Simulation of Precise and Safe Landing near a Plume Source on Enceladus

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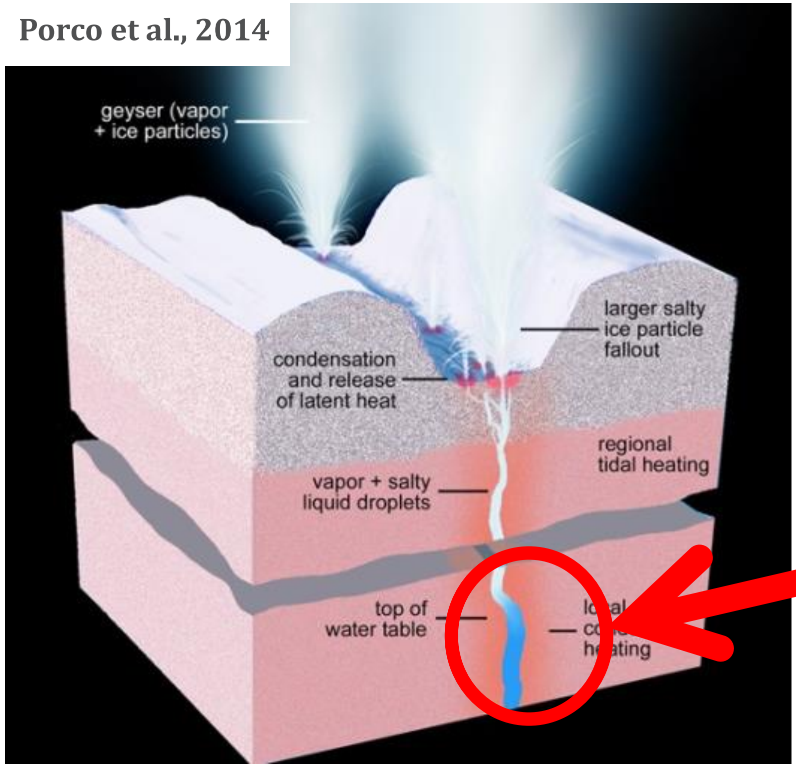
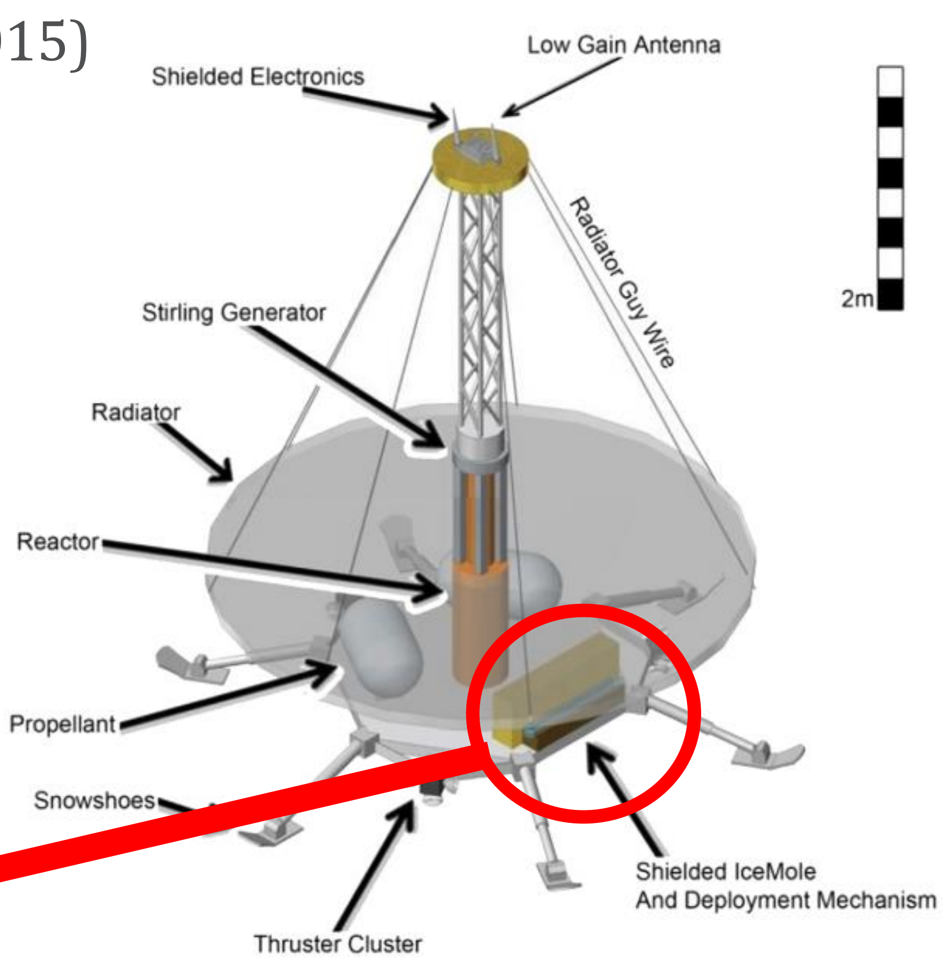
Motivation - Enceladus Lander mission

- **ISTA** involved in EnEx-1 project (2012-2015) for **Enceladus Lander mission design**
- Critical technology identified for landing mission: **Advanced landing GN&C**

Porco et al., 2014





K. Konstantinidis et al., A lander mission to probe subglacial water on Saturn's moon Enceladus for life, Acta Astronaut. 106 (2015) 63–89

ENCELADUS EXPLORER EnEx — an initiative of DLR Space Administration

DLR

ICE MOLE Subsurface Icecraft

Landing on the south pole of Enceladus

Topography

- “V” shaped canyons, 100–150 m high, 200–250 m deep
- Bottom: 50–100 m wide
- floor is interspersed with obstacles

Terrain texture

- plume fallout deposit layer up to 10s of meters near plumes
- Also exposed icy crust

Thermal environment

- Concentrated hotspots around plume sources (~10 m)

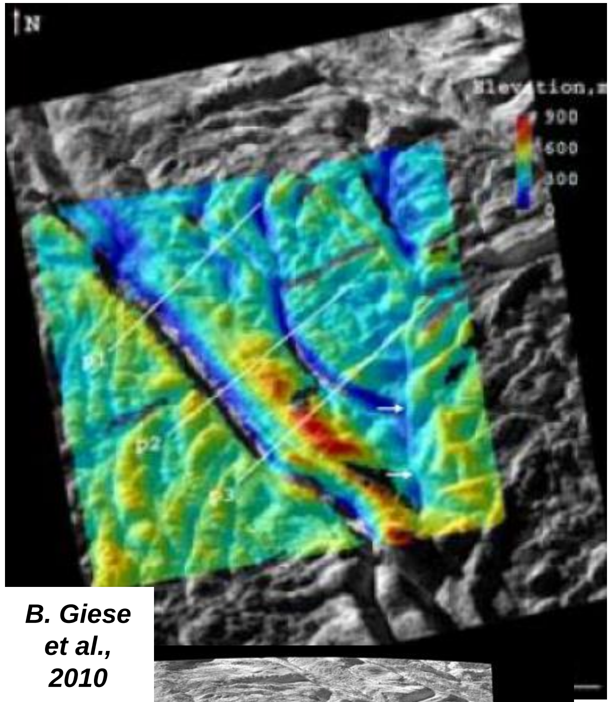
Albedo of Enceladus: 0.99

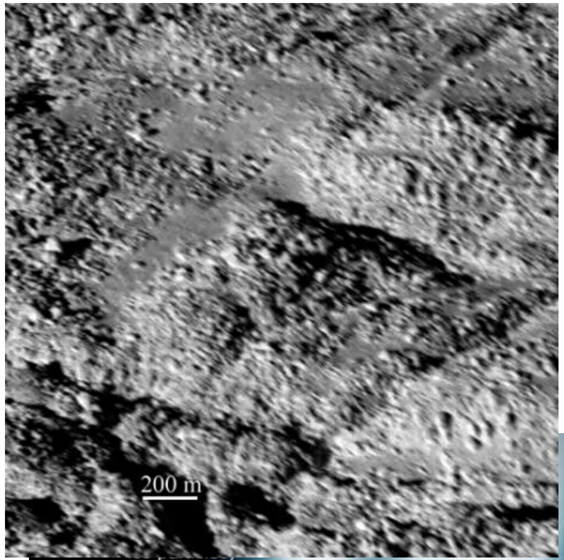
Polar region

- low sun elevation angles
- canyon floors often in darkness

Planetary protection

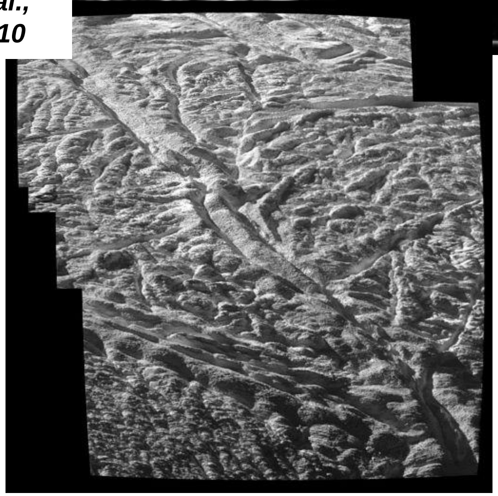
- possible direct access to ocean, PP more strict than e.g. Mars special regions

