



A Literature Review on the Applications of Deformable Mirror

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Abstract: High resolution space telescopes need large primary mirror. In order to limit weight of this mirror, light weighting is done which will generate gravity and thermo-elastic deformations. These deformations along with alignment errors and mirror fabrication induced errors will result in addition of aberrations in optical wavefront compromising optical image quality. This aberrated wavefront will be corrected by deformable mirror whose shape is adjusted to compensate for aberrations. Optical wavefront. Deformable mirrors (DM) are mirrors with a deformable surface that can be used for wavefront control and optical aberration correction. Adaptive optics use deformable mirrors along with wavefront sensors and real-time control systems. Mirror will be deformed by applying forces away from active surface. This will limit generation of higher order optical aberrations. Thus, the major objective would be to design a deformable mirror that would correct optical wavefront aberrations for a high radial order by using a suitable actuation method. This paper presents a review of deformable mirrors and their different types of mirrors working on different principle and present advantages and test setup with reference to opto-mechanical devices.

Index Terms– *Opto-mechanical, Wavefront Correction, Deformable Mirror, Actuator*

I. INTRODUCTION

Deformable mirrors are mirrors with deformable surface that can be used for wavefront control and optical aberration correction. Adaptive optics use deformable mirrors along with wavefront sensors and real-time control systems. When compensating for dynamic aberrations in the optical system, the shape of a DM can be controlled quickly enough. In reality, the DM form should be modified much more quickly than the process that needs to be corrected because even a static aberration may require numerous repetitions of the correction procedure. A DM typically has a wide range of options. These degrees of freedom are typically connected to mechanical actuators, and one actuator is roughly equal to one degree of freedom. Therefore, a deformable mirror can be utilised to correct more complex types of wavefront distortion in addition to simple optical aberrations like defocus and astigmatism. In the context of adaptive optics, this is especially significant. However, there are also deformable mirrors with very few degrees of freedom and even single-general devices, where the only variable is the focal length; they can be utilised, for instance, in lasers or for the autofocus features of cameras. Deformable mirrors are frequently used in astronomy research, microscopy, imaging for the military, pulse shaping, and laser optimization.

II. FUNDAMENTAL CONCEPT OF DEFORMABLE MIRROR FOR SPACE APPLICATION

The types of fundamental mirror and their wavefront correcting capacities are examined. Mirror meshing and optical influence functions are used to explain the properties of curve fitting. For the entire system, fundamental design equations and finite element models are created. The deformable mirror design has been covered in their study using basic design equations and critical elements that may be traced to system implementations. The optical effect function and Zernike polynomials have been used to provide a quick review and comparison of modal against zonal systems and correctors. In terms of mirror fitting error coefficients, a summary and comparison of zonal mirror types has been made. The design equations are offered to make a first order design easier and to demonstrate how the equations in the mirror design are interdependent. [1]

Cila's most recent optical correction technologies that are applied to astronomical adaptive optics. Based on certain recently explored evolutions, the paper demonstrates how piezo technology can produce big aperture deformable mirrors with a 2.5 m diameter and narrow spacing very high order deformable mirrors as shown in Figure 1. The DM was tested using a 63x63 actuator array by the authors. The results for using various actuator counts, the mirror surface's zygo results, the frequency response of the actuators, and the impact of temperature differences on the mirror as demonstrated by zygo are all presented. [2]

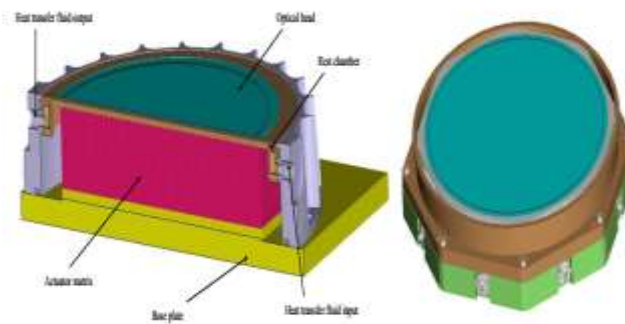


Figure 1: Mirror Assembly used by authors [2]

The primary forces for the construction of DMs—including atmospheric aberration adjustment as well as other factors like the surroundings or mechanical limitations—are recalled in this study by P Y Madec. It also describes the various technologies that are being used to produce DMs, and analyses their advantages and disadvantages. The number of actuators needed, their mechanical strokes, and the deformable mirror's error response are all discussed in this study. Also covered are various potential ideas for deformable mirrors as shown in Figure 2. The current technologies adequately address the DM requirements for telescopes in the 8m class. The current technologies that are available can mostly meet the AO requirements for telescopes in the 40m class, but XAO still need some time for development and experimentation. [3]

