02$ m, baro drift 0.2 m/min

Ground truth — Kalman filter Baro/Vision — Vision meas. — Vision

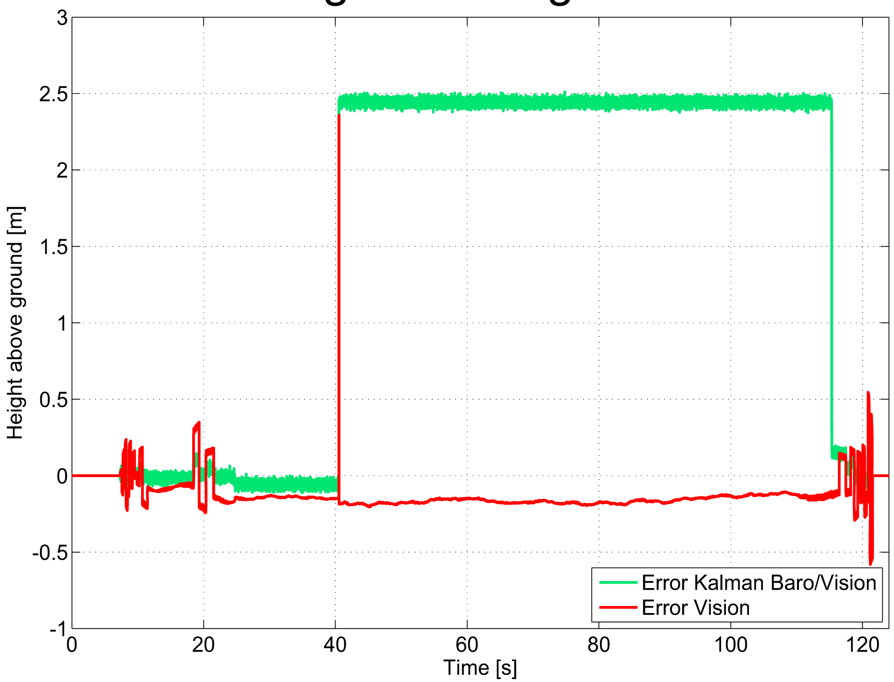
Results

Hovering at defined position and landing

Height above ground estimation



Error of height above ground

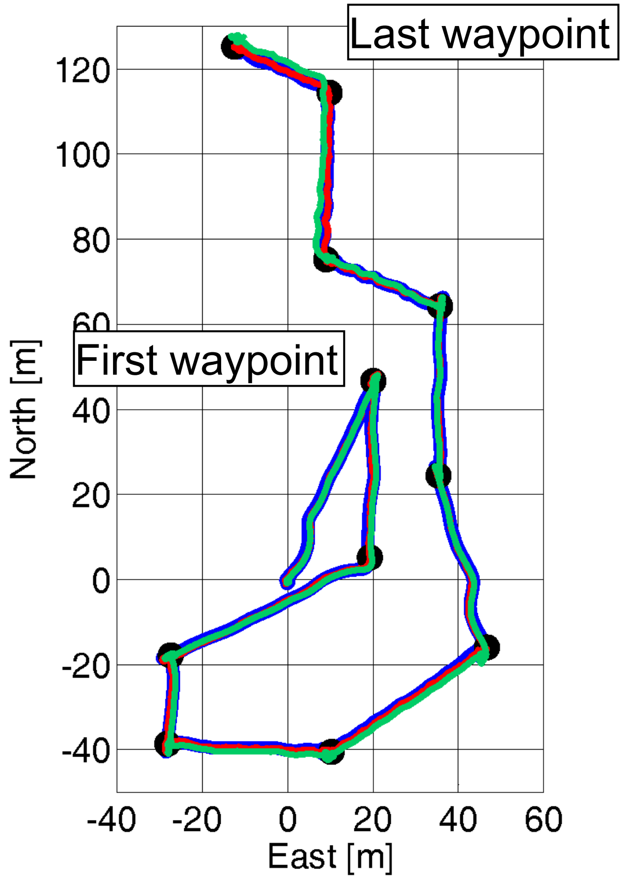


Simulated step of ground elevation of 2.5 m

Ground truth — Kalman filter Baro/Vision — Vision meas. — Vision

Results

2. Simulation: Waypoint flight



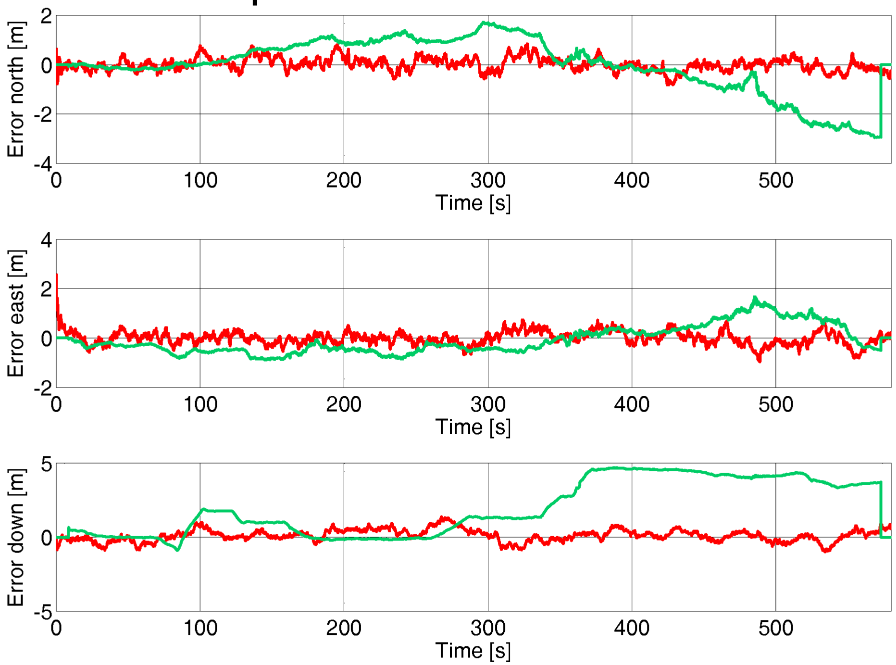
Waypoint flight
- 11 waypoints
- Hover-and-stare points
- ~ 10 min
- Height up to 30 m

