3D-printed freeform objectives and wide-angle cameras with extremely flat form factors

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We present concepts, correction methods and realizations towards freeform multi-aperture wide-angle cameras fabricated by femtosecond direct laser writing. Our designs feature dimensions below ~ 300 µm (vertical) and ~ 1 mm (lateral) with stitched full fields of view up to 180°×360°.

1 Introduction

Simultaneous realization of ultra-large field of view (FOV), large lateral image size, and a small form factor is one of the challenges in imaging lens design and fabrication. All combined this yields an extensive flow of information while conserving ease of integration where space is limited. To tackle this goal, several conventional and biomimetic approaches with limited FOVs have been demonstrated [1, 2]. Here, we make use of a 3D-printing process giving us the design freedom to create 180°×360° cameras with a flat form factor in the micrometer range by splitting the FOV into several apertures [3]. Highly tilted and decentered non-rotational lens shapes as well as catadioptric elements are used in the optical design to map the FOV onto a flat surface. We present methods to measure and correct freeform surfaces with large tilts by confocal measurements, and iterative fabrication via femtosecond direct laser writing (fsDLW). Finally, two realizations of freeform multi-aperture wide-angle cameras are presented.

2 Optical design

The optical design is developed and optimized using the sequential mode of *Zemax OpticStudio*. We examine three different lens types to realize the ultra-large FOV (Fig. 1). Small field angles are imaged by a rotationally symmetric center lens. Moderate field angles are imaged by a freefrom refractive lens with an aperture tilted towards its median field angle. Extreme field angles are redirected to the image plane by a total internal reflection (TIR) surface in a freeform catadioptric lens design. The arrangement of these three lens types in a linear (1× center lens, 2× refractive lens, 2× catadioptric lens) or annular shape (1× center lens, 12× refractive lens, 16× catadioptric lens) enables panorama and dome imaging, respectively.

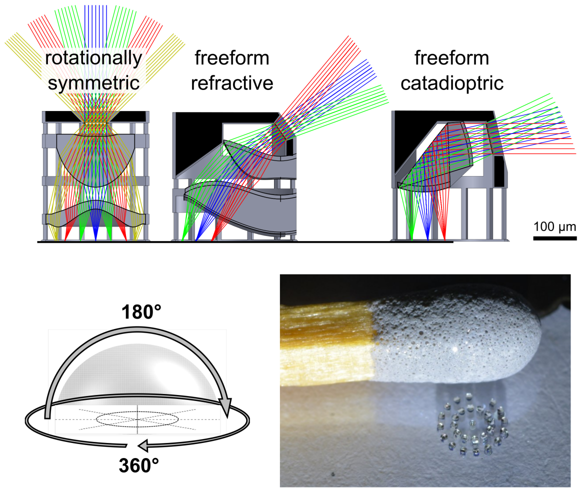

Fig. 1 *The FOV is split into multiple apertures. In an annular arrangement the complete imaging dome (180°×360°) can be mapped by three lens types: rotationally symmetric, freeform refractive, and freeform catadioptric.*

3 Fabrication

From the optical designs printable computer aided design (CAD) models are derived which include microfluidic structures for aperture fabrication as described in [4], indicated in Fig. 1 in black. The lenses are 3D-printed with *Nanoscribe Professional GT* and *GT2* printers. All lenses are fabricated using the photoresist *IP-S*, developed in propylene glycol methyl ether acetate, rinsed with isopropanol, and dried with a nitrogen blower. Printing times per objective are in the order of single hours.

4 Measurement and shape improvement

Due to shrinkage of the photoresist, surface shapes show a deviation from the original design after fabrication. On our lens scales of ~300 µm typical deviations on the order of 1-5 µm can be observed. Itera-

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tive measurement and fabrication of accordingly pre-compensated CAD models enable sufficient shape correction within a second or third fabrication attempt. While this approach seems rather straight forward, measurement of (hidden) freeform surfaces can be challenging. We therefore propose a set of measurement helpers (Fig. 2) to flip and orientate lenses and lens parts during measurement.

