National Aeronautics and Space Administration

Advanced Navigation for Future Mars Rotorcraft

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Program: FY21 R&TD Strategic Initiative **Strategic Focus Area: Mars Science Helicopter**

Project Objective:

Provide a future Mars Science Helicopter with advanced navigation and safe landing capabilities for all terrain access

- Visual-inertial state estimation relative to the take-off point for flights over any type of terrain
- Onboard hazard detection and avoidance to enable autonomous safe landing in terrain with landing hazards
- Onboard map-based localization to provide global reference position – to enable precision navigation to distant science targets

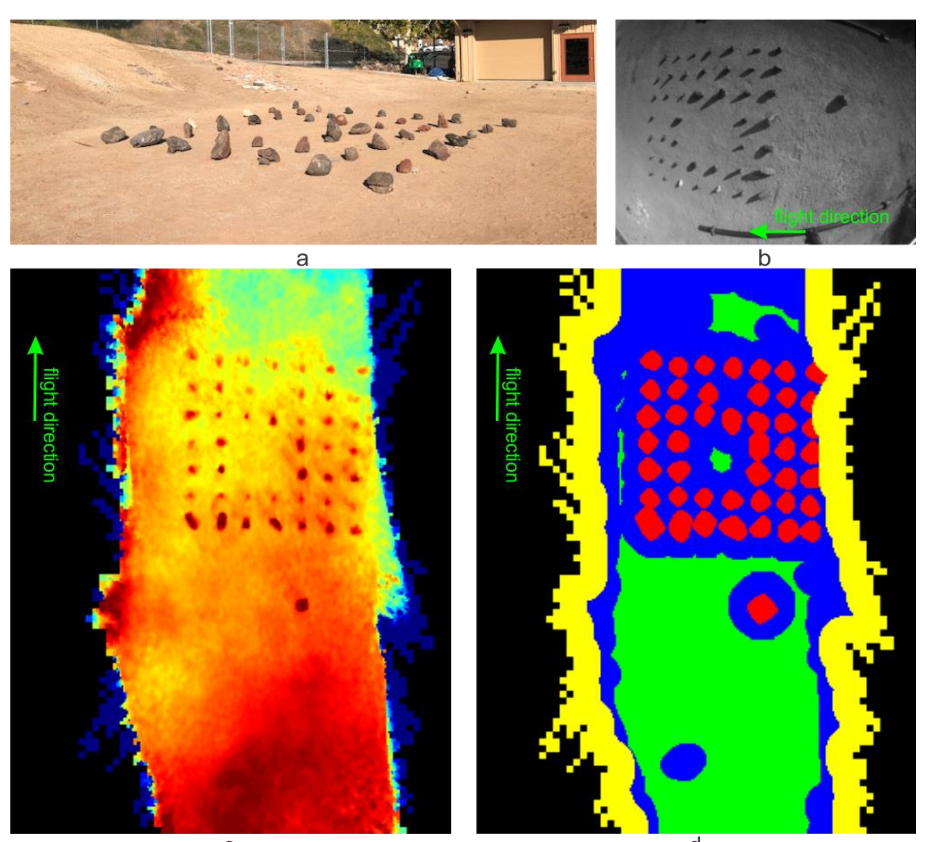
FY21 Results:

- Improved safe landing site detection and demonstrated hazard detection and safe landing site detection on UAS flights (MarsYard and Arroyo)
- Developed new map-based localization (MBL) algorithm to localize a rotorcraft based on aerial image maps (ortho-image + Digital Elevation Map (DEM)) with a HiRISE equivalent resolution
- Demonstrated map-based localization with data from UAS flights in Arroyo
- Developed loop-closure module to detect flights over previously visited locations

Benefits to NASA and JPL:

A highly capable Mars Science Helicopter (MSH) could have major impacts on future Mars exploration by enabling high priority investigations addressing all four of the top-level themes of Mars science (Life, Climate, Geology, and Prepare for Human Exploration). A science helicopter on Mars would extend the scope of possible science far beyond the range of a traditional lander or rover, enabling science data acquisition in extreme terrains inaccessible for current rover systems.