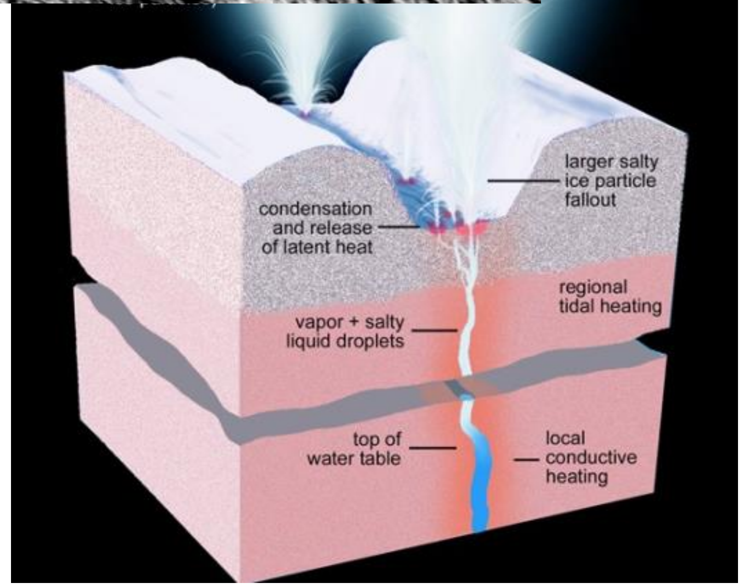




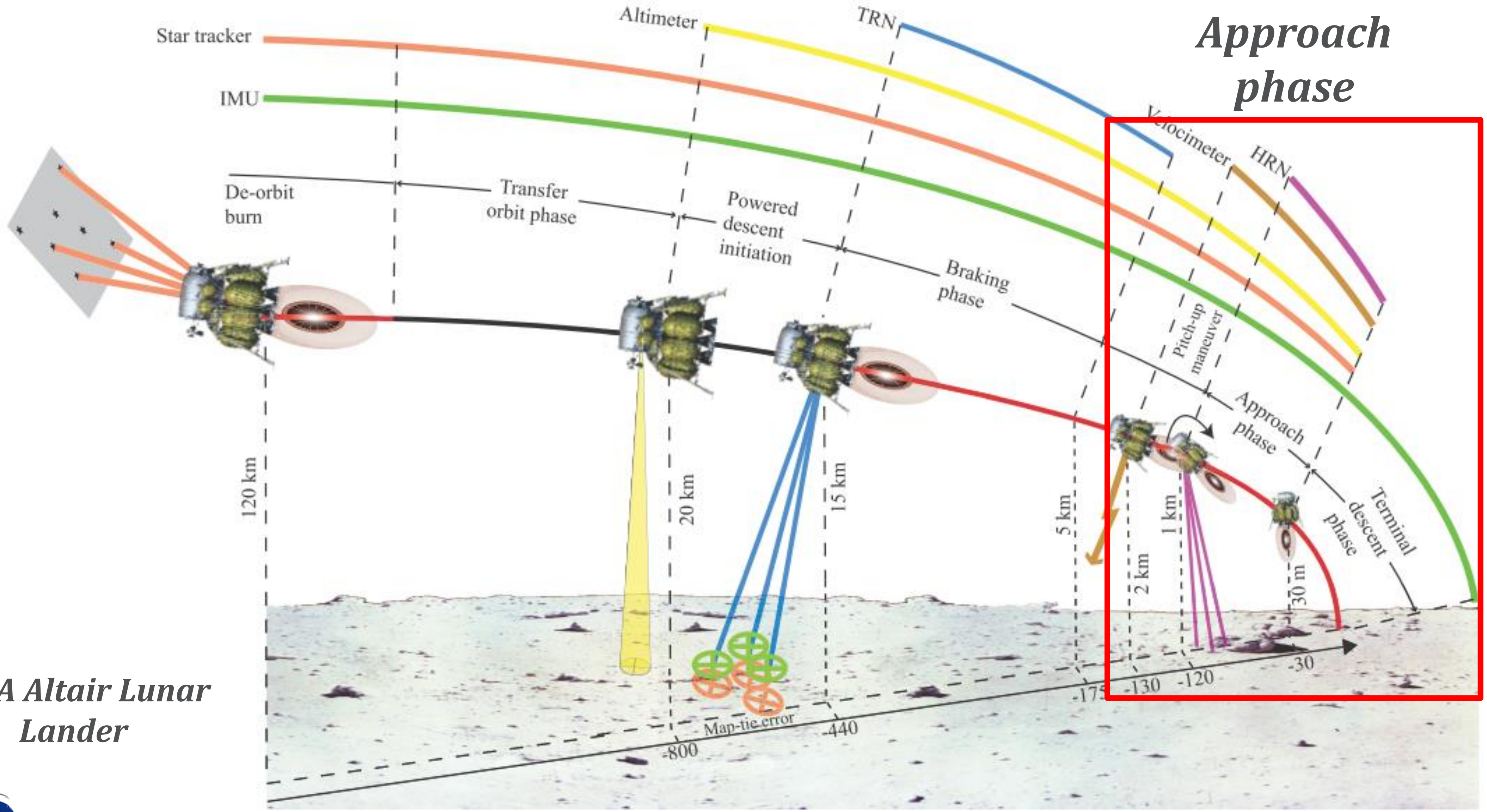
C. Porco et al., 2014

B. Giese et al., 2010





Lander GN&C operations

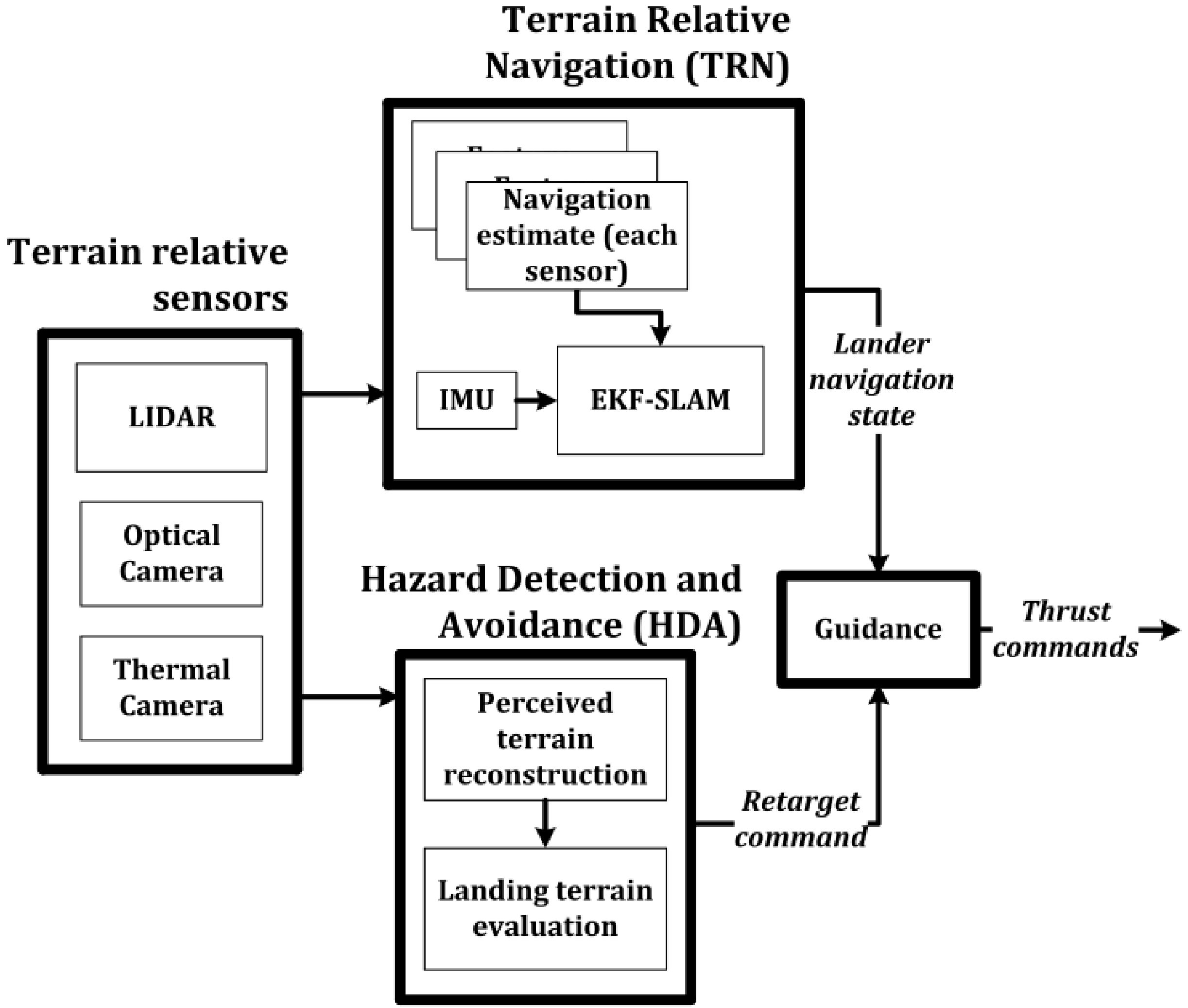


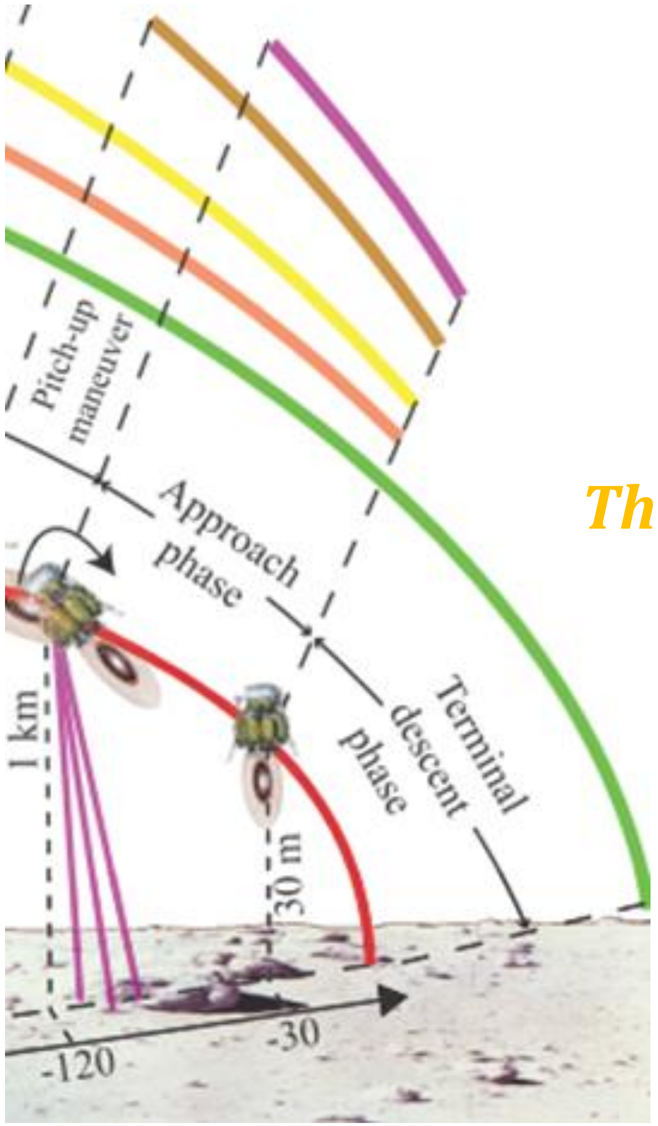
Approach phase

NASA Altair Lunar Lander

Lander GN&C system

Approach phase GN&C system





Lidar

VisCam

ThermCam

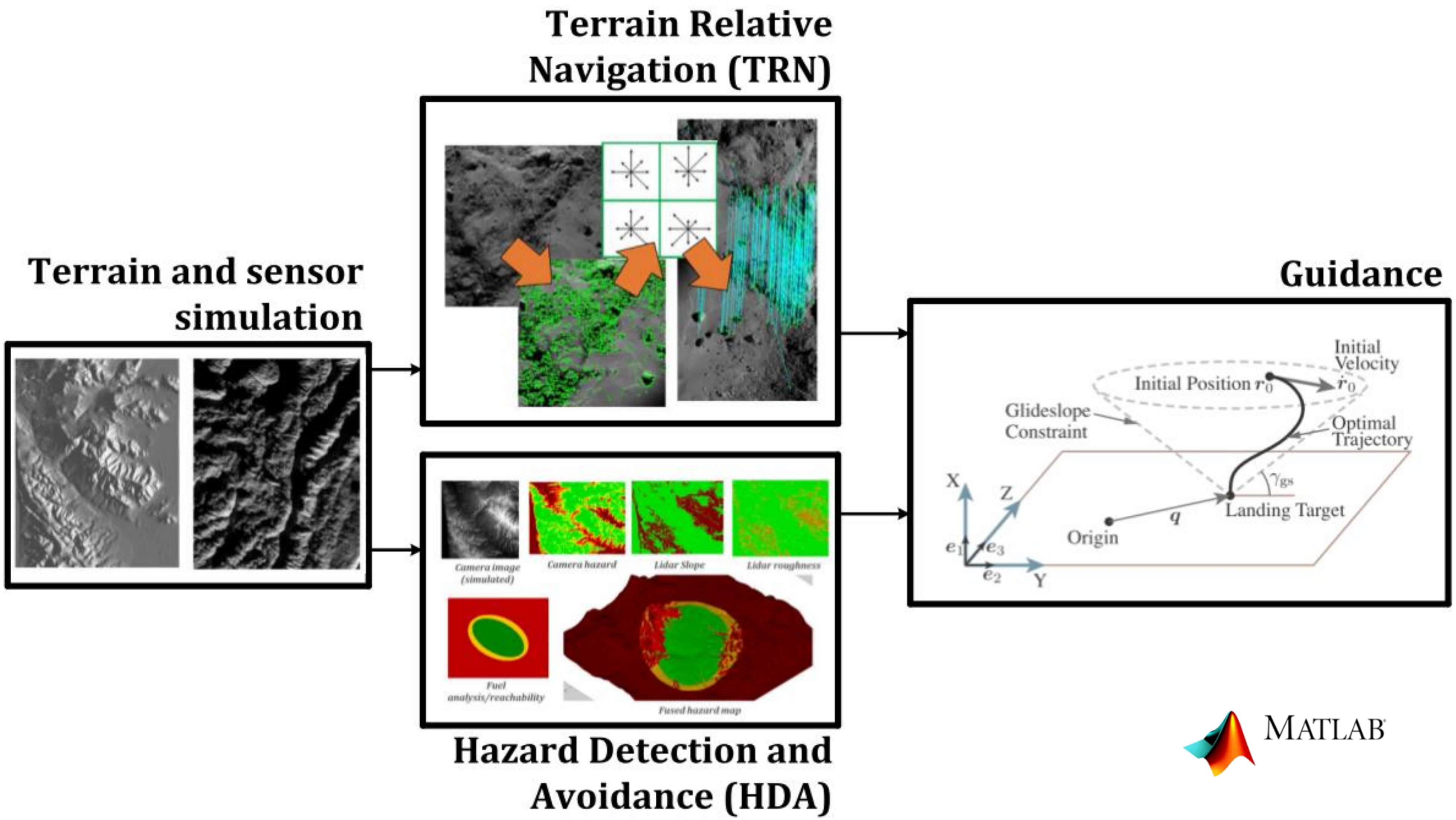
IMU

****also:***

- *altimeter*
- *velocimeter*
- *star tracker*

Current research - GN&C for Enceladus Landing

Purposes of tool:
- *GN&C design*
- *Proof of concept*
- *Requirements validation*
- *Simulation based Fault Management*



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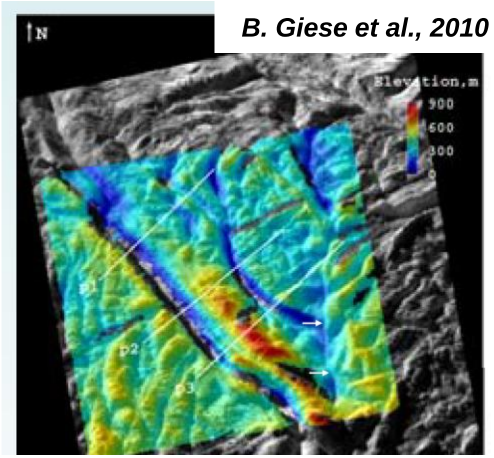