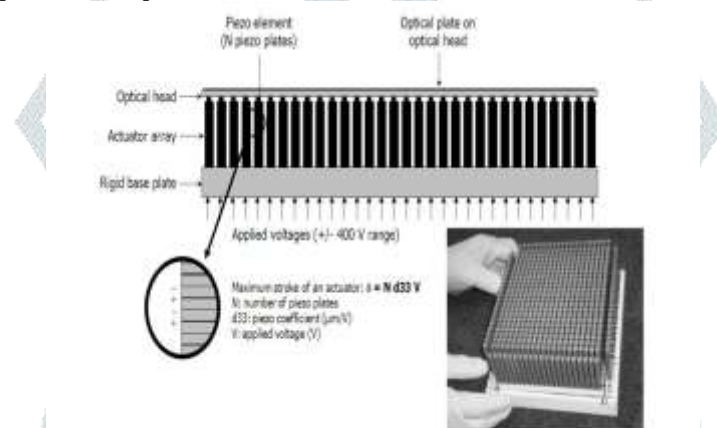


Figure 2: Assembly of DM with optical head [3]

A water-cooled, piezoelectric-actuated deformable mirror system as a phase-correction tool for a high-power laser beam. The mirror and electronics' functionality, key characteristics, and design considerations are presented. Performance characteristics for a cooled, deformable mirror with 52 actuators have been given. In low servo bandwidth applications, the mirror can be utilised as a corrector mirror, while in high servo bandwidth applications, it can be used as a dither mirror as shown in Figure 3. For usage in mid-IR adaptive optical systems, it has a suitable stroke. The 52-channel multi-dither zonal COAT system was intended for and has been successfully employed in high-power laser settings with the cooled all-metal molybdenum deformable mirror. Within the range of measurement accuracy of the diagnostic tools, the performance model accords with the experimental findings. [4]

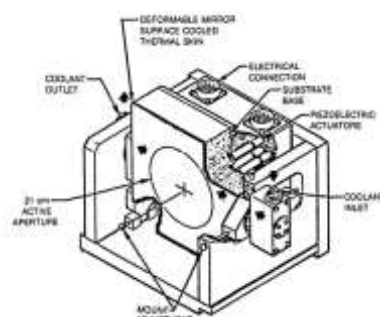


Figure 3: Schematic Diagram of Deformable Mirror Developed [4]

III. DEFORMABLE MIRROR WITH ACTUATORS

The essential characteristics of a nine-electrode bimorph piezoelectric adaptive mirror intended to correct low-order aberrations shown here. This mirror's control coefficients for defocus, astigmatism, pure coma, and spherical aberration as well as the temperature stability of its profile are measured and discussed in the study. The effectiveness of a straightforward adaptive optical system for imaging through turbulence created in a lab is examined. Small telescopes with a diameter of less than 1 m and non-astronomical adaptive optics applications can both benefit from this low-order gadget as shown in Figure 4. A bimorph mirror's primary spatial and temporal characteristics were examined. A straightforward adaptive system was used to test the mirror in order to compensate for turbulence that was created in the lab. While the authors only managed to boost the Strehl parameter in their closed-loop system, the performance of this system demonstrated the potential to improve beam quality in the presence of high turbulence. [5]

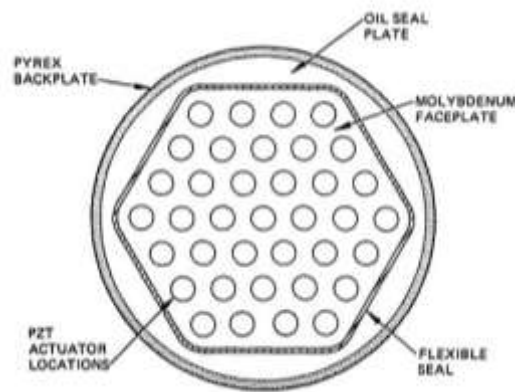


Fig 4: Assembly of Actuators for DM [5]

Measurable features of two alternative deformable mirror designs are given. Each mirror has 37 piezoelectric actuators and is uncooled. The performance measurements of two uncooled deformable mirror designs are presented in their study, along with some of the design and application considerations for such mirrors in multi-dither Coherent Optical Adaptive Technologies (COAT) systems. Two significantly distinct deformable mirrors' performance characteristics have been demonstrated. Both mirror types could be utilized as a corrector mirror in low servo bandwidth infrared (IR) applications or as a dither mirror in high bandwidth applications with a few minor adjustments. However, due to its wide frequency response and ability to be employed for cooled-mirror applications, the all-metal construction is more agreed upon. A large-exursion phase corrector mirror in the infrared can also be made using the same fundamental design, but with less frequency response. [6]

A deformable mirror to eliminate flaws and reduce scattering in localized areas. They have focused on imaging fields with dynamic ranges using this method. They demonstrate that compared to merely eliminating the RMS figure error, the dark-hole approach yields a lower scattering level. They have produced dark holes with rectangular and annular shapes using simulations with a 37X37 deformable mirror and data from Hubble Space Telescope optics without spherical aberrations. A monolithic, fully integrated, high-density deformable mirror that can be employed for this kind of space application is also presented as an early concept by the authors. The authors of this work have demonstrated that scattered light is a barrier to high dynamic range imaging. The use of a deformable mirror on a pupil plane can be used to suppress the scattering in particular places known as black holes. Small error figures in telescope mirrors causes the scattering. By applying a dark-hole algorithm to control the deformable mirror's actuators, adaptive optics can be utilized to cancel scattered light in the focal plane, suppressing it at low spatial frequencies and reducing scattering levels close to the optical axis. Simulations using various geometries of dark holes have produced low scattering levels. [7]