Ground truth GPS/INS/Mag/Baro Vision

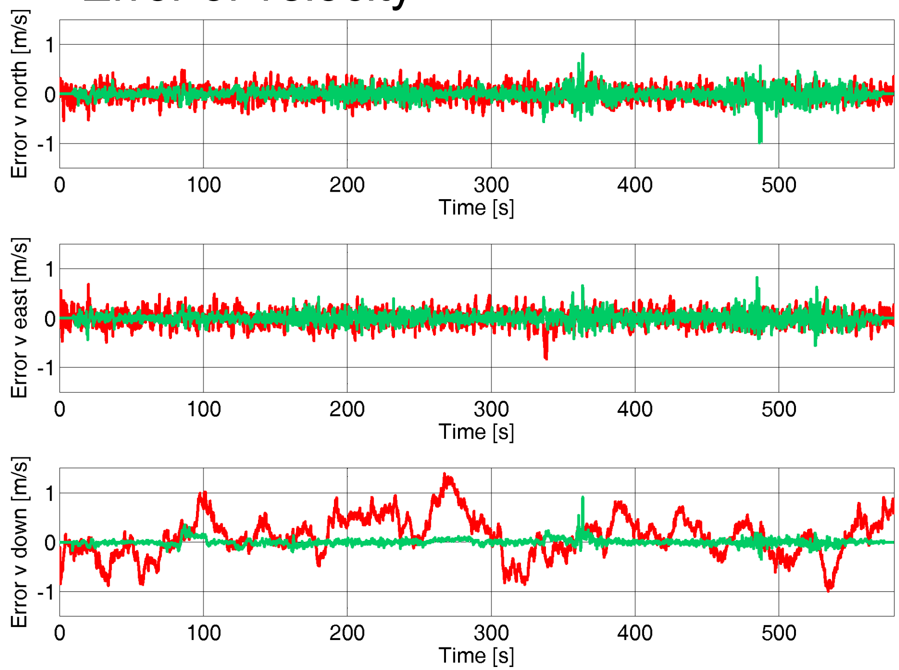
Results

Waypoint flight

Error of position



Error of velocity

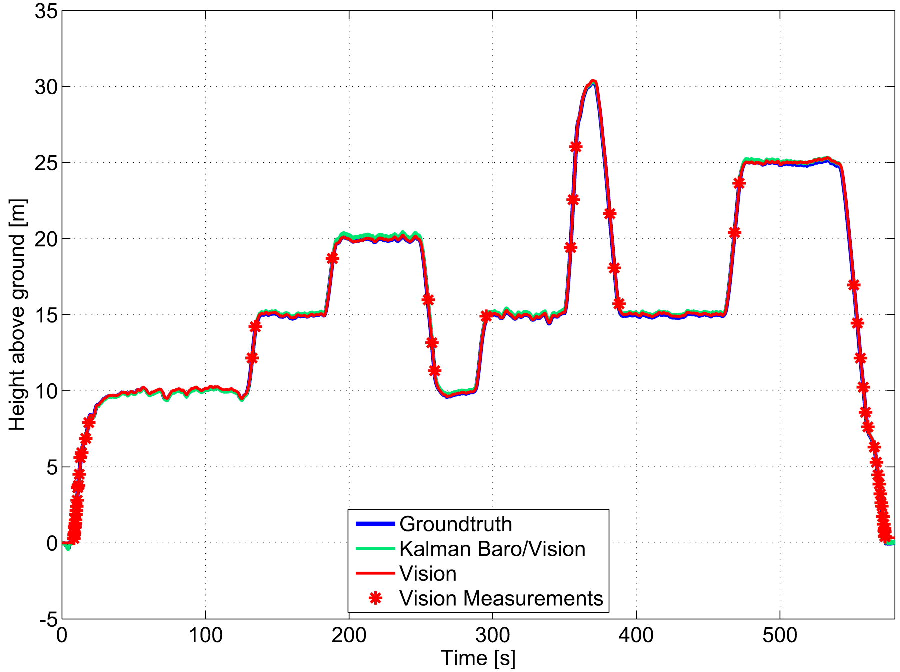


Frame rate 25 fps, image size 640x480, 200 features, feature noise $\sigma = \frac{1}{3}$ pix.

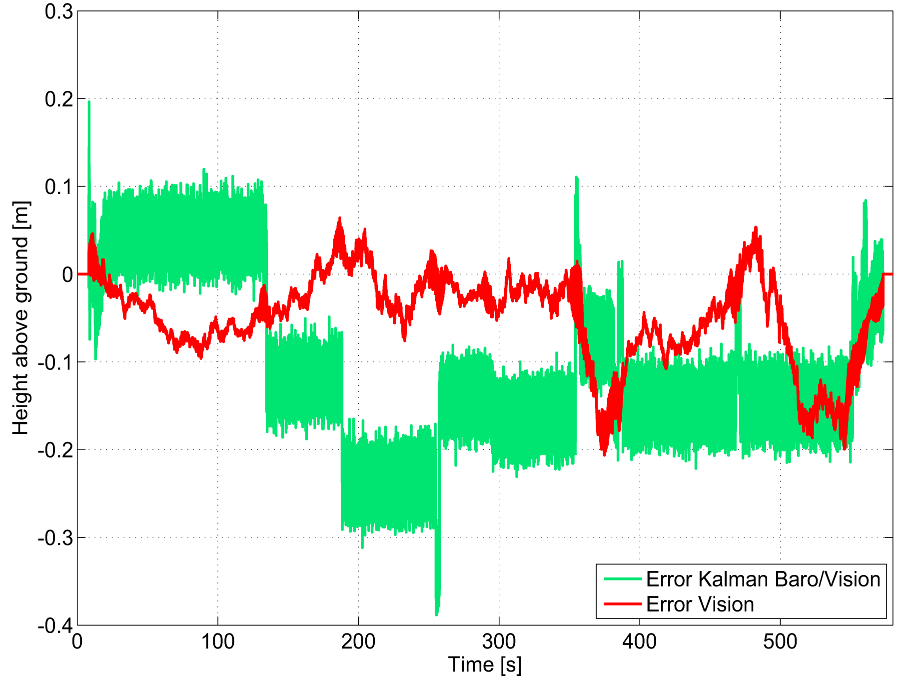
GPS/INS/Mag/Baro Vision

Waypoint flight

Height above ground estimation



Error of height above ground



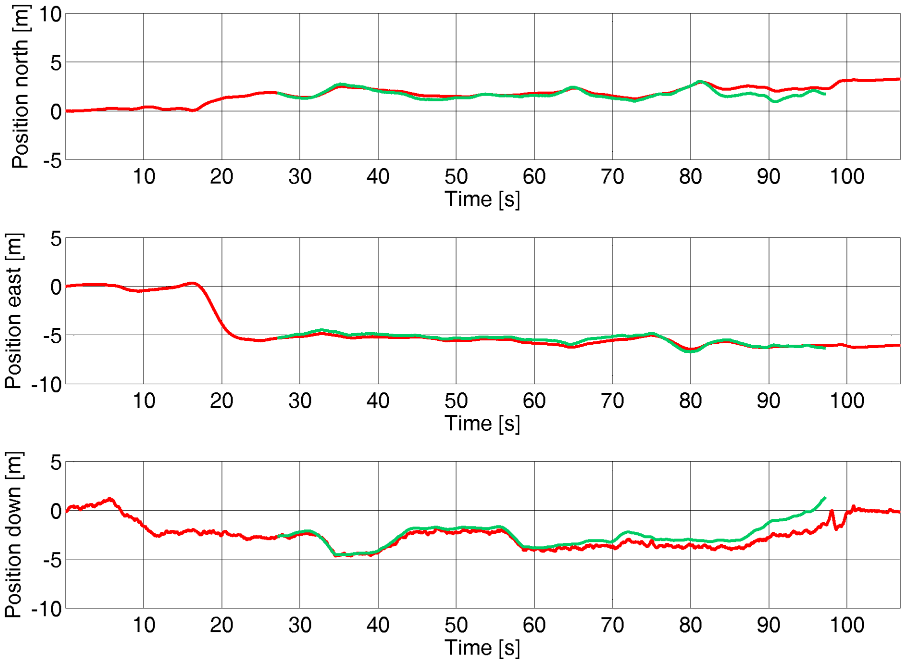
Baro rate 25Hz, baro offset -5m, baro noise $\sigma = 0.02$ m, baro drift 0.2 m/min

