RC SPACE Research Center Space Universität der Bundeswehr München

Session D3: Space Navigation and Observation

LiDAR-Based Autonomous Landing on Asteroids: Algorithms, Prototyping and End-to-End Testing with a UAV-Based Satellite Emulator

Max Hofacker[1], Harvey Gómez Martínez[1], Martin Seidl[1], Fran Domazetović[2],

Larissa Balestrero Machado[1], Roger Förstner[1], Thomas Pany[1]

[1]*Universität der Bundeswehr München*

[2]*Department of Geography, University of Zadar*

Introduction

- Asteroids are in focus of planetary researchers
  - Understanding of the early solar system
  - Planetary protection
  - Asteroid mining
  - ➢ In situ measurements and sample return missions
- Challenges:
  - Autonomously GNC and hazard detection
  - Development of new algorithm is simulation dependent
  - ➢ Easy to use and cost-efficient *hardware-in-the-loop* emulation with multicopter UAVs in relevant environments
  - ➢ Increasing *Technical Readiness Level*

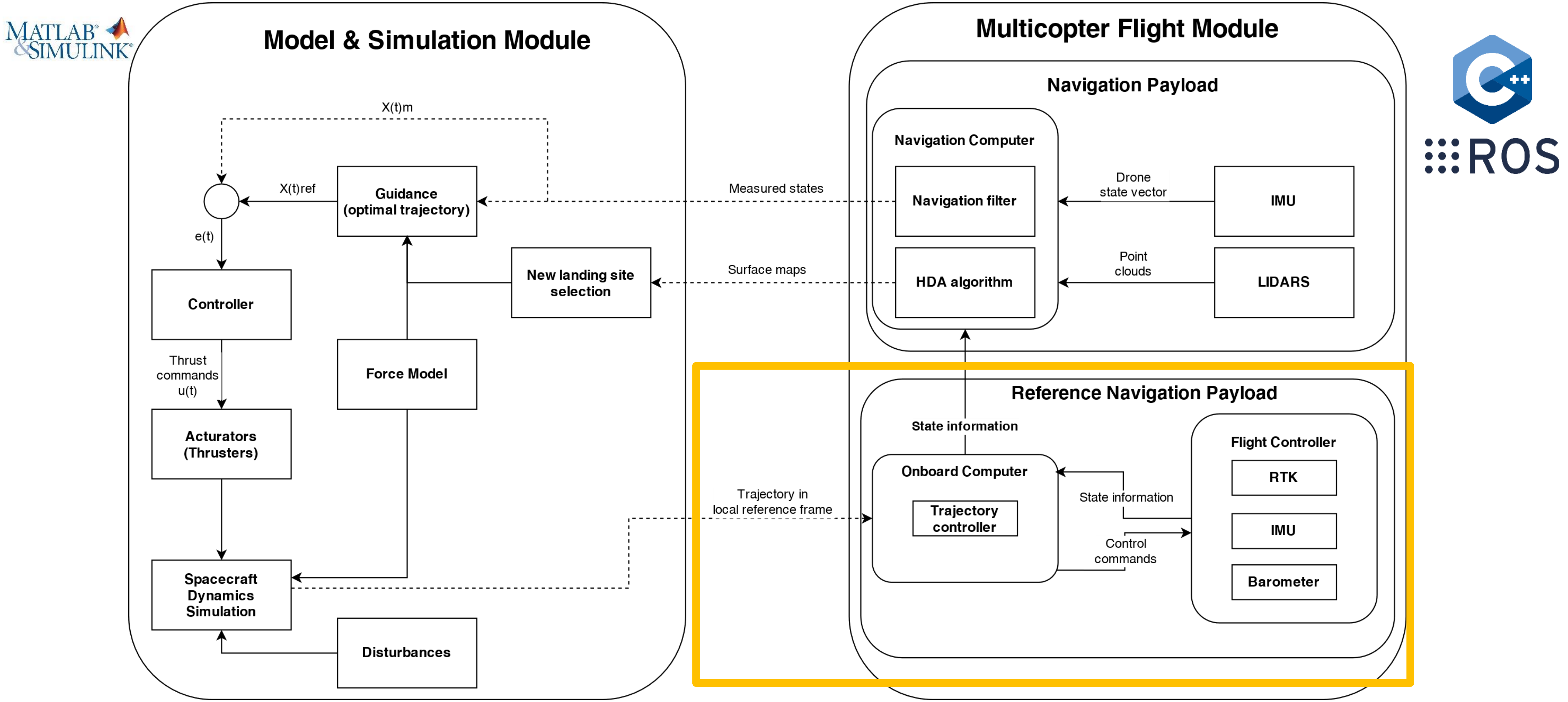
Rosetta & Philae [1]

[2]

Introduction

- Multicopter UAV-based satellite emulator
  - Payload up to 6 kg
  - Flight time up to 30 minutes
  - Open-Source Pixhawk flight controller and the MRS UAV System [3]
  - ublox F9P RTK as reference navigation
- Asteroid Navigation Sensors
  - Two automotive LiDARs to mimic a space-grade Flash-LiDAR

