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MILANO 1863

DEVELOPMENT, VALIDATION AND TEST OF OPTICAL BASED ALGORITHMS FOR AUTONOMOUS PLANETARY LANDING

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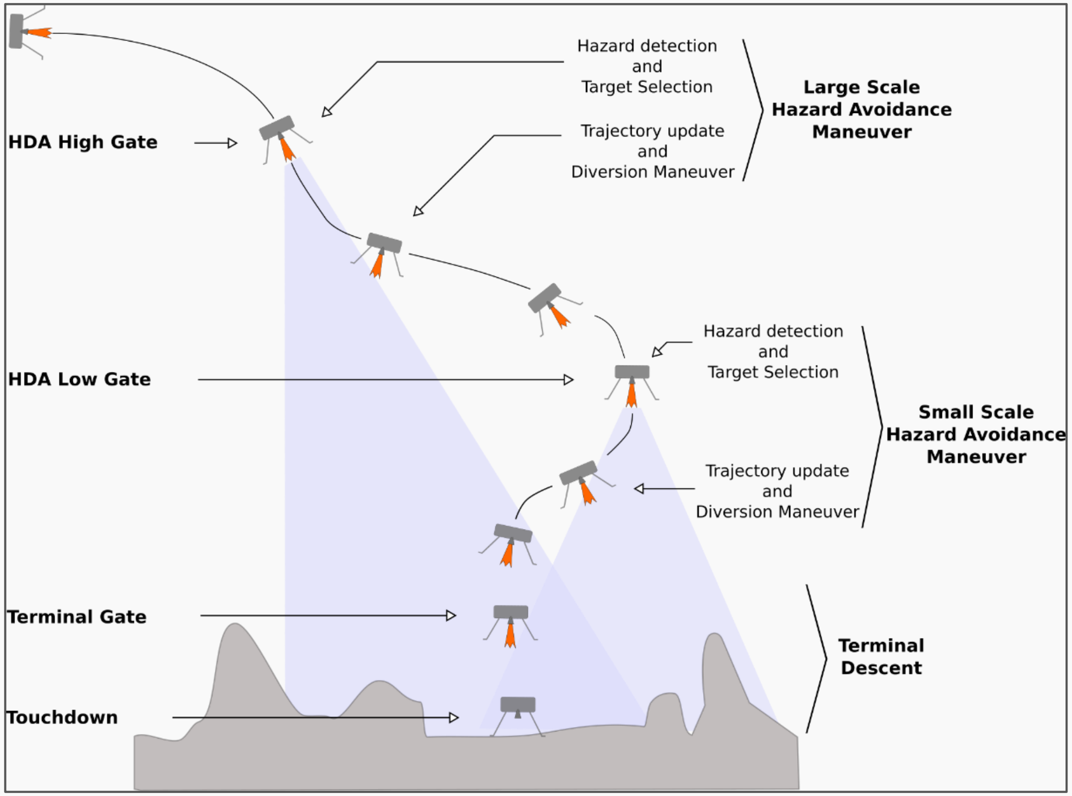
Autonomous vision-based landing system

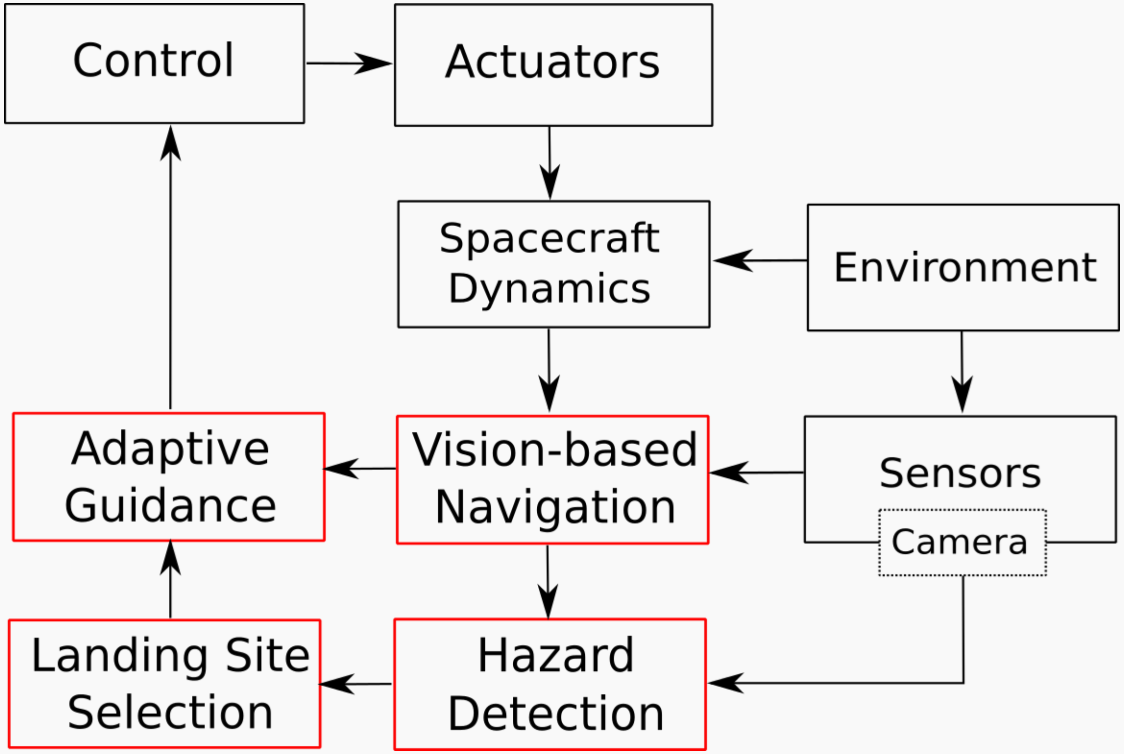
PoliMi-DAER since some time is **developing building blocks** for on board **HD** and **GNC** for autonomous landing on planets and small bodies based on **single camera.**

It needs to be able to:

- **Scan** the area around the Nominal Landing Site
- **Verify** target reachability according to the safety requirements
- If not possible to reach the target, seek **backup site**
- Compute **new landing trajectory**
- Execute **divert maneuver**



