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# Plenoptic cameras for in-situ micro imaging

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## PROBLEM STATEMENT

- In-situ micro imaging requires micrometer resolution at small working distances
- Small working distances result in shallow Depth Of Field (DOF) down to 1 mm
- Extended DOF (EDOF) and depth estimation are only possible from image sequences
- Image sequence recording needs a focus mechanism and focus stack processing
- Focus mechanism increases size, mass and complexity of the camera

**Figure 1:** Example images and derived data products from an image sequence recorded on Mars during sol 998 with the MAHLI camera at 8 different focus positions. From left: 1) Focus on background, 2) focus on foreground, 3) EDOF image from focus stacking, 4) depth map from focus stacking. Image credit: NASA/JPL-Caltech/MSSS

## BENEFITS OF PLENOPTIC CAMERAS

1. **Single passive sensor without mechanisms for depth and brightness data**
2. One plenoptic recording provides more data than an image sequence
3. DOF multiple times larger and with a more open aperture than conventional camera
4. Depth map over a large depth range with high density and small details
5. Depth and 2-D data implicitly synchronized and calibrated due to the same recording
6. Creation of novel, slightly shifted views in software from recorded data
7. Image based calibration for metric measurements directly from the data
8. Opportunity to modify space qualified hardware to gain new plenoptic sensor