For ophthalmic applications, a unique deformable mirror utilizing 52 magnetic actuators is introduced and discussed. The ability of the apparatus to recreate various surfaces, in particular Zernike polynomials up to the fifth order, is thoroughly examined. The analysis of the deformable mirror's impact functions reveals a sizable linear response to the applied voltage. Additionally, the production of surfaces by the correcting device exhibits remarkable fidelity. Even in the case of severely aberrated eyes, the Zernike polynomials' production ranges completely match those commonly found in the human eye. The resulting ranges are compared to data from keratoconic eyes, demonstrating the deformable mirror's capacity to correct for these severe aberrations. The deformable mirror and an achromatizing lens are used in tandem to correct for the monochromatic and chromatic aberrations. The results from real eyes, including one with 4.66 D of myopia and one with a near pathological cornea with noticeable high order aberrations, demonstrate a nearly complete aberration correction. They have represented the working, principle and application of magnetic deformable mirror as shown in Figure 5. [8]

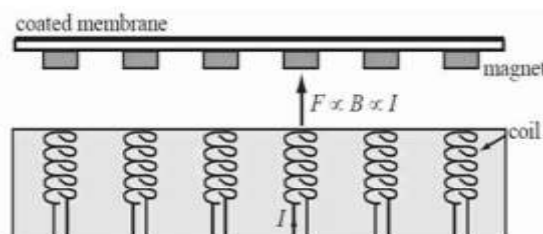


Figure 5: Magnetic Deformable Mirror [8]

A closed-loop system with a tip/tilt mirror and a Shack-Hartmann sensor in the initial phase to address the lateral instability that occurs during through-focus scanning. With this system, they were able to maintain the plane position within a peak-to-valley of 33 nm. The tip/tilt mirror was replaced by a deformable mirror that performs through-focus scanning by deforming its mirror surface in order to create a motion-free through-focus scanning optical microscope that eliminates instability. With a reference TSOM picture library created by a Fourier modal approach and matching various observation conditions, it was shown that the tool had an identification accuracy of 4 nm for critical dimension values in the range of 60-120 nm. [9]

The DeMi mission is a 6U CubeSat that will improve the MEMS deformable mirror hardware's TRL showing its functionality in space environment. DeMi will also show closed-loop wavefront control in space, correcting both swiftly changing tip-tilt faults and slowly fluctuating high-order aberrations. The DM actuators must be controlled and their locations precisely measured in order to achieve the primary goal of proving deformable mirror operation in space. The Shack Hartmann Wavefront Sensor (SHWFS), which uses wavefront reconstruction to measure the optical surface. A 3D-printed version of the DeMi structure was used to do fit-checks and test the optical alignment process. After the initial fit-checks, some changes were made, and a second version was 3D

printed. The 3D-printed model was equipped with optical components, and using a Zygo Verifier QPZ interferometer, the optics were initially coarsely aligned. For the DeMi payload, thermal study was done to determine the temperature ranges that the various parts will encounter throughout the mission. [10]

Here presents a description of the downsized DM driver characterization procedure. The downsized DM driver circuits were tested by the DeMi team using a Zygo interferometer. The DM was put in front of the interferometer in order to detect the actuator displacements directly. The testing approach started with taking a measurement when the DM was turned on but not activated. This measurement was used to take noise from each actuation image during image processing. The actuator displacement was set to 15% and 30% of the maximum voltage for each actuator, and an interferometer measurement was made. The interferometer was unable to reliably measure displacements higher than this. In order to evaluate these measurements, the unactuated measurement was subtracted, the measurement was cropped to include the area around the displaced actuator, and the measurement was then fitted with a Gaussian to determine the size of the displacement. For comparison, a representative sample of the actuators was also tested using the Zygo instrument and the BMC driver. The downsized DM driver has been confirmed to work properly, and the fluctuation in these values is probably caused by measurement error in the interferometer. [11]

For optical applications requiring phase modulation, a silicon-based, micromachined deformable mirror device. The design, construction, and testing of several generations of individual actuators as well as parallel arrays of actuators with segmented/continuous mirrors has been completed as shown in Figure 6. In terms of yield, reproducibility, and frequency response; devices have been discussed. The shooting approach has been used to simulate an electromechanical model of the system numerically, and the results show good agreement with the actual data. A MEMS deformable mirror's early development is discussed in their study. Adaptive optics theoretical and empirical models served as the foundation for the development of the mirror parameters. With a common, reliable actuator, sufficient yield was shown. The results of actuator characterization showed that the device performed at better levels of repeatability and bandwidth. [12]