Autonomous vision-based landing system



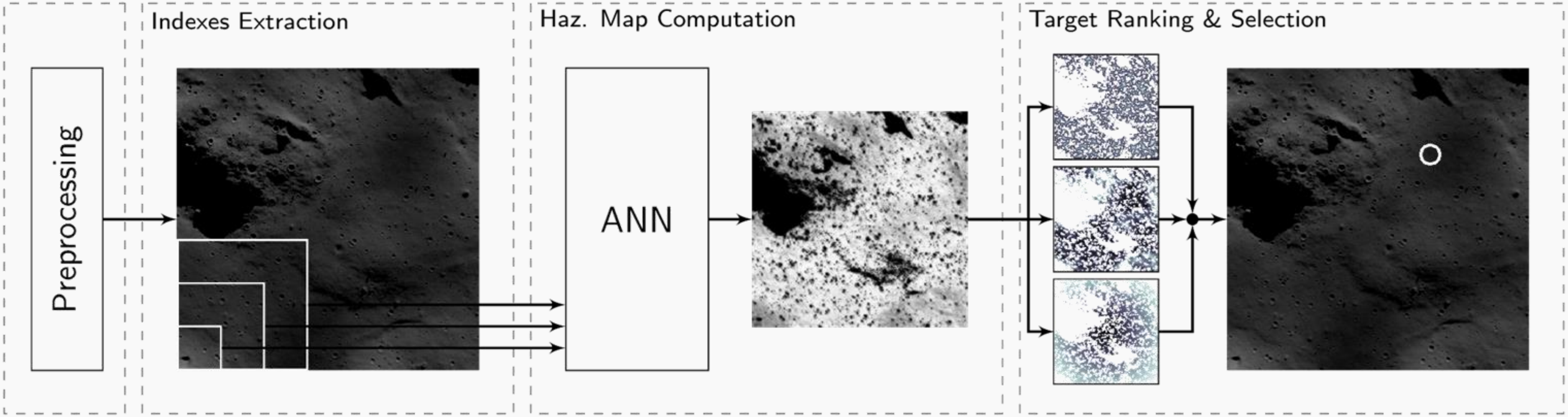
In red: building blocks under development @ Politecnico di Milano DAER

Hazard Detection System

A landing site is classified **safe** if:

- is **in light**
- its **roughness** complies with lander characteristics
- its **slope** does not roll over the lander
- its **size** is large enough for lander footprint and expected position error (due to GNC)

Our hazard detector is based on **Artificial Neural Networks** that produces an **hazard map** with each pixel indicating the hazard index (0 is safe, 1 is unsafe) of the corresponding image area. **Target Landing Site** is then computed on the hazard map.



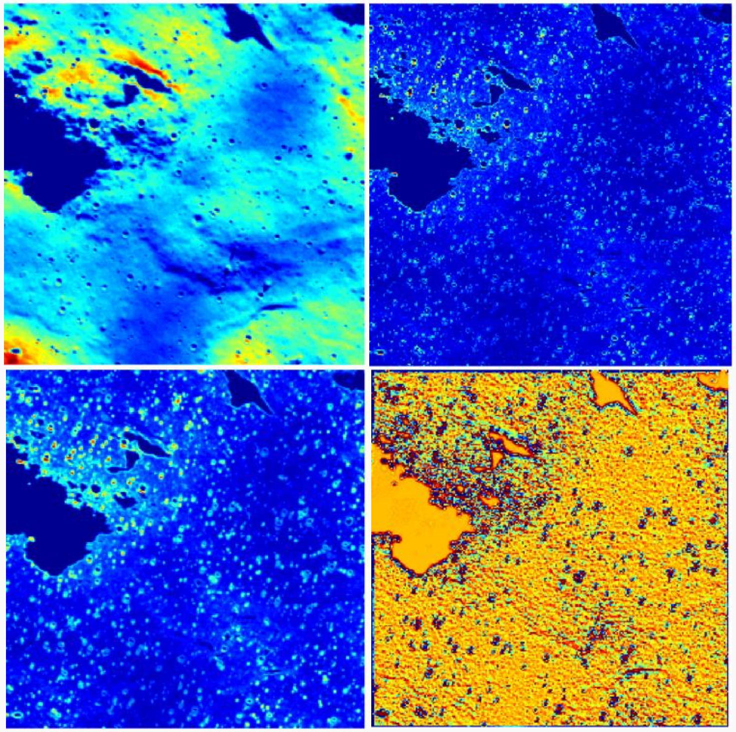
Hazard Detection System - Hazard map generation

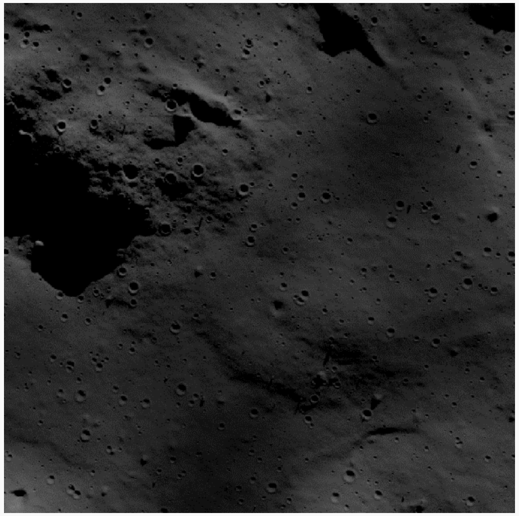
Input:
- 1024x1024 pixels 8-bit grayscale image
- Nav Camera FoV: 60°
- Perspective image correction if view is inclined from vertical attitude

Indices extraction:
- Mean of pixels intensity
- Standard deviation of pixel intensity
- Image gradient (Prewitt Filter)
- Laplacian of Gaussian

extracted at three different scales 256x256, 128x128, 64x64 pixels

Also **Sun inclination angle** is added: **13 indices total**

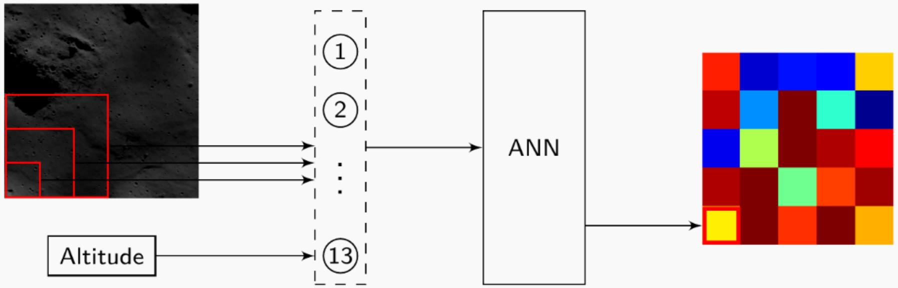




original frame

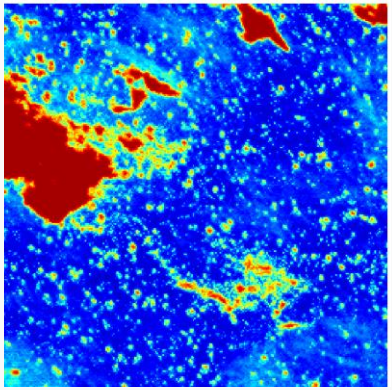
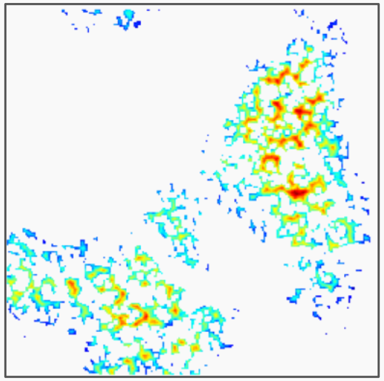
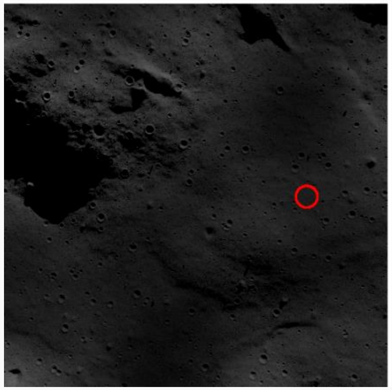
Hazard Detection System - Target selection

