Hex Tip-Tilt-Piston Deformable Mirror

Fast and precise control over the angle and piston of various mirror segment arrays

Device Overview

The Hex Tip-Tilt-Piston Deformable Mirror (TTP-DM) was developed for use in fiber coupling applications in which the DM is used to modify the phase and angle of individual beam components to transfer light into a large fiber array. Since its development, its use has expanded to an array of other applications in such areas as biological imaging and astronomy that are much more diverse and varied. The device design is based on BMC's heritage deformable mirror technology that uses hysteresis-free electrostatic actuators to deform a continuous or segmented mirror facesheet. In the case of the Hex-TTP DM, these actuators have been adapted to an array of hexagonal surfaces. A schematic of a seven-segment subsection of a micro-mirror array is illustrated in Figure 1. Each silicon hexagonal mirror segment is supported by attachment posts to three electrostatic actuators. Each group of silicon actuators is situated so that each row is offset from the next, making hexagonal segments each with 3 actuators available to act in concert. In operation, the actuator exerts a downward force on the post. To achieve piston motion for a mirror segment, all three of its associated actuators will be deflected by the same amount. To achieve tilt motion, the actuator deflections will be unequal.

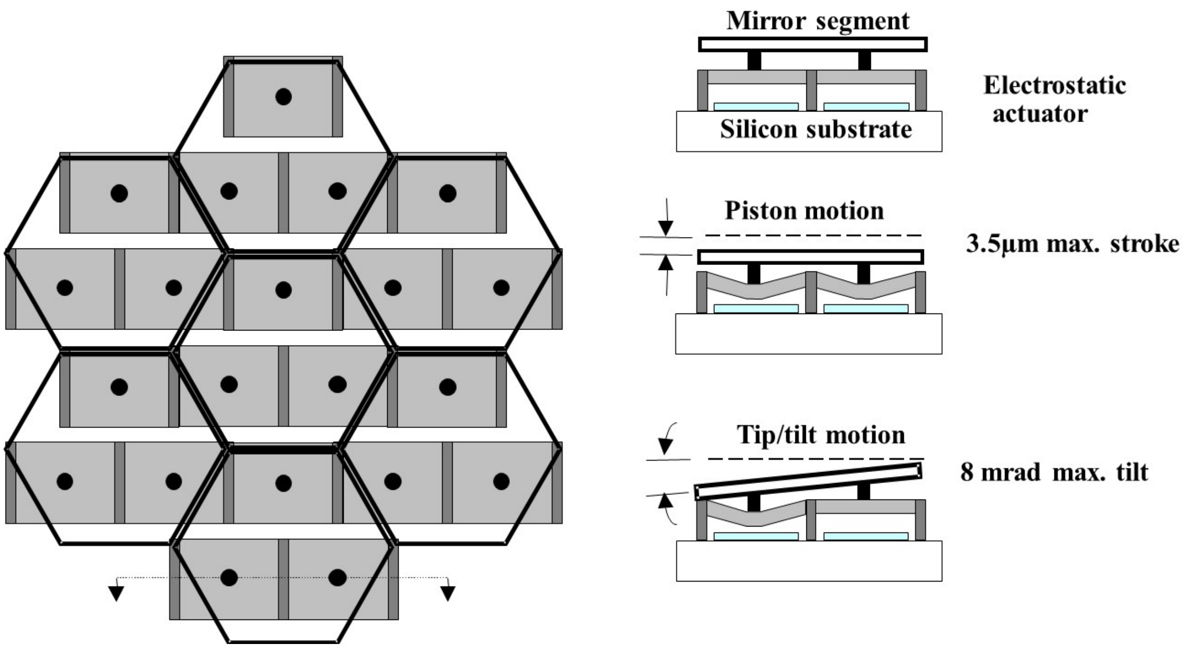


Figure 1. Conceptual schematic of the micromirror array. Hexagonal mirror segments are arranged in a close-packed array, with 2µm spacing between segments to yield a fill factor of 99.2%. Each segment in the array is supported by three posts attached to an underlying array of "double-cantilever" electrostatic actuators. A cross section of one pair of actuators (top right) illustrates the basic parallel-plate design. Common or differential deflection of actuators yield piston or tilt motions of the mirror segment (middle right and bottom right, respectively).