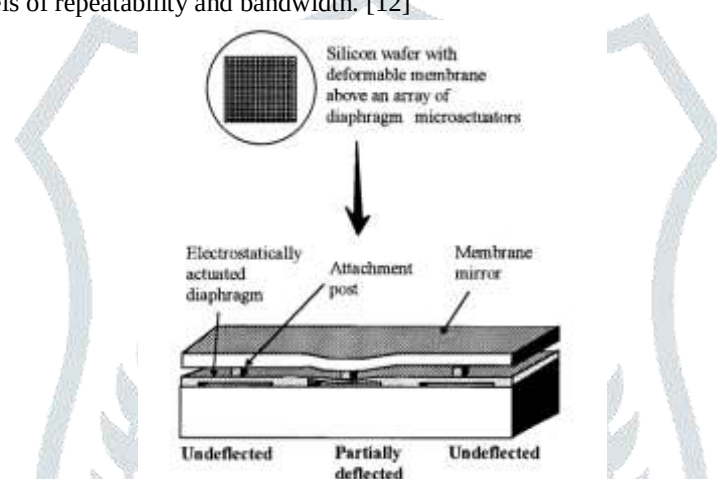


Figure 6: Schematic cross section of a deformable mirror array showing actuator deflection [12]

Two techniques have been used for to characterize deformable membrane reflectors and train adaptive optics systems using these mirrors. In one instance, the deformable mirror employs a quickly convergent iterative method based on orthogonal mirror deformation modes to rectify aberrations caused by a wave-front generator. In the second mirror, fringe analysis and phase-unwrapping methods are applied with an interferometer. The choice of singular values has been proposed as a means of controlling the pseudo-inversion of the control matrix. Characterization of deformable membrane mirror for adaptive optics has also been discussed. Normally, the choice of characterization scheme would be determined by the hardware's accessibility. The interferometric approach presented in this study is more suitable since it relies on common optical laboratory components. The interferometric method, in contrast to the wavefront generator method, also enables greater in-depth analysis of the DMs' performance. [13]

For space imaging missions, a compact Deformable Mirror controller that uses active optics. The volume, weight, and power consumption of the wavefront control hardware has been greatly reduced, resulting in a turnkey solution that lowers mission costs while reducing risk for missions. A new DM controller and a BMC Kilo DM are both used in the miniature wavefront control system. An array of 96 channel High-Voltage Digital Analog Converters ASICs is the basis of the system architecture. A single microprocessor receives a FITS file containing the actuator voltages and simultaneously transmits the orders to each ASIC. This architecture makes it simple to scale up to more actuators. The system is intended to develop into a space-capable version without undergoing significant changes. To prevent outgassing, the majority of the cables are isolated with Kapton. The primary advancements to make a space-capable version are to coat all the electronics and PCBs to prevent outgassing, provide radiation shielding, and make sure that mechanical strain relief is allowed for differential expansion of the PCB and the boards. [14] Listed the outcomes from previously flown missions as well as goals for the upcoming flights. The development of DM driver electronics that can endure the radiation environment of a long-duration space travel requirements is one of the major problems. Using the DM to handle higher order optical aberrations and tip-tilt faults is difficult. The development of DM mounts with tip-tilt control is suggested as a solution to this issue so that these aberrations can be rectified without adding extra path length to the optical design. With a 140-actuator BMC MEMS DM, the DeMi mission seeks to demonstrate wavefront control in orbit.. Their article provides an overview of the technology demonstrations that have been made to enhance this technology for uses with space telescopes. [15]

Developed a low-cost adaptive optics system. Using a single processor, the device runs at frame rates up to 800 Hz while using a membrane mirror with 37 actuators. To optimize system parameters, the membrane mirror is modelled numerically as shown in Figure 7. Using a ferroelectric spatial light modulator-based diffractive wavefront generator, the system's dynamic performance is thoroughly examined. Using the wavefront generator, an experimental evaluation of the system's capacity to compensate for Kolmogorov turbulence at various intensities and effective wind speeds is made. The ideal active optical diameter of the mirror and the impact of the number of spatial modes used on the fitting performance of the mirror were both determined by numerical modelling of the mirror. [16]

A method to correct for slowly fluctuating wavefront aberrations of telescope mirrors, for lowering the surface wavefront error of low-cost multi-meter-diameter mirrors. A technique for active optical correction will use a deformable mirror. The quick production of an affordable, high-quality optical system with dynamic adjustment of the system as the thermal and mechanical environment influences will be made possible by the cost-effective application of active optical compensation technique. An active optical system using a deformable mirror may significantly correct wavefront aberrations of a 0.3-meter telescope caused by either poor mirror quality or external causes. It will be necessary to use a bigger deformable mirror array size to apply this technology to mirrors with multiple meters in diameter. Deformable mirrors that are thermally actuated have shown to be highly affordable and scalable to a large number of actuators. [17]

