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Plenoptic cameras for in-situ micro imaging

Martin Lingenauber (1), Ulrike Krutz (2), Florian A. Fröhlich (1), Christian Nissler (1) and Klaus H. Strobl (1)
(1) DLR e.V., Institute of Robotics and Mechatronics, Germany, (2) DLR e.V., Institute of Optical Sensor Systems, Germany
(martin.lingenauber@dlr.de)

Abstract

This work discusses the benefits of plenoptic cameras for future hand lens imagers for in-situ planetology. Such cameras offer advantages over conventional cameras, especially at the small working distance that are common for in-situ micro imaging. For example, the extension of the depth of field without a focus mechanism while maintaining a more open aperture at the same time. Additionally, textured depth maps as well as views with small perspective changes are possible, all from a single recorded image. We present a brief introduction of the plenoptic camera technology and examples from laboratory experiments.

1. Introduction

A Hand Lens Imager (HLI) is a camera with a macro lens, on board a rover or a lander, that works as a remote version of a geologist's hand lens. Its primary purpose is to provide high resolution images of small geological features with a resolution of a few $\mu m/\,pixel$. This allows to categorize rocks or dust as well as to find hints on the geological history of a site. HLIs are also useful for tasks such as the planning and documentation of the operation of other instruments [1]. Examples of HLIs include the Mars Hand Lens Imager (MAHLI) on board the Mars rover Curiosity [1] or the Close Up Imager (CLUPI), which is currently developed for the ExoMars 2020 rover [2].

The minimum working distance for MAHLI and CLUPI is $21\,mm$ and $100\,mm$, respectively, with a maximum ground resolution of $14\,\mu m/\,pixel$ and $7\,\mu m/\,pixel$, respectively. The short working distance results in a narrow Depth of Field (DOF) as small as approximately $1\,mm$ [1, 2]. MAHLI and CLUPI are equipped with focus mechanisms in order to record a sequence of images, each focused to a different distance [1, 2]. This enables the creation of an Extended Depth Of Field (EDOF) image and a depth map by applying a z-stacking algorithm. However, it increases the complexity of the camera system.

1.1. Benefits of plenoptic cameras

In order to overcome these physical limitations, we propose the use of plenoptic cameras for future HLIs. They offer multiple advantages, which become most evident at small working distances. In addition, from a single plenoptic recording it is possible to derive more data products than from a focus image sequence of a conventional camera. First, the creation of 2-D images with a DOF multiple times larger than the one of a conventional camera while maintaining an open aperture at the same time [5]. Second, depth maps which directly can be textured with the EDOF image without a dedicated texture mapping process. Third, it is possible to compute novel views with a small perspective shift, as if the camera would have been moved slightly left or right. This might, for example, be used to detect glints from mineral enclosures or alike. Fourth, without a focus mechanism it is now possible to apply purely image based camera calibration to achieve precise metric depth values as shown in [6]. The calibration procedure can be repeated during the mission given a calibration target with a known geometry. As can be seen, a plenoptic camera can help to reduce the mechanical complexity by delegating some tasks to software. This becomes particularly beneficial in a demanding space environment such as the dusty surface of Mars or the Moon.

2 Plenoptic Cameras

A plenoptic camera is similarly constructed as a conventional camera, with an additional Micro Lens Array (MLA), i.e. a matrix of lenslets each with a diameter of a couple of μm, which is mounted in a short distance B in front of the sensor plane as shown in Fig. 1. The main lens, with focal length f_M, projects an image of an 3-D object at an object distance of a_M into the camera to the main lens image distance b_M. Similar to the object, its image has also a depth extend scaled by the magnification of the main lens. In a conventional camera, the 3-D main lens image is projected

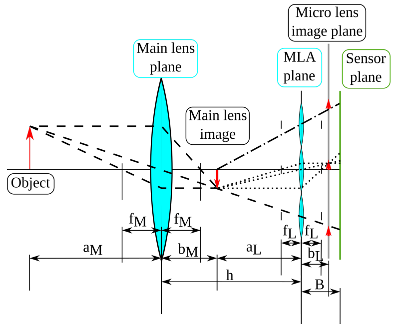


Figure 1: Concept of a focused plenoptic camera and its image formation process.

onto the sensor plane and the inherent 3-D information is lost.

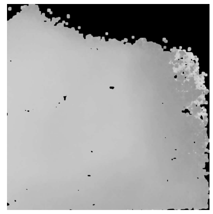
In contrast, a plenoptic camera maintains the 3-D nature of the main lens image. Here, each lenslet of the MLA acts as a single camera with a focal length f_L that views the main lens image from a slightly different vantage point. The lenslets are focused on the main lens image at distance a_L and on the lenslet image distance b_L, which is not equal to the distance B. The fields of view of adjacent lenslets overlap and the parallax between them allows to triangulate the depth of an image point. By using lenslets with different focal length and grouping them accordingly, it is possible to achieve a significantly increased object space DOF only due to the camera concept [5]. Such a Multi-Focus Plenoptic Camera (MFPC) provides an image whose size is approximately a quarter of the sensor pixel amount. More details on the image formation process are provided in [3].

(a) Raw plenoptic color image (4 MPx)

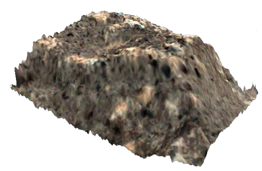
(b) EDOF image (1 MPx)

Figure 2: Image of a rock recorded from approximately 140 mm

Fig. 2a shows a raw plenoptic image of a rock surface recorded with a 4 MPx color plenoptic camera (Raytrix R5-C). The micro images formed by the lenslets are visible. From the raw image it is possible to derive the different data products shown in Fig. 2b and Fig. 3. At the current state of the art, the plenoptic data processing is computationally demanding. However, as discussed in [4], algorithmic optimization and parallelization can result in higher efficiency, making it feasible for a planetary exploration mission.



(a) Depth map (1 MPx) black = no depth



(b) 3-D model with an EDOF image texture

Figure 3: Derived data products

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