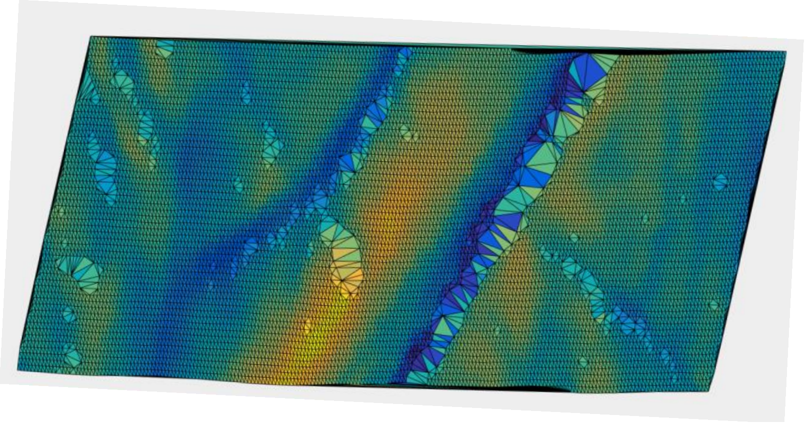
Terrain and sensor simulation

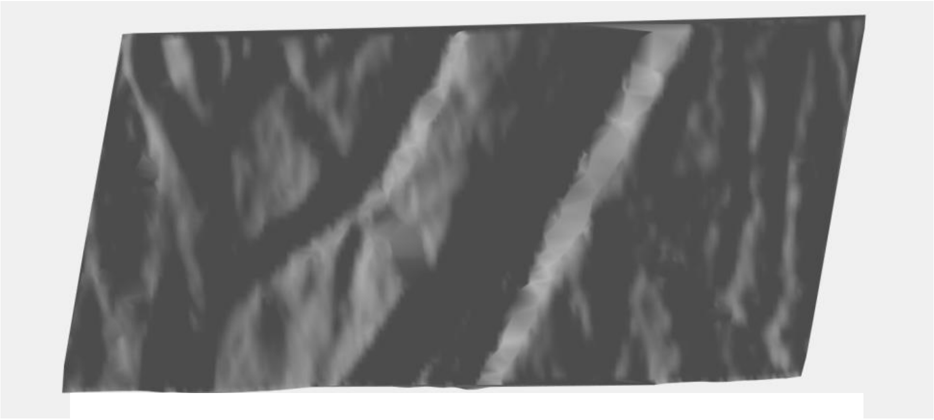


B. Giese et al., 2010

***1**. Input terrain model*

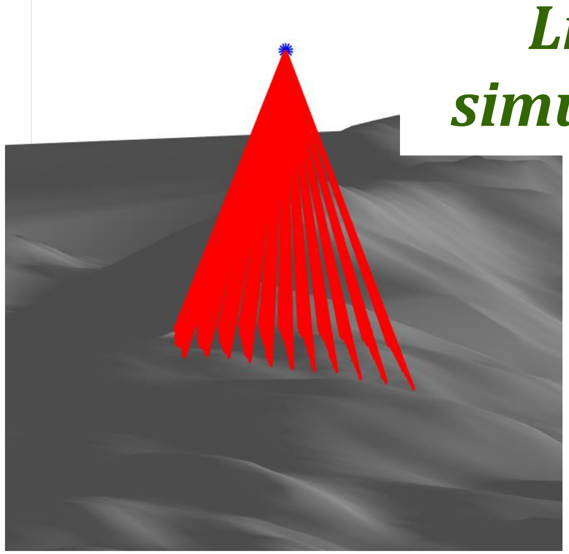


***2**. Delaunay triangulation*

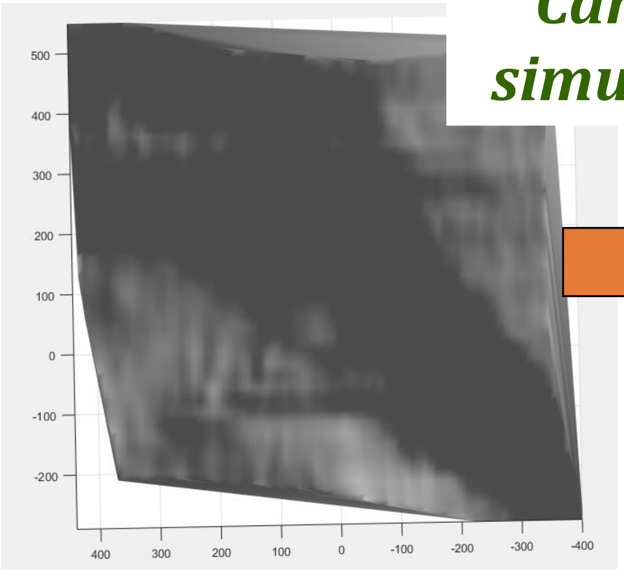


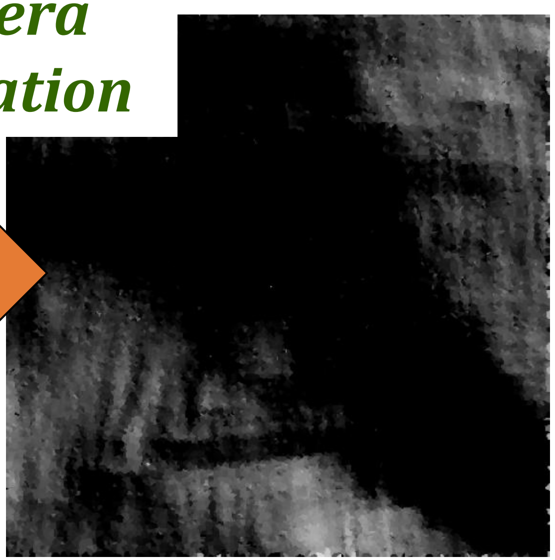
***3**. Terrain illumination*

Lidar simulation



Camera simulation





TRN-aided inertial navigation

1. Lander nav. state

$$\hat{\mathbf{x}}_k = \begin{bmatrix}\text{position}\\ \text{velocity}\end{bmatrix}$$

$$\mathbf{P}_k = \begin{bmatrix}\Sigma_{pp} & \Sigma_{pv}\\ \Sigma_{vp} & \Sigma_{vv}\end{bmatrix}$$