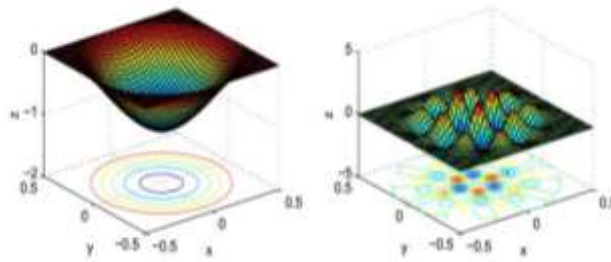


Figure 7: Largest and smallest mode of the membrane mirror [17]

A continuous deformable polymer mirror for adaptive optics which is Lorentz-force actuated. On either side of a stiff crossbar holding a small contact pillar, single crystal silicon flexible serpentine springs are used to create an actuator array that is fastened to the mounting rail. An epoxy-based photoresist is utilized for the mirror for low voltage functioning. High mechanical stiffness and high operation voltage are drawbacks of conventional silicon-based electrostatic DM. The proposed method overcomes it by utilizing Lorentz force and an epoxy-based polymer for the mirror's structural components. The findings of a static performance test indicate a significant push stroke is obtained at extremely low current and voltage. This mechanical reaction would provide a drive frequency of up to 2 kHz. This Lorentz DM may therefore be appropriate for particular applications that demand significant distortion at the expense of slow response times. This paper describes the fabrication techniques of actuators and mirrors. Characterization of actuator mirror deformation at the center as a function of actuator force is obtained by observing actuator movement under a microscope and a low-order Zernike Polynomials is reconstructed. [18]

In order to correct low-order aberrations of deformable mirrors (DMs) in high power laser applications used a new moment actuator. A flattening technique is usually necessary to correct for the DM's low-order aberrations, which inevitably limits the actuator's remaining stroke. In this study, the authors offer 16 bending moment actuators that are inserted at the baseplate for independent correction of the DM's low-order aberration. As a result, the high-order compensation uses the entire dynamic range of the intrinsic actuators. Utilizing a novel theoretical influence function, the moment actuator's configuration is optimized. When weighted IF is computed, the authors presented a coupling coefficient for the moment actuator and demonstrated improved correlations with experiments. An in-house DM is fabricated to confirm the experimental performance of the bending moment actuator as shown in Figure 8. [19]

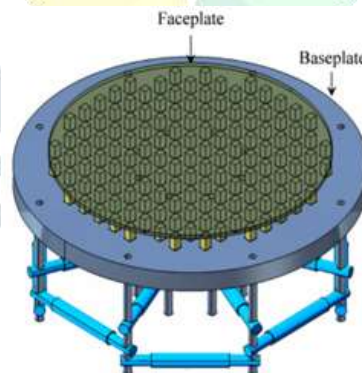


Figure 8: DM with Bending Moment Actuator [19]

The Modal Deformable Mirror based on the continuous voltage distribution over a resistive layer. The DM corrects spherical, coma and low order aberrations, which reduces the need for high voltage. By providing a mathematical description of the mirror, an experimental characterization, and a comparison with discrete actuator DMs, technological benefits have been shown. The experimental findings for picture sharpening optimization have been presented. Demonstration of how the distributed actuator technique can be used to implement a modal deformable mirror with the introduction of a modal control of low order aberrations with outstanding quality and linearity while using the fewest possible electrodes is presented. [20]

IV. WAVEFRONT CORRECTION FOR THE DEFORMABLE MIRROR

An optical system solution using a high precision deflectometry system (DS) operated deformable mirror (DM). The DS and DM are configured to be an independent integrated DCDM unit and can be mounted in a single base plate. Any adaptive optics system can use the DS to directly supply the industrial computer in the DCDM unit with the influence functions and surface shape of the DM. The DCDM unit can be used in optical systems to achieve aberration adjustment as shown in Figure 9. The DCDM unit's configuration and operating concept are also explained in the study. A theoretical simulation of the DCDM unit's close-loop performance is run. [21]

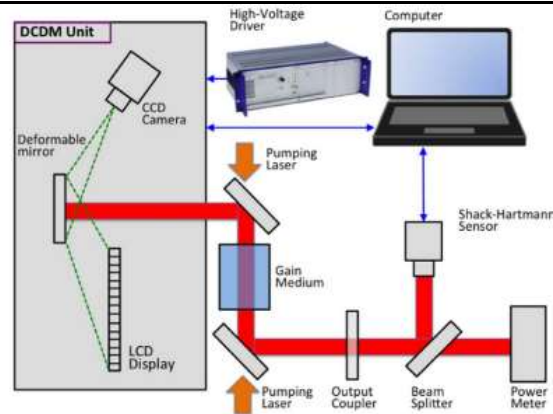


Figure 9: Layout of DCDM Unit [21]

