Synopsis of paper

--Xuan Wang

Paper title: **Optomechanical design of multiscale gigapixel digital camera**

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1. Introduction

In traditional single aperture imaging systems, the maximum attainable resolution is determined by either the geometric aberrations or the diffraction limit of the optics. An efficiently designed camera matches this resolution to the pixel-limited resolution of the sensor. A multigigapixel camera therefore requires optics that can effectively resolve billions of image points with corresponding sensors capable of acquiring these image points. However, in conventional imaging systems, increasing the resolution typically necessitates an increase in the size of the optics, in turn increasing geometric aberrations, which scale with system size. Traditional approaches to correct these aberrations across the entire field require many optical elements, leading to excessive levels of complexity, weight, and size.

A multiscale camera circumvents these difficulties by splitting the work of imaging the field over several small-scale optics and using digital image processing to form the composite image. Figure 1 illustrates the basic elements of a multiscale design. A main objective lens, shown as a sphere, captures the total field and produces an intermediate image. This image is then further corrected and relayed through a set of smaller optics (called "micro camera" optics) to produce partial images at corresponding focal planes. These partial images are designed to contain the total field of interest and can be manipulated in postprocessing to produce a continuous image. Here "multiscale" refers to the use of a large objective lens combined with smaller micro-optics to achieve both small-scale aberrations and increased clear aperture diameter.

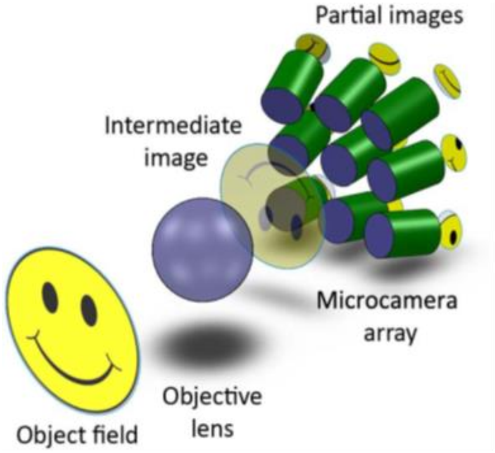

Fig. 1. Schematic illustration of a multiscale imaging system.

The division of the imaging work in multiscale systems allows each set of micro camera optics to be much simpler than a single monolithic design and creates the potential for massively parallelizable image acquisition. However, precisely holding and aligning each of these micro cameras to form proper images and overlap requires an innovative optomechanical approach.

The overall goal of their optomechanical design is the same as that of traditional optical systems: build a stable platform to position the optical components according to the optical design in a way that can be readily manufactured and assembled. However, the details unique to multiscale design require the resolution of several mechanical design, assembly, and tolerancing issues to successfully construct a multiscale gigapixel scale digital camera.

2. Design of AWARE-2 Camera

In this design, they investigated a monocentric multiscale design. Monocentricity refers to the spherical symmetry of the objective lens, in this case a ball lens, which allows identical micro cameras to be arrayed radially from the center of the objective. For a monocentric camera, the main support structure is a spherical dome which precisely places each micro camera in the correct position.

AWARE-2 was designed to realize a platform capable of capturing up to 120° field of view (FOV) in all directions with diffraction-limited resolution of over two gigapixels and the ability to focus from infinity to 30 m in object space, achieving an instantaneous FOV (iFOV) of 40 μrad with 1.4 μm pixel pitch CMOS sensors. This is the first of their full-scale gigapixel systems and serves as a testbed for optimization of future cameras.

A ZEMAX optical design of AWARE-2 is shown in Fig. 2. The main objective lens is a two-layer glass ball and the micro-optics consist of three plastic optical groups. This design has a focal length of 34.2 mm and an f -number of 2.2 at infinity focus. Table 1 shows the alignment tolerance budget dictated by the optical design to achieve the target image quality of above 20% modulation transfer function at the Nyquist frequency (357 cycles / mm).