Ground truth Kalman filter Baro/Vision Vision meas. Vision

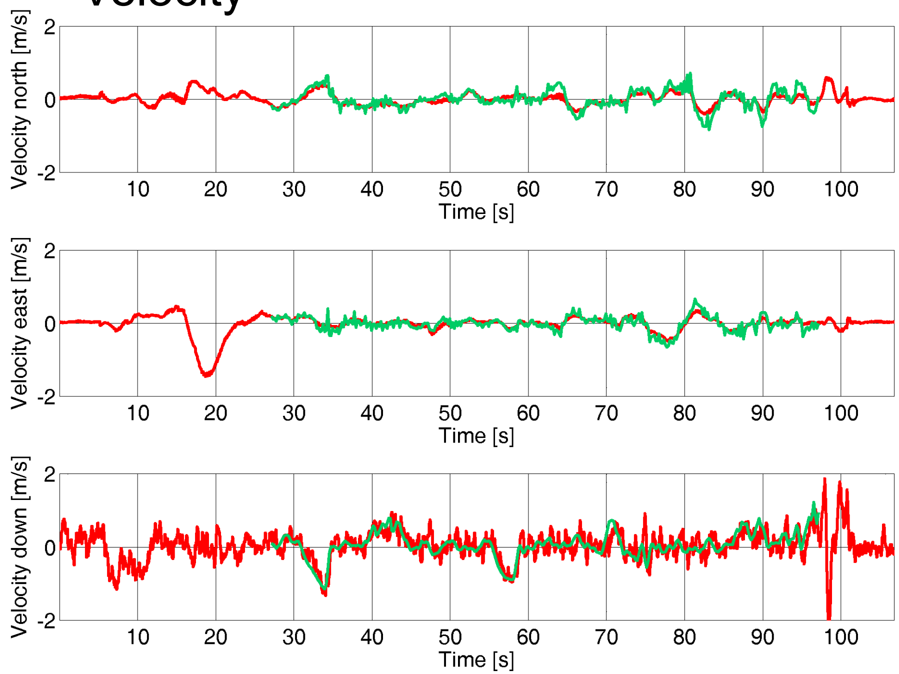
Results

3. Processing of in-flight data

Position



Velocity



First results on processing of in-flight data

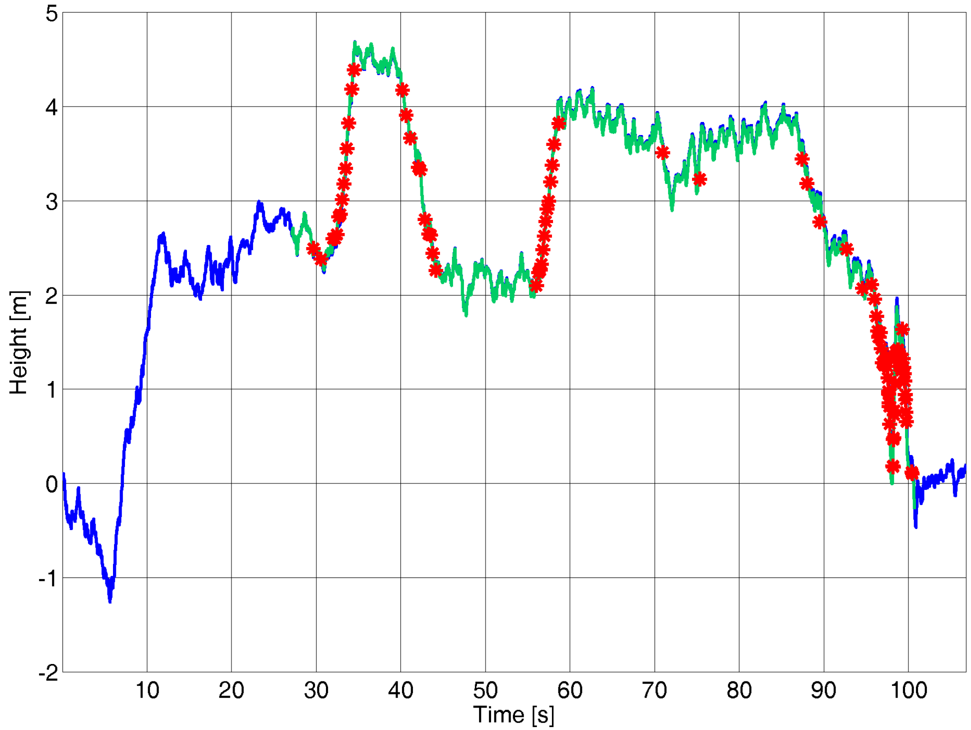
Positions divided by 1/30fps,
Averaging with n = 6, data rate 5Hz

GPS/INS/Mag/Baro Vision

Results

Processing of in-flight data

Height above ground estimation



First tests with
in-flight data confirm
results of simulations

Augmentation of
navigation system
possible

Barometric sensor data   Kalman filter Baro/Vision   Vision

Conclusion

Conclusion

- Image based navigation aiding based on homographies in cases of
  - + hovering and
  - + landing
- Height above ground estimation solely with
  - + optical flow and
  - + barometric sensor data

Future Work

- Integration in navigation and guidance modules
- Implementation of algorithms on on-board image processing hardware

Institute of Systems Optimization

Thank you for your attention.

[redacted]

Image based navigation

Optical flow with census transform

- Comparison of gray values in neighborhood W

$$\xi_i = \begin{cases} 0 & , \mathbf{F}(\vec{x}) - \mathbf{F}(\vec{x}_i) > \sigma \\ 1 & , |\mathbf{F}(\vec{x}) - \mathbf{F}(\vec{x}_i)| \leq \sigma \\ 2 & , \mathbf{F}(\vec{x}) - \mathbf{F}(\vec{x}_i) < -\sigma \end{cases} \quad \text{with } \vec{x}_i \in W$$

222	33	69
15	142	127
127	235	191

$\rightarrow$

2	0	0
0		1
1	2	2

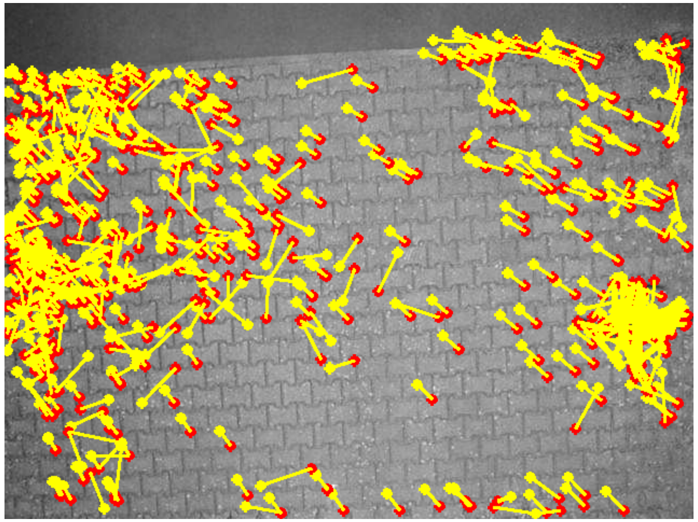
$\rightarrow$ ‘ 20001122‘

- Conversion of signature vector $\vec{\xi}$ to decimal integer
- Store points according to signature vector in table
- Correspondences $\vec{x}_k, \vec{x}_{k+1}$ between images by comparing tables

Image based navigation

Optical flow with census transform

- Use neighbors in distance $\delta > 1$, e. g. $\delta = 4$
- Filtering of signatures of one image
  - Use only signatures including useful information e. g. reject ‘11111111’
  - Use only infrequent signatures e. g. less than 5 times in the image
- Filtering of correspondences
  - Hamming-Distance of 0
  - Distance between points not too large e. g. less than 50 pixels
  - Gray values of pixels similar e. g. less than 20% deviation