Electrostatics is used to achieve mirror deformation at each actuation point using an actuator, as illustrated in Figure 2. The actuator has an initial gap, ***g***, between the flexure and the fixed electrode. An applied potential, ***V***, results in an attractive electrostatic force that bends the actuator membrane downward. As the flexure bends, an elastic (mechanical) restoring force acts in the opposite direction. At equilibrium, these two forces balance and the equilibrium deflection at the membrane mid-span is ***z***.

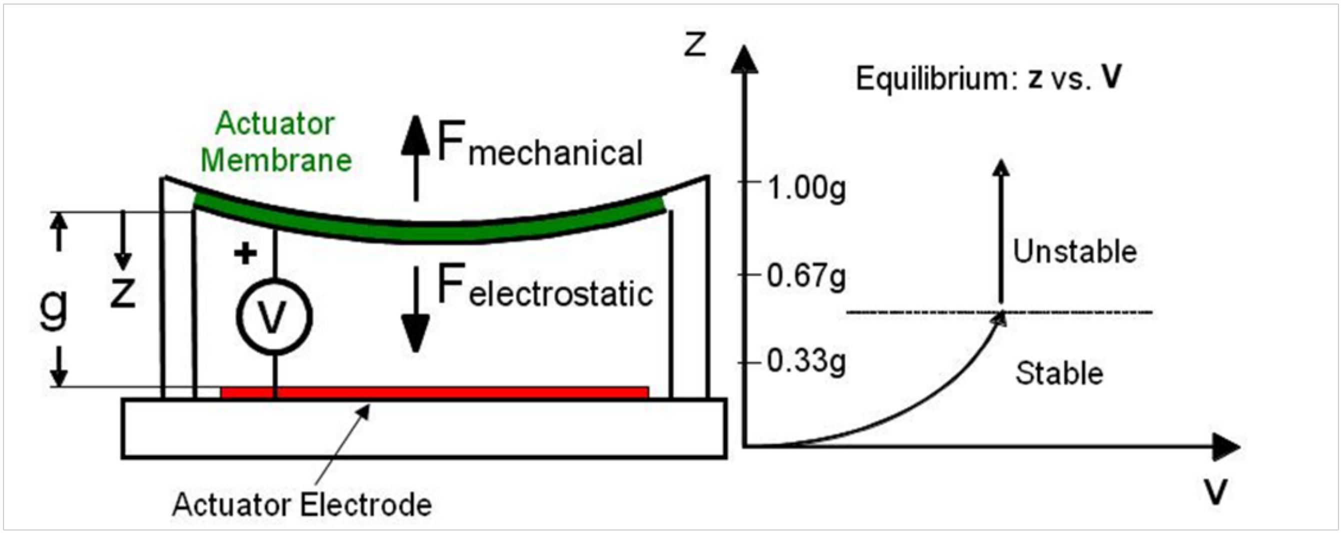
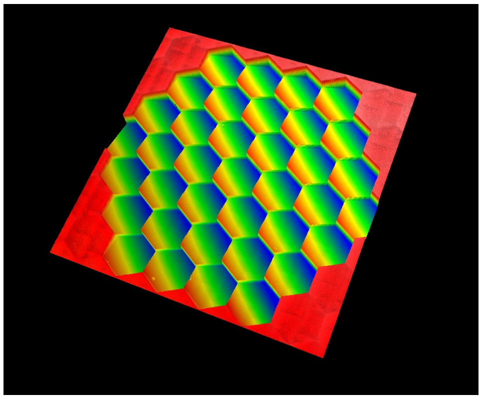
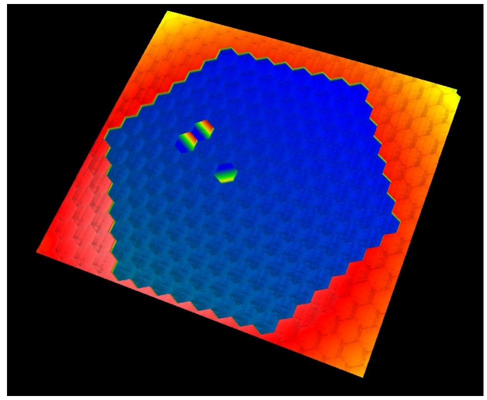


Figure 2. Schematic of electrostatic actuation of a double cantilever actuator used in the MEMS deformable mirror design. The MEMS DM consists of an array of these actuators each supporting a post attached to the back of the segmented mirror facesheet (not shown in illustration).