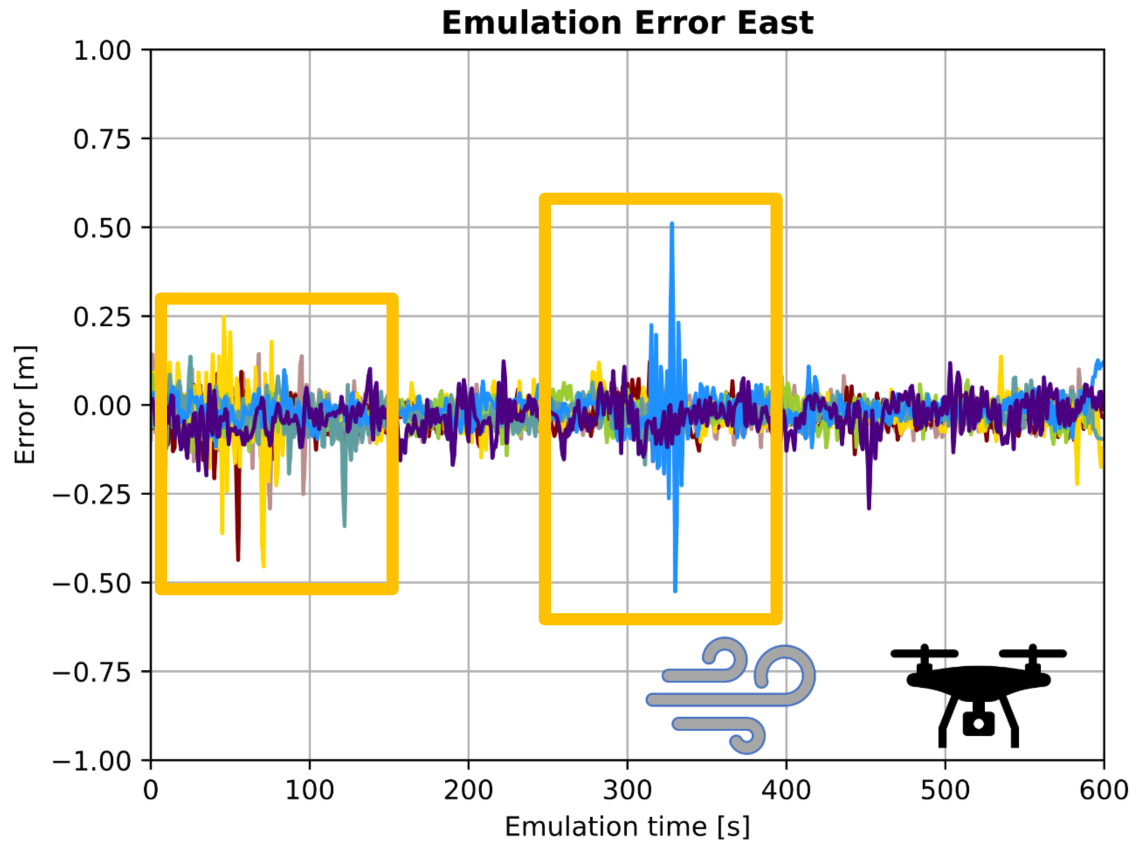
UAV-based emulation platform

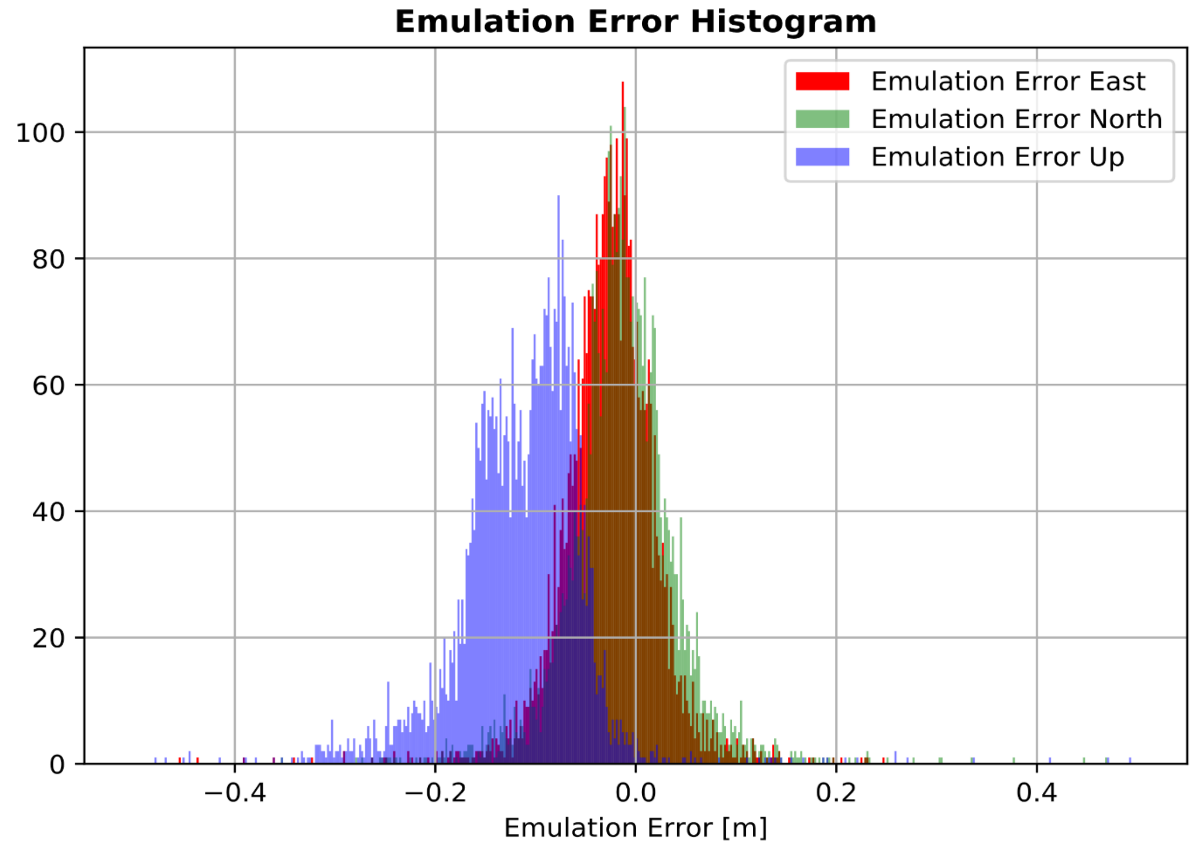


UAV-based emulation platform

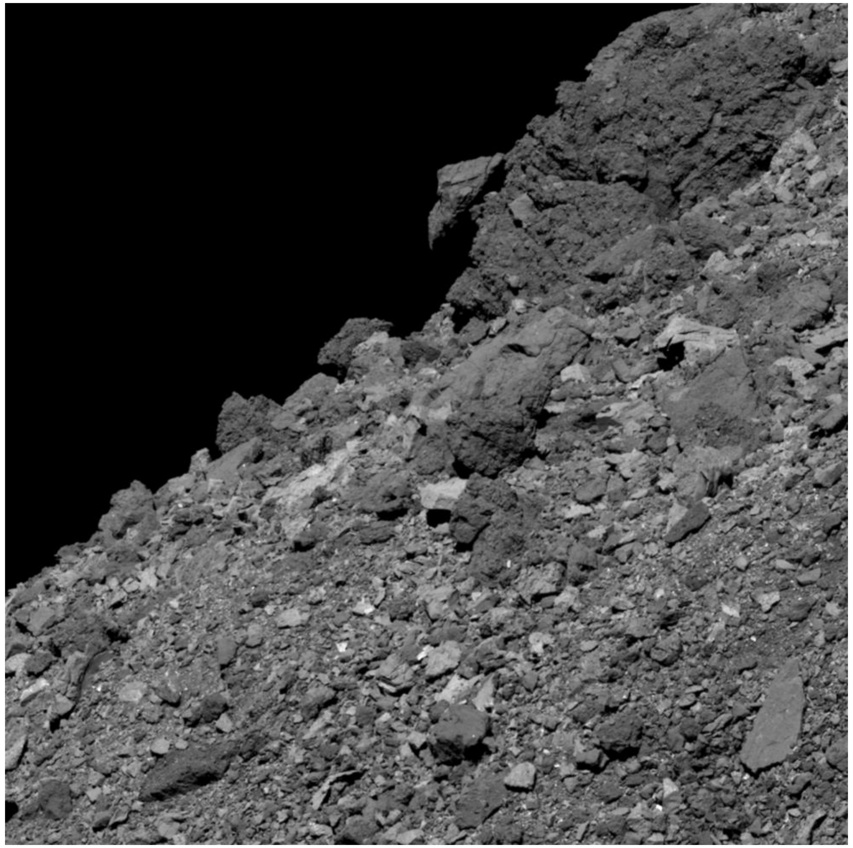
- Emulation performance $Error_{Pos}$ is better than 30cm (95%)

$$Error_{Pos} = Pos_{Sat} - Pos_{UAV}$$





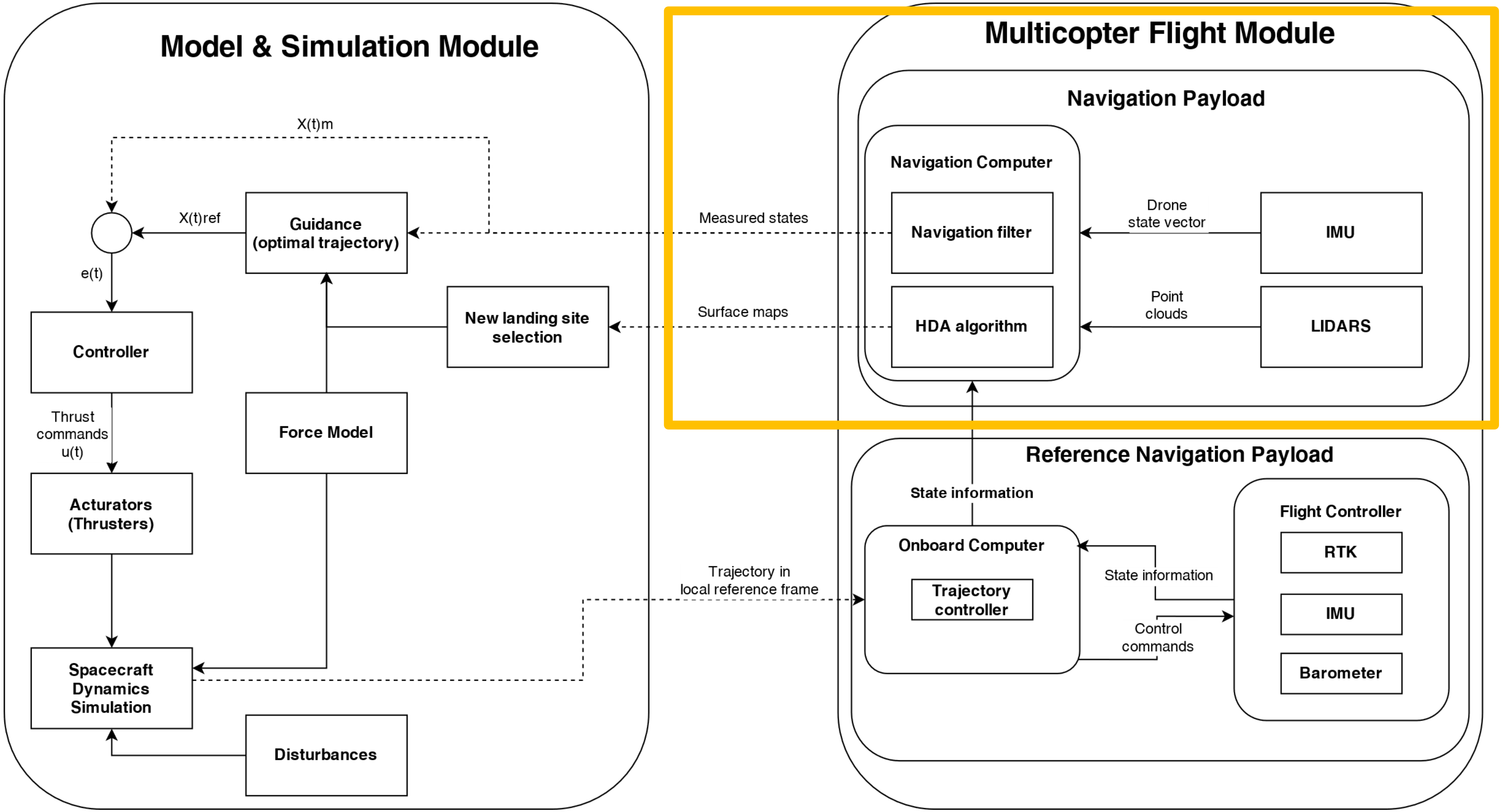
Emulation environment



Bennu’s bolder covered surface [6]