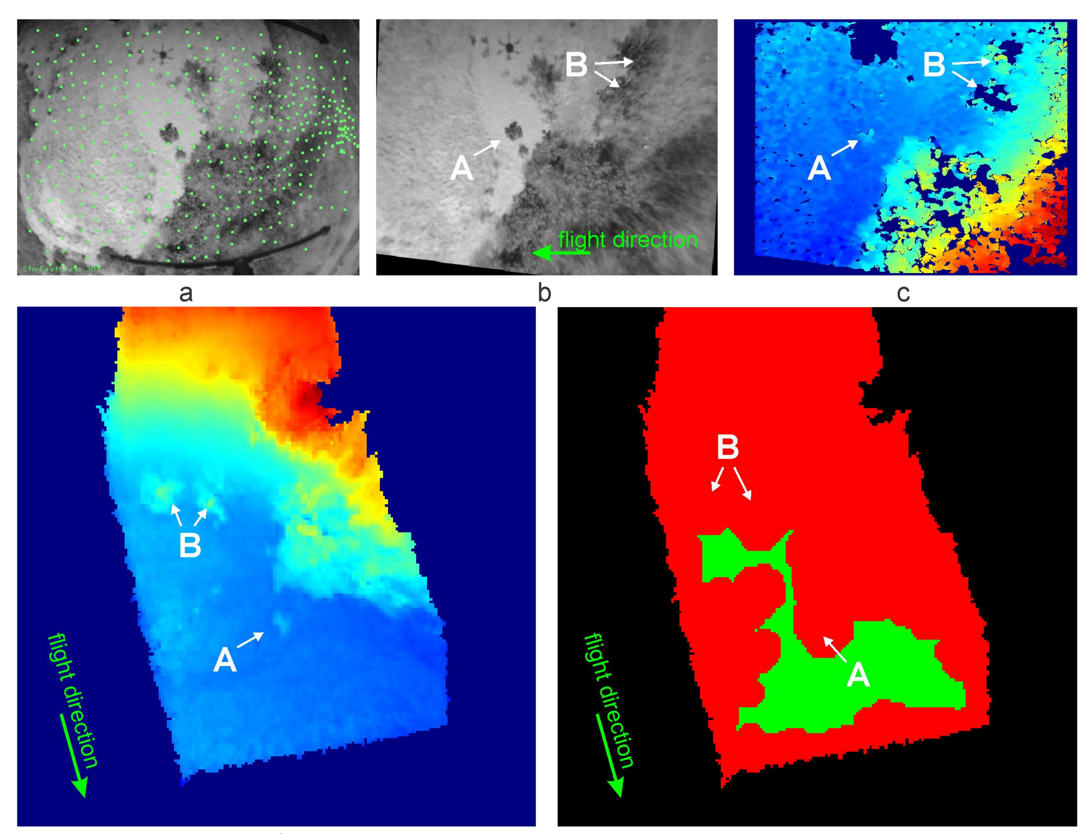
Safe Landing Site Detection Results



UAV flight over a rock field in Mars Yard: a) 7x7 rock field; b) Raw camera image; c) Aggregated elevation map; d) Evaluated landing site map based on annotated rocks (green: safe landing site, blue: false landing hazard, yellow: border region assumed to be hazardous, not evaluated, red: correctly detected hazards). Flight altitude: 5 m.

Rock detection rates for different map cell sizes

Rock Height [m]	0.14-0.22	0.22-0.30	0.30-0.38	0.38-0.46
Rock Diameter [m]	**0.28-0.44**	**0.44-0.60**	**0.60-0.76**	**0.76-0.92**
3 cm Cell Size [%]	100.0	100.0	100.0	100.0
6 cm Cell Size [%]	100.0	100.0	100.0	100.0
12 cm Cell Size [%]	98.4	100.0	100.0	100.0
20 cm Cell Size [%]	59.3	89.1	100.0	100.0
Number of Rocks	25	14	4	2