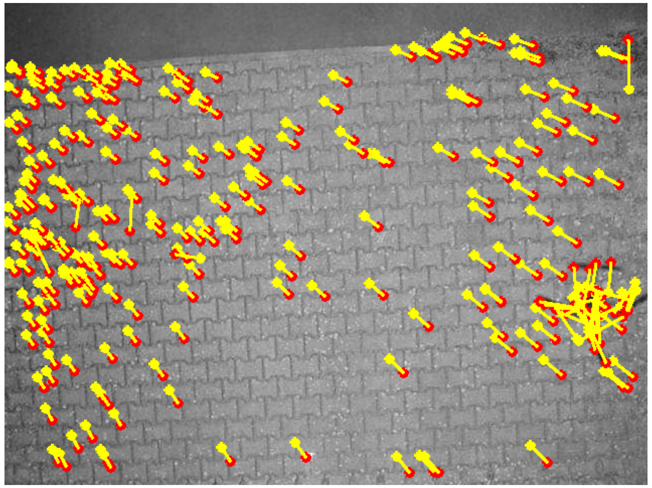


Result not robust

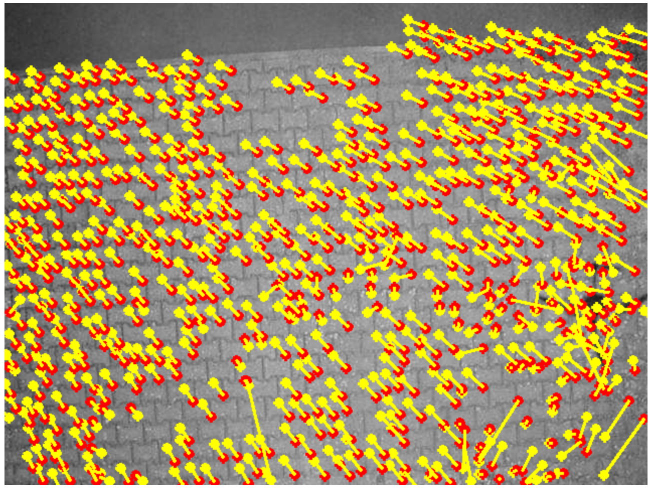
Image based navigation estimation

Results of optical flow calculation

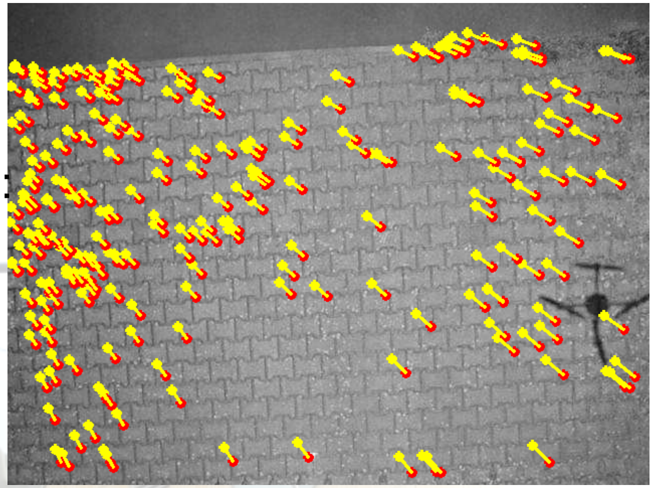
Census:



LK:



Census after RANSAC:



LK after RANSAC:

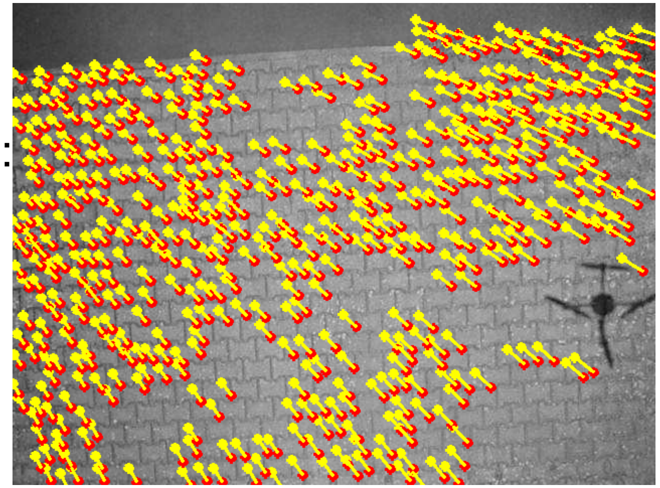
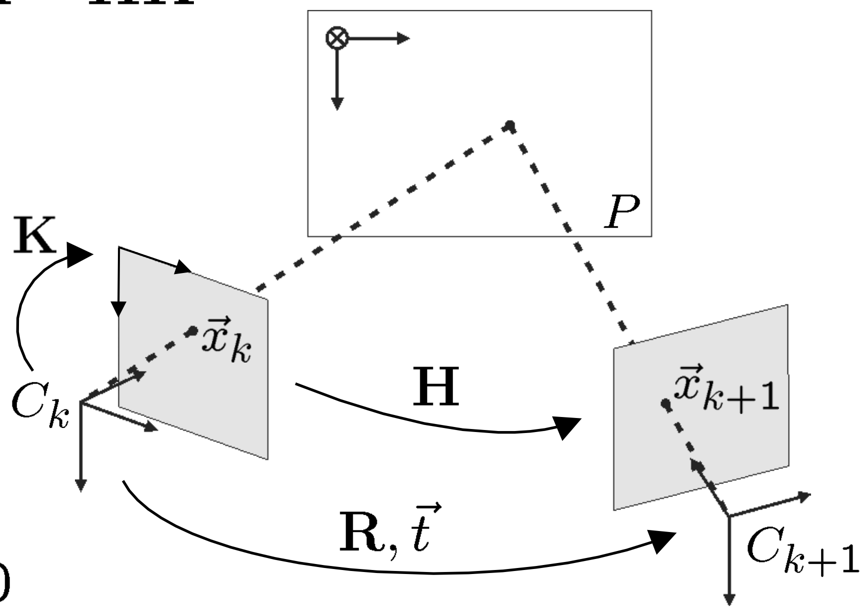


Image based navigation estimation

Homography estimation and decomposition

- Estimation with RANSAC (RANdom SAmple Consensus)
  $\vec{x}_{k+1} \sim \mathbf{H}\vec{x}_k$
- Calibrated homography $\mathbf{H}_{cal} = \mathbf{K}^{-1}\mathbf{H}\mathbf{K}$
- Decomposition:
  $\mathbf{H}_{cal} = \pm\lambda\left(\mathbf{R} + \frac{1}{d}\vec{t}\vec{n}^T\right)$

  with $\mathbf{R}$ rotation matrix
  $\vec{t}$ translation
  d distance to scene plane P
  $\vec{n}$ normal vector of P in camera coordinates



- Rotation $\mathbf{R} = \mathbf{C}_{c_{k+1},c_k}$
- Sign by $\vec{x}_{k+1}\,\mathbf{K}\,\mathbf{H}_{cal}\,\mathbf{K}^{-1}\,\vec{x}_k > 0$
- Singular value decomposition gives 2 physically possible solutions

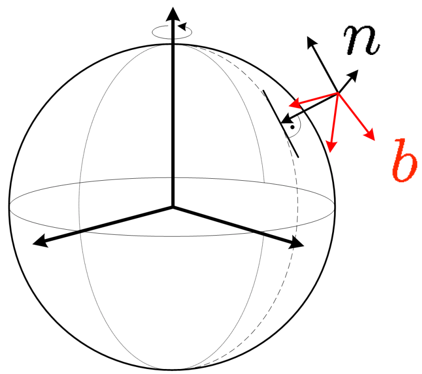
Image based navigation estimation

Propagation of attitude and position

- Integration in navigation coordinate system n

$$\mathbf{C}_{n,b_{k+1}} = \mathbf{C}_{n,b_k}\mathbf{C}_{b,c}\mathbf{R}^T\mathbf{C}_{c,b}$$

$$\vec{x}^{n}_{\mathsf{MAV},k+1} = \vec{x}^{n}_{\mathsf{MAV},k} - \mathbf{C}_{n,b_k}\mathbf{C}_{b,c}\mathbf{R}^T\vec{t}$$



  with $\mathbf{R}$ and $\vec{t}$ from images
- Camera fixed on MAV: $\mathbf{C}_{b,c}$= const, centers coincide