Surface morphology of emulation area
on Pag Island, Croatia

LiDAR Odometry and Terrain-Relative-Navigation

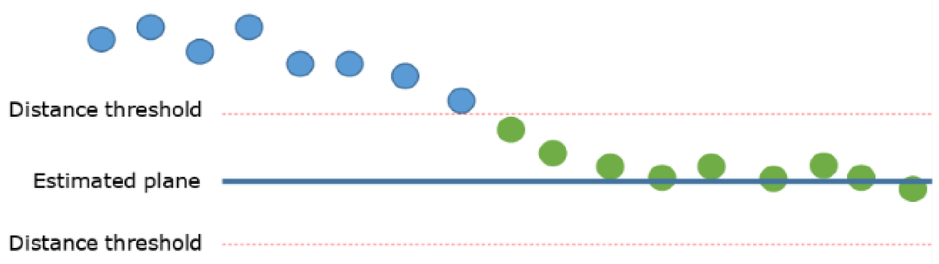


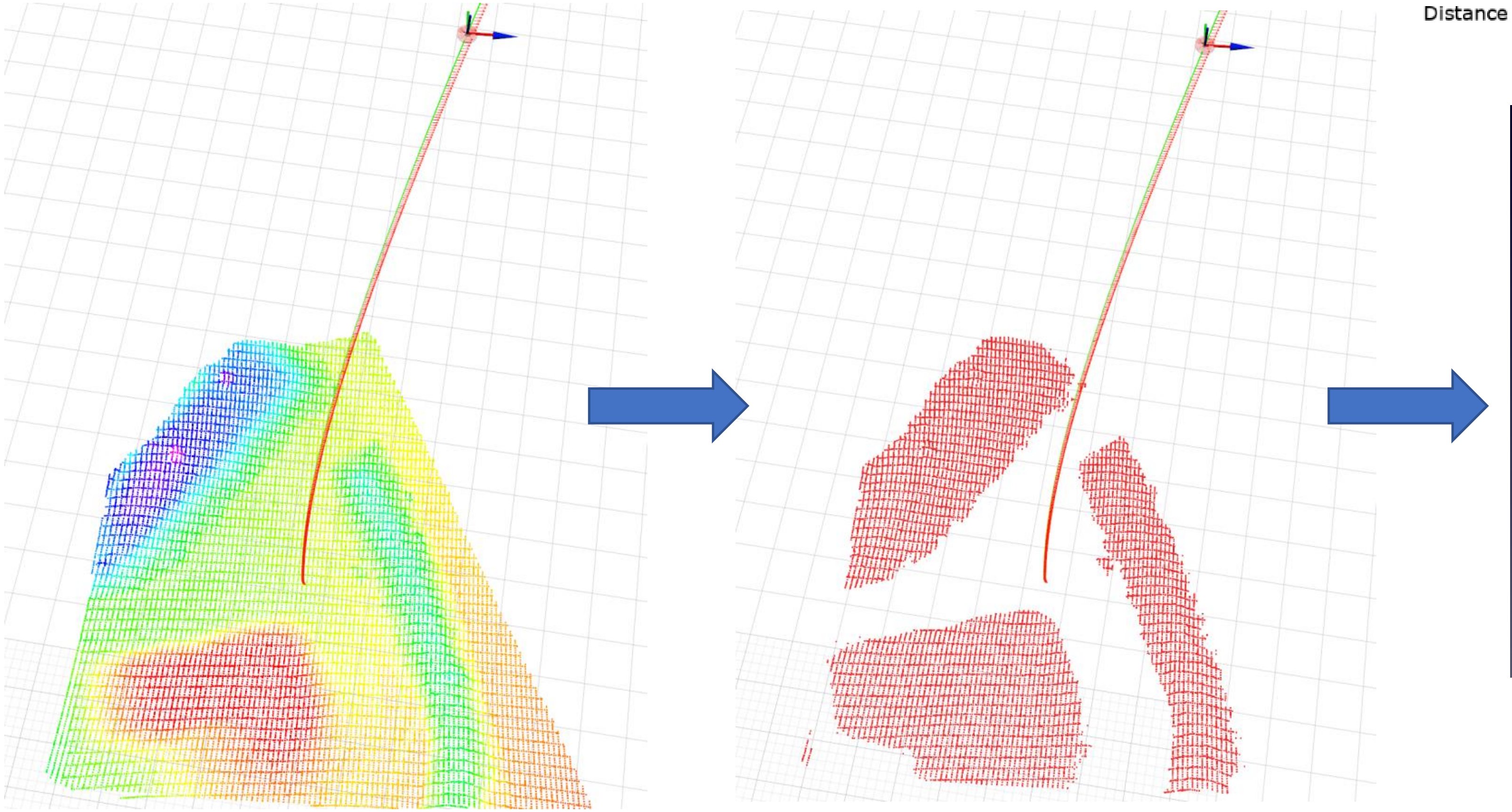
Navigation filter and sensor fusion

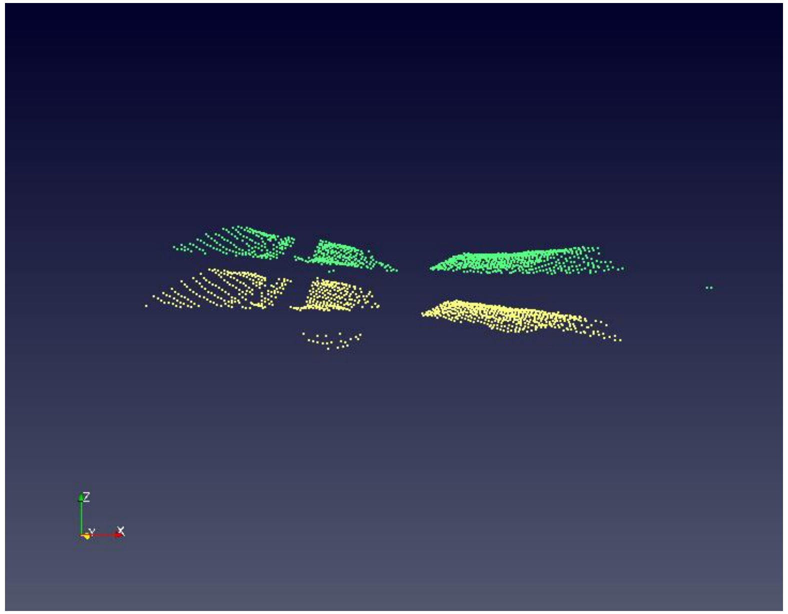
- The navigation filter is implemented as 6-state *Linear Kalman Filter* (position and velocity) using a *constant-velocity* dynamic model
- As the attitude could not be emulated, it was neglected in the navigation filter (but included within the spacecraft control-part)
- Local asteroid coordinate frame corresponds to the UAV-ENU coordinate system
- Observations:
  - LiDAR Odometry
  - LiDAR Relative Position Updates
  - LiDAR Altimetry
- External Forces:
  - Thruster commands
  - Gravity

ICP-based LiDAR Odometry and Altimetry

- Plane-based feature extraction of original point clouds:
  - ➢ Terminal decent uses full point cloud
- Point-to-Point ICP by LibPointMatcher library [7]



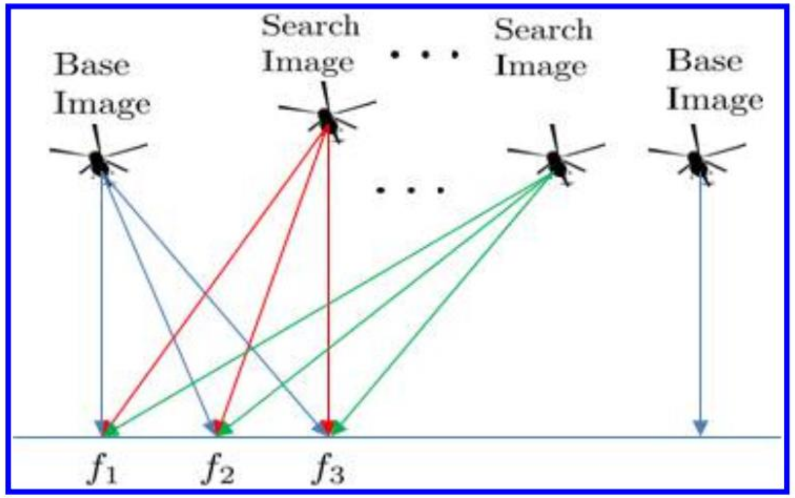




ICP-process with extracted feature point cloud

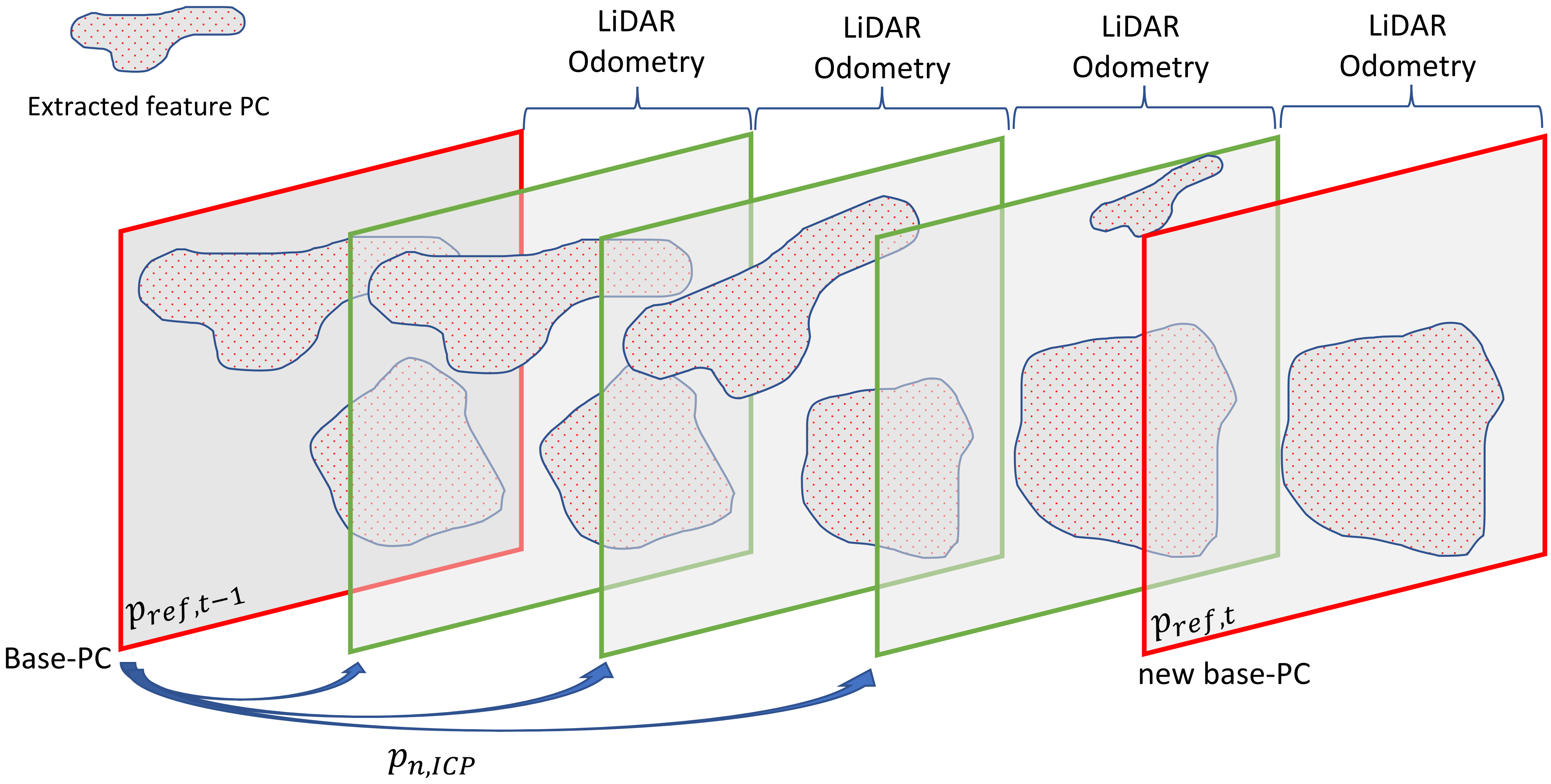
ICP-based LiDAR Odometry and Altimetry

- LiDAR-Odometry:
  - ➢ Average velocity of spacecraft *between two* point clouds
  - ➢ Dead-reckoning lead to random walk
- LiDAR-relative position updates:
  - ➢ ICP-process between *base* and *current* point cloud
  - ➢ Long-baseline visual odometry
  - ➢ Inspired by NASA's MAVeN algorithm [8]
  - ➢ Performance and dynamic based logic for resetting the base point cloud