- Indices are the input to the **Cascade Neural Network**
- Network output is a pixel of the hazard map
- A light **blur filter** is applied to relate nearby pixels
- Hazard map resolution is 256x256 pixels



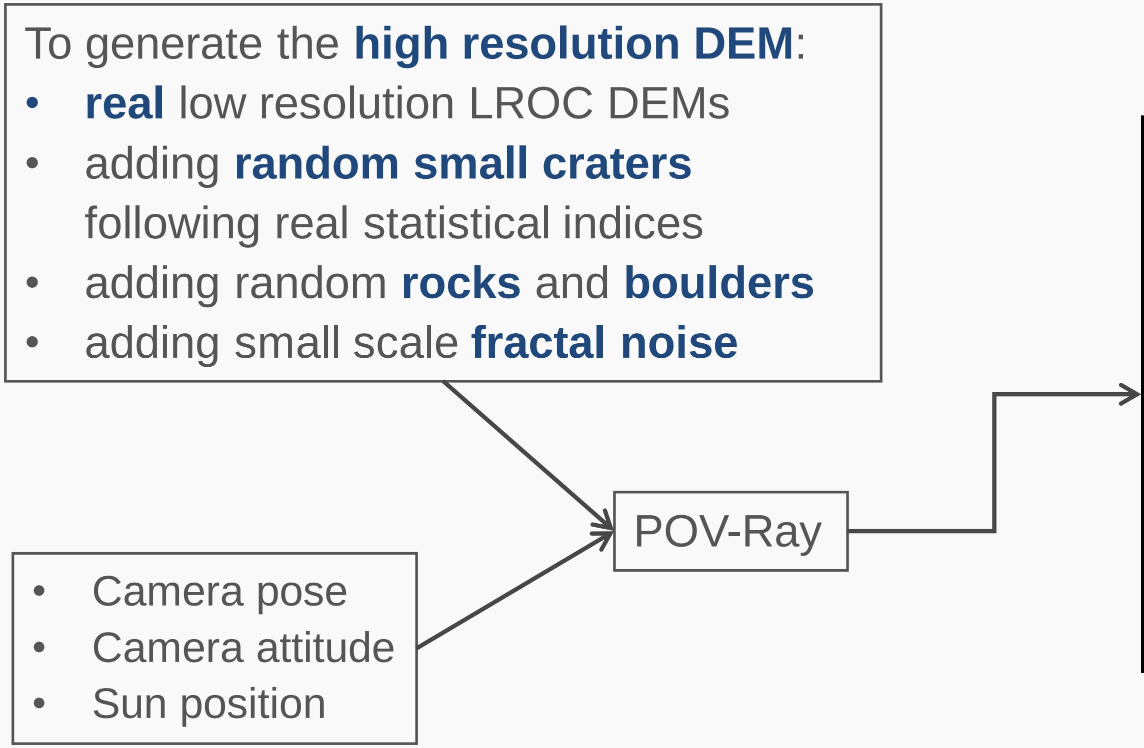
Landing site selection:

- all sites are ranked taking into account site **radius**, **mean hazard index**, **distance with Nominal Landing Site**
- Three corresponding weights can be tailored to user preference
- The first in ranking is **Target Landing Site**
- The second is **Backup Landing Site**

Hazard Detection System – Dataset generation

- Performances of a neural network are directly related to the **completeness** and the **coherence** of the training dataset.
- **Real** images usually do not include all the metadata (s/c altitude and attitude, camera model etc) and miss detailed terrain models.
- **Artificial** images supply those deficiencies, but they must be realistic to be coherent with the real planetary surface.

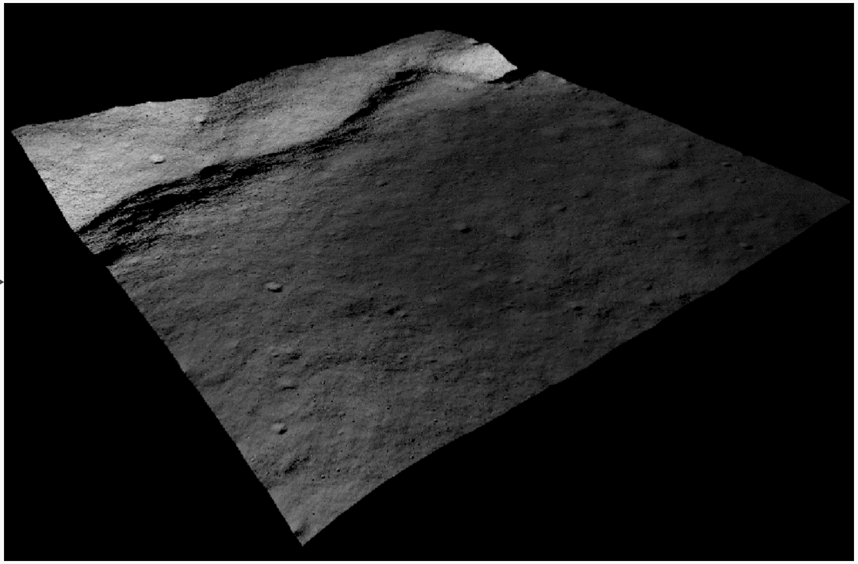


To generate the **high resolution DEM**:

- **real** low resolution LROC DEMs
- adding **random small craters** following real statistical indices
- adding random **rocks** and **boulders**
- adding small scale **fractal noise**