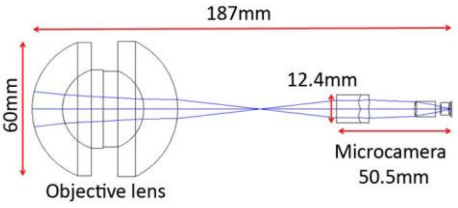

Fig. 2. Zemax optical design of AWARE2

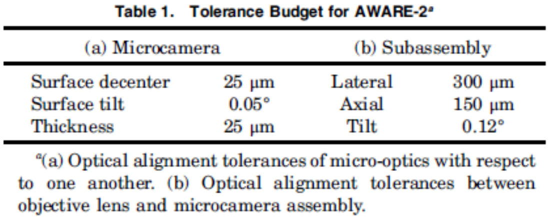

Table 1. Tolerance Budget for AWARE-2[a]

(a) Microcamera		(b) Subassembly	
Surface decenter	25 μm	Lateral	300 μm
Surface tilt	0.05°	Axial	150 μm
Thickness	25 μm	Tilt	0.12°

[a] (a) Optical alignment tolerances of micro-optics with respect to one another. (b) Optical alignment tolerances between objective lens and microcamera assembly.

2.1 Micro-Camera Design

Micro camera designs require special considerations uncommon to most imaging systems. Due to the need to tightly pack the micro cameras side by side in the array, the optics and mechanical supports must be laterally compact. The micro-optics for the AWARE-2 camera are shown in Fig. 3 and consist of three groups of plastic elements. The front optic has a hexagonal profile to maximize light collection when close packed.

Optical components for each micro camera are assembled into machined aluminum lens barrels as shown in Fig. 3(b). The plastic optics are positioned and aligned in machined seats in the barrels and cemented down, which hold axial and lateral misalignments to within 13 μm of the design, well within the micro-optics tolerance indicated in Table 1. The outer diameter of the barrel serves as a datum for centering, and a flange serves as a datum for tip/tilt and alignment along the axis. The sensor module, shown in Fig. 4, consists of the sensor and the associated circuit boards for receiving and transmitting data. The sensor package itself is mounted to a flexible circuit board, which can be translated along the optical axis Attachment of the two components was accomplished by flexible wire clips, which provide compression of the sensor face against the barrel. A fully assembled micro camera is shown in Fig. 5.

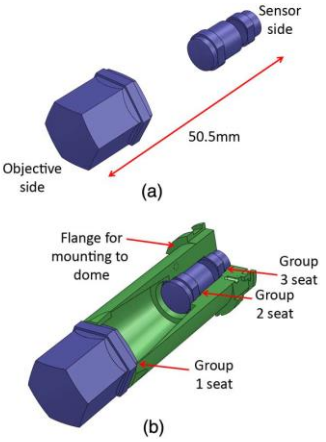

Fig. 3. (a) Solid drawing of micro-optics for AWARE-2. (b) Solid drawing of micro-optics assembled into a cutout barrel.

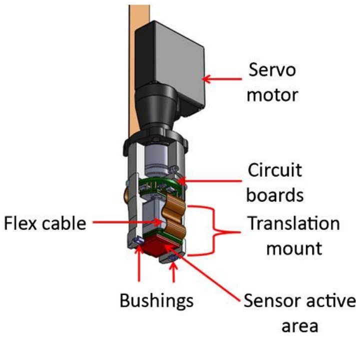

Fig. 4. (Color online) Solid drawing of complete sensor module assembly.

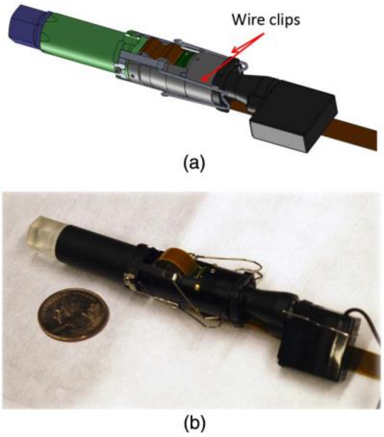

Fig. 5. (Color online) (a) Solid drawing of micro camera assembly. (b) Photo of actual micro camera with a US quarter coin for size comparison.