Base and Search frames within NASA's Ingenuity Mars UAV navigation system [8]

ICP-based LiDAR Odometry and Altimetry



ICP Translation:

$$p_{n,ICP} = \begin{bmatrix} p_{n_x} \\ p_{n_y} \\ p_{n_z} \end{bmatrix}$$

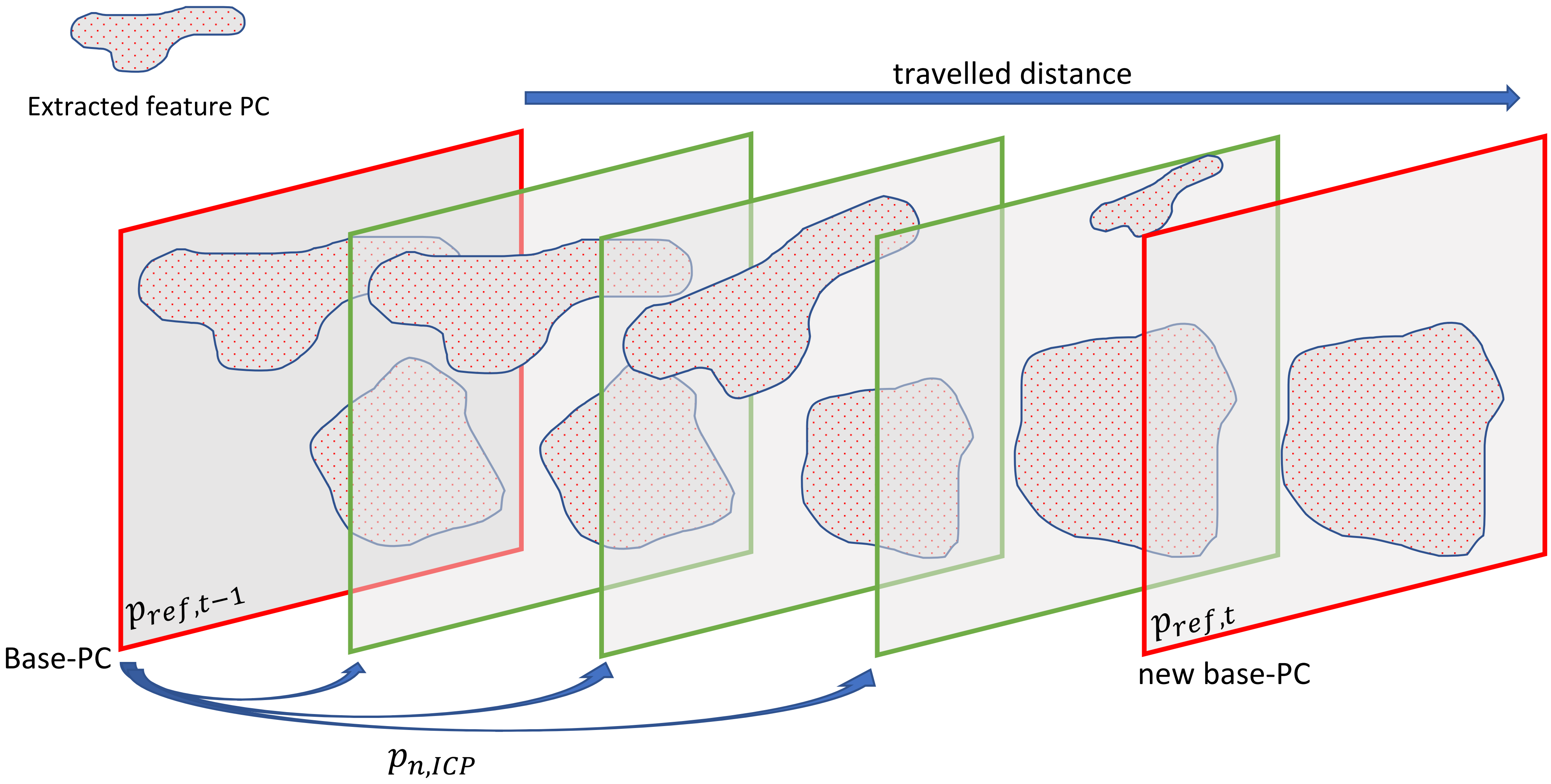
LiDAR Odometry:

$$z_{n,v} = \begin{bmatrix} p_{n_x}/\Delta t \\ p_{n_y}/\Delta t \\ p_{n_z}/\Delta t \end{bmatrix}$$

LiDAR rel. position updates:

$$z_{n,p} = \begin{bmatrix} p_{n_x} + p_{x,ref} \\ p_{n_y} + p_{y,ref} \\ p_{n_z} + p_{z,ref} \end{bmatrix}$$

ICP-based LiDAR Odometry and Altimetry

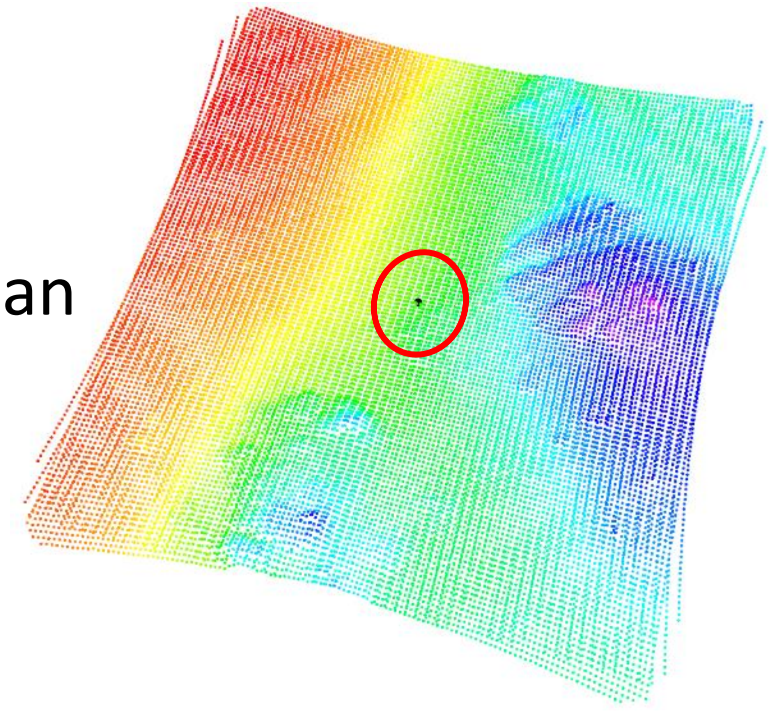


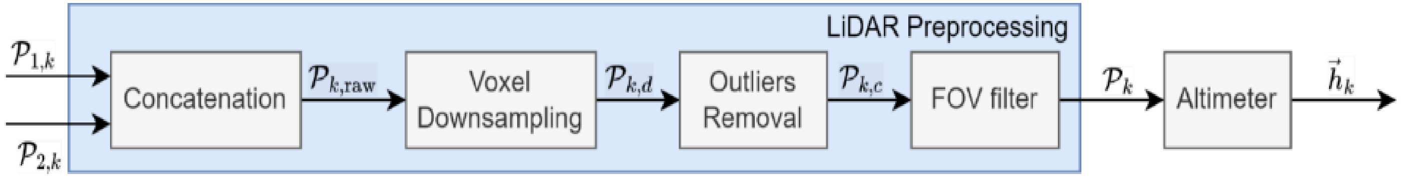
Logic for base-PC reset:

- ICP RMSE
- traveled distance
- relation of numbers of extracted points

LiDAR Altimetry

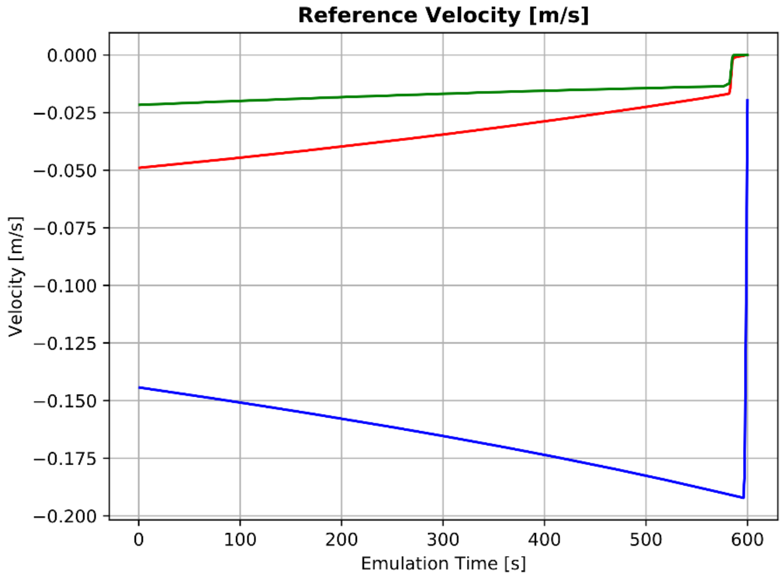
- Transforming point cloud to local coordinate system
- Conic Field-of-View filter to extract points of the spacecraft footprint
- Calculating the altitude by the mean of all Euclidean distances of each point within the footprint
  - ➢ Compensating inclined terrain
  - ➢ Compensating possible boulders