2. Prediction step

$$\hat{\mathbf{x}}_k = \mathbf{F}_k\hat{\mathbf{x}}_{k-1} + \mathbf{B}_k\overrightarrow{\mathbf{u}_k}$$

$$\mathbf{P}_k = \mathbf{F}_k\mathbf{P}_{k-1}\mathbf{F}_k^T + \mathbf{Q}_k$$

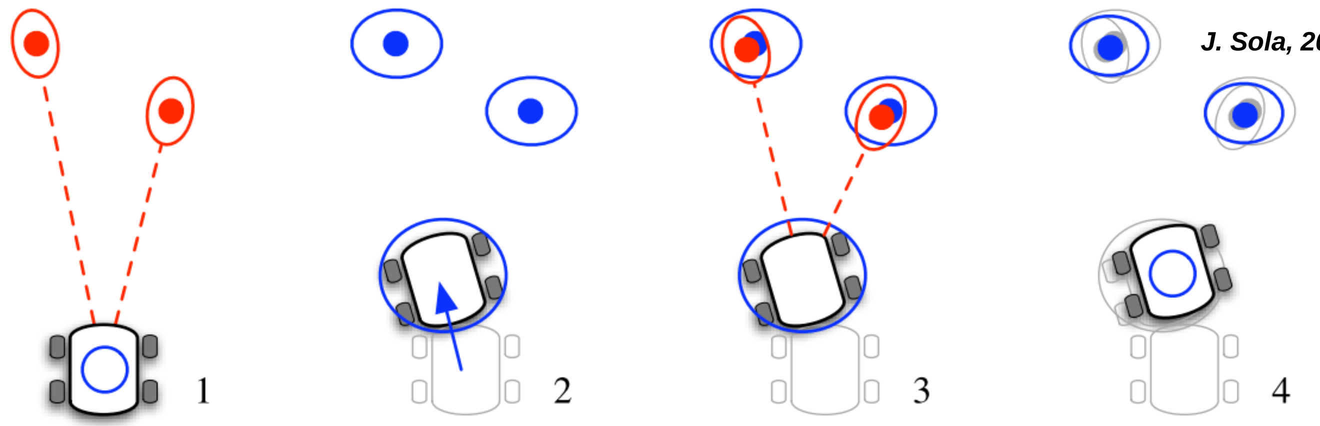
3. Correction step

$$\hat{\mathbf{x}}'_k = \hat{\mathbf{x}}_k + \mathbf{K}'(\overrightarrow{\mathbf{z}_k} - \mathbf{H}_k\hat{\mathbf{x}}_k)$$

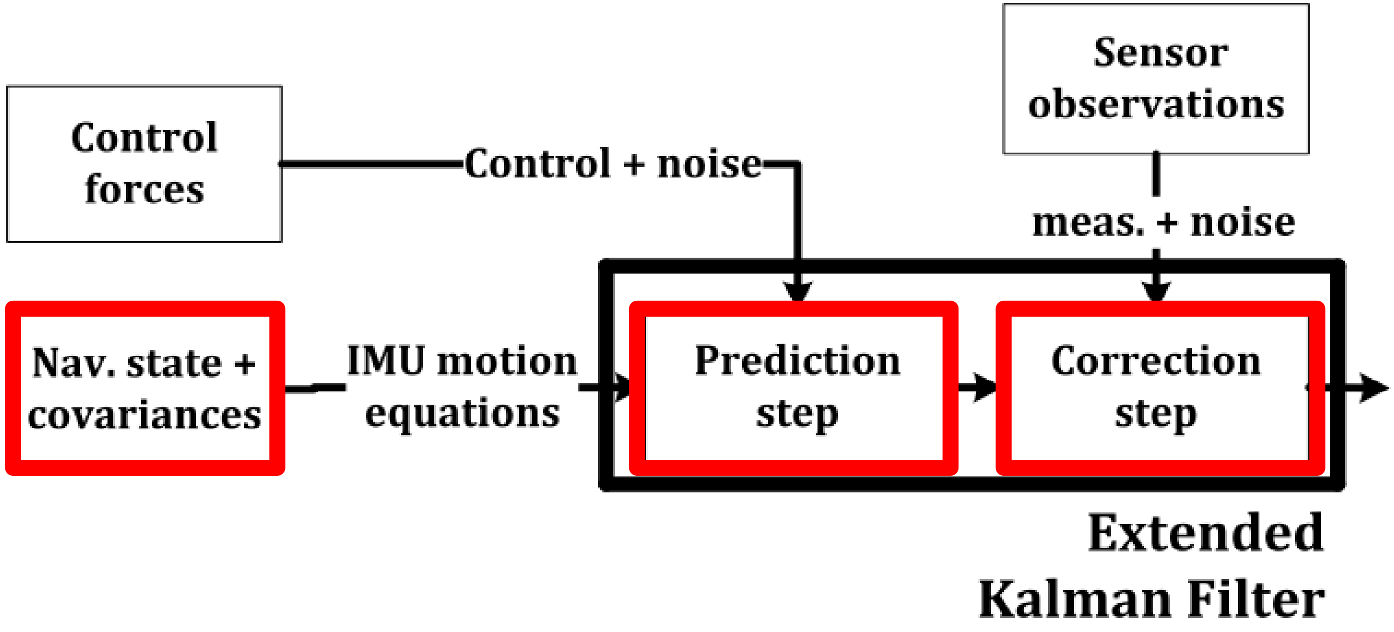
$$\mathbf{P}'_k = \mathbf{P}_k - \mathbf{K}'\mathbf{H}_k\mathbf{P}_k$$

$$\mathbf{K}' = \mathbf{P}_k\mathbf{H}_k^T(\mathbf{H}_k\mathbf{P}_k\mathbf{H}_k^T + \mathbf{R}_k)^{-1}$$

bzarg.com



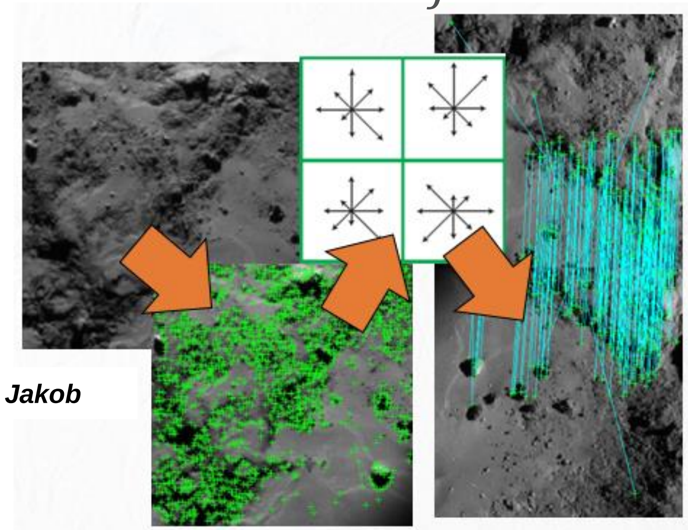
J. Sola, 2007



Sensor observations

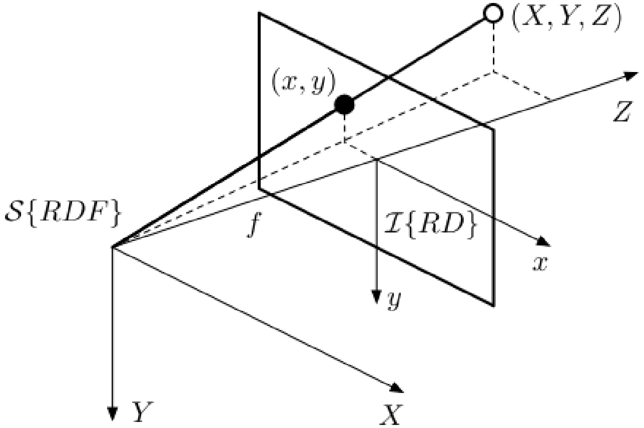
Camera: Simultaneous Localization and Mapping (SLAM)