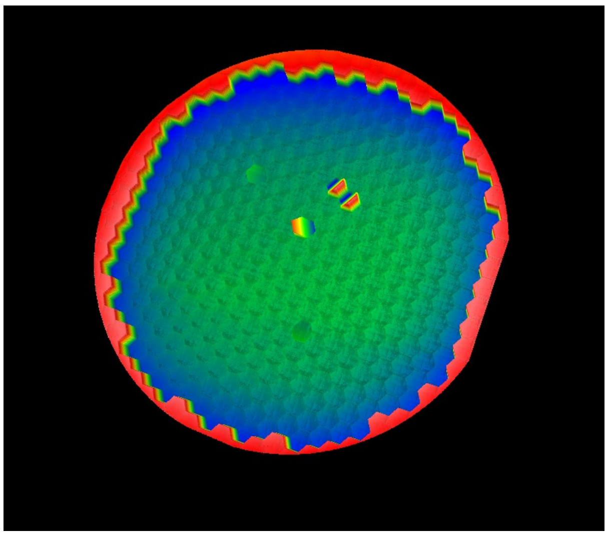
Each actuator can be controlled independently to drive the DM surface to the desired shape. Figure 3 shows examples of actuators in various states on different Hex-TTP DMs. These shapes were achieved by applying pre-defined voltages to each of the actuators resulting in the desired surface deformation.



a) Hex-111 DM, all segments tilted



b) Hex-507 DM, offset with 3 segments tilted



c) Hex-1011 DM, offset with various segments deflected

Figure 3. Surface measurements of example Hex-TTP segmented facesheet DM. Pre-defined voltage maps applied to the device using 14-bit resolution DM drive electronics result various device profiles including a Hex-111 device with all segments tilted (a), a Hex-507 DM offset with three segments tilted at different angles (b) and a Hex-1011 DM offset with select segments tilted and actuated(c).

Device Notation and Electro-Mechanical Performance

The actuators within each segment are defined as actuators A, B and C, shown in Figure 4. Measurements for deflection and tilt can be seen in the subsequent figures. In the figure on the left, +x tilt is being achieved by deflecting the C and B actuators on a given segment by different amounts in order to prevent actuation in the y-direction. In the figure on the right, +y tilt is shown by actuating the B only as it is the sole actuator controlling this deflection in this direction.

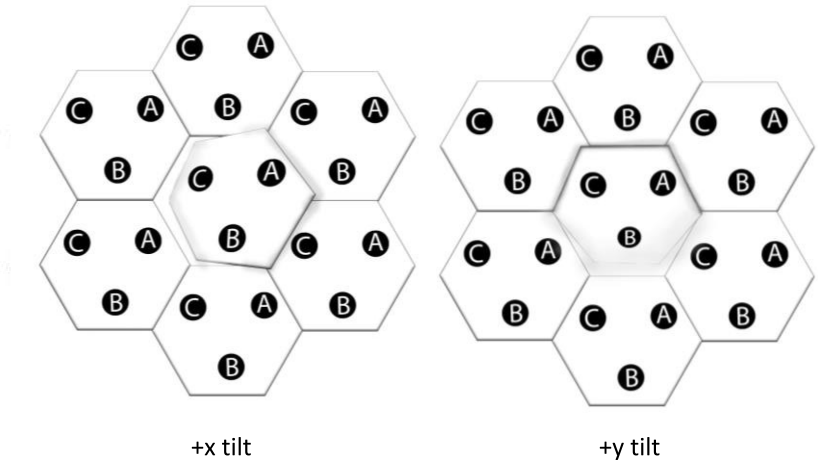


Figure 4. Diagram showing the nomenclature for actuator locations on each segment and definition of tilt direction. +x tilt is defined as deflecting down in the plane in the direction of the "C" actuator. +y tilt is defined as deflecting down in the direction of the "B" actuator.