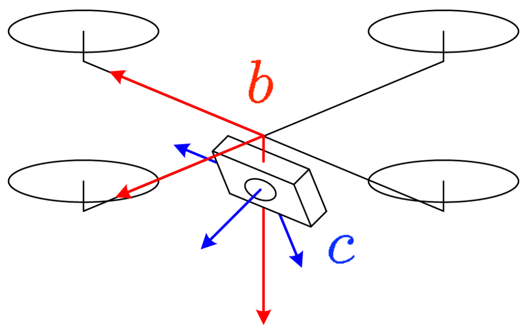


Image based height above ground estimation

ITE

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$$d_{k+1} = \frac{\Delta d_{k,k+1}}{1 - \frac{\Delta x_{k+1}}{\Delta x_k}}$$

Conditions

- Orientation of MAV and camera compensated

$$\vec{x}_{k,corr} = \mathbf{K}\hat{\mathbf{C}}_{c,b}\hat{\mathbf{C}}_{b,n}\mathbf{C}_{n,b_k}\mathbf{C}_{b,c}\mathbf{K}^{-1}\vec{x}_k$$

$$\vec{x}_{k+n,corr} = \mathbf{K}\hat{\mathbf{C}}_{c,b}\hat{\mathbf{C}}_{b,n}\mathbf{C}_{n,b_{k+n}}\mathbf{C}_{b,c}\mathbf{K}^{-1}\vec{x}_{k+n}$$

$$\hat{\mathbf{C}}_{b,n} = \mathbf{I}, \quad \hat{\mathbf{C}}_{b,c} : \hat{\phi}_{bc} = 0^\circ, \hat{\theta}_{bc} = 0^\circ, \hat{\psi}_{bc} = -90^\circ$$

- Motion in vertical direction: $\left|\frac{\Delta d_{k,k+1}}{d_k}\right| > t_1$

  e. g. $t_1 \in [0.1 \ldots 0.2]$

- Displacement not from noise: $\left|\Delta d_{k,k+1}\right| > t_2$

  e. g. $t_2 = 3\sqrt{2}\,\sigma_{\text{baro}}$

Image based height above ground estimation

Estimation

$$d_{k+1} = \frac{\Delta d_{k,k+1}}{1 - \frac{\Delta x_{k+1}}{\Delta x_k}}$$

- $\Delta d_{k,k+1}$ from barometric pressure sensor
- Δx_k, Δx_{k+1} from optical flow

Conditions

- Motion in vertical direction: $\left| \frac{\Delta d_{k,k+1}}{d_k} \right| > t_1$

  e. g. $t_1 \in [0.1 \ldots 0.2]$
- Displacement not from noise: $\left| \Delta d_{k,k+1} \right| > t_2$

  e. g. $t_2 = 3\sqrt{2}\,\sigma_{\text{baro}}$

➡ Continuous estimation of height above ground with Kalman filter
$\Delta d_{k,k+1}$: known inputs, d_{k+1} :easurements

Simulation environment

Simulation of vision system

$\mathbf{C}_{n,b}, \vec{x}^{n}_{\text{MAV}}$

Generation of optical flow data

$\vec{x}_k, \vec{x}_{k+1}$

Image based system

$\hat{\mathbf{C}}_{n,b}, \hat{\vec{x}}^{n}_{\text{MAV}}$

- Generation of feature points in camera coordinates
- Projection on earth plane and storage in database
- Search of features visible in last and current pose

- Estimation of height above ground
- Estimation of homography $\mathbf{H}$, rotation $\mathbf{R}$ and translation $\vec{t}$

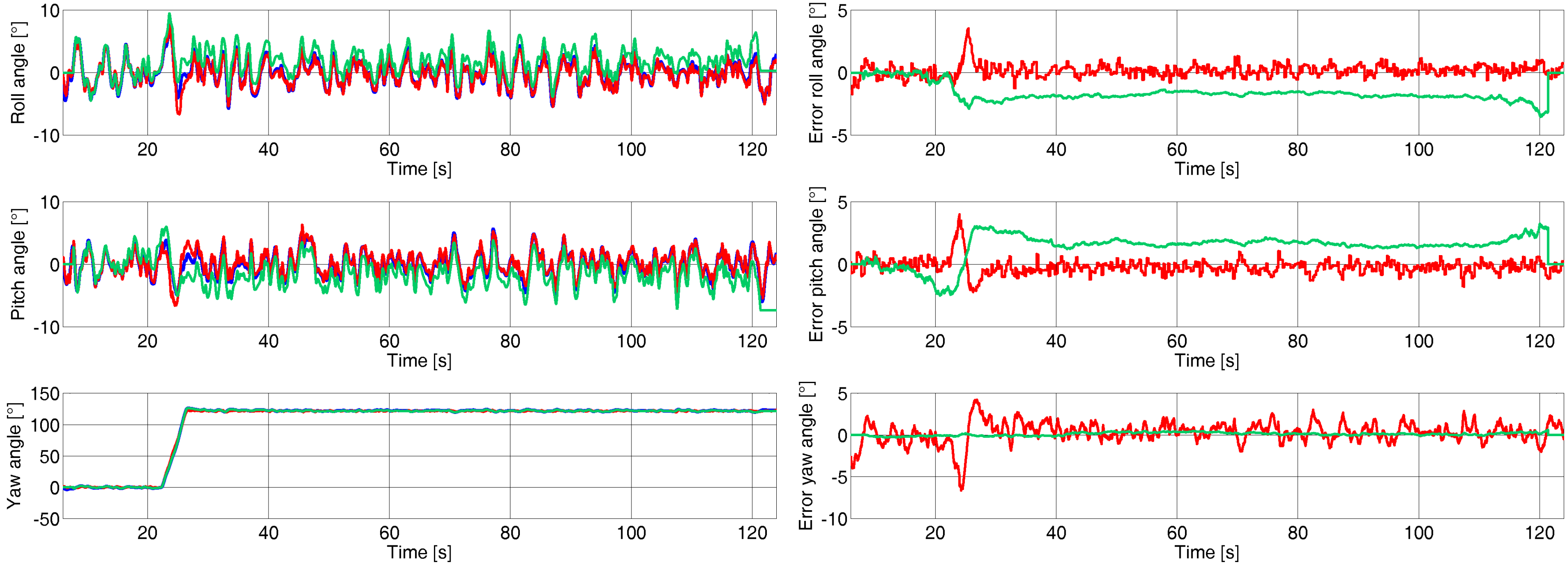
Adjustable parameters:
image size, image rate, internal camera parameters, number of features, feature noise …