***1**. Detect and match SURF features*

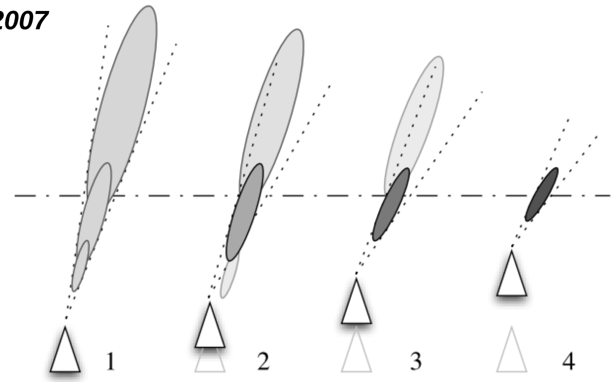


R. Jakob

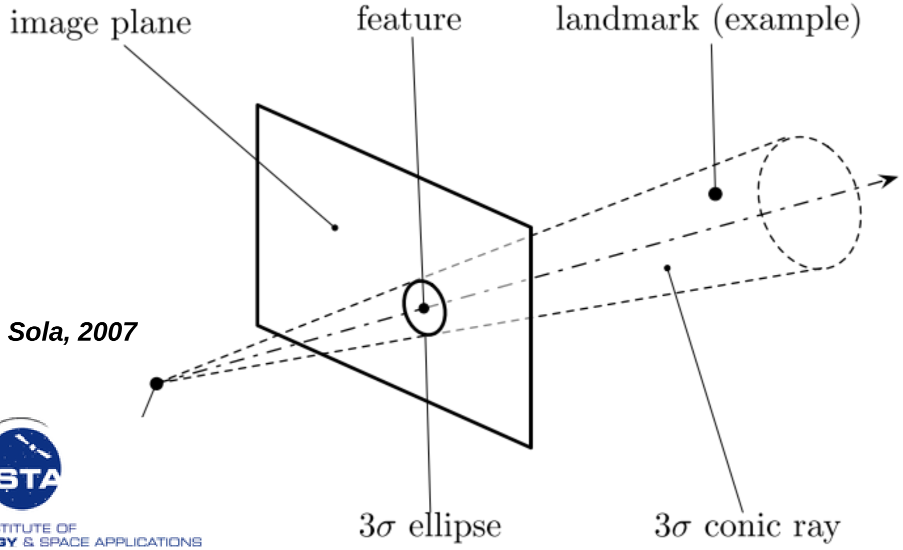
***2**. Project features on 3D world*



J. Sola, 2007



***3**. Retro-project features to make measurement*



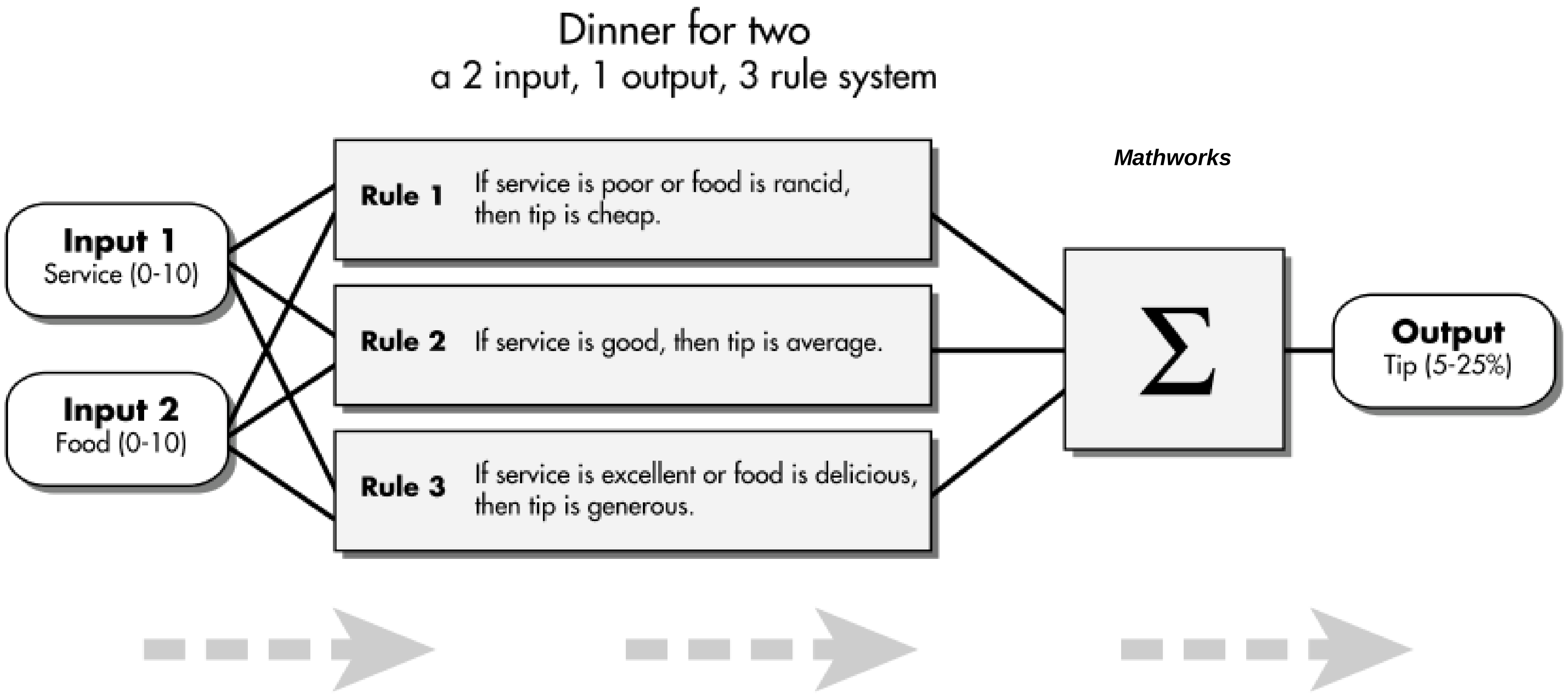
J. Sola, 2007

Lidar: Iterative Closest Point (ICP)

Alismail et al.

***1.** Minimize difference between point clouds*
***2.** Give translation and rotation matrix*
***3.** Use T and R as measurements in nav. filter*

Hazard Detection and Avoidance – Fuzzy reasoning



The inputs are crisp (non-fuzzy) numbers limited to a specific range.

All rules are evaluated in parallel using fuzzy reasoning.

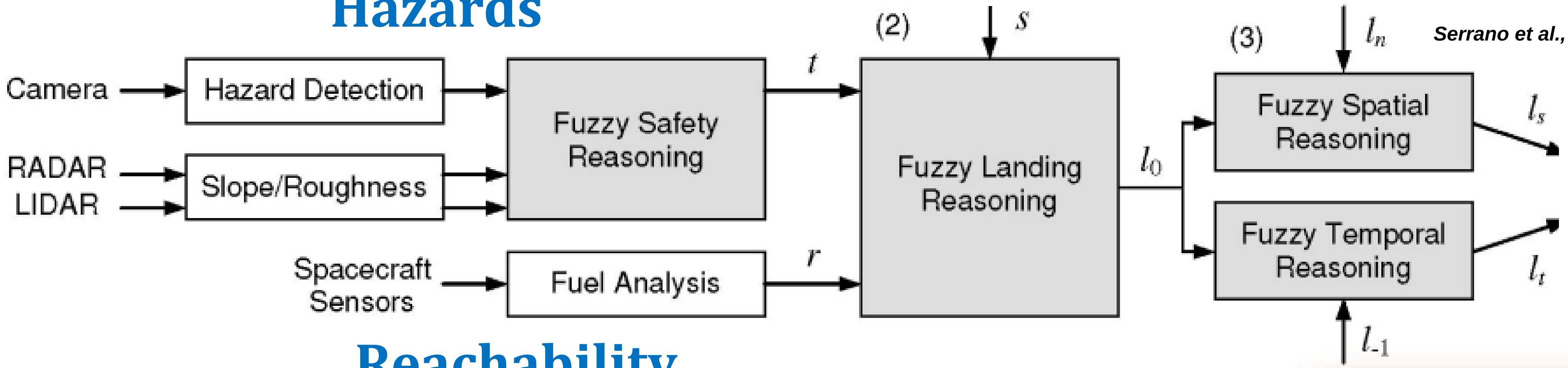
The results of the rules are combined and distilled (defuzzified).

The result is a crisp (non-fuzzy) number.

Hazard Detection and Avoidance – Landing site evaluation

Scientific interest

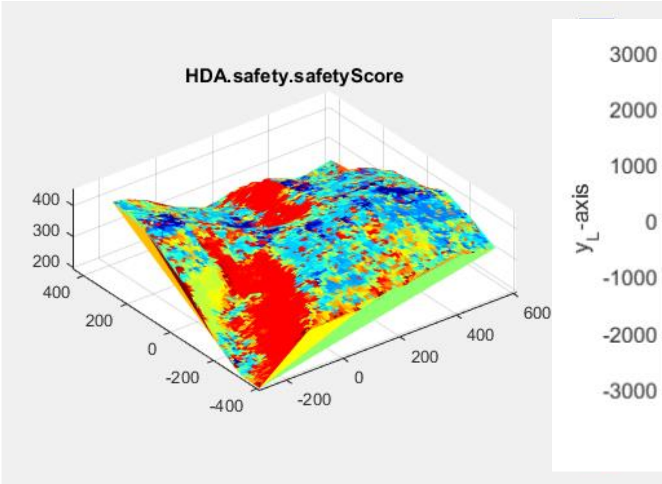
Hazards

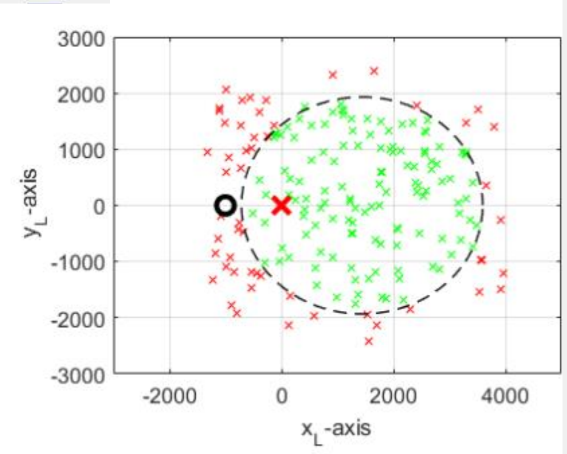


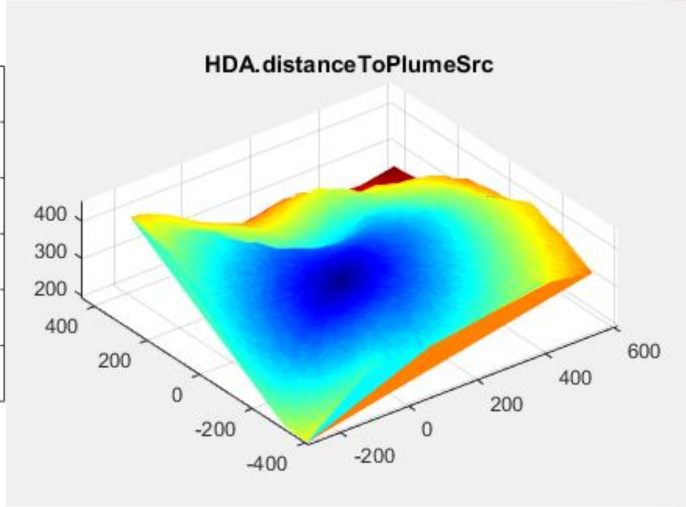
Serrano et al., 2007

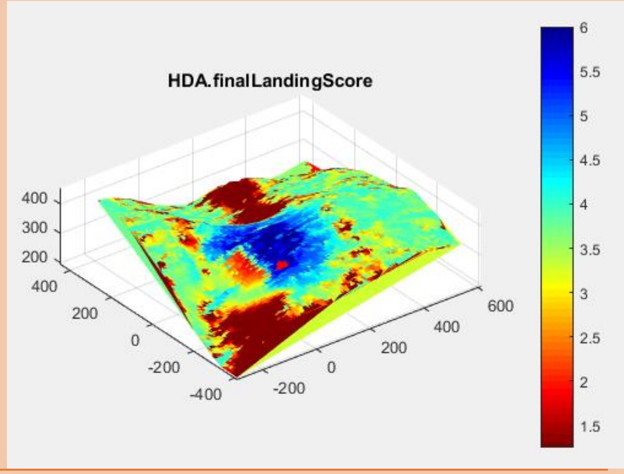
Landing goodness

Reachability









Guidance – Convex guidance (G-FOLD)