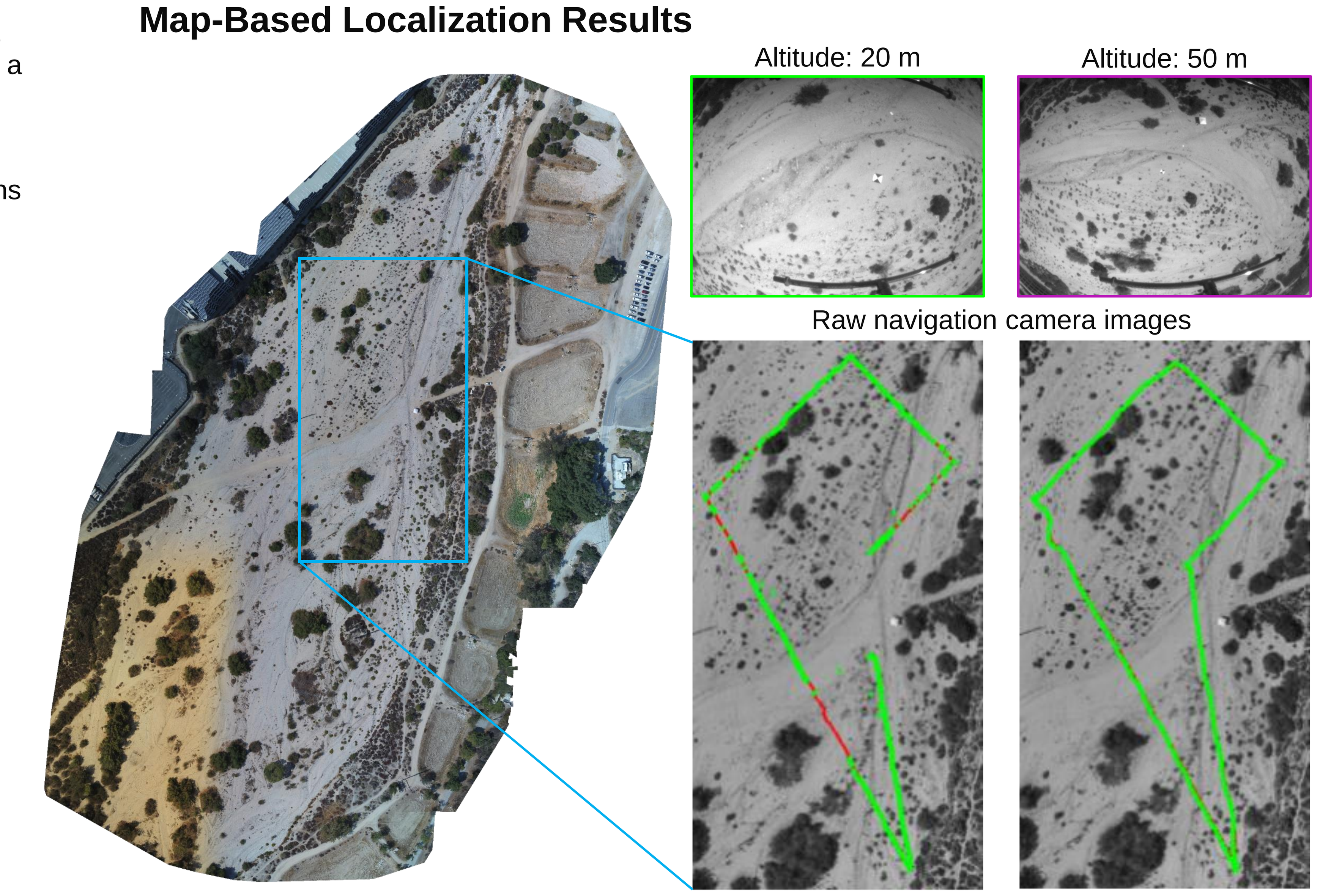
UAV flight in Arroyo: a) Raw camera image with overlaid features that are tracked by the state estimator; b) Reference view (rectified); c) Height map; d) Aggregated elevation map; e) Landing site map (green: safe landing site, red: landing hazard; black: no data). A and B label selected landing hazards for illustration. Note, that the map is rotated ~105◦. Flight altitude: 8 m.

TurboAce Infinity 6 UAV used for test flights

Conclusion

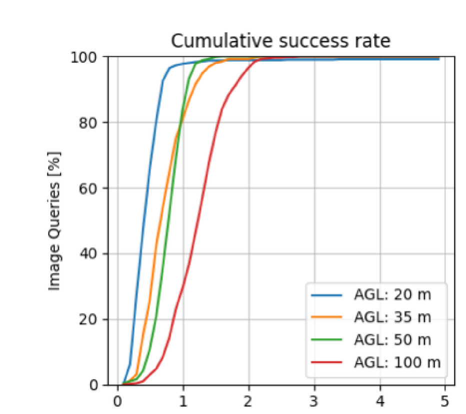
- Landing Hazards of >15cm height are detected reliably with map resolutions of ~1/3 the hazard height for flights below 10m altitude

Map-Based Localization Results



Ortho-image map (25 cm/pixel)

Flight path with GPS position (red) and overlaid localization result (green)



Cumulative localization error for flights at different altitudes

Error Bound	Altitude above take-off position			
	20 m	**35 m**	**50 m**	**100 m**
1 m	97.5 %	80.8 %	83.3 %	29.5 %
2 m	98.2 %	99.2 %	100 %	96.0 %
5 m	99.0 %	100 %	100 %	100 %
10 m	99.4 %	100 %	100 %	100 %

Percentage of localization results below error threshold

Evaluation setup

- Exhaustive search results shown above
- Equal resolution of query image pixels and ortho map pixels at 110m altitude

Conclusion

- Vast majority of MBL tests yields localization accuracy of better than 2m position error for flights above 20m altitude
- Below 20m altitude localization degrades significantly

Publications

[1] M. Domnik, P. Proenca, J. Delaune, J. Thiem, R. Brockers: Dense 3D-Reconstruction from Monocular Image Sequences for Computationally Constrained UAS, WACV 2021
[2] R. Brockers, J. Delaune, P. Proença, P. Schoppmann, M. Domnik, G. Kubiak, T. Tzanetos: Autonomous Safe Landing Site Detection for a Future Mars Science Helicopter. IEEE Aerospace 2021
[3] M. Scheiber, J. Delaune, S. Weiss, R. Brockers: Mid-Air Range-Visual-Inertial Estimator Initialization for Micro Air Vehicles. ICRA 2021
[4] J. Delaune, D. S. Bayard, R. Brockers: Range-Visual-Inertial Odometry: Scale Observability Without Excitation. RAL / ICRA 2021
[5] P. Schoppmann, P. F. Proenca, J. Delaune, M. Pantic, T. Hinzmann, L. Matthies, R.Siegwart, R. Brockers: Multi-Resolution Elevation Mapping and Safe Landing Site Detection with Applications to Planetary Rotorcraft. IROS 2021

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