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DIY Deformable Mirrors for Focal Spot Optimisation in a High Energy Laser System

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1. Background

Deformable Mirror

- A deformable mirror (DM) is an adaptive element, the shape of its reflective surface can be altered locally using an array of actuators (Fig.1).
- The actuators are made of a piezoelectric material which exhibits a mechanical strain (displacement) when subject to an electric field (potential difference) [1].

Optical Aberrations

- Optical systems are subject to static and thermal aberrations due to misalignments and local changes in the refractive index respectively.
- The aberrations distort the wavefront which leads to a non-optimum focal spot.
- This reduces the intensity at the target ($I \propto r^{-2}$).

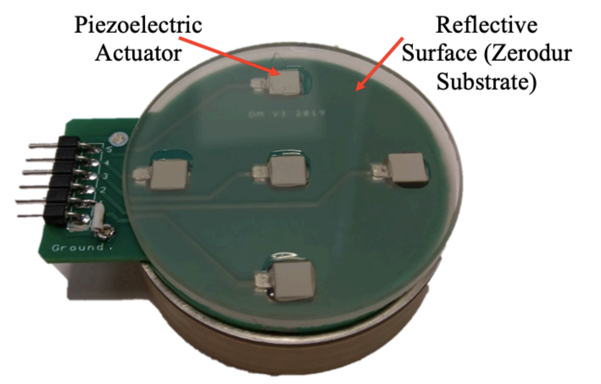

Figure 1: The 5-actuator piezostack deformable mirror built in house at Imperial College London used in this project. It has a 50mm optical diameter and a 3μm stroke.

2. Objective

- To **optimize the focal spot (maximise intensity)** of the Cerberus **high energy laser system** by **correcting the wavefront** of the laser beam using a DIY **deformable mirror (DM)** built in house at Imperial College London.
- The DM is built in house as commercial DMs either have a low damage threshold ($\sim 10^8\ Wcm^{-2}$) [2] compared to the peak performance of Cerberus ($\sim 10^{11}\ Wcm^{-2}$) or are too expensive (£60,000-£100,000) [3].

3. Method – Genetic Algorithm

An adaptive optics (AO) loop consisting of a **DM**, a **focal spot camera** and a **genetic algorithm** was used to correct the wavefront of the laser beam.

Genetic Algorithm

A genetic algorithm (GA) is a stochastic algorithm that uses the concept of natural selection to find the "fittest" or best solution.

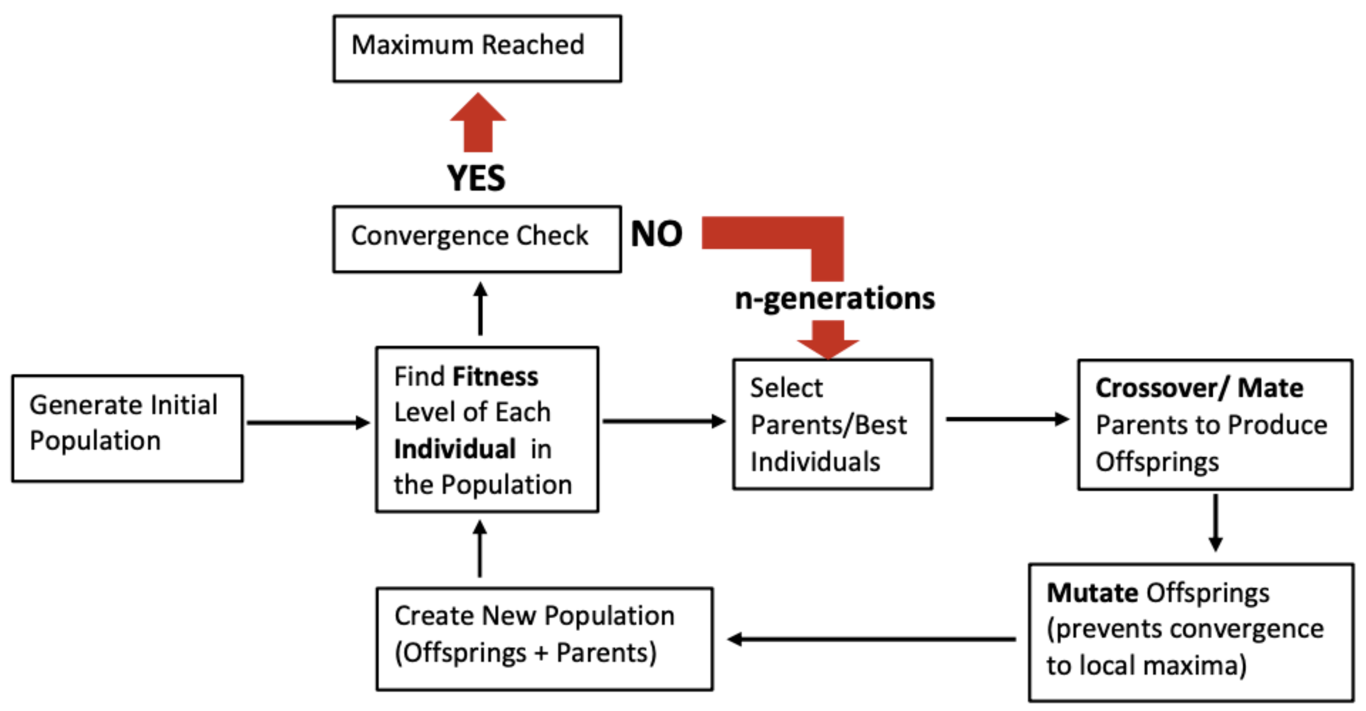

Figure 2: Block diagram for the Genetic Algorithm built for the project in Python.