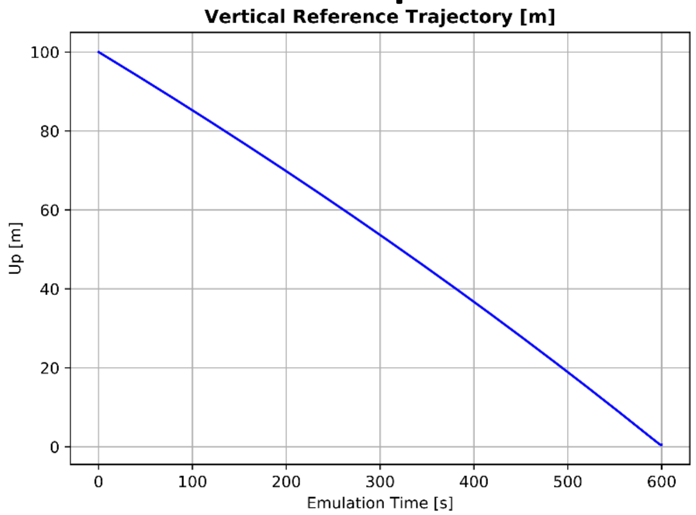


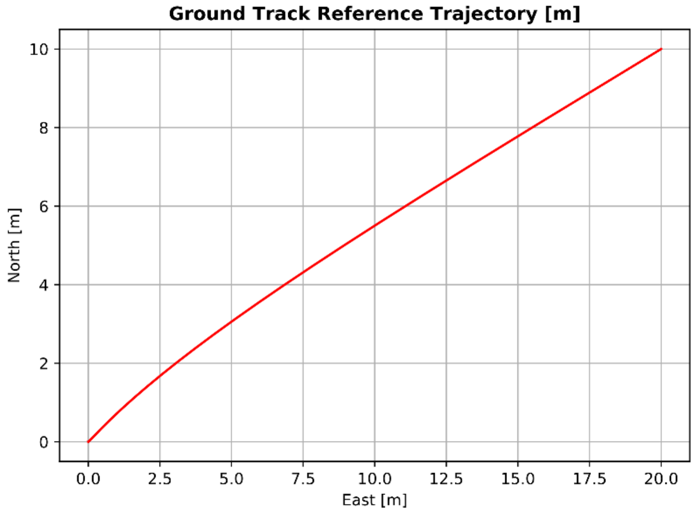


Navigation Performance

- Example landing approach on Bennu
  - No re-targeting
  - Free-Fall until terminal decent
  - Error-free initial position
- Compared to the RTK-reference trajectory
- Emulation performed on Pag Island





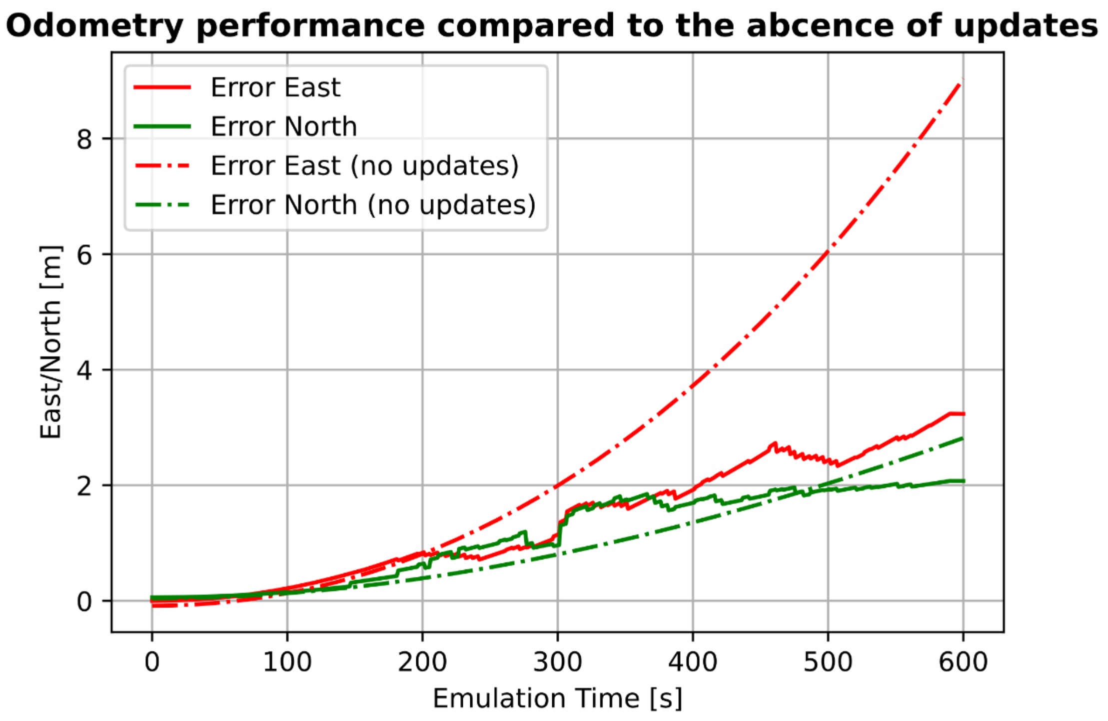


Navigation Performance

- Example landing approach on Bennu
  - No re-targeting
  - Free-Fall until terminal decent
  - Error-free initial position
- Compared to the RTK-reference trajectory
- Performed in emulation area on Pag Island

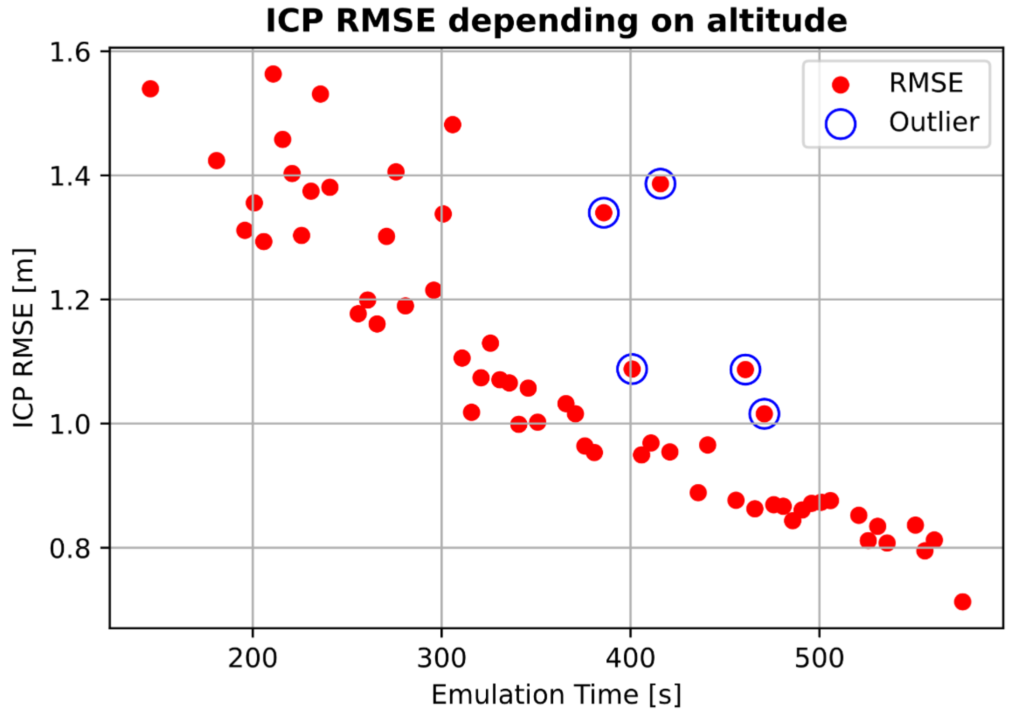
Navigation Performance

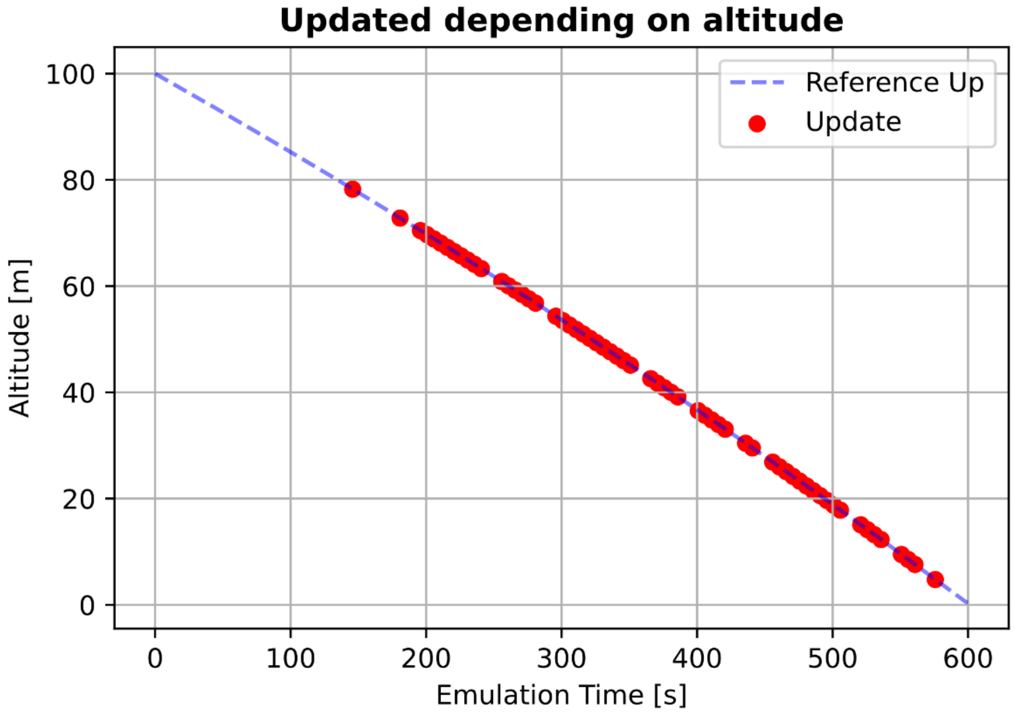
- How do the relative position updates improve the horizontal navigation performance?
  - ➢ It reduces the drift in the higher dynamic eastern component
  - ➢ No significant impact for the less dynamic northern component
  - ➢ Without updates the spacecraft would have reached hazardous regions