To evaluate deflection characteristics, a typical segment is pistoned from 0 to its maximum normalized voltage by deflecting each actuator by the same amount, shown in Figure 5. For each measurement, the unpowered shape was subtracted from the measurement of powered shape to produce the data plotted in the command value versus deflection curve. Measurements for tilt in the direction of two actuators, A and B, can be seen in Figure 6.

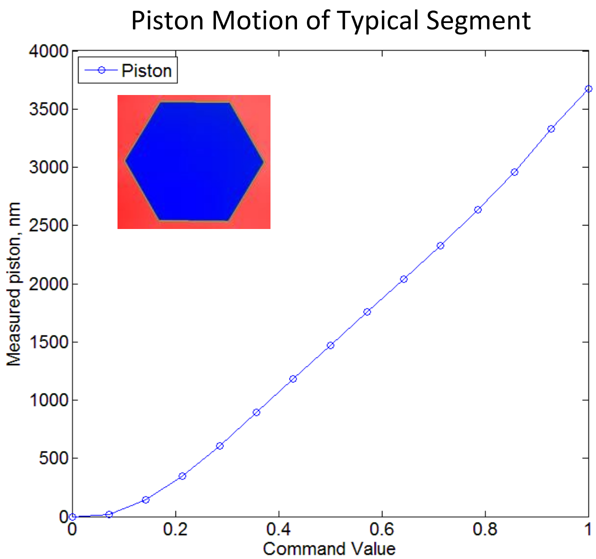


Figure 5. Commanded value versus piston deflection characteristic for a typical segment for zero to maximum command (normalized voltage). The inset image is the actual interferometer profile at maximum command.

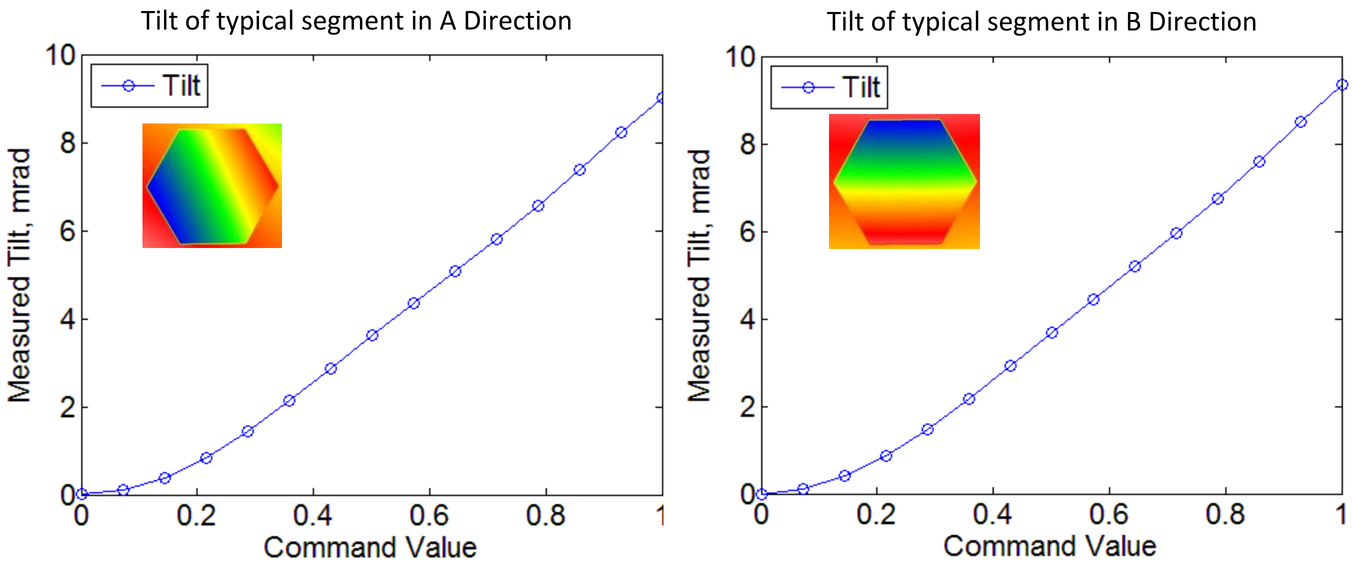


Figure 6. Commanded value versus tilt characteristics for a given segment for actuator A (left), and B (right) The insets are the interferometer profiles at the segment maximum tilt angle.