Results

1. Simulation: Hovering at defined position and landing

Attitude

Error of attitude

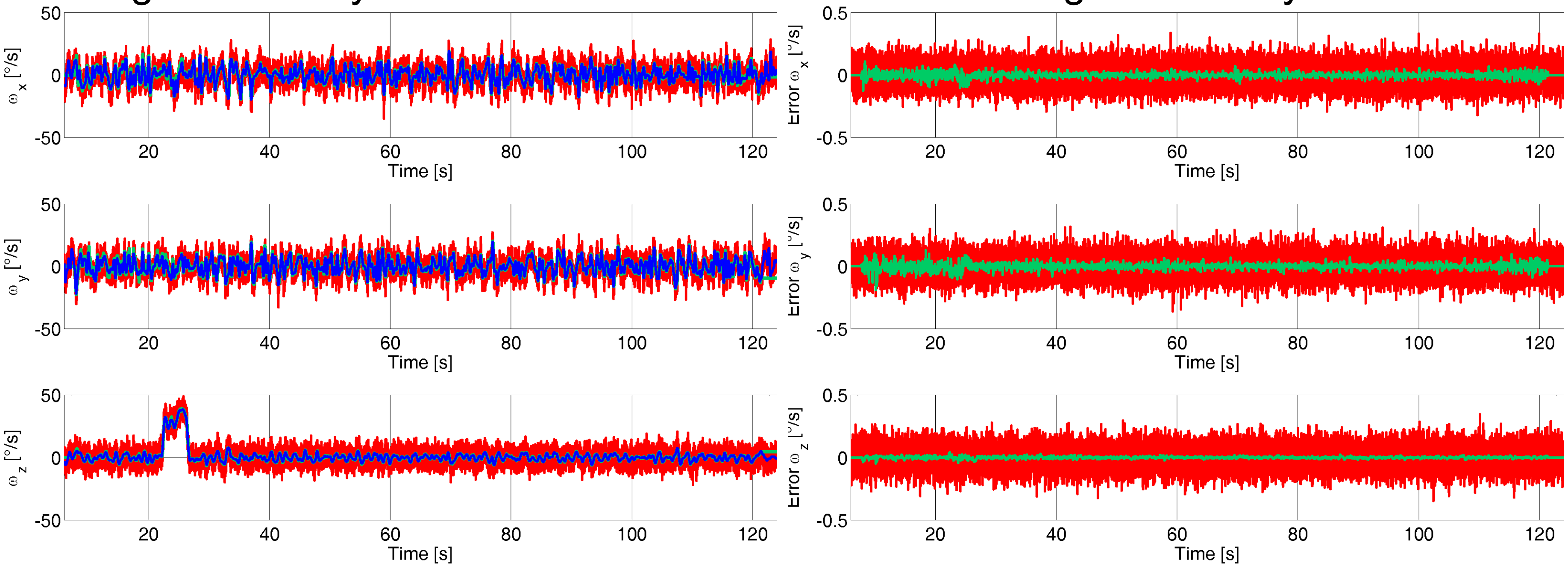


Ground truth   GPS/INS/Mag/Baro   Vision

Results

Hovering at defined position and landing

Angular velocity　　　　Error of angular velocity



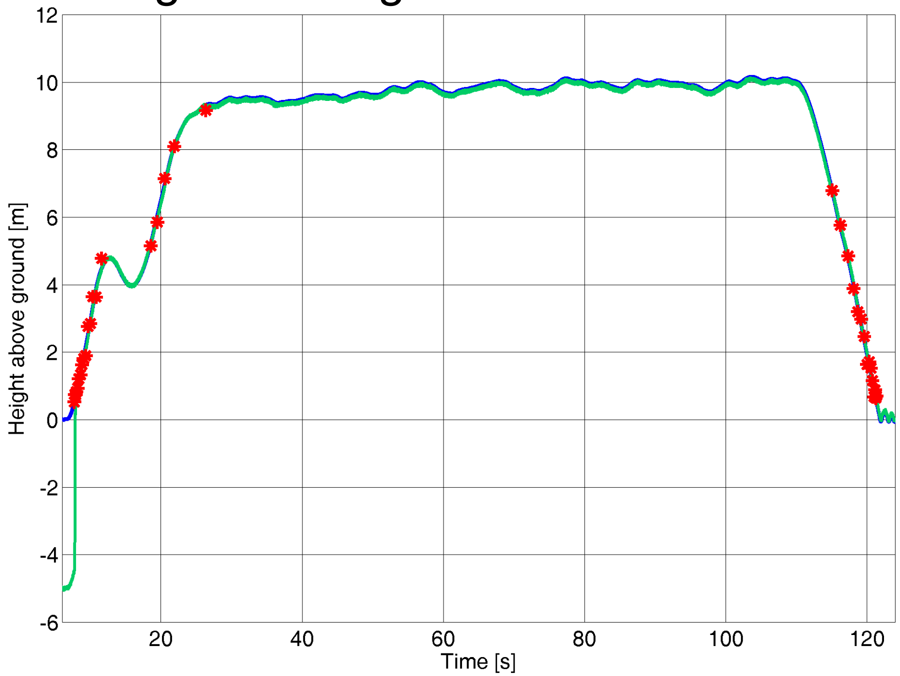
Angles divided by 1/25fps

Ground truth　GPS/INS/Mag/Baro　Vision

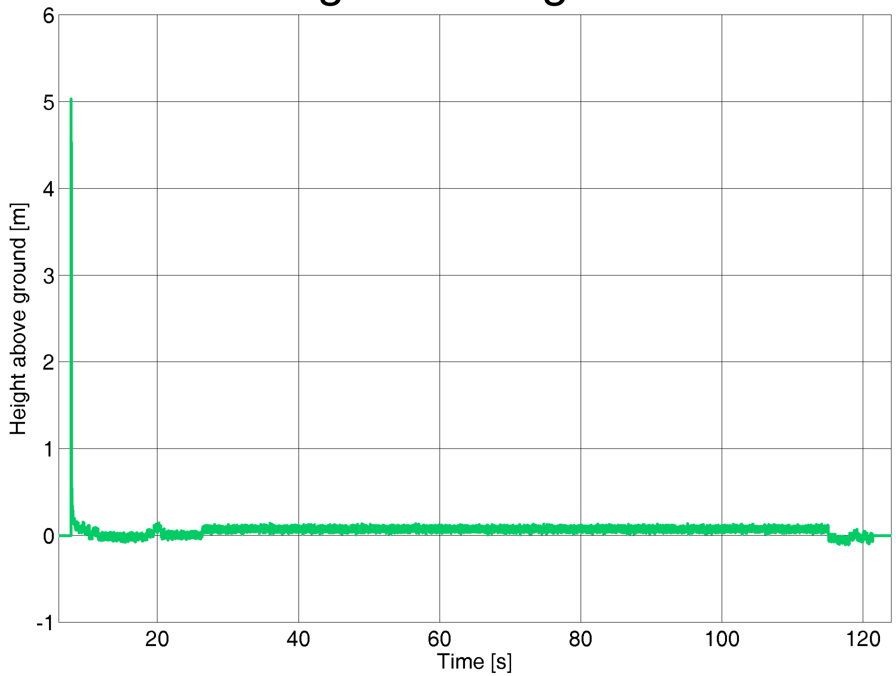
Results

Hovering at defined position and landing

Height above ground estimation



Error of height above ground



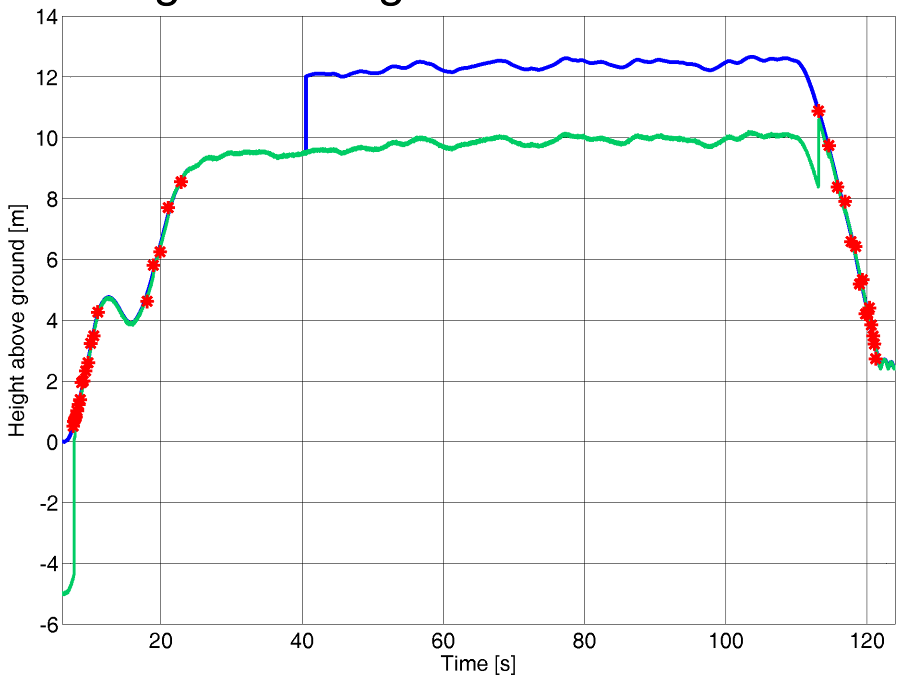