- Camera pose
- Camera attitude
- Sun position

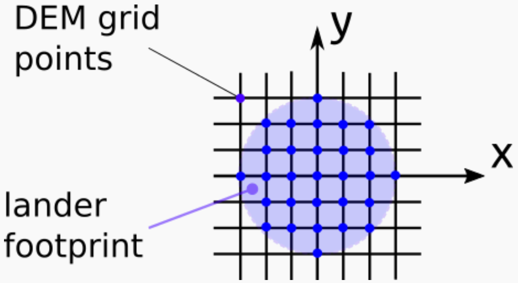
POV-Ray



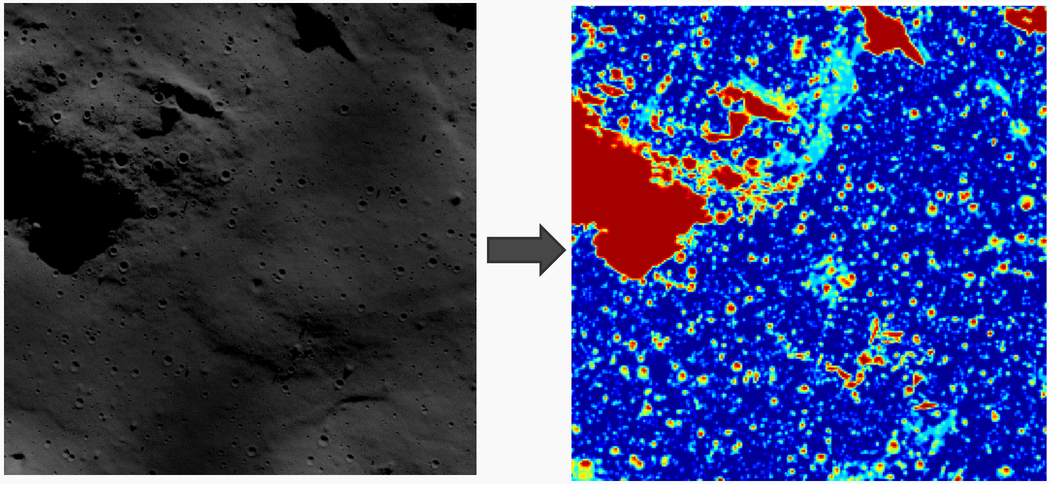
Hazard Detection System – Ground truth

Ground truth is computed through DEM morphology:

- Sliding circular window with diameter equal to lander footprint
- **Least Squares plane** of points in the window computes mean plane
- **Slope** is mean plane inclination
- **Roughness** is difference between max and min deviation from mean plane
- **Shadows** are computed through histogram thresholding of the rendering



- If roughness and/or slope exceed the lander limits the terrain is classified unsafe
- Max hazard is assigned to areas in shadow



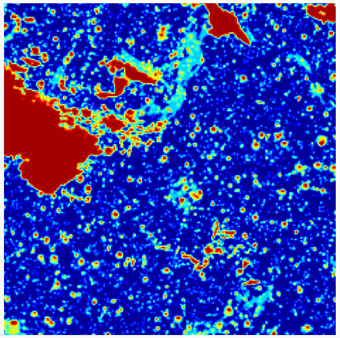
Hazard Detection System - Performances

Test dataset of 8 images:

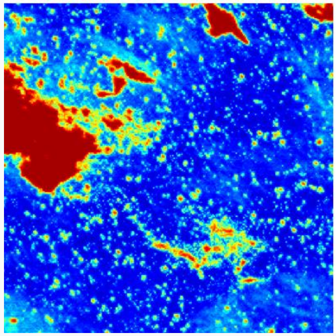
- 4 different landscapes
- 2 different Sun elevation angles (15° and 80°)
- **not** used in training

Results:

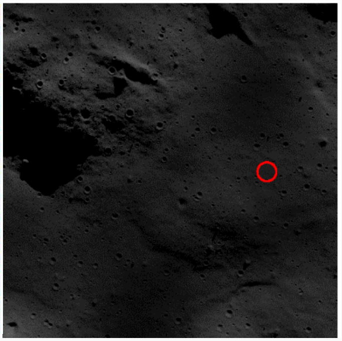
- Always a **safe landing site** is selected as target
- Always a **safe backup site** is available
- more than **96%** of the found landing sites are safe



Ground truth

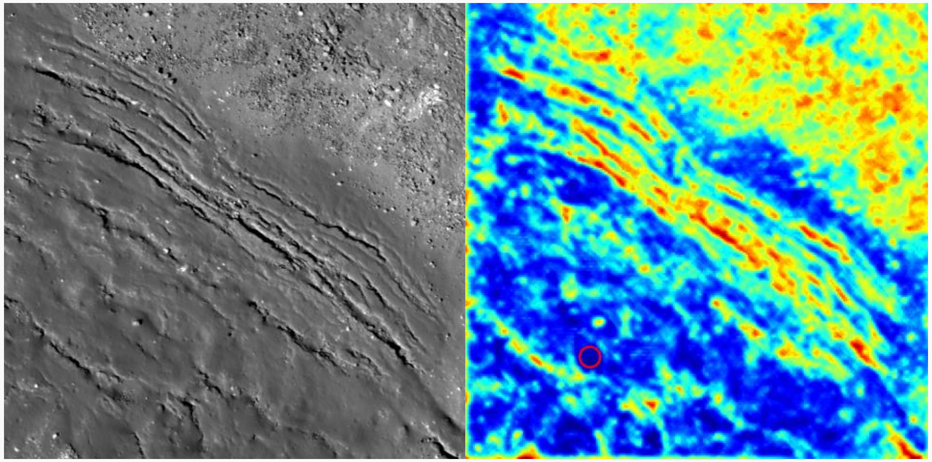


Hazard map

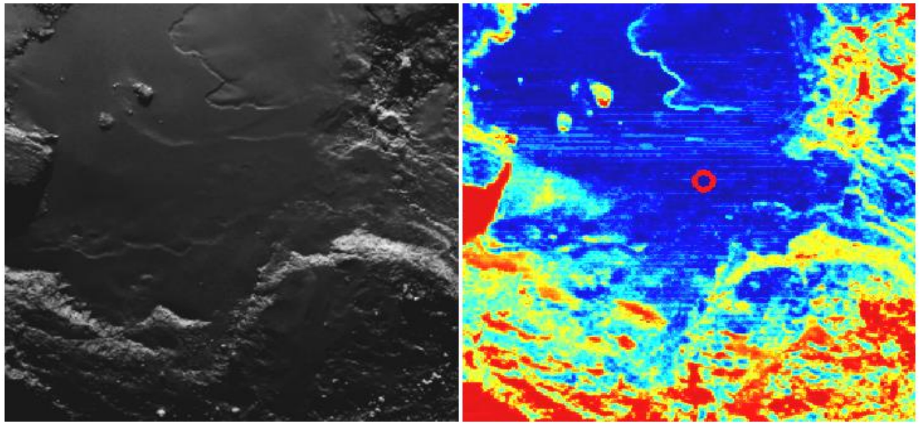


Target landing site

Test on **real images** - no ground truth available



Larmor Q crater floor - Image width: 800m - res: 1024x1024 px



Imhotep landing region from NavCam – Rosetta s\c

Adaptive Guidance – Dynamics and TPBVP

Once a target is selected, a **feasible trajectory** is needed

- 3DoF + Mass dynamics, throttleable thrust
- Thrust vector tightened to S/C body:
  Control acceleration depends on **attitude** and **thrust magnitude**

$$\begin{cases} \dot{\mathbf{r}} = \mathbf{v} \\ \dot{\mathbf{v}} = \dfrac{\mathbf{T}}{m} + \mathbf{g} \\ \dot{m} = -\dfrac{T}{I_{\mathrm{sp}} g_0} \end{cases}$$