2.2 Dome Structure

They concluded that for the AWARE-2 system, a passive alignment method based on using a structure machined on a five-axis mill is sufficient. Specialty machine shops can easily obtain tolerances on the order of 25–50 μm and 0.05°, which are well within the subassembly tolerances in Table 1. For the monocentric case, the passive alignment structure follows a spherical dome, which was machined out of aluminum, as shown in Fig. 6. Each micro camera has a corresponding hole in the dome. The micro cameras sit in counterbore holes and are locked down with press fit pins on the sides.

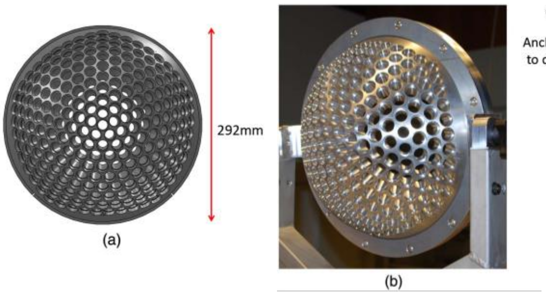

Fig. 6. (Color online) (a) Solid drawing of dome. (b) Photo of actual machined aluminum dome.

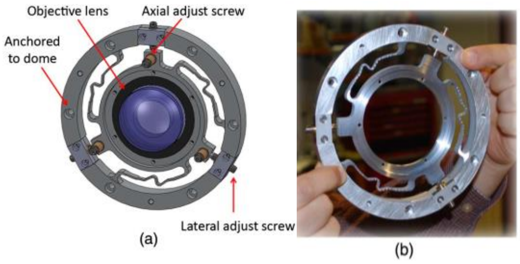

Fig. 7. (Color online) (a) Solid drawing of flexure mount for main objective lens. (b) Photo of machined flexure.

2.3 Objective Lens Mount

An aluminum flexure frame capable of translating the position of the objective lens in all three directions was constructed in case passive alignment strategies proved inadequate (Fig. 7). The flexure is actuated by precision set screws that are able to translate the lens with a resolution of tens of micrometers. Lateral actuation is achieved via two set screws and a third screw to lock the position. Axial translation is actuated by three screws placed directly over the lateral actuation screws.

3. Assembly and Alignment of AWARE-2

Most of the components in AWARE-2 were designed to be passively aligned using machined features for ease of assembly and low assembly costs. However, an active alignment step was required to center the sensor to the micro camera barrel axis to ensure proper image overlap. This alignment procedure and the subsequent installation of the micro cameras into the dome are described below.

The sensor is aligned to the barrel by adjustable bushings. The back of the optics barrel has two alignment pins, which are precisely positioned relative to the axis of the barrel [Fig. 8(a)]. The sensor module has corresponding bushings on its matching side [Fig. 8(b)], which control the lateral and rotational position of the sensor.

Ninety-eight micro cameras capture a 1 gigapixel image with a FOV of approximately 120° × 40°. Insertion of the micro camera into the dome is illustrated in Fig. 9. A clocking pin is used to properly align the orientation of the sensor face for maximum overlap. The micro cameras are held in the dome by press fit roll pins. The face of the counterbore hole in the dome serves as the datum that sets the pointing angle and axial position of each micro camera, while the sidewalls of the body of the hole set the lateral position.

Figure10 shows the assembly process of the AWARE-2 camera system. Figure 13(a) shows the front plate of the camera enclosure that holds the dome that houses the micro cameras and some of the electronics. Figure 13(b) shows the full enclosure completely assembled.

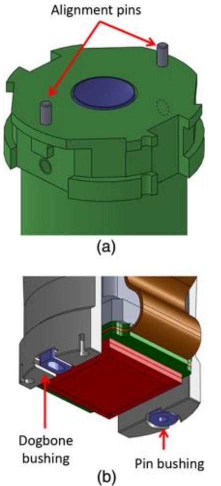

Fig. 8. (Color online) (a) Back of optics barrel showing alignment pins. (b) Front of sensor module showing pin and dogbone bushings.