Baro rate 25Hz, baro offset -5m, baro noise $\sigma = 0.02$ m, baro drift 0.2 m/min

Ground truth — Kalman filter Baro/Vision — Vision

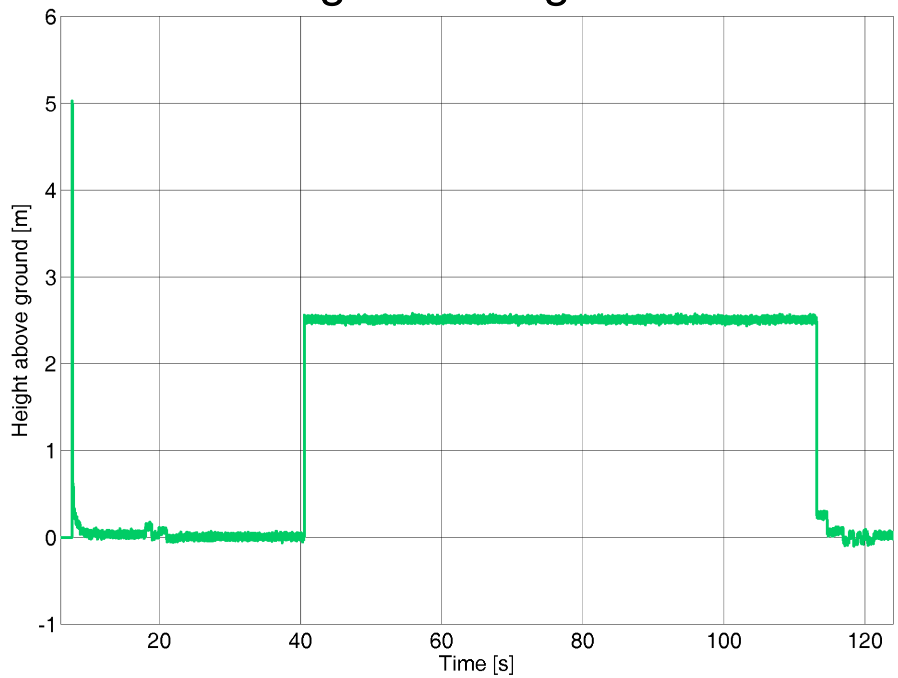
Results

Hovering at defined position and landing

Height above ground estimation



Error of height above ground



Simulated step of ground elevation of 2.5 m

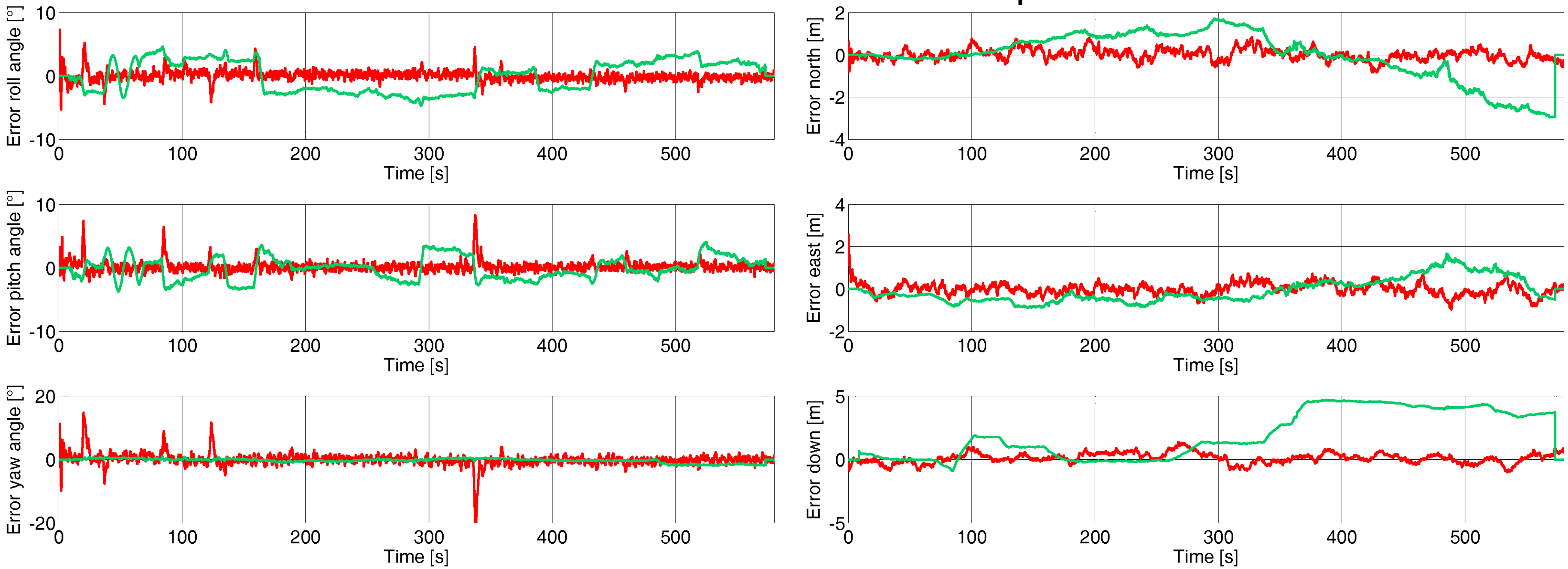
Ground truth   Kalman filter Baro/Vision   Vision

Results

2. Simulation: Waypoint flight

Error of attitude

Error of position



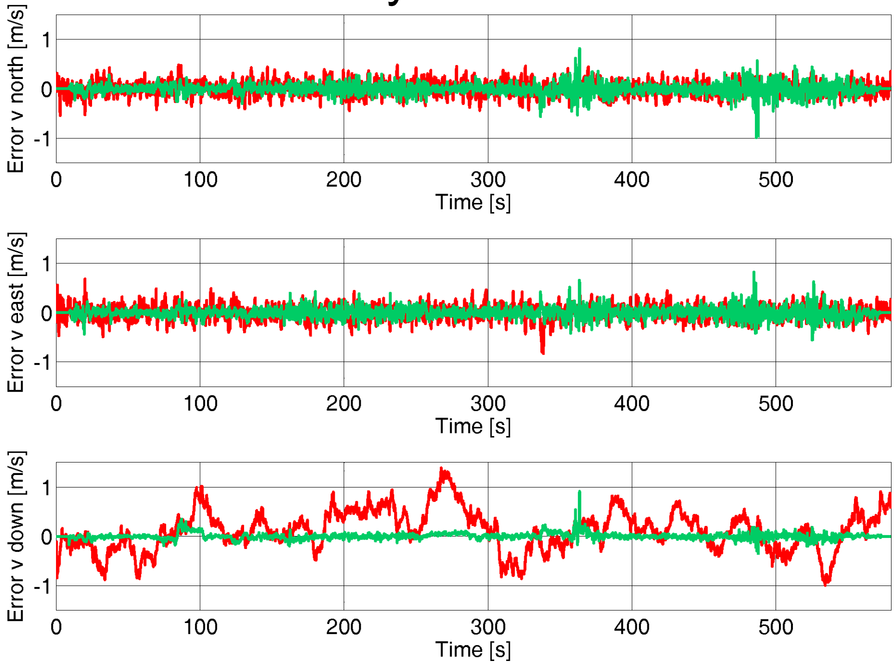
Frame rate 25 fps, image size 640x480, 200 features, feature noise $\sigma = \frac{1}{3}$ pix.