Initial states

(retarget epoch)

$$\mathbf{r}(0) = \mathbf{r}_0$$
$$\dot{\mathbf{r}}(0) = \mathbf{v}_0$$
$$\ddot{\mathbf{r}}(0) = \mathbf{a}(T_0, \mathbf{e}_0)$$

Minimum order polynomial acceleration

$$\ddot{\mathbf{r}}(t) = \begin{bmatrix} \ddot{r}_{\mathrm{x}} \\ \ddot{r}_{\mathrm{y}} \\ \ddot{r}_{\mathrm{z}} \end{bmatrix} = \begin{bmatrix} \ddot{r}_{0\mathrm{x}} + c_{1\mathrm{x}} t + c_{2\mathrm{x}} t^2 \\ \ddot{r}_{0\mathrm{y}} + c_{1\mathrm{y}} t + c_{2\mathrm{y}} t^2 + c_{3\mathrm{y}} t^3 \\ \ddot{r}_{0\mathrm{z}} + c_{1\mathrm{z}} t + c_{2\mathrm{z}} t^2 + c_{3\mathrm{z}} t^3 \end{bmatrix}$$

Final states

(desired target)

$$\mathbf{r}(t_{\mathrm{tof}}) = \mathbf{r}_f$$
$$\dot{\mathbf{r}}(t_{\mathrm{tof}}) = \mathbf{v}_f$$
$$\ddot{\mathbf{r}}(t_{\mathrm{tof}}) = [\mathrm{free}, 0, 0]^T$$

Control thrust vector from acceleration: $\mathbf{P} = \ddot{\mathbf{r}} - \mathbf{g} \Longrightarrow \dot{m} = -\dfrac{P}{I_{\mathrm{sp}} g_0} m \Longrightarrow \mathbf{T} = m\mathbf{P}$

Optimization variables: $\mathbf{x} = \begin{cases} T_0 & \text{Initial thrust magnitude} \\ t_{\mathrm{tof}} & \text{Time of flight} \end{cases}$

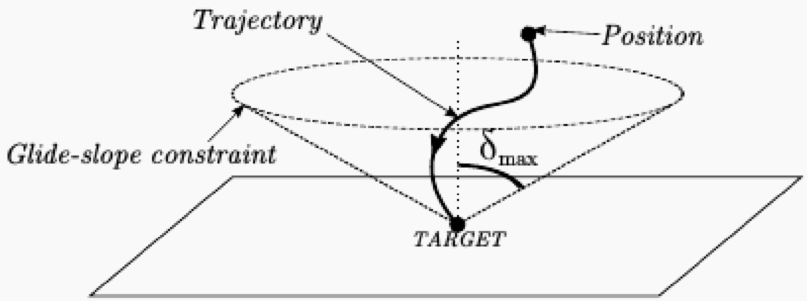
Adaptive Guidance – Optimization problem

Additional Constraints:

- **Box** contraints (optimization domain):
  - Thrust magnitude: $T_{\text{min}} \leq T_0 \leq T_{\text{max}}$
  - Time of flight: $t_{\text{min}} \leq t_{\text{tof}} \leq t_{\text{max}}$

- **Final mass** constraint: $m_{\text{dry}} \leq m(t_{\text{tof}}) \leq m_0$

- **Path** constraints:
  - Thrust magnitude: $T_{\text{min}} \leq T(t) \leq T_{\text{max}}$
  - Glide slope constraint: $\sqrt{r_y^2 + r_z^2} \leq \tan(\delta_{\text{max}})\, r_x$
  - Control torque: $-M_{\text{max}} \leq I_{\text{max}}\dot{\omega} \leq M_{\text{max}}$



Optimization problem: $\underset{\mathbf{x}}{\arg\min} f(\mathbf{x})$ subjected to $\mathbf{g}(\mathbf{x}) \leq 0$

Constraints:

$$\mathbf{g}(\mathbf{x}) = [g_0(\mathbf{x}), g_1(\mathbf{x}), \ldots, g_n(\mathbf{x})]^T$$

Objective function:

$$f(\mathbf{x}) = -m(t_{\text{tof}})$$

$$\mathbf{x} = \begin{cases} T_0 \\ t_{\text{tof}} \end{cases}$$

Adaptive Guidance – Differential Algebra Formulation

- Quantities are represented not by their value at a specified point, but with their **Taylor expansion** about that point up to an arbitrary order
- Single variables: $x = x_0 \quad \longrightarrow \quad [x] = x_0 + \delta x$
- Functions: $f(x, y) \quad \longrightarrow \quad [f] = \mathcal{P}_f(\delta x, \delta y)$
- A DA object carries more information than its mere values

Algebra of Real Numbers → **Algebra of Taylor Polynomials**

- All the **standard mathematical operators** are defined between DA objects as well as between floating points numbers;
- Plus: **derivation**, **integration** and **map inversion** are simple operations between Taylor coefficients in the DA domain;
- By expanding the objective function as a DA variable, its **sensitivity w.r.t. the optimization variables** is automatically obtained and exploited to build a fast ad hoc optimization algorithm.