Device Physical Properties

The most common variant of the Hex-TTP device has 111 actuators, 37 segments, shown below. The active mirror area is supported by an array of electrostatic actuators, spaced at a pitch of 375µm. The active DM area is surrounded by two rows of dummy (inactive) segments required to optimize device optical quality and electromechanical performance when fabricated using MEMS wafers since rounding occurs as you approach the edge of the device. The Hex-111 device is shown below with applicable dimensions noted.

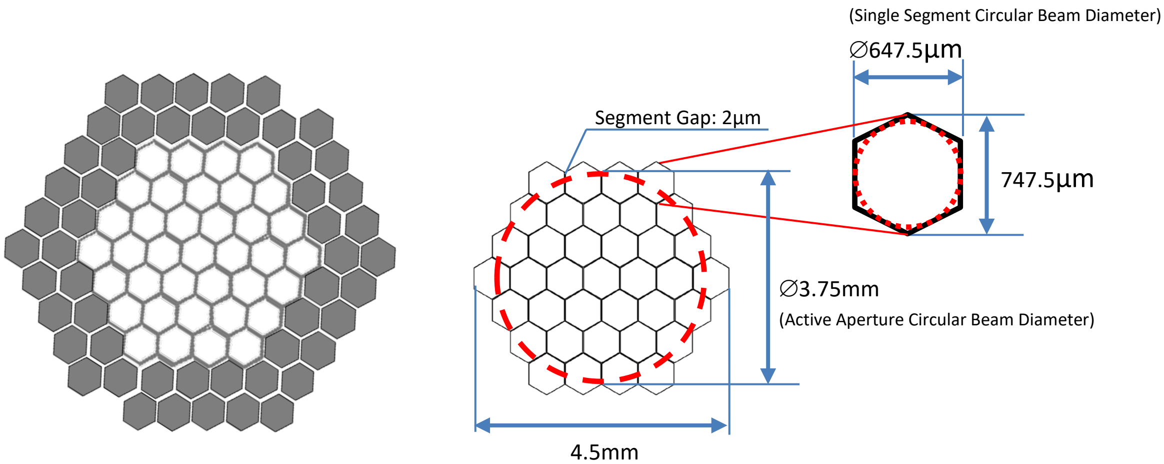


Figure 7. Overview of Hex-111 DM layout. The entire area is shown on the left. Gray segments are inactive and white segments are active. Each segment of the DM consists of three actuators ganged together to act in concert to tip, tilt and piston the segment. The dimensions of the device and each segment are shown on the right.

Device Surface Figure

The Hex-TTP DM surface figure varies from device-to-device. However, BMC maintains a surface flatness over the active area of 30 nm RMS (root mean squared), after flattening. Below are interferometric images of a typical device, unpowered. Shown are the complete surface, a reduced hexagonal sub aperture and a single segment. The best possible flat achievable is the single surface flatness.