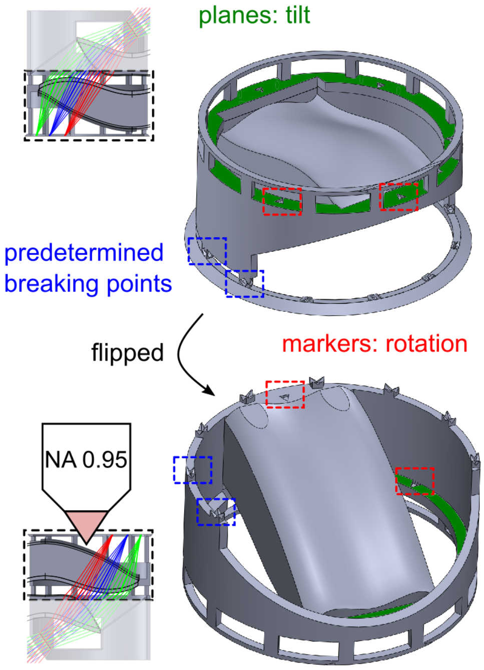

Fig. 2 *Reference structures are included in the CAD model to enable topography measurements from different directions.*

5 Wide-angle camera implementations

Finally, we present two implementations of ultra-wide-angle cameras: a panoramic version printed directly onto a Raspberry Pi image sensor (Fig. 3) and a ring-shaped arrangement for dome imaging (Fig. 4). The first implementation features image stitching but suffers from insufficient image quality. Here, iterative shape improvement had not been implemented. In contrast, the second implementation was realized with iteratively improved lenses and shows superior image quality which is represented by imaging the inside of a checker board cube from different orientations.

6 Conclusion

In this work, we presented two freeform multi-aperture cameras with wide-angle imaging capabilities and extremely flat form factors. While imaging quality can still be improved by combining all learnings from our study, we introduced a methodology to design, fabricate and realize 3D-printed freeform lenses as a broadly applicable toolbox.

For further details and funding, please refer to reference [3]. Figures and text have been reproduced and adapted in parts from this reference.

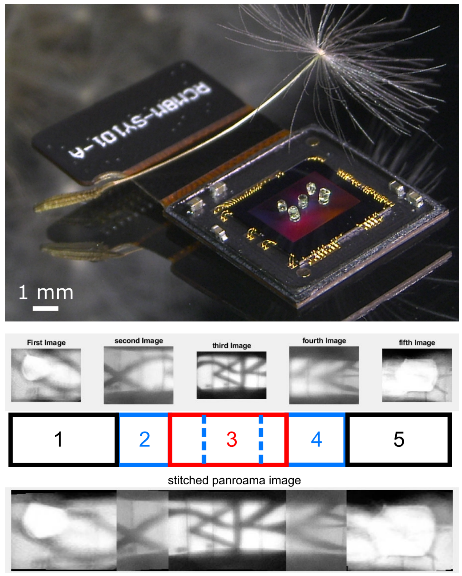

Fig. 3 *Wide-angle camera realized by 3D printing directly onto an image sensor. A panorama image can be stitched from the five individual image planes observing different portions of a custom bow target.*

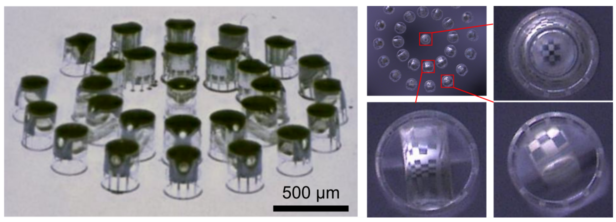

Fig. 4 *Multi-aperture camera in a ring arrangement 3D-printed onto a glass substrate and imaging of the inside of a hollow checker board cube.*

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