Adaptive Guidance – Test results

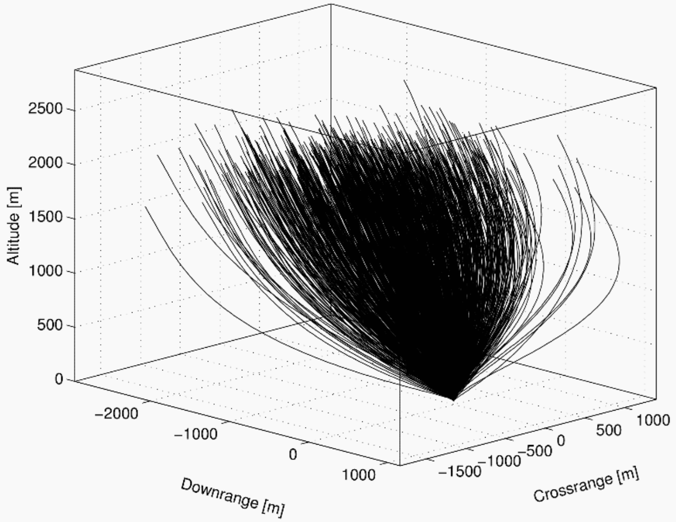
Lunar Landing as test case

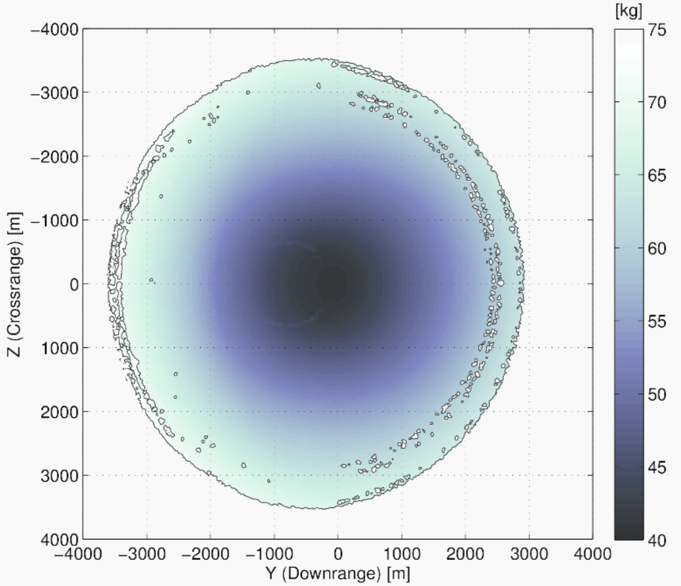
- Medium/Small lander size (dry mass 790kg)
- **Monte Carlo** simulation from initial altitude of 2000 m:
  - dispersion for **large scale hazard avoidance** maneuver in horizontal position is ±1800 m at 3σ
- Additional dispersion:
  - Initial conditions (velocity, attitude, fuel)
  - Model (specific impulse, thrust, inertial properties, gravity)

Always feasible trajectory found

Attainable Area:

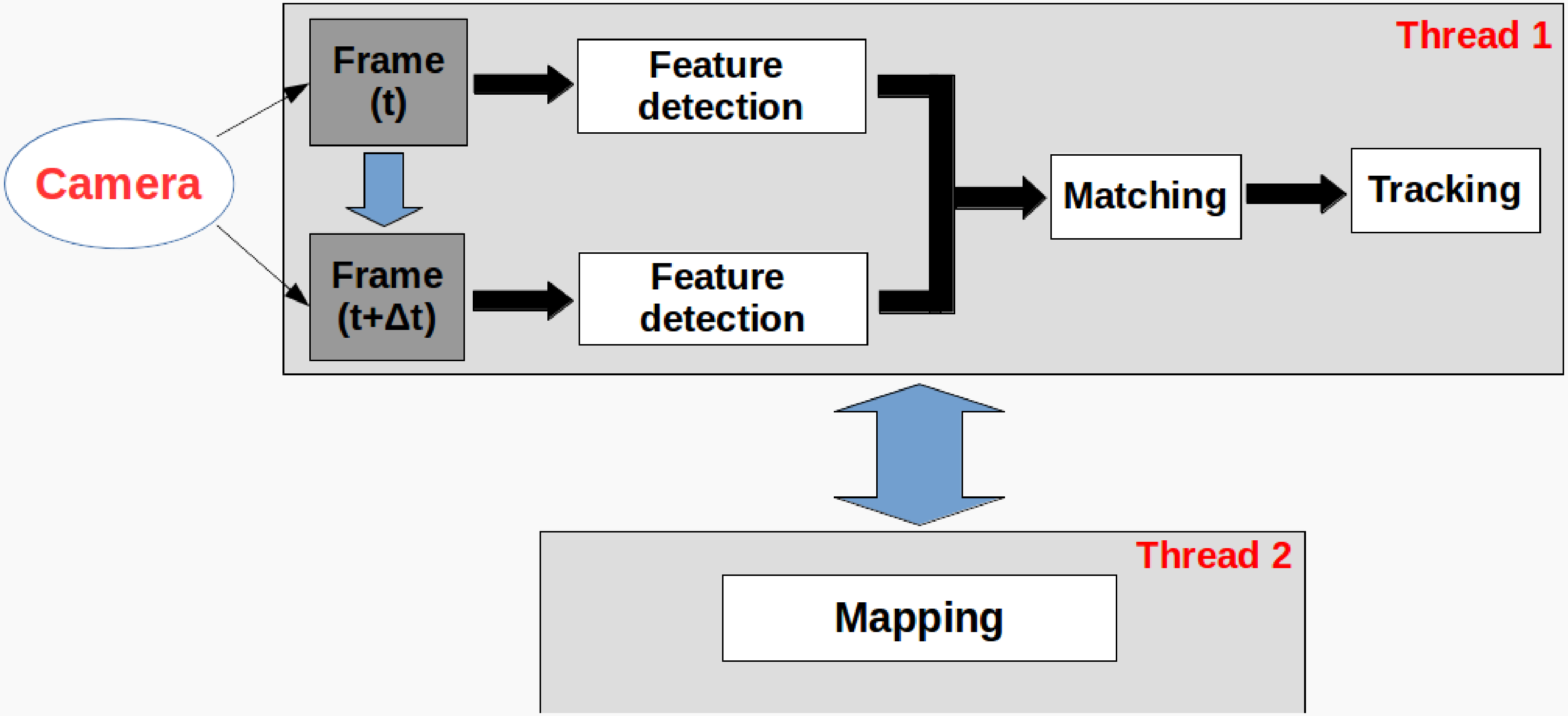
- Diversion ordered at altitude 2000 m
- Random diversion (uniform distribution ±4000 m)
- 1e5 MC samples
- **Attainable diversion >2300m from nominal target**





Navigation

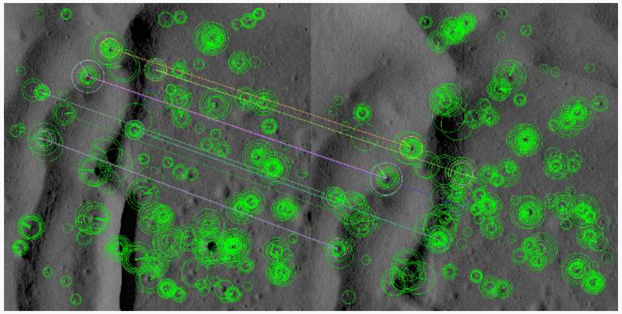
- Optical navigation from monocamera
- based on **Simultaneous Localization and Mapping (SLAM)**
- **Two parallel CPU threads** for feature extraction and mapping



Navigation - Thread 1

Oriented FAST* and Rotated BRIEF** (ORB) **Features Detection**:

- allow **fast** features extraction and matching
- High **invariance** level to different viewpoints and scales
- **Resilient** to different light conditions