The creation of a new deformable mirror technology in this research study. The mirrors were created with consideration for the requirements of ultra-intense laser applications. Their primary characteristics are that no power is needed to maintain shape, so no heat is produced; the shape is perfectly stable over time, but the correction speed is only around 1 Hz; dynamic range is very large, and residual is very small in comparison to current technologies; no footprint effect is anticipated; technology is easily scalable to produce large mirrors; and design allows for simple removal and replacement of the optical surface as shown in Figure 10. This study represents the principle of mechanical deformable mirrors, mechanical characterization and dynamic range for different zernike errors in μm . [22]

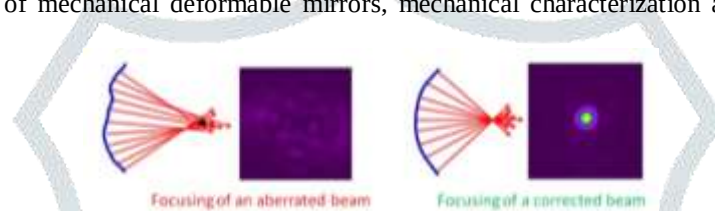


Figure 10: Wavefront Correction [22]

Atmospheric turbulence in free space optical (FSO) communication systems is compensated using deformable mirrors (DM) in adaptive optics (AO) systems. The combinational-deformable-mirror (CDM) adaptive optics (CDM-AO) system is established to rectify wave-front aberrations and increase coupling efficiency at the receiver in order to get rid of the restrictions generated by the characteristics of deformable mirror (DM) itself. Analysis of the FSO communication system's performance reveals a rise in the average coupling coefficient and a decrease in energy dissipation. [23]

The piezoelectric deformable mirror (DM) for adaptive optics (AO) applications is described in this study. It has a silicon mirror powered by 61 unimorph micro actuators. Low-order Zernike modes up to the 14th term were replicated to show the DM's capacity to correct. Additionally, a 633 nm helium-neon laser system was rectified for close-loop laser beam. After compensating for system aberrations, a focus point that was obtained. The authors have successfully created a low initial aberration piezoelectric DM based on a unimorph micro actuator array as shown in Figure 11. A Twyman-Green interferometer-based setup was created to evaluate the performance of the DM. Replicated low-order Zernike aberrations up to the fourteenth term showed how effectively the device can correct low-order Zernike aberrations as shown in Figure 12. A successful close-loop correction in a 633 nm helium-neon laser system was accomplished. [24]

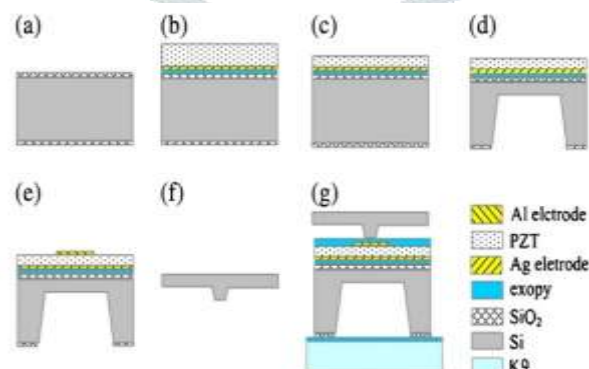


Figure 11: Fabrication of Piezoelectric DM [24]

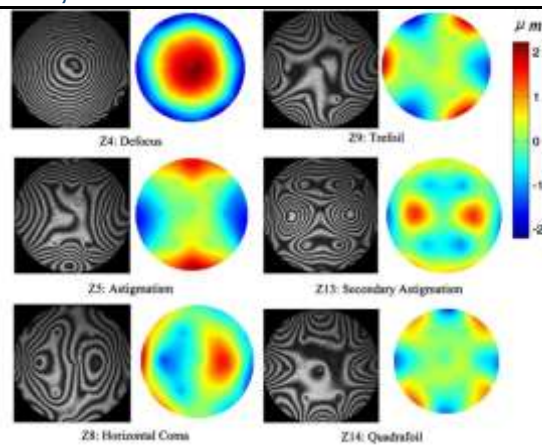


Figure 12: Comparison between interferogram and profile of Zernike modes [24]

The concept for the predictive control of thermally induced wavefront aberrations in optical system. The proposed adaptive optics controller can predict and correct future aberrations based on a model of thermally induced wavefront aberrations and utilizing just previous wavefront measurements. Additionally, the suggested controller can rectify wavefront aberrations even when some model parameters are unknown. In high power optical systems, where the predictive correction of thermally generated wavefront aberrations is a key concern, the proposed control method can be applied. Demonstration of the principle of TIWA predictive correction in optical systems is done. [25]

A deformable mirror using thermoelectric cooler (TEC) actuators. The actuators' reaction mechanisms are investigated. Additionally, a close-loop wavefront control experiment is carried out in which the astigmatism and defocus were adjusted. According to the findings, it can conclude that the design will be used to fix static aberrations. The TEC actuator has access to both heating and cooling driving power, making it possible to regulate the mirror's upward and downward surface shape. An open-loop flattening experiment was the initial step in evaluating the mirror's capacity to correct. In the end, a close-loop wavefront correction experiment was carried out to finish correcting the astigmatism and defocus as shown in Figure 13. Even though the thermal DM's reaction is somewhat slow, there is a good chance that the design will be deployed in situations with static aberrations. [26]