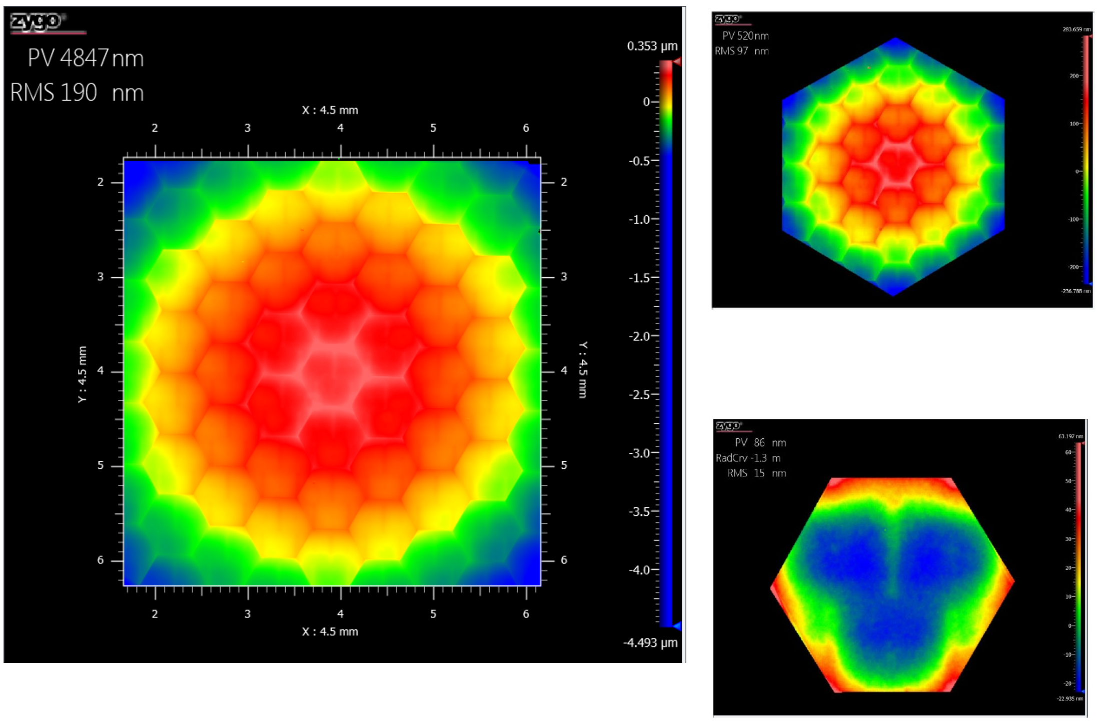


Figure 8. Surface figure of a typical Hex-111 DM. An image of the entire active surface (left) of an unpowered device is shown (190 nm RMS flatness). This device has some surface topography from the manufacturing process. Also shown is a hexagonal sub-aperture (top right, 92 nm RMS flatness)) as well as a single segment (bottom right, 15nm RMS flatness). The surface flatness of the single element is theoretically the best flat achievable for this given device.

The following is the same device shown above that has been actively flattened. As you can see, the images demonstrate that the device has the approximate flatness of a single segment over the active aperture.

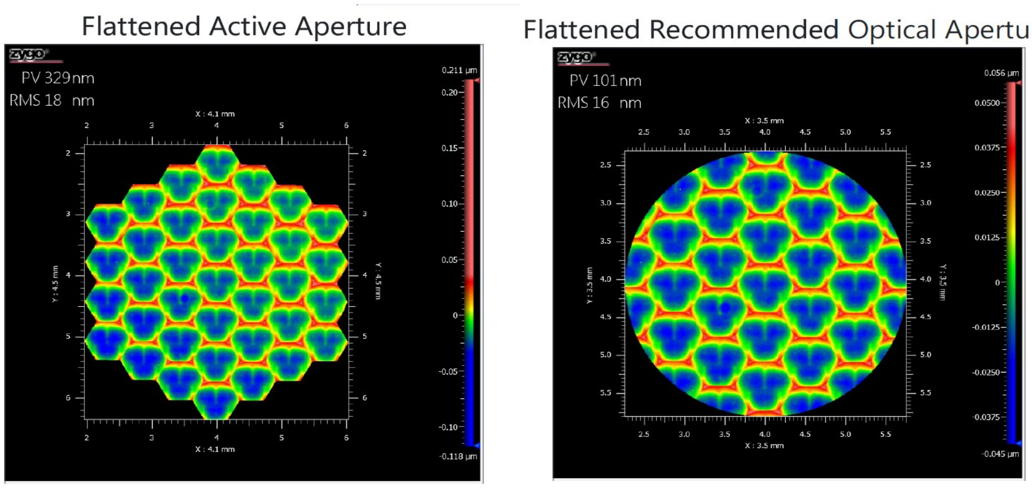


Figure 9. Flattened surface figure of a Hex-111 DM. The active area (left) and the recommended optical aperture (left) are shown. The active area represents the entire area that can be actuated (4.0mm). The recommended optical aperture is the largest circular aperture that is covered by actuated surface area (3.75mm). Images are not on the same scale as the P-V of the total active area is approximately three times that of the optical aperture due to edge effects of the device.

Hex-TTP DM: Array Sizes

The Hex-TTP mirror architecture is available in an array of sizes. Various devices that are currently available are shown below. The deformable mirror device has a segmented mirror facesheet version as shown in Figure 10 below, with an active diameter from 3.75mm to 20.6mm available.