Problem 1 Non-Convex Minimum Fuel Planetary Landing Problem

$$\boxed{\max_{t_f, \mathbf{T}_c} m(t_f)} \quad \text{subject to:} \tag{3}$$

$$\left.\begin{aligned} \dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + B\left(\mathbf{g} + \frac{\mathbf{T}_c(t)}{m}\right) \\ \dot{m}(t) &= -\alpha \|\mathbf{T}_c(t)\| \end{aligned}\right\} \quad \forall\, t \in [0, t_f], \tag{4}$$

$$\mathbf{x}(t) \in \mathbf{X} \quad \forall\, t \in [0, t_f], \tag{5}$$

$$0 < \rho_1 \le \|\mathbf{T}_c(t)\| \le \rho_2, \quad \hat{\mathbf{n}}^T \mathbf{T}_c(t) \ge \|\mathbf{T}_c(t)\| \cos\theta, \tag{6}$$

$$m(0) = m_0 \tag{7}$$

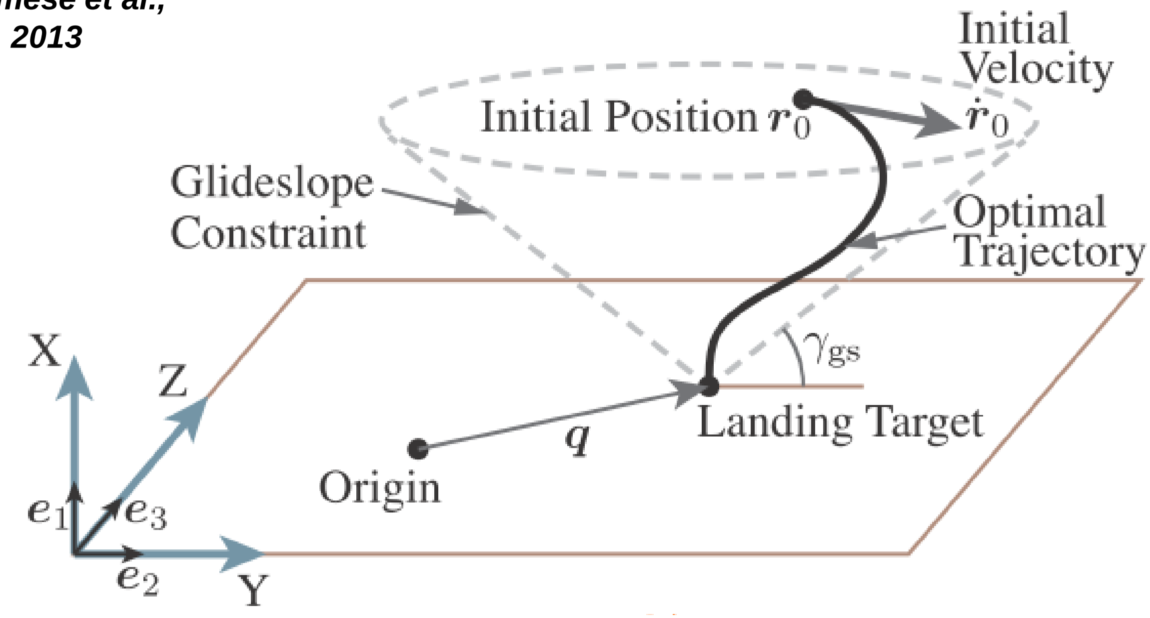
$$\mathbf{r}(0) = \mathbf{r}_0, \quad \dot{\mathbf{r}}(0) = \dot{\mathbf{r}}_0, \tag{8}$$

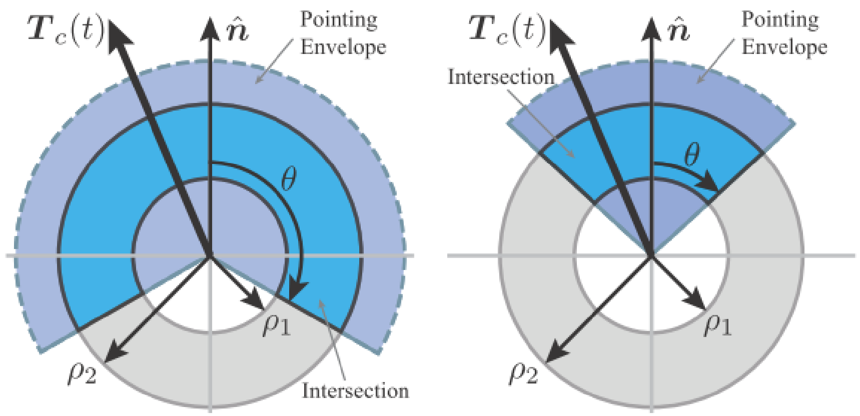
$$\mathbf{r}(t_f) = 0, \quad \dot{\mathbf{r}}(t_f) = \mathbf{0}. \tag{9}$$

- ***Optimization objective:*** *minimize propellant used*
- ***Dynamics***
- ***Constraints***
- ***Initial and final conditions***

Convex Optimization: *G-FOLD algorithm*

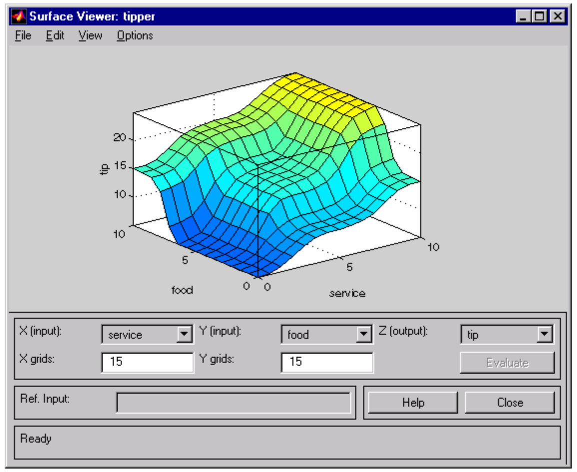
Acikmese et al., 2013



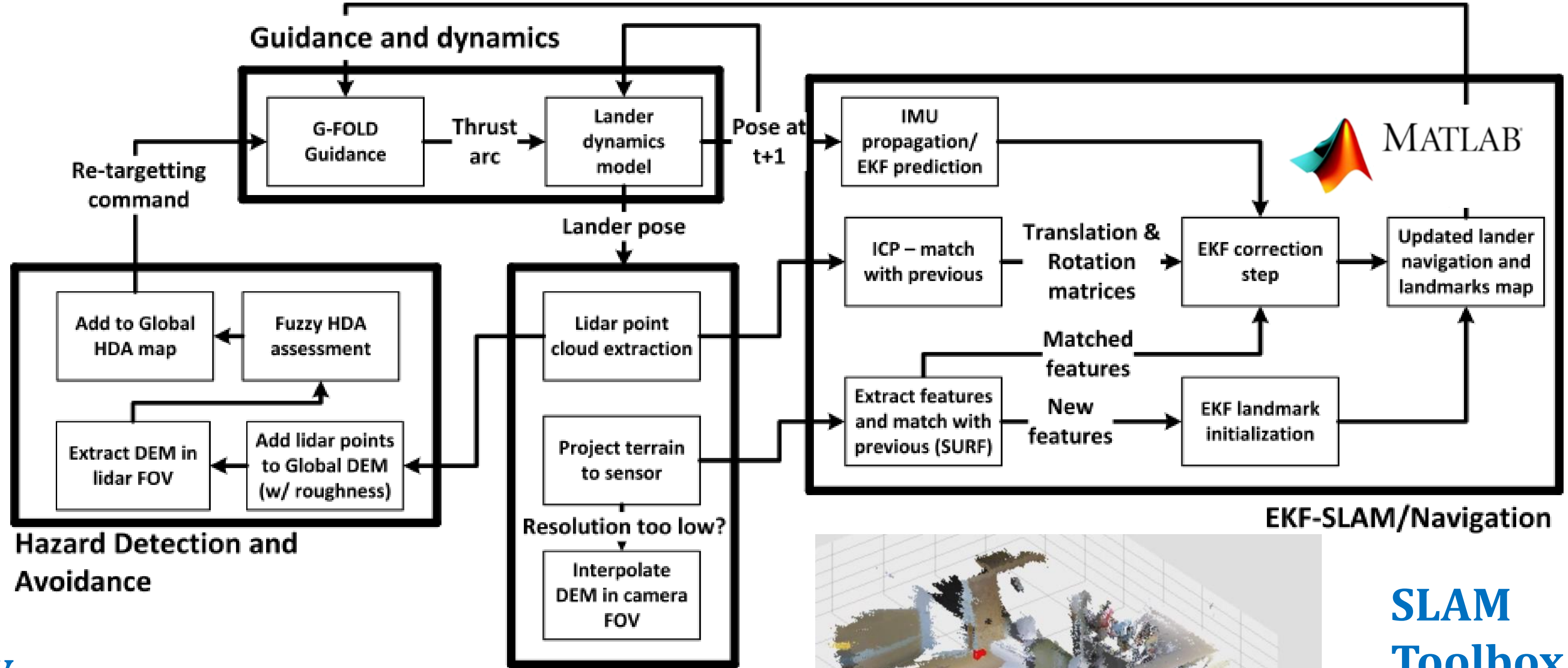


Landing simulation tool structure

FALCON optimizer
(open source, by TUM Munich)