Navigation Performance

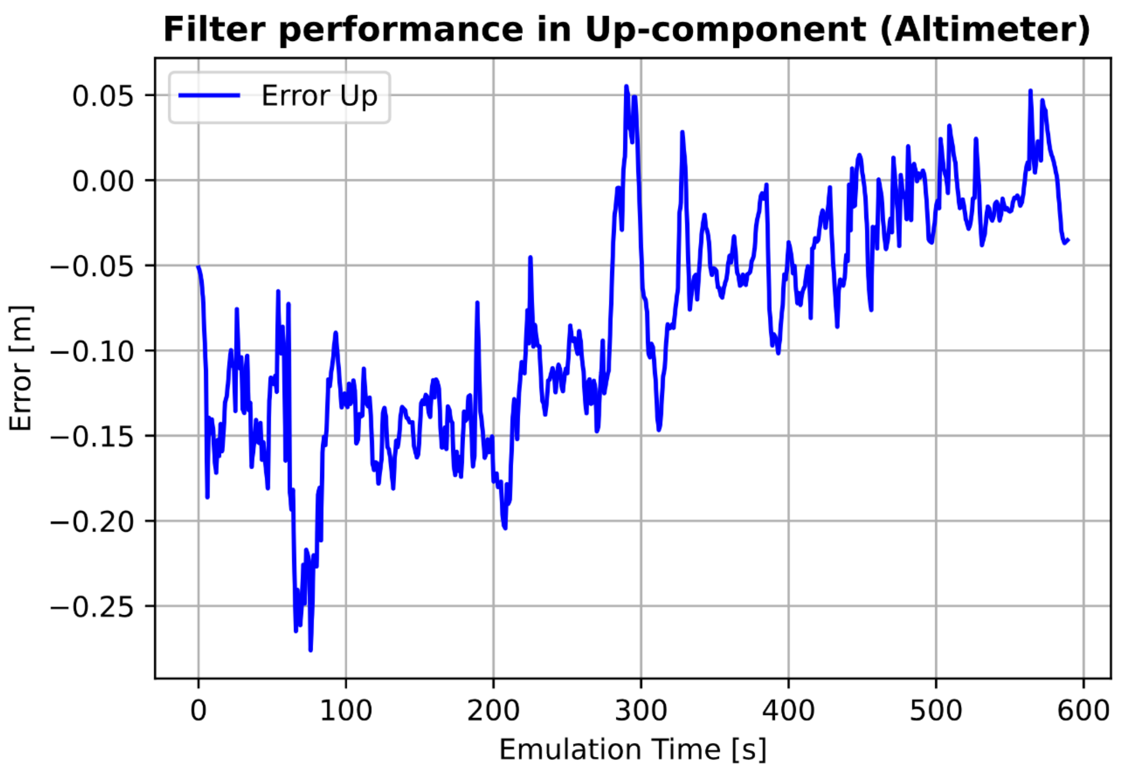
- ➢The ICP-process is altitude dependent
- ➢The RMSE clusters and their outlieres suggest that the base PCs are not chosen/reset in an optimal manner





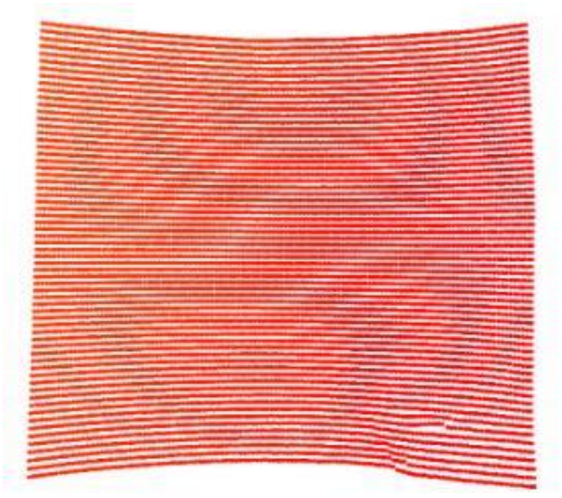
Navigation Performance

- Altimeter performance is very accurate
- Altitude dependent (“scale factor”)

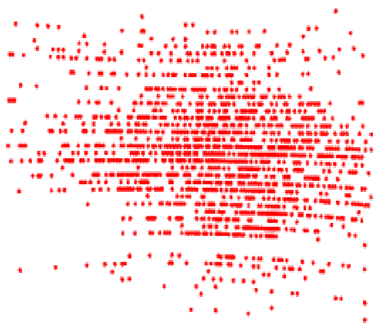


Navigation Performance

- The used automotive LiDAR suffers from large reflection losses in altitudes > 70 m
- The standard sensor simulation models did not include this error behavior for long range measurements



Original simulated PC

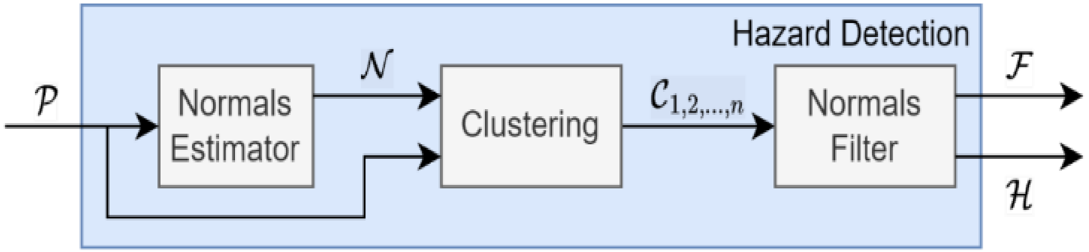


Real PC

Adopted simulated PC

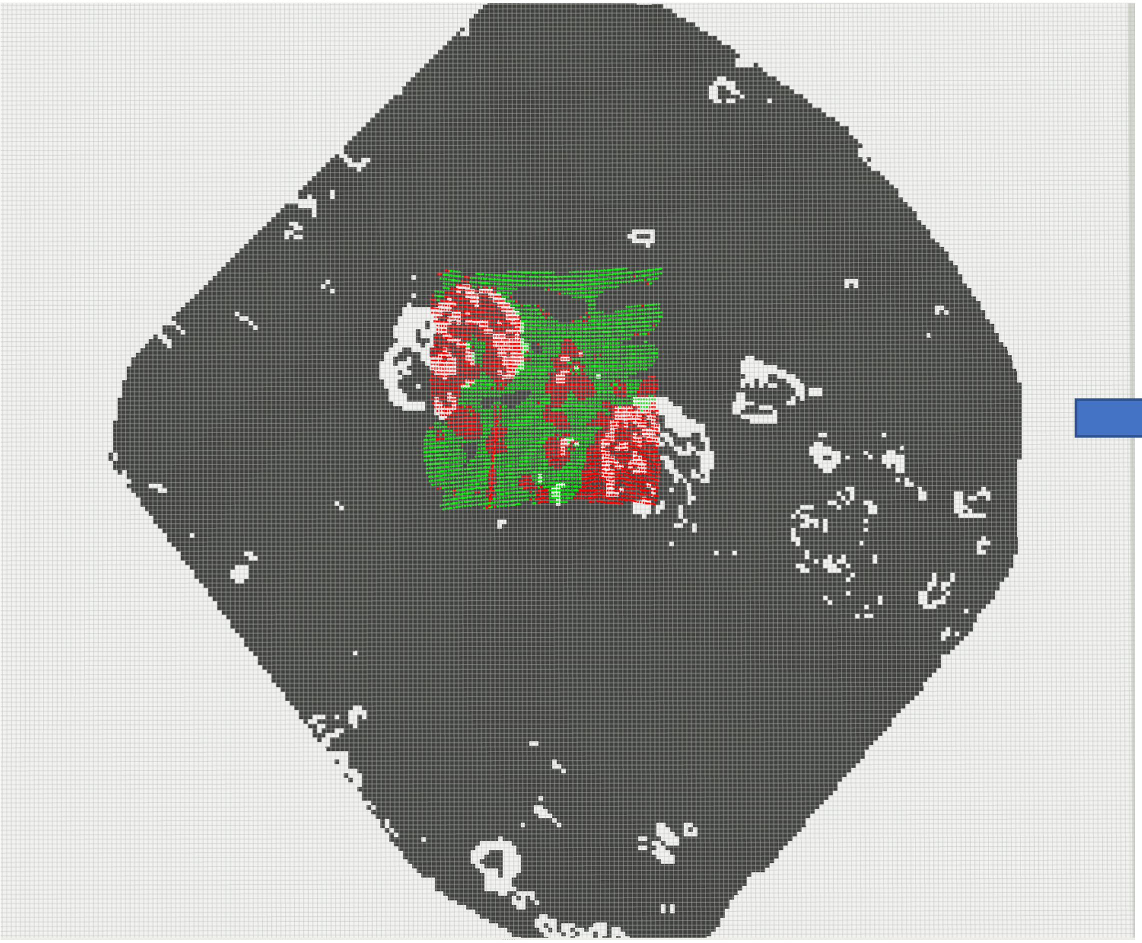
Hazard detection

- Hazard detection is necessary for full autonomous navigation
  - The landing area should not have slopes of > 15°
  - Calculating normal vectors of all points
  - Clustering hazardous areas
  - Projection into 2D hazard maps