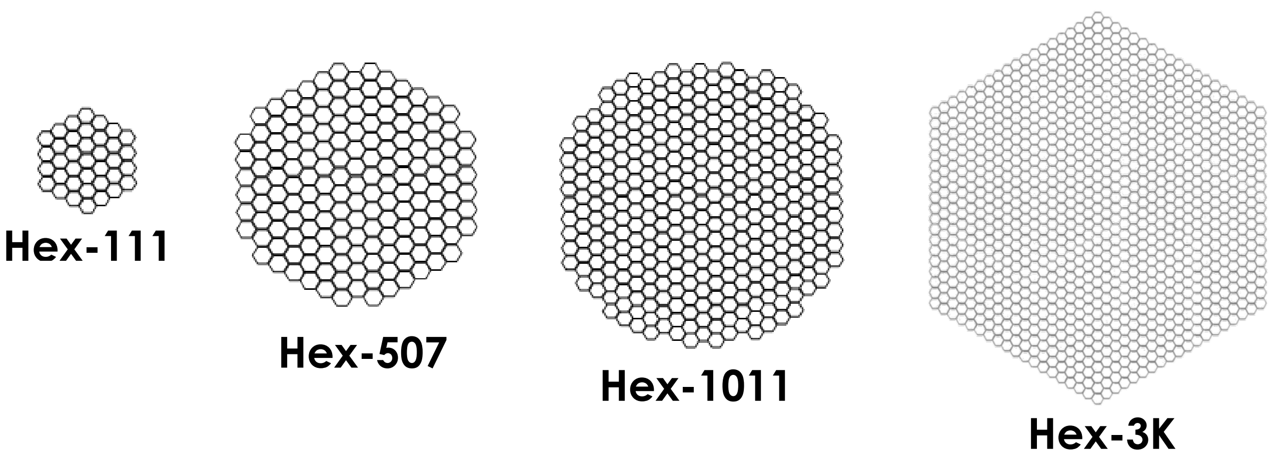


Figure 10. Various standard layouts of Hex-TTP arrays currently available (not to scale). Standard sizes shown have 111, 507, 1011 and 3063 actuators, respectively. Custom sizes are available upon request.

Applications

There is an array of applications in which the Hex-TTP DM architecture is used across applications in microscopy and astronomy. Publications related to these applications are listed below followed by a publication which gives greater detail on the architecture's design.

Applications

Microscopy

Q. Zhang, D. Pan, and N. Ji, "High-resolution in vivo optical-sectioning widefield microendoscopy," Optica Vol. 7, Issue 10, pp. 1287-1290 (2020); doi: https://doi.org/10.1364/OPTICA.397788

C. Rodríguez, A. Chen, J. Rivera, M. Mohr, Y. Liang, W. Sun, D. Milkie, T. Bifano, X. Chen, N. Ji, "An adaptive optics module for deep tissue multiphoton imaging in vivo," bioRxiv 2020.11.25.397968; doi: https://doi.org/10.1101/2020.11.25.397968

S. Leemans, A. Dvornikov, T. Gallagher, and E. Gratton, "AO DIVER: Development of a three-dimensional adaptive optics system to advance the depth limits of multiphoton imaging," APL Photonics 5, 120801 (2020); doi: https://doi.org/10.1063/5.0032621

Flow Cytometry

C. Ba, W. Shain, T. Bifano, and J. Mertz, "High-throughput label-free flow cytometry based on matched-filter compressive imaging," Biomed. Opt. Express 9, 6145-6153 (2018). doi: https://doi.org/10.1364/BOE.9.006145

Astronomy

P. Bierden, S. Cornelissen, C. Lam, T. Bifano, "MEMS Deformable Mirrors in Astronomical AO." Second International Conference on Adaptive Optics for Extremely Large Telescopes. doi: http://ao4elt2.lesia.obspm

Mirror Design

J. Stewart, T. Bifano, S. Cornelissen, and B. Levine, "Design and development of a 331-segment tip–tilt–piston mirror array for space-based adaptive optics," Sensors and Actuators A Physical 138(1):230-238, doi: https://doi.org/10.1016/j.sna.2007.04.051

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