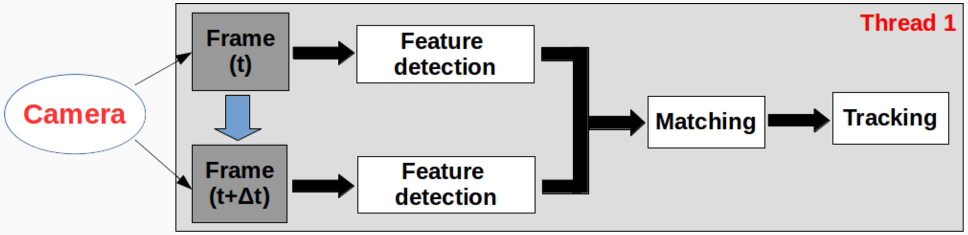


Frame to frame **matching** of ORB features:

- For each BRIEF descriptor in the first frame, find the closest in the second frame
- **Hamming distance** as **similarity measure** among the descriptors betwen two frames
- at least 5 matches are required to solve roto-translation of camera between two frames
- data fusion needed to solve absolute scale

Tracking to reconstruct motion frame by frame to implement visual odometry:

- solve five point relative pose problem (Essential matrix E) to relate position of points in two frames
- compute rotation matrix and translation vector with SVD of E



*Feature from Accelerated Segment Test

**Binary Robust Independent Elementary Features

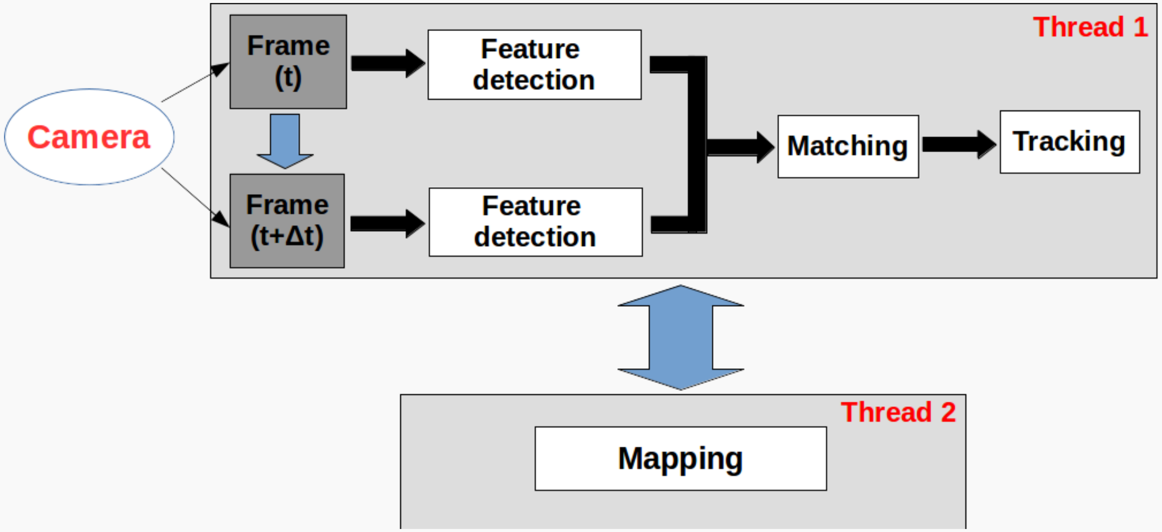
Navigation - Thread 2

Mapping works separately on another CPU thread:

- Triangulated 3D points used for tracking are improved in their 3D location (i.e. through bundle adjustment)
- With such points, the **map** is built
- Map is exploited by the feature extractor thread to improve pose estimation solving the Efficient Perspective-n-Point problem.

Current development state:

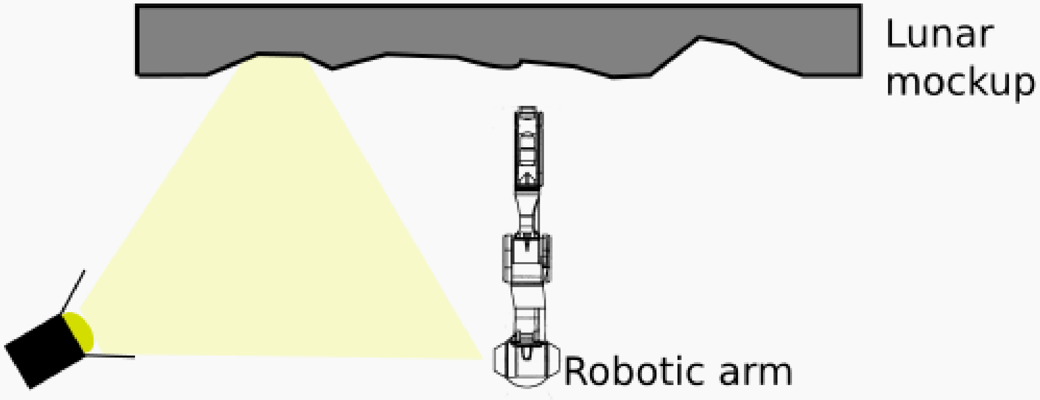
- Thread 1 (feature extraction and tracking) is coded and working. Currently under performances optimization
- Thread 2 (mapping) not yet implemented, under heavy development



Experimental Facility

Motivations

- available mission datasets lack of sensor metadata and telemetry needed to run the algorithms
- synthetic images have been used and they need to be validated
- assessments of single subsystems dependencies in closed loop simulations
- TRL increase of optical breadboard up to 4



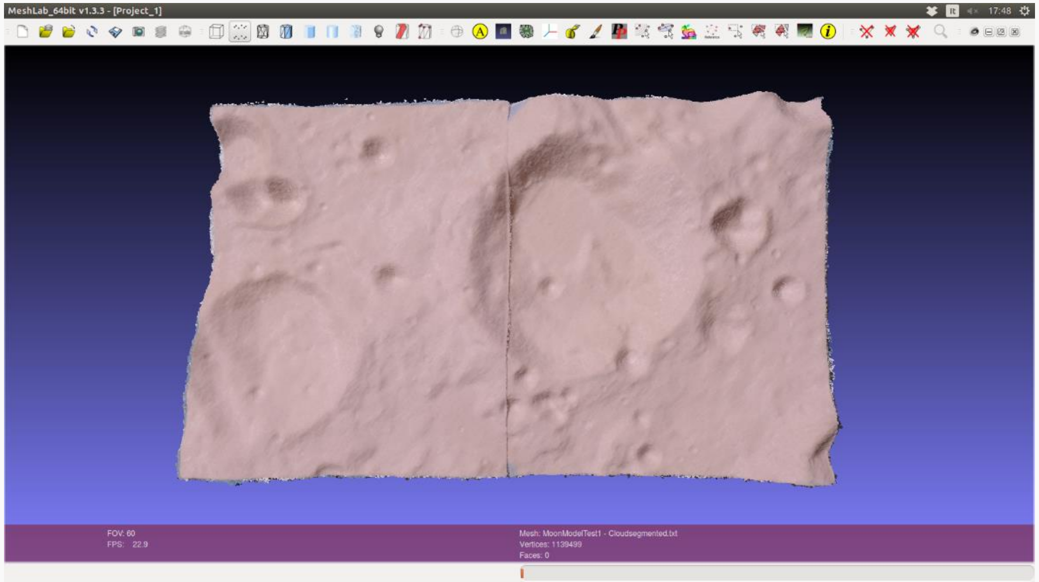
First application for the facility is to verify, validate and test the hazard detector in lunar environment