## HOW PLENOPTIC CAMERAS WORK

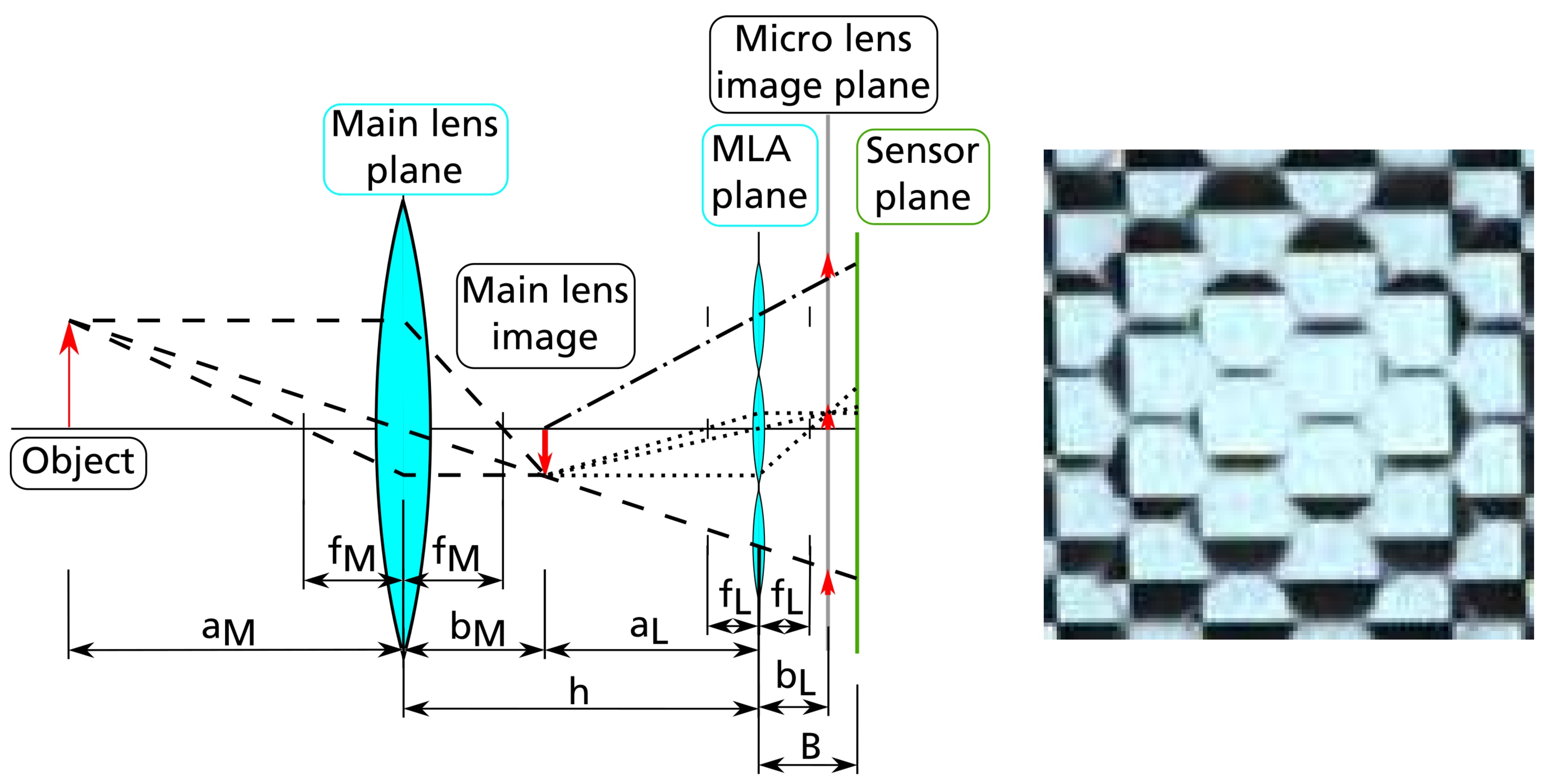


**Figure 2:** Recording concept of the focused plenoptic camera and close-up of the MLA showing the different vantage points and the overlapping field of view of single lenslets on edges of a checkerboard.

- Conventional camera modified with a Micro Lens Array (MLA)
- MLA is a matrix of lenslets each with a diameter of some micrometer
- Lenslets view and focus on main lens image from slightly different vantage points
- Parallax between lenslets enables depth estimation with triangulation
- Plenoptic recording maintains the 3-D nature of the main lens image
- Lateral resolution lowered by ¼ in exchange for depth resolution
- Processing of plenoptic raw data enables to shift hardware operations, e.g. focusing, to software

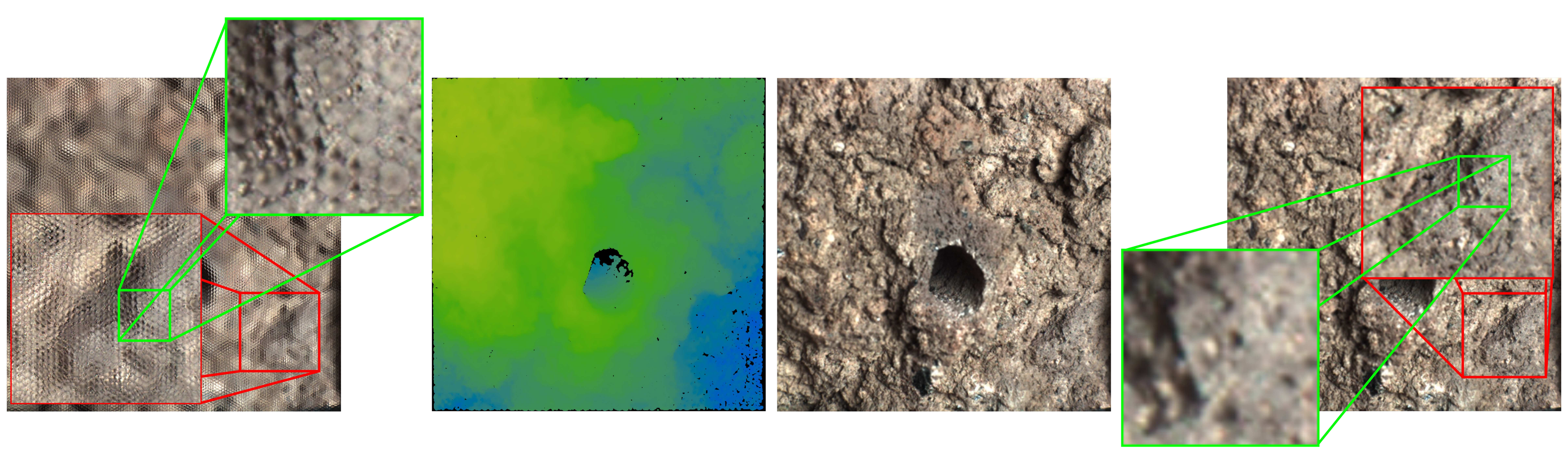

**Figure 3:** Plenoptic processing chain. From left: 1) Plenoptic raw image (4 MPx) with close-ups that show the single micro images, 2) depth map required for correct pixel correlation, 3) EDOF image (1 MPx) gained from depth map and pixel correlation, 4) close-ups from the EDOF image for comparison with the raw image close-ups

## EXPERIMENTAL SETUP

**Figure 4:** The experimental setup during recording.

- Raytrix R-5C camera
- CMV4000 sensor, RGB Bayer pattern
- Fujinon HS-35SA 35 mm objective
- Field of view: $20.41° \approx 5.5$ cm (hor.)
- Working distance: approx. 14 to 16 cm
- Raw image size: $2048\times2048$ px
- Processed image size: $1024\times1024$ px
- Red rock with rough surface, deep grooves and pore structures
- Granitoid rock with mineral inclusions and drill holes