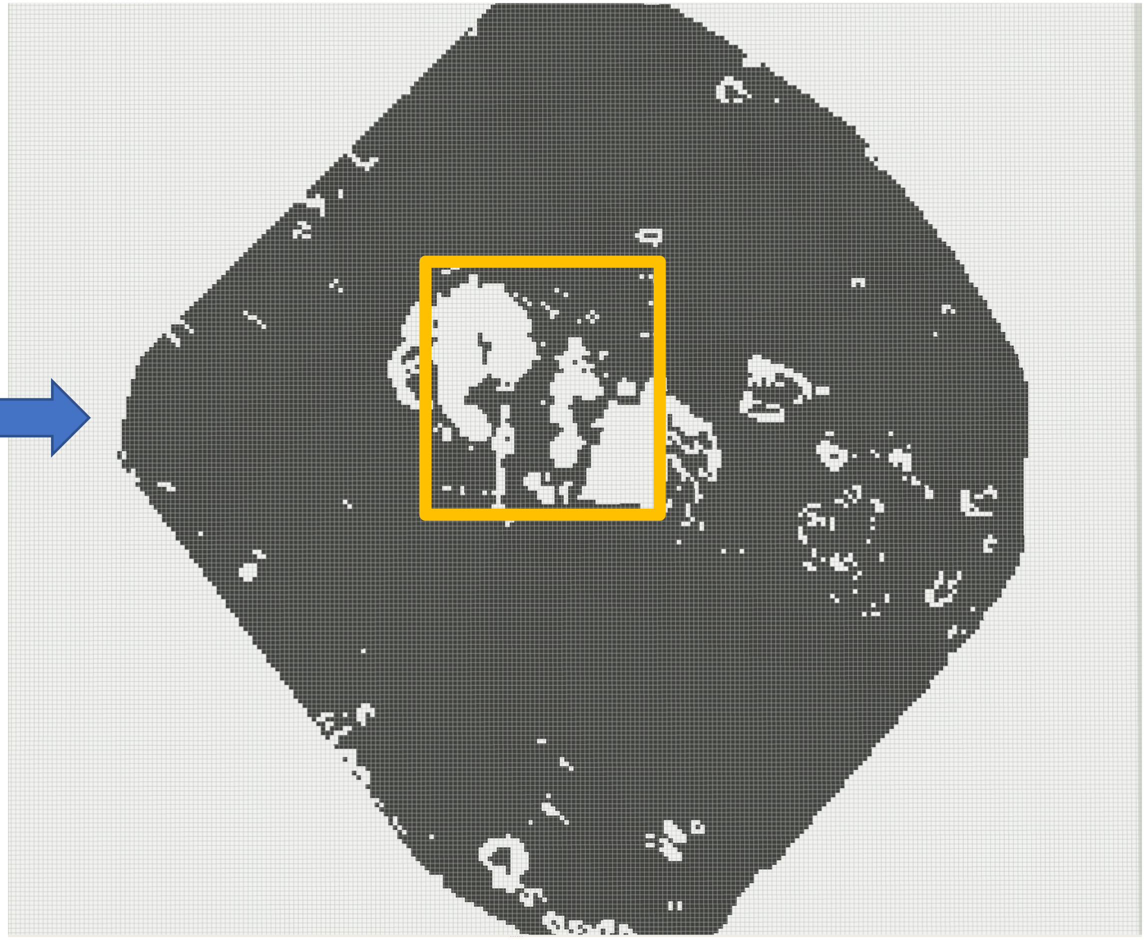


Hazard detection

Hazard detection



Hazard point cloud



Updated hazard map

Conclusions & Future Work

- The UAV-based emulation system allows *representative* Hardware-in-the-loop asteroid landing emulations
- A prototype LiDAR-based navigation system for end-to-end testing was presented
- Transfer of UAV-emulation system from an asteroid environment to a Mars environment
- More sophisticated navigation system
  - Visual-LiDAR-Inertial factor graph-based system
  - Using a space-rated computational platform
- Validation of a swarm-simulation system with real sensor data from our emulation system

https://www.vamex.space/

Research Center Space
Universität der Bundeswehr München

Thank you for your attention!

Contact:

Max Hofacker, M.Sc.

Institute of Space Technology and Space Applications

University of the Bundeswehr Munich

Email: max.hofacker@unibw.de

Phone: +49 (0)89 6004 4597

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DLR

Sources

[1] ESA–C. Carreau/ATG medialab

[2] https://www.nasa.gov/image-feature/osiris-rex-logo

[3] T. Baca, M. Petrlik, M. Vrba, et. al., "The MRS UAV System: Pushing the Frontiers of Reproducible Research, Real-world Deployment, and Education with Autonomous Unmanned Aerial Vehicles.,“ J Intell Robot Syst 102, 26, 2021, https://doi.org/10.1007/s10846-021-01383-5

[4] Ouster OS1-128 ©

[5] ASC GoldenEye flash 3D LiDAR ©

[6] B. Steigerwald, "NASA Spacecraft Observes Asteroid Bennu’s Boulder ’Body Armor’“, [Online], NASA/Goddard/University of Arizona, Available: https://www.nasa.gov/feature/goddard/2022/bennubody-armor

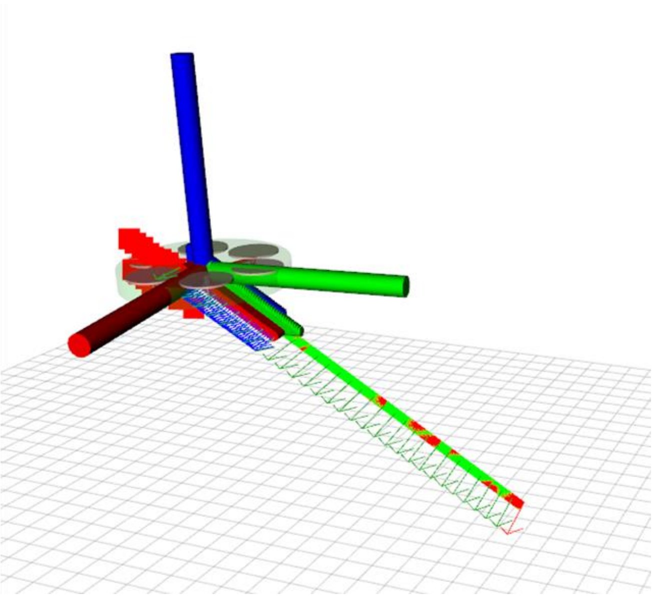
[7] F. Pomerleau, C. Francis, R. Siegwart, S. Magnenat "Comparing ICP Variants on Real-World Data Sets", Autonomous Robots, vol. 34, no. 3, pp. 133-148, 2013

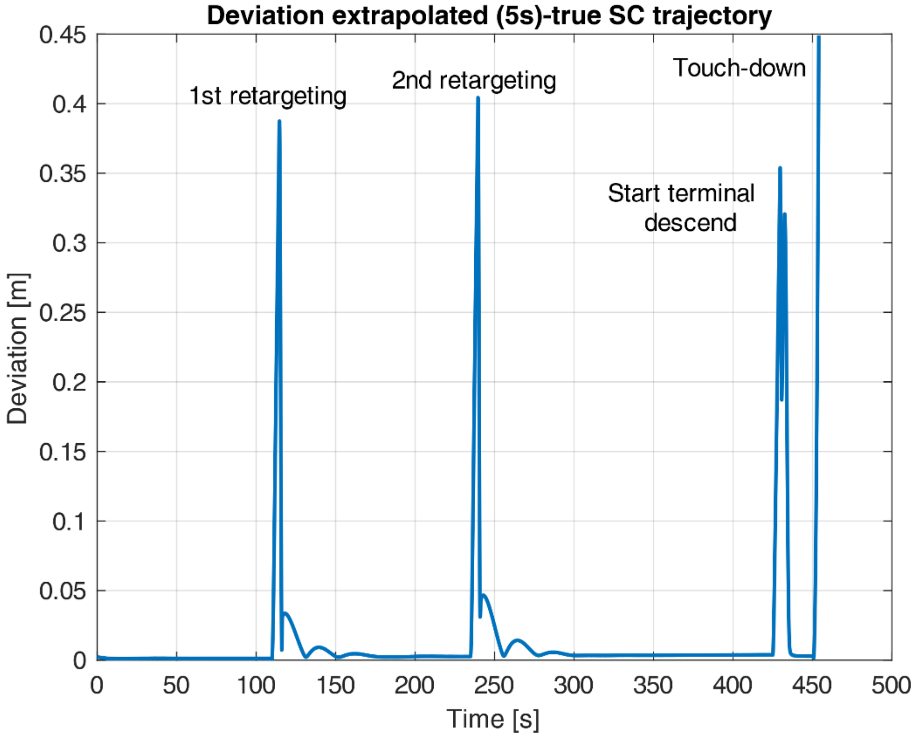
[8] D. Bayard, D. Conway, R. Brockers, J. Delaune, L. Matthies, H. Grip, G. Merewether, T. Brown and A. Martin, "Vision-Based Navigation for the NASA Mars Helicopter,“ 2019.