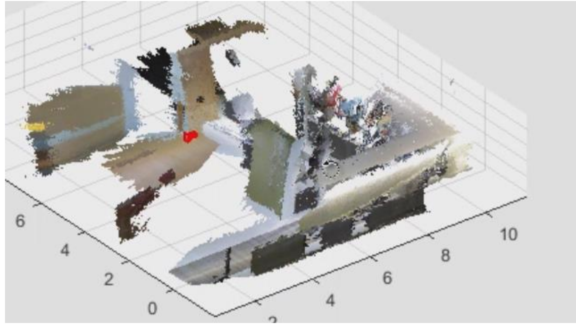


Fuzzy Logic Toolbox



T. McClure

MATLAB graphics



Computer Vision System Toolbox

SLAM Toolbox
(open source, by J. Sola)

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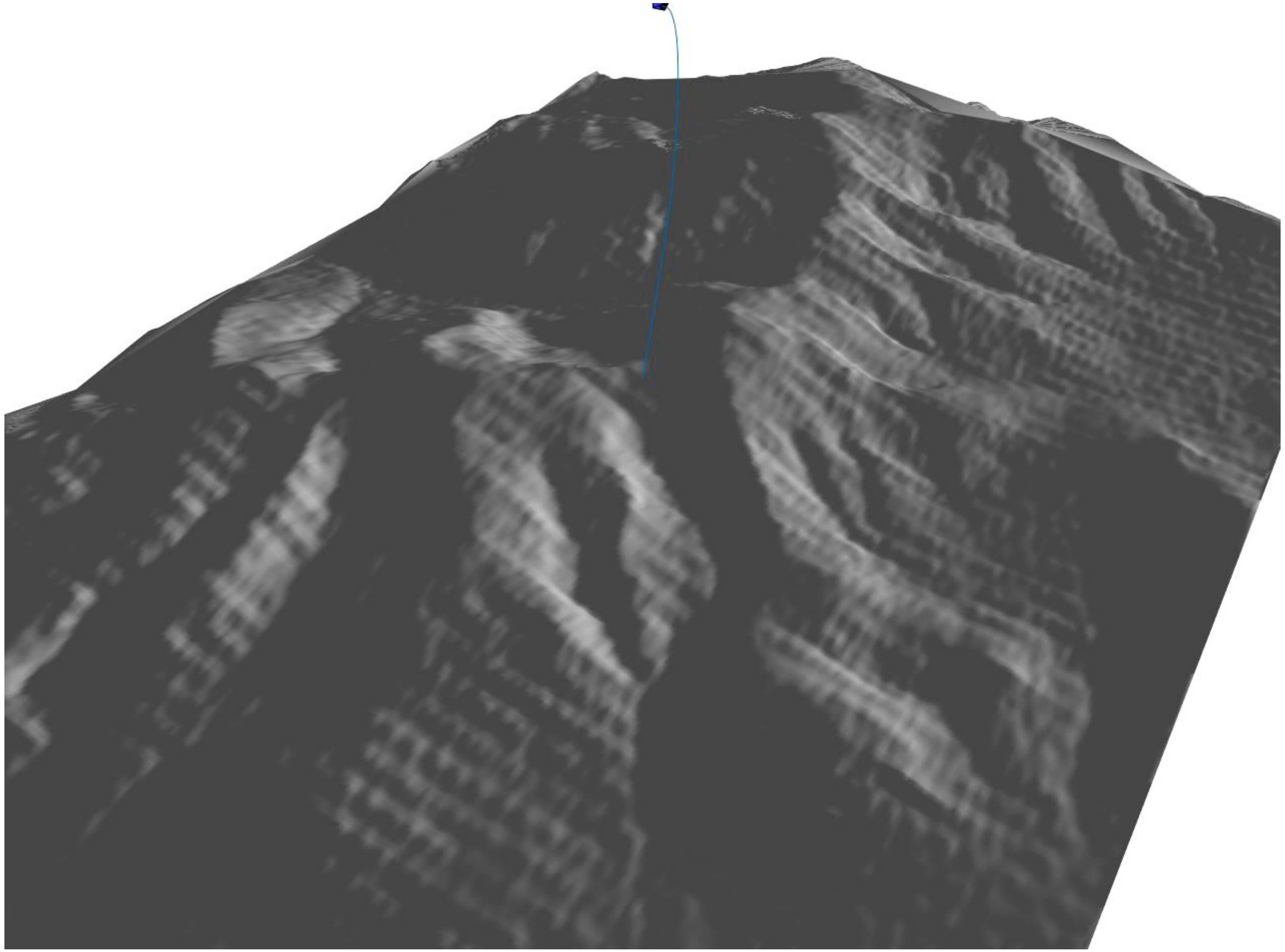
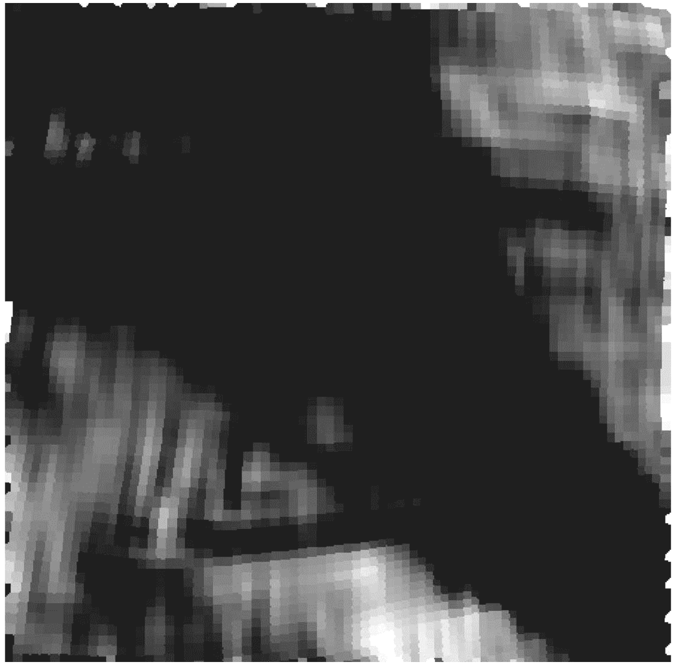
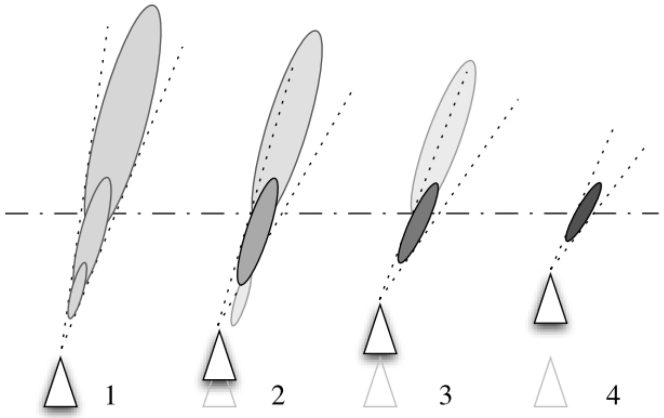
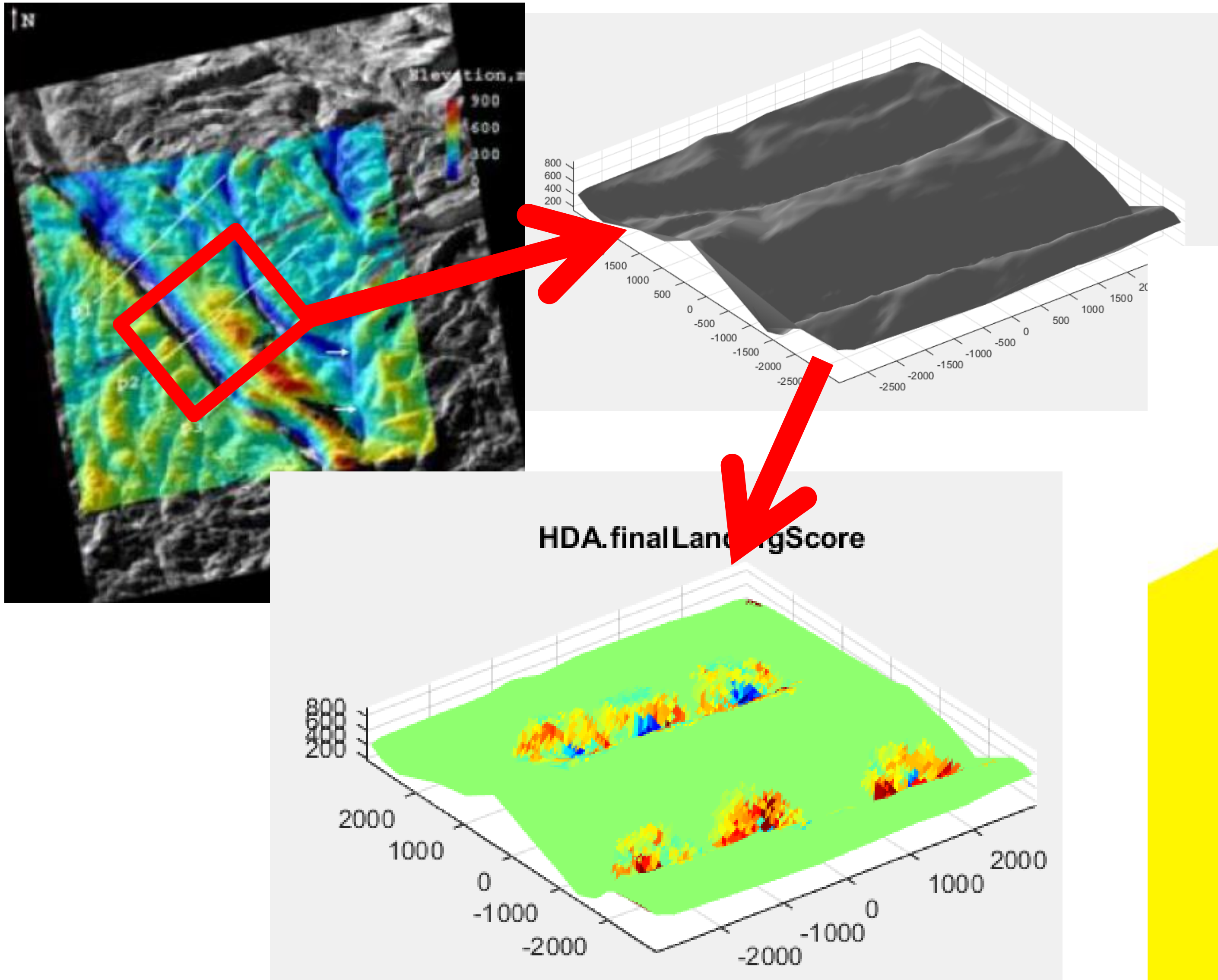
Visual navigation simulation