## RESULTS

### Depth range up to 50% of the working distance

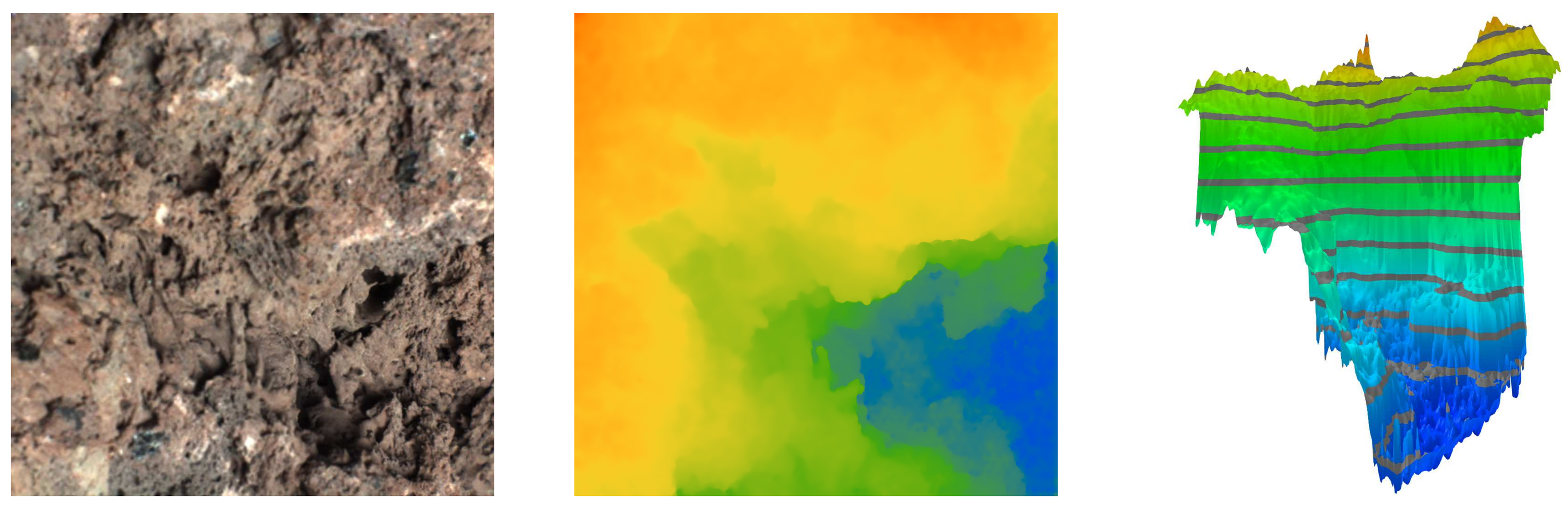

**Figure 5:** EDOF image, colored depth map and 2.5-D model showing depth measurements over a range of approximately 70 mm. From left: 1) Shows enlarged DOF but also limitations of current algorithm for EDOF generation. 2) Dense and detailed depth map (red=near, blue=far) 3) 2.5-D side view showing the full extent of the depth measurement, the isolines indicate distances of 5 mm.