GPS/INS/Mag/Baro   Vision

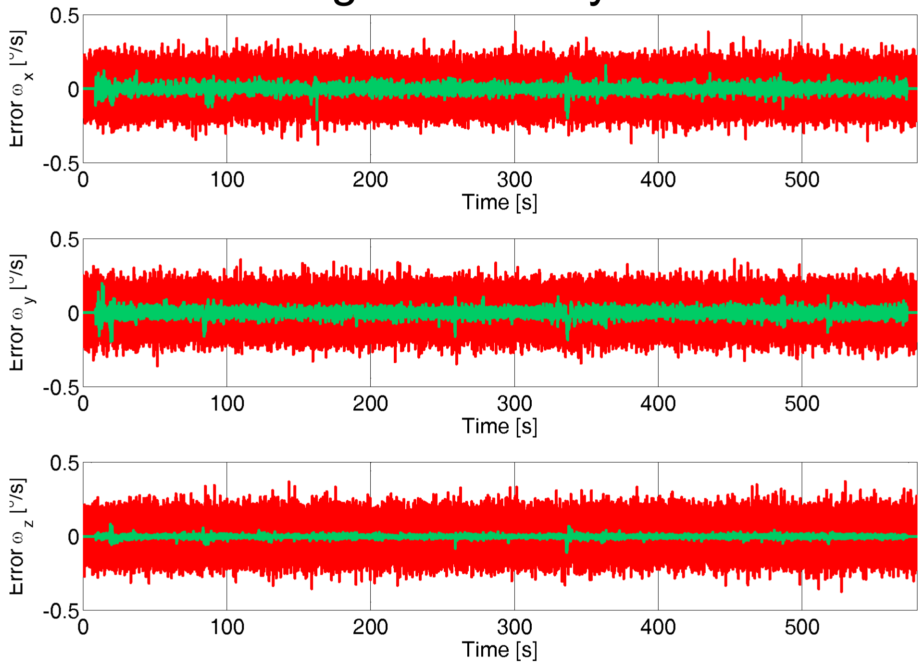
Results

Waypoint flight

Error of velocity



Error of angular velocity



Positions divided by 1/25fps,
Averaging with n = 6, data rate 4.16Hz

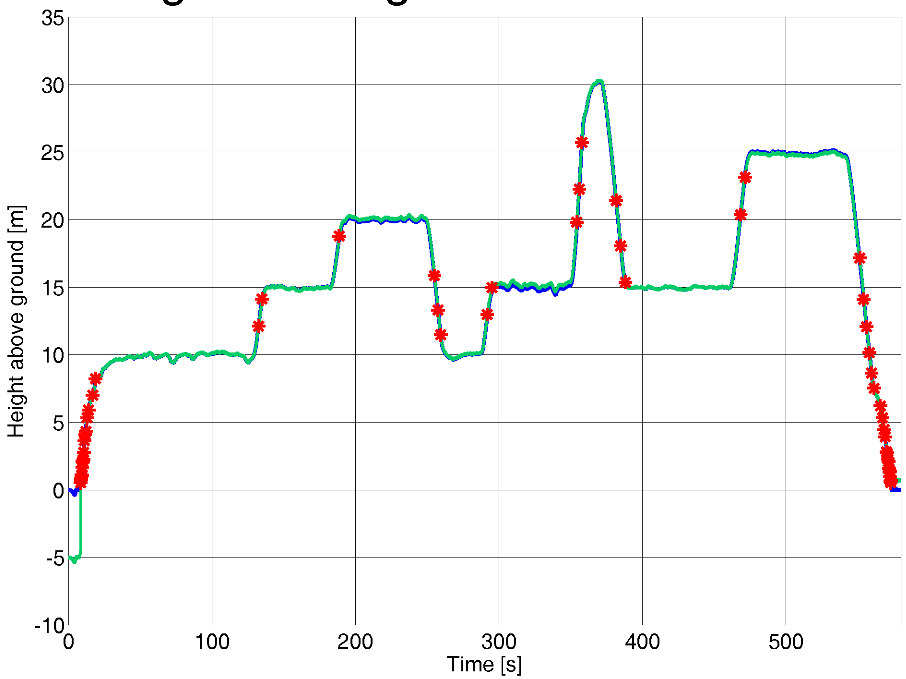
Angles divided by 1/25fps

GPS/INS/Mag/Baro   Vision

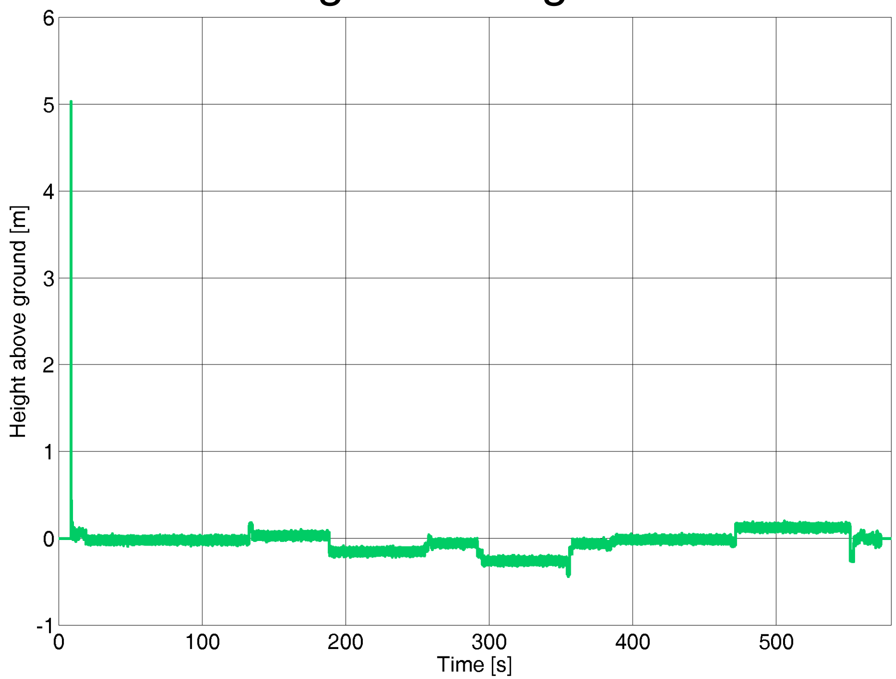
Results

Waypoint flight

Height above ground estimation



Error of height above ground



Baro rate 25Hz, baro offset -5m, baro noise $\sigma = 0.02$ m, baro drift 0.2 m/min

Ground truth Kalman filter Baro/Vision Vision

Karlsruhe Institute of Technology

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