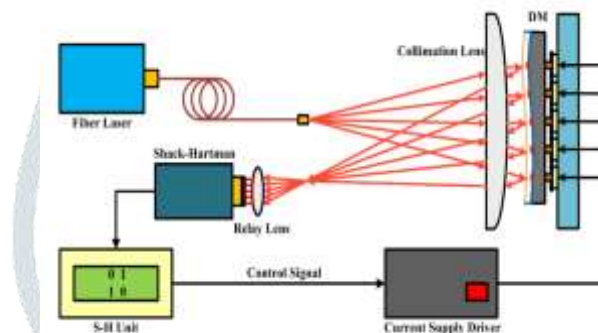


Figure 13: Configuration of the Wavefront correction system [26]

The mirror may bend when thermomechanical actuators are positioned perpendicular to the surface. Two deformable mirrors—one with seven actuators and the other with 19—are modelled, implemented, and validated. The force loop is confined and a reduced actuator connection is accomplished by mounting the actuators on a thin back plate. As a result of no mechanical hysteresis, thermomechanical actuators have excellent position resolution and good repeatability. To increase actuator stroke and decrease input power, extensive Finite Element Analysis is performed. With the help of thermocouple temperature measurements and interferometer surface measurements, the mirrors are examined and validated. [27] demonstrates an analytical solution for the unique class of upwards-concave profiles to the well-known issue of computing a focusing mirror PSF from the profile defects. A significant advantage is the ability to reverse the formalism and derive a mirror profile deformation from a desired PSF. This can sometimes be accomplished analytically and always numerically. The resultant profile is the simplest one that can be produced, and as it lacks undulations, it should be feasible to recreate it. The profile will only show kinks that may make shaping more challenging if a PSF shows gaps. [28]

In order to address the unidentified dynamic aberrations, there are two phases in the design of this adaptive controller. Designing the J block, which is utilized to choose a non-adaptive control system configuration for attenuating the random signals, is the initial stage. The second stage then adds the Q block, an adaptation mechanism whose goal is to establish regulation for unidentified deterministic dynamic signals, to the J block. In order to adjust the parameters online to the desired values that can accomplish regulation against the deterministic signals, a recursive least squares (RLS) method with forgetting factor is applied. The experimental findings show that the suggested adaptive controller can successfully handle the unidentified dynamic aberrations. [29] The experimental setup used is shown in the Figure 14.

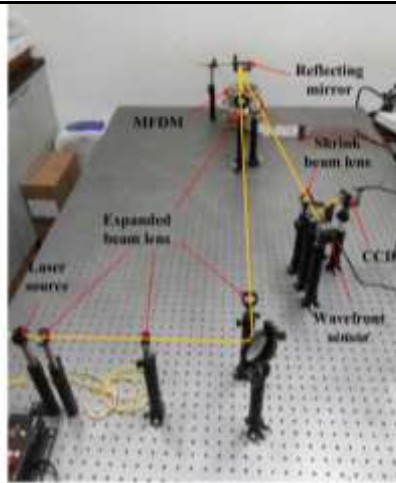


Figure 14: Experimental Setup used [29]

V. CONCLUSION

This literature review includes details on various kinds of deformable mirrors, their uses and their applications in different aspects of technology. The study shows an examination of different such articles. It can be concluded that mirrors have several space applications for focusing of images, mirror geometry, and mirror design. This work also includes critical test setup design, selection criteria for actuators. The paper also gives an insight to how a deformable mirror can be applicable in different application. Therefore, this review article would prove beneficial for future researchers and reviewers.