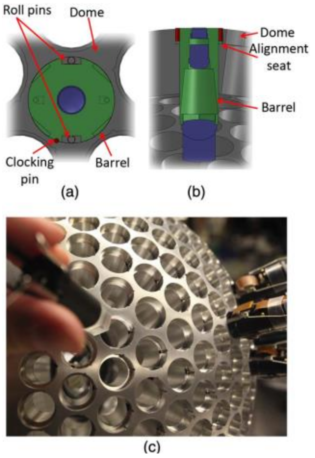

Fig. 9. (a) View from sensor perspective of micro camera retention and clocking mechanisms. (b) Cross-sectional view of micro camera in dome showing how the camera seats into the counterbore. (c) Photo of assembly step

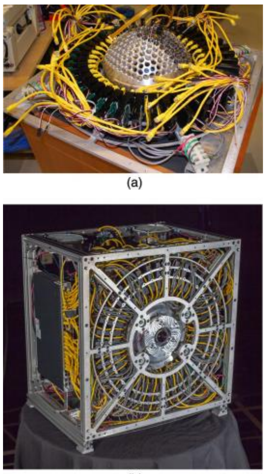

Fig. 10. (Color online) (a) Photo of assembly of camera to front faceplate of enclosure. (b) Full camera in enclosure with electronics

4. Mechanical Stress and Thermal Considerations

A. Mechanical Simulation

To ensure that the weight of the micro cameras does not excessively deform the dome, load simulations were performed in SolidWorks. Each micro camera was modeled as a 41 g weight evenly distributed on the inside surface of the counterbore holes in the dome. Material displacements of less than 1 μm are predicted, indicating that the dome is structurally very rigid.

B. Thermal Simulations

To investigate changes in environmental temperature, a first-order thermal analysis was performed where the system temperature was varied as a uniform thermal bath between 0 °C and 40 °C from an initial temperature of 20 °C. With its spherical symmetry and uniform use of T6061 aluminum throughout the structural components, all the micro cameras in AWARE-2 expand or contract about the center of the dome under uniform temperature variation. The change in BFL for various temperature values and changes in optimized image spot size near the edge of the field for AWARE-2 are shown in Fig. 11. Figure 12 shows the simulated temperature distribution of a symmetric section of the dome in SolidWorks when each micro camera dumps 1 W of heat directly into each hole of the dome.

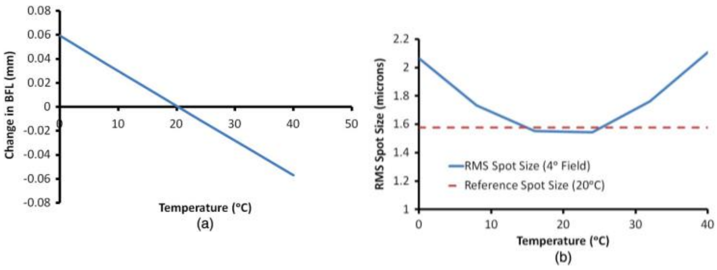

Fig. 11. (Color online) (a) Change in BFL as a function of uniform temperature of dome. (b) Change in spot size at edge of field as a function of uniform temperature of dome.

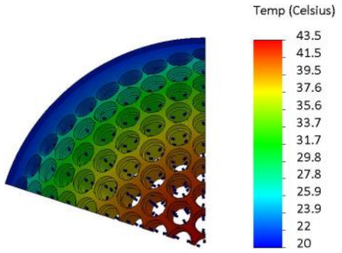

Fig. 12. Temperature gradient induced in dome by internally generated heat from micro cameras. 1 W of heat per micro camera at 20°C room temperature

5. Conclusion

In this work, they have presented general mechanical guidelines for designing a multiscale, gigapixel camera and details on a working prototype based on these principles. Some key points that are currently being investigated for next-generation cameras are the mechanisms for installation and assembly of the micro cameras, micro camera focus, and thermal management. While many challenges remain for higher pixel-count systems, the current 1 gigapixel AWARE-2 is fully operational and has been collecting images at various sites.