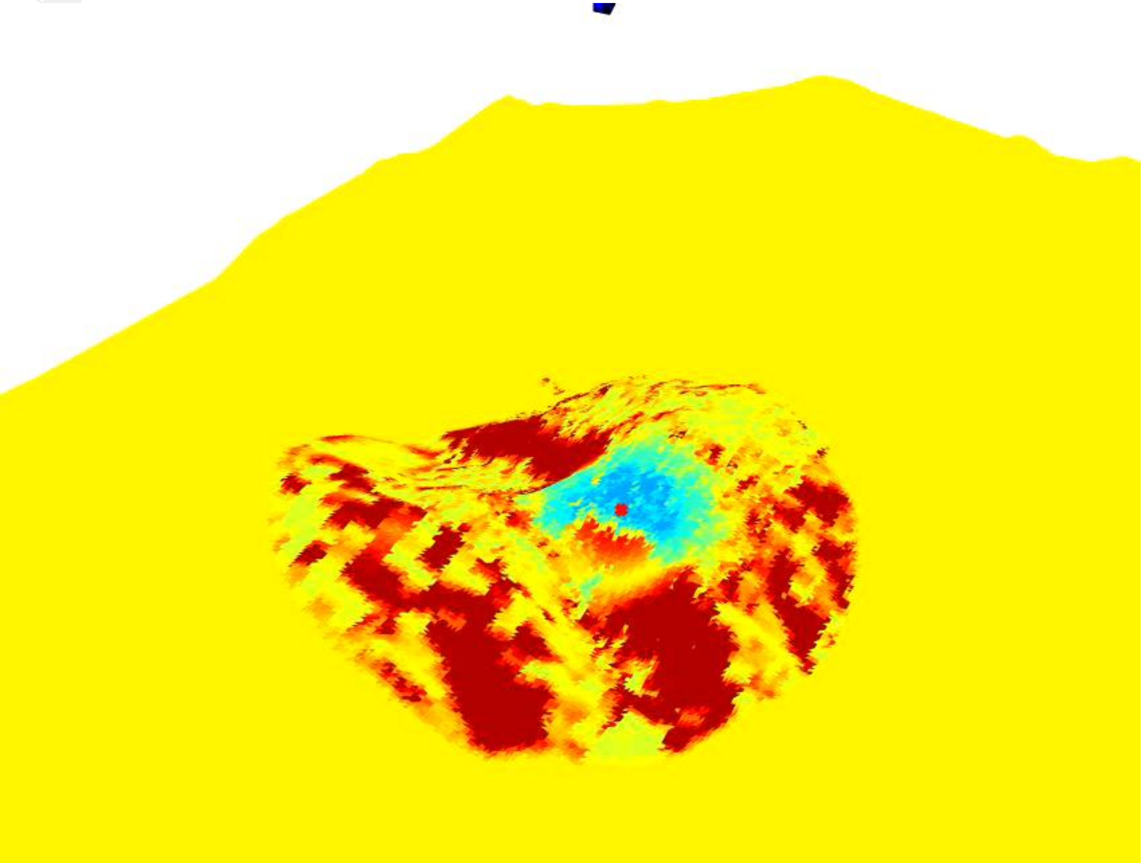






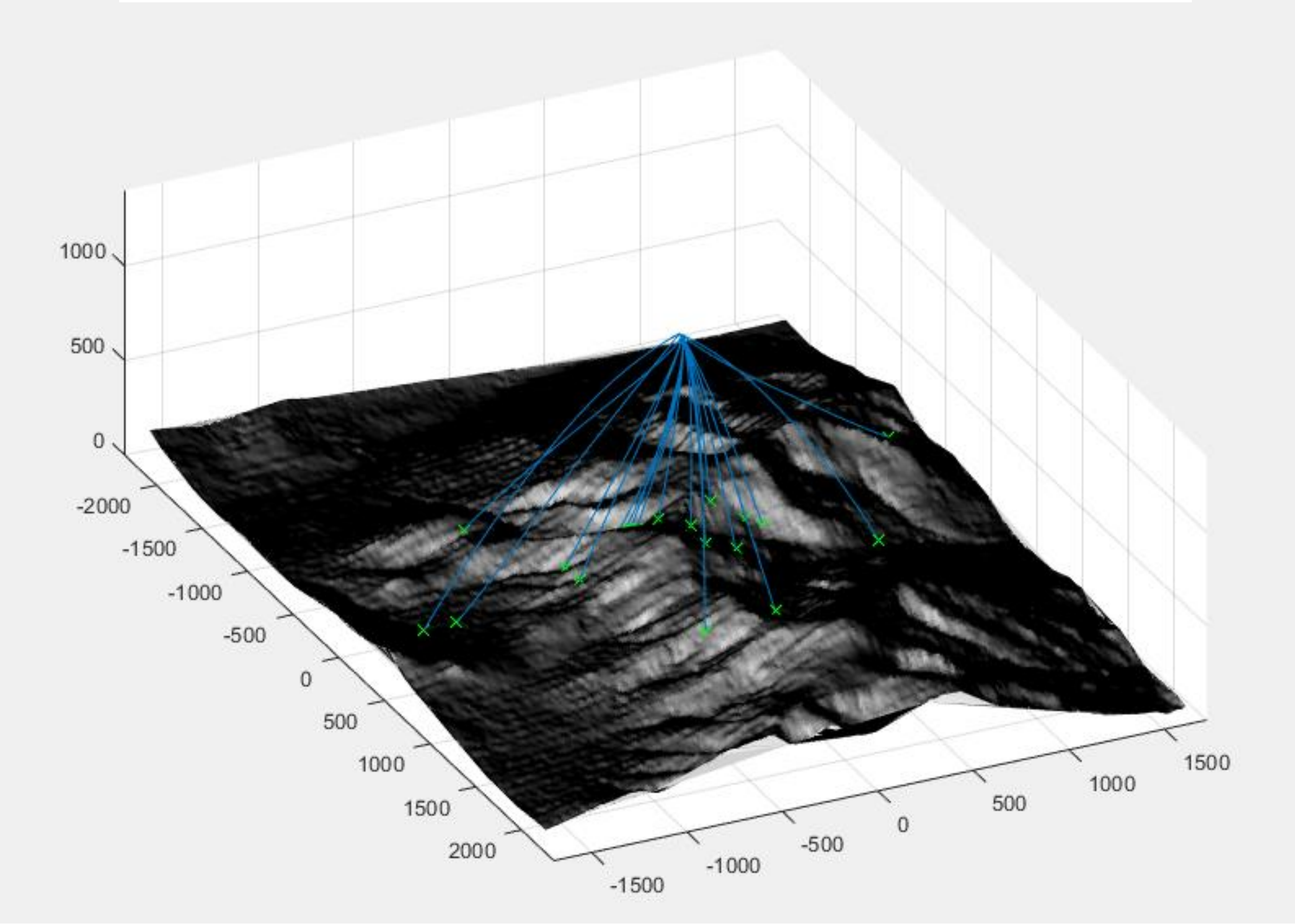
Hazard Detection and Avoidance simulation



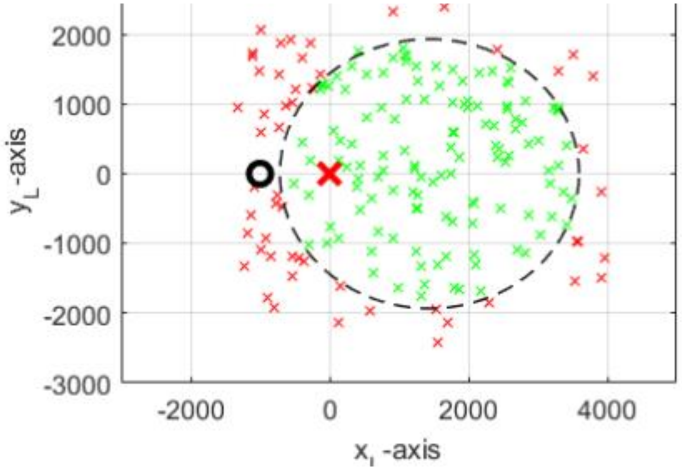


Guidance Simulation

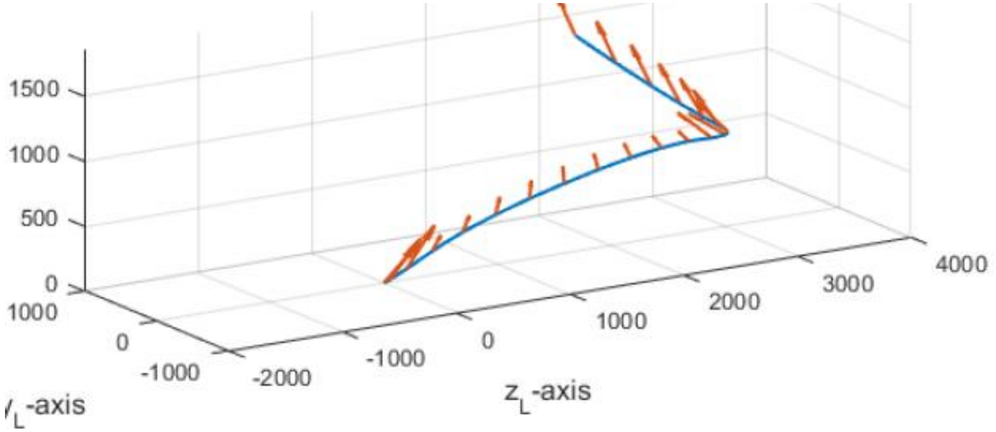
Demonstation of G-FOLD capabilities



Modified reachability ellipse verification



Example challenging trajectory and thrust arc



Summary and future work

What we did so far

- Created ***tool to simulate landing*** on Enceladus
- Incorporating all functions necessary:
  - ***Terrain Relative Navigation***
  - ***Hazard Detection and Avoidance***
  - ***Guidance***
  - ***Realistic sensor input simulation***

Work remaining to be done

- Finalize tool development
- Monte Carlo simulations and sensitivity analyses to ***verify fulfilment of landing requirements***
- ***Focus on reliability***: apply fault management methods and simulate deduced fault scenarios

Future work

- ***Test landing on quadrocopter testbed*** under development in ISTA

Thank you!
Questions?

Contact: k.konstantinidis@unibw.de