REFERENCES

- [1] Mark A. Ealey, John Wellman (1989), "Fundamentals of Deformable Mirror Design and Analysis," Proc. SPIE 1167, Precision Engineering and Optomechanics; doi: 10.1117/12.962930
- [2] Jean-Christophe Siquin, Jean-Marie Lurçon, Claude Guillemard (2008), "Deformable mirror technologies for astronomy at CILAS," Proc. SPIE 7015, Adaptive Optics Systems, 70150O; doi: 10.1117/12.787400
- [3] P.-Y. Madec (2012), "Overview of deformable mirror technologies for adaptive optics and astronomy," Proc. SPIE 8447, Adaptive Optics Systems III, 844705; doi: 10.1117/12.924892
- [4] Freeman, R. H., & Garcia, H. R. (1982). High-speed deformable mirror system. *Applied Optics*, 21(4), 589-595.
- [5] Dainty, J. C., Koryabin, A. V., & Kudryashov, A. V. (1998). Low-order adaptive deformable mirror. *Applied optics*, 37(21), 4663-4668.
- [6] Pearson, J. E., & Hansen, S. (1977). Experimental studies of a deformable-mirror adaptive optical system. *JOSA*, 67(3), 325-333.
- [7] Malbet, F., Yu, J. W., & Shao, M. (1995). High-dynamic-range imaging using a deformable mirror for space coronagraphy. *Publications of the Astronomical Society of the Pacific*, 107(710), 386.
- [8] Fernández, E. J., Vabre, L., Hermann, B., Unterhuber, A., Považay, B., & Drexler, W. (2006). Adaptive optics with a magnetic deformable mirror: applications in the human eye. *Optics Express*, 14(20), 8900-8917.
- [9] Lee, J. H., You, B. G., Park, S. W., & Kim, H. (2017). Motion-free TSOM using a deformable mirror. *Optics Express*, 28(11), 16352-16362.
- [10] <https://directory.eoportal.org/web/eoportal/satellite-missions/d/demi>
- [11] Holden, B., et. al. (2015). Calibration and Testing of the Deformable Mirror Demonstration Mission (DeMi) CubeSat Payload.
- [12] Mali, R. K., Bifano, T. G., Vandelli, N., & Horenstein, M. N. (1997). Development of microelectromechanical deformable mirrors for phase modulation of light. *Optical Engineering*, 36(2), 542-548.
- [13] Booth, M., Wilson, T., Sun, H. B., Ota, T., & Kawata, S. (2005). Methods for the characterization of deformable membrane mirrors. *Applied optics*, 44(24), 5131-5139.
- [14] Bendek, E., Lynch, D., Pluzhnik, E., Belikov, R., Klamm, B., Hyde, E., & Mumm, K. (2016). Development of a miniaturized deformable mirror controller. In *Adaptive Optics Systems V* (Vol. 9909, pp. 2321-2332). SPIE.
- [15] Morgan, R. E., et. al. (2017). MEMS deformable mirrors for space-based high-contrast imaging. *Micromachines*, 10(6), 366.
- [16] Paterson, C., Munro, I., & Dainty, J. C. (2000). A low-cost adaptive optics system using a membrane mirror. *Optics express*, 6(9), 175-185.
- [17] Hemmati, H., Chen, Y., & Crossfield, I. (2006). Telescope wavefront aberration compensation with a deformable mirror in an adaptive optics system. In *Free-Space Laser Communication Technologies XVIII* (Vol. 6105, pp. 177-180).
- [18] Park, B., Afsharipour, E., Chrusch, D., Shafai, C., Andersen, D., & Burley, G. (2017). A low voltage and large stroke Lorentz force continuous deformable polymer mirror for wavefront control. *Sensors and Actuators A: Physical*, 280, 197-204.
- [19] Ahn, K., & Kihm, H. (2016). Moment actuator for correcting low-order aberrations of deformable mirrors. *Optics and Lasers in Engineering*, 126, 105864.

- [20] Bonora, S. (2011). Distributed actuators deformable mirror for adaptive optics. *Optics Communications*, 284(13), 3467-3473.
- [21] Huang, L., Zhou, C., Zhao, W., Choi, H., Graves, L., & Kim, D. (2017). Close-loop performance of a high precision deflectometry controlled deformable mirror (DCDM) unit for wavefront correction in adaptive optics system. *Optics Communications*, 393, 83-88.
- [22] Lefaudeux, N., Levecq, X., Dovillaire, G., Ballesta, J., Lavergne, E., Sauvageot, P., & Escolano, L. (2011). Development of a new technology of deformable mirror for ultra-intense laser applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 653(1), 164-167.
- [23] Li, Z., Cao, J., Zhao, X., & Liu, W. (2014). Combinational-deformable-mirror adaptive optics system for atmospheric compensation in free space communication. *Optics communications*, 320, 162-168.
- [24] Ma, J., Liu, Y., Chen, C., Li, B., & Chu, J. (2011). Deformable mirrors based on piezoelectric unimorph micro actuator array for adaptive optics correction. *Optics Communications*, 284(21), 5062-5066.
- [25] Haber, A., Polo, A., Maj, I., Pereira, S. F., Urbach, H. P., & Verhaegen, M. (2013). Predictive control of thermally induced wavefront aberrations. *Optics express*, 21(18), 21530-21541.
- [26] Huang, L., Ma, X., Gong, M., & Bian, Q. (2015). Experimental investigation of the deformable mirror with bidirectional thermal actuators. *Optics express*, 23(13), 17520-17530.
- [27] Ravensbergen, S. K., Rosielle, P. C. J. N., & Steinbuch, M. (2013). Deformable mirrors with thermo mechanical actuators for extreme ultraviolet lithography: design, realization and validation. *Precision Engineering*, 37(2), 353-363.
- [28] Spiga, D., Raimondi, L., Svetina, C., & Zangrando, M. (2013). X-ray beam-shaping via deformable mirrors: Analytical computation of the required mirror profile. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 710, 125-130.
- [29] Wu, Z., Qian, F., Wang, Y., Wu, J., Dziki, M., & Zhang, Z. (2017). Decentralized Youla parameterized adaptive regulation with application to surface shape control for magnetic fluid deformable mirrors. *Mechatronics*, 68, 102346.