### Small details and structures in depth maps

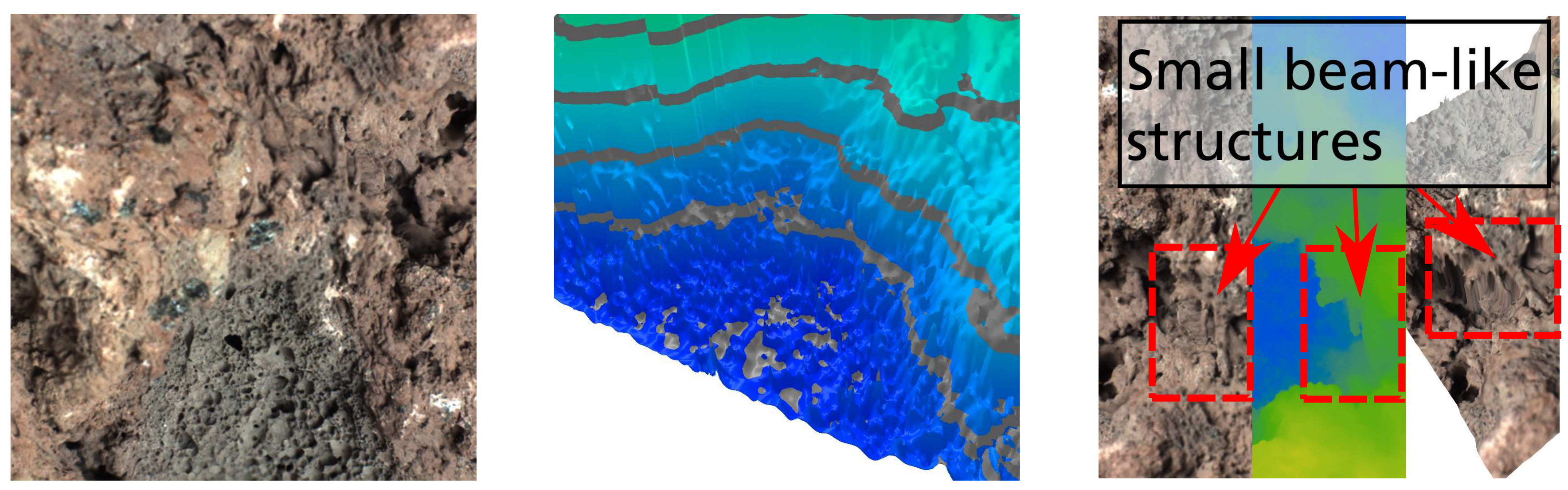


**Figure 6:** EDOF image, 2.5-D model and close-ups showing the possibility to detect small details. From left: 1) Small details of pore structures and surrounding material, 2) close-up of the pore structures in 2.5-D showing the depth resolution, 3) combination of 2-D, depth and 2.5-D data reveals the nature of small structures.

### Precise metric measurements directly from the data

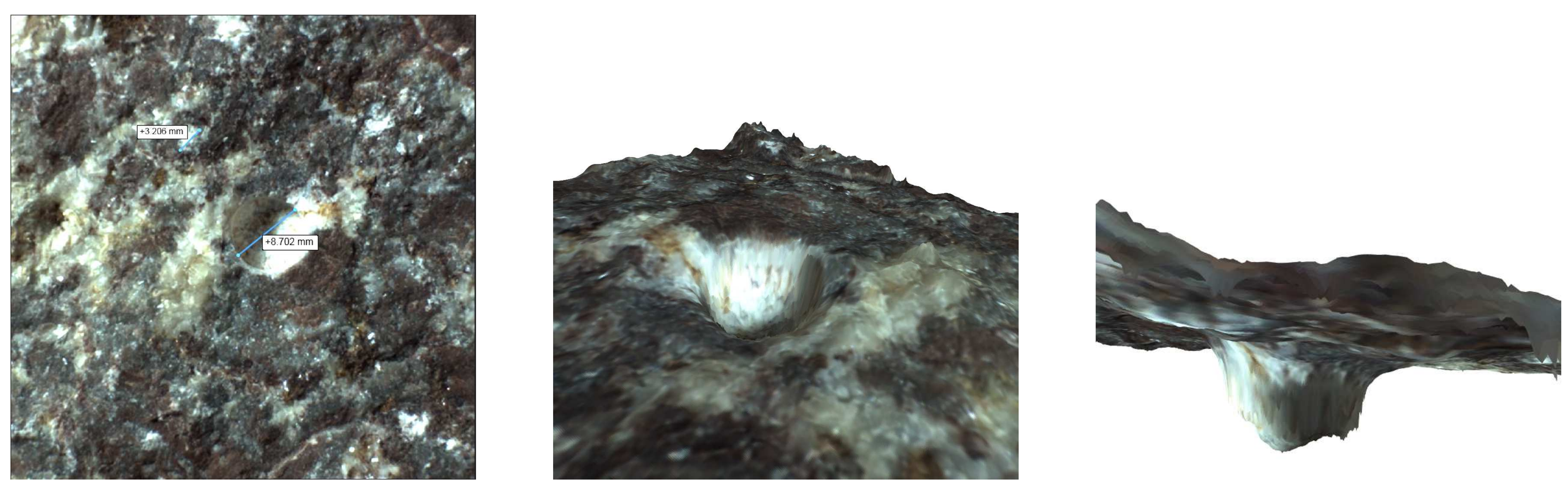

**Figure 7:** EDOF image and close-ups from a 2.5-D model of a granitiod rock with mineral enclosings and a drill hole. From left: 1) Metric measurements taken directly from the data. Difference to manual measurements $\pm1\%$, 2) close up view of the hole and surrounding mineral structures, 3) side view of the hole to show its depth extent and the conic bottom due to the drill's shape.

## CONCLUSION

- Plenoptic cameras are suited for in-situ micro imaging
- First experiments show promising results, both for 2-D images and depth maps
- Future work: Quantify resolution and camera performance, improve processing algorithms and increase the Technology Readiness Level (TRL) from TRL 2 to TRL 3