- 1 Lunar terrain 3D mockup
- Robotic arm
- Lightning system
- Sensors assembly
- Control PC
- Test PC

Lunar mock-up

- Diorama (2,4x2m) **manufactured at PoliMi** through numerical controlled milling machine
- Material: RenShape BM5460 urethane foam.
- Scale is 2000:1 (hazard detection starts at 2000 m).
- 10 m of accuracy at touchdown=5 mm in scale. Diorama resolution needs min 0.5 mm
- DEM to create the diorama is on LRO data adding craters, boulders, fractal noise following lunar statistical distribution: DEM resolution is increased to 0.25 m/px.

Lunar surface sample milled with a 5 mm spherical cutter and a milling step of 0.2 mm

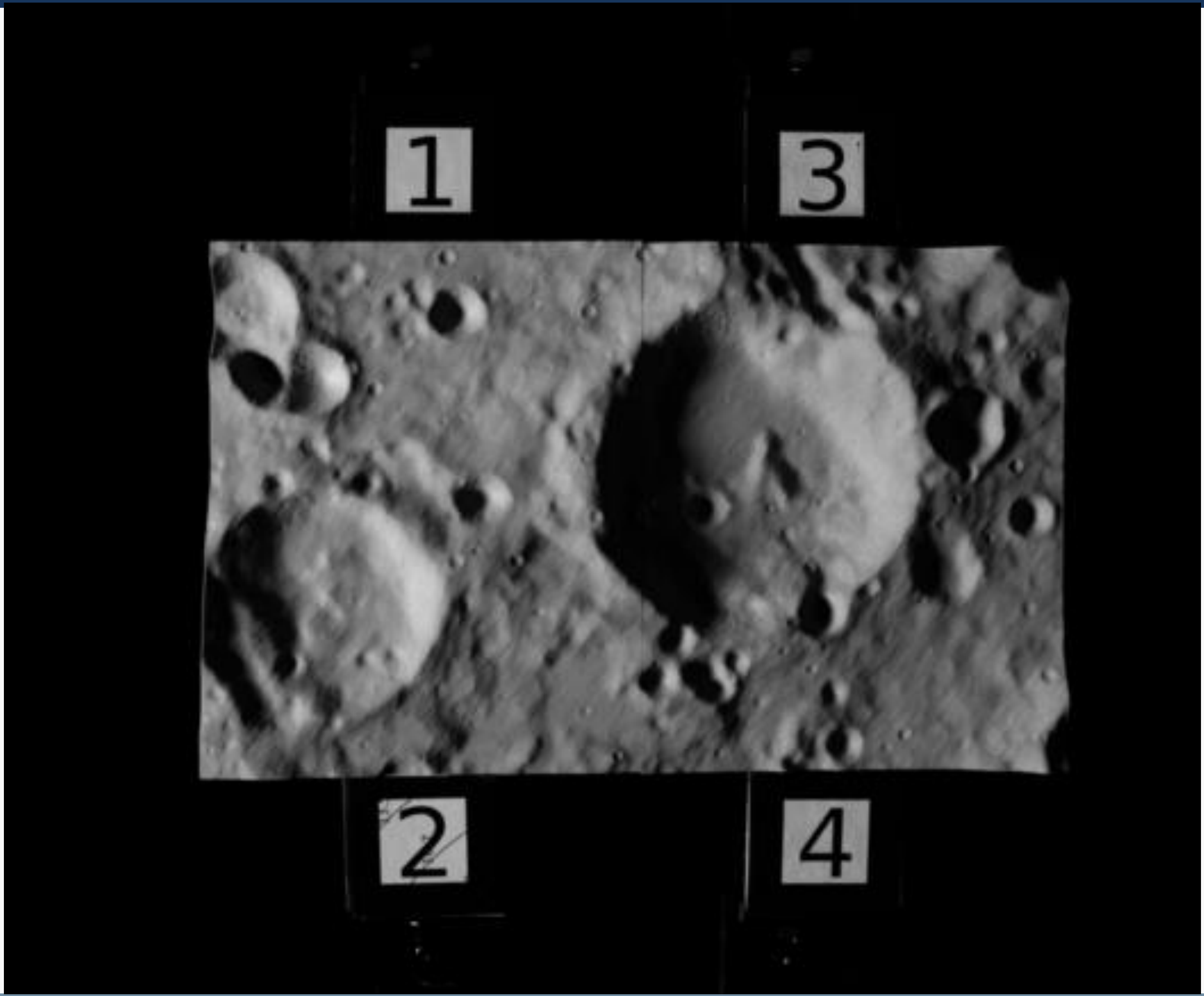


```
FOV: 60
FPS:   22.9
```

```
Mesh: MoonModelTest1 - Cloudsegmented.txt
Vertices: 1139499
Faces: 0
```

Lunar sample cloud points reconstructed through *dense matching* technique.

Lunar mock-up



Robotic arm, sensors assembly, illumination

7 DoF Mitsubishi PA-10/7C
to simulate lander dynamics

Mass	40 kg
Payload mass	10 kg
Speed about shoulder	28.5° /s
Speed about elbow	57° /s
Speed about wrist	180° /s
Spatial envelope	1.03 m
Number of DoF	7
Position repeatability	0.1 mm

Sensors assembly mounted on the end effector:

- Camera: 8-bit greyscale, 1Mpx resolution, ~50° FoV
- Ranging sensor to simulate LASER altimeter
- IMU is simulated

Light source:

- CAME-TV LED array of 1024x1024 LEDs.
- Narrow beam angle
- High Color Rendering Index (CRI)
- Light temperature from 3200 to 5600 K

Dimming system:

- Matte black structure.
- Prevents external light and internal
- Reflections to interfere with the simulation
- Fabric or thick paper can be used

Conclusion & future developments

- A suite of vision-based tools and algorithms for autonomous landing on planets and small bodies is under development at PoliMi - DAER
- An **hazard detector** based on artificial neural networks and a semi-analytical **adaptive guidance** algorithm are completed and ready
- An **optical navigation** based on SLAM technique is under heavy development and it is expected to be operative in Summer 2016
- An **experimental facility** dedicated to validation and testing of optical navigation algorithms is under construction at PoliMi premises

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