Backup slides

UAV-based emulation platform

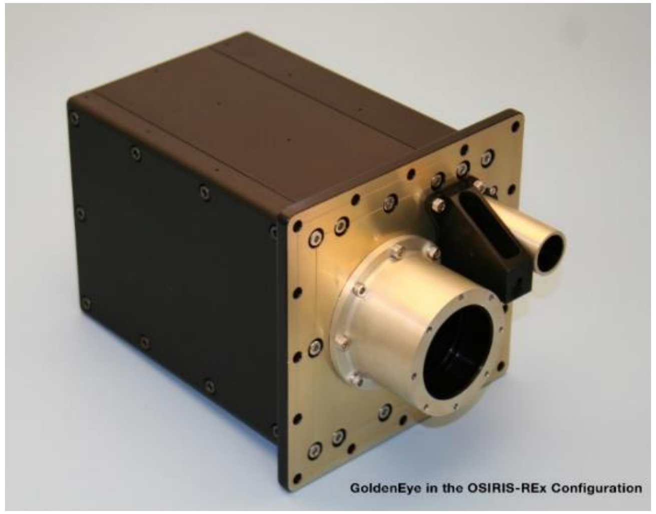
- Trajectory set-points are extrapolated (constant velocity assumption)
  - Smooth trajectory for UAV controller
  - Robustness for lost setpoint in decentralized setup





Used LiDARs:

[4]



[5]

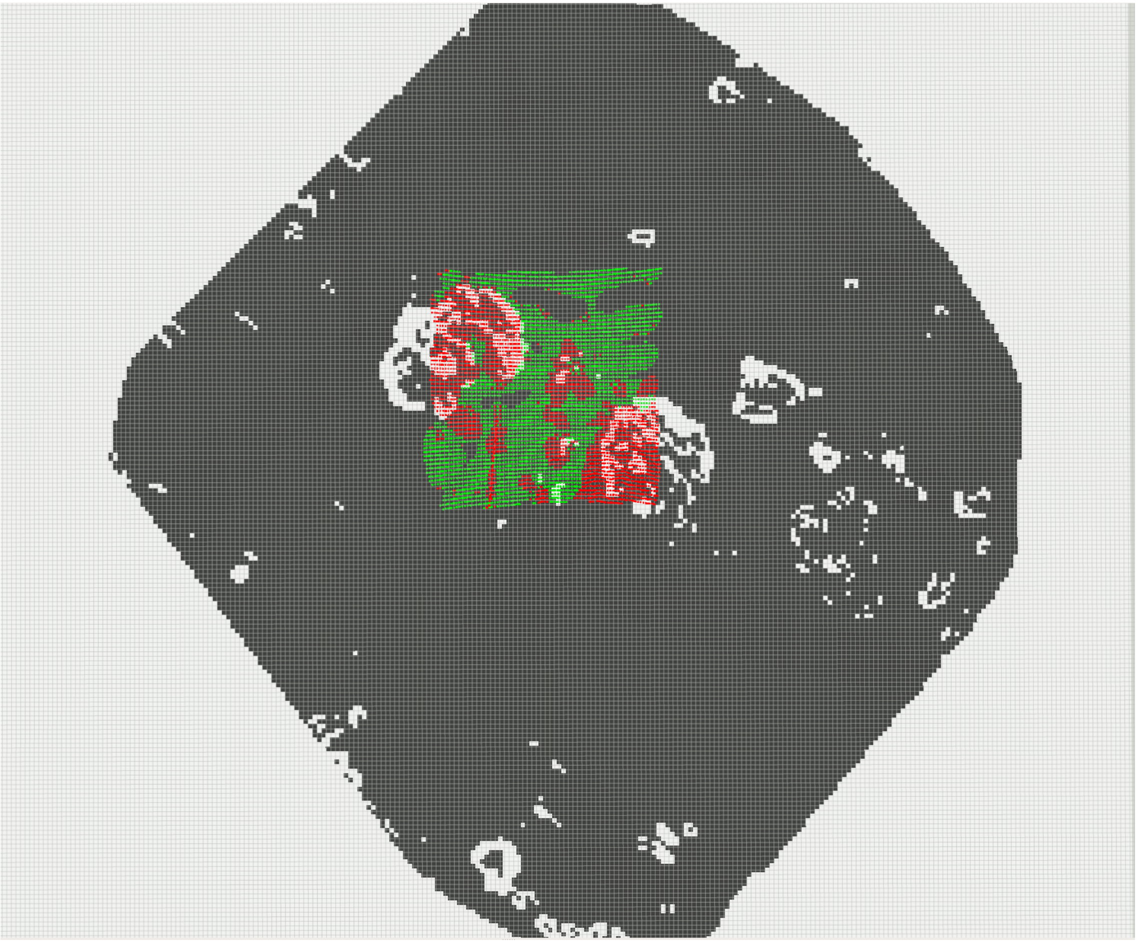
- Using one Ouster OS-128 and one Ouster OS-64
- Orthotogolal arangement to mimic space-rated flash LiDAR (OSIRIS-Rex)

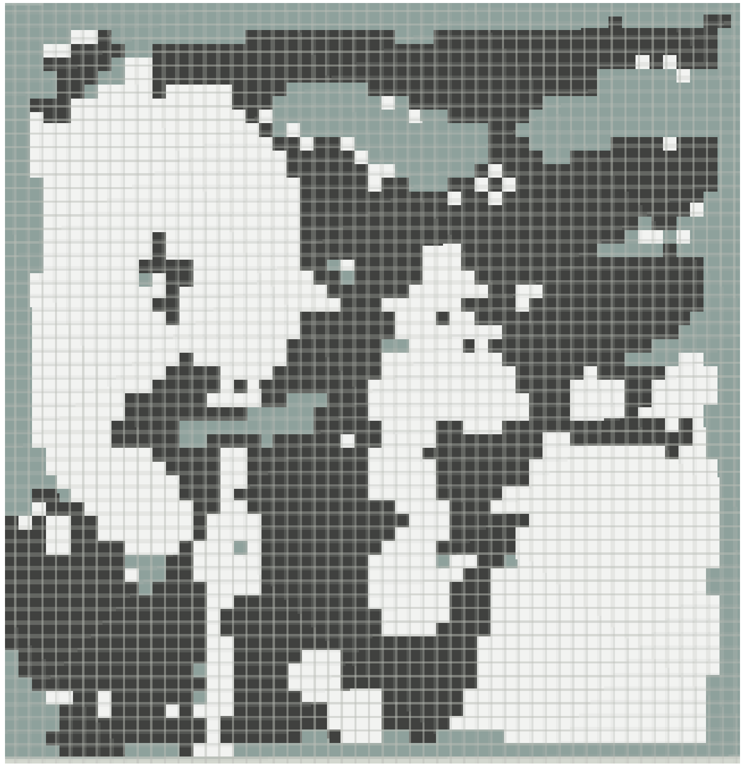
Performance Summery

Emulation performance	
Emulation performance (3D)	< 0.3 m
Current max. Emulation velocity	< 0.75 m/s
Payload for emulating sensors	< 6 kg

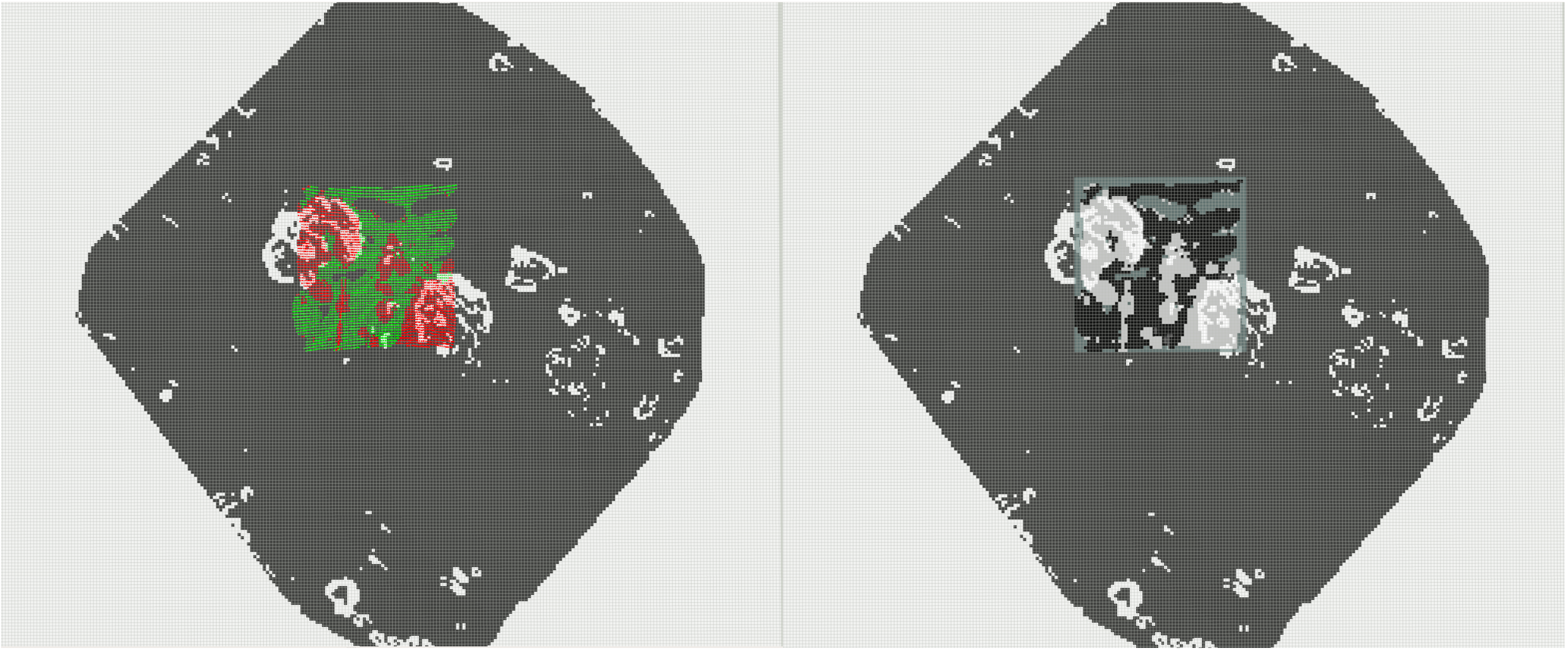
TRN and HDA performance	
Max. altitude TRN	75 m
Horizontal max. navigation error per distance traveled	< 20 %
Vertical position accuracy	< 0.3 m
Max. altitude HDA	50 m

Hazard detection





Hazard detection



Hazard detection