Key Terms:

- **Individual:** Specific configuration of the mirror surface
- **Fitness:** How "good" is the focal spot corresponding to the mirror surface
- **Genes:** The 5 voltage values sent to the actuators for each mirror configuration
- **Crossover:** Swapping genes between the best individuals (parents) to produce offspring
- **Mutate:** Randomly change the value of a gene of an offspring

4. Method – Setup

Fitness of a Focal Spot

- A "good" focal spot must be compact and circular to maximise intensity.
- Fitness was measured by taking the sum of the pixel values squared from the CCD image of the focal spot.

$$Fitness = \sum_{i=1}^{no.\,of\,pixels} \frac{(pixel_i - background_i)^2}{pixel_{total}} \propto Intensity^2$$

Setup and Adaptive Optics Loop

- The optical setup in the laboratory projected the laser beam (532nm) onto the DM, the beam was then focused onto a CCD focal spot camera (Fig. 3).

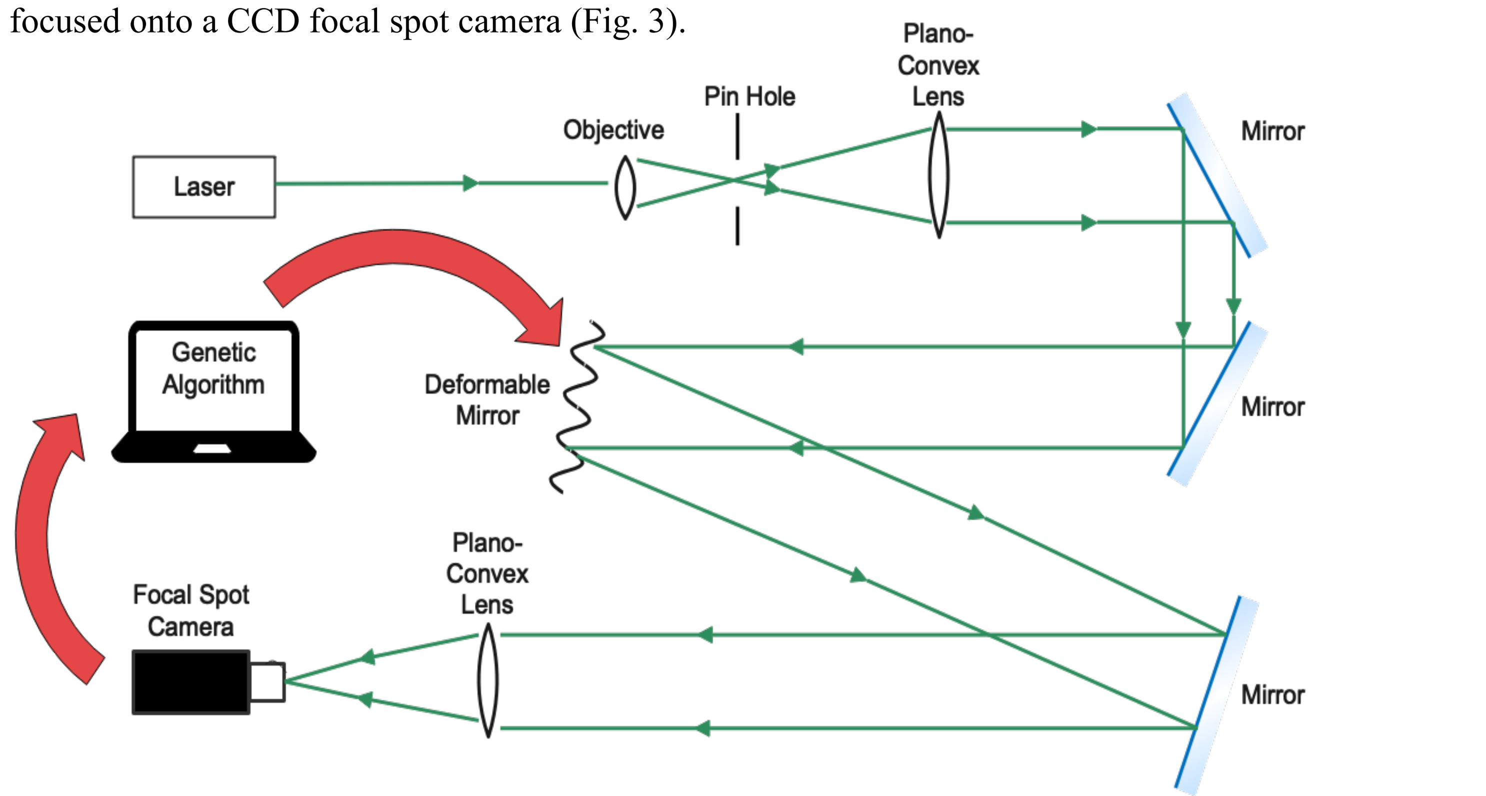

Figure 3: Optical setup in the laboratory connected to the remote desktop (Genetic Algorithm).

- A remotely situated desktop ran the GA which communicated with the DM to change the mirror surface.
- The image taken by the camera was then sent to the GA to calculate its fitness.

5. Results – I

- The adaptive optics system was successful in correcting cylindrical and cylindrical-defocus aberrations in the system (Fig. 4).
- These are the most common aberrations in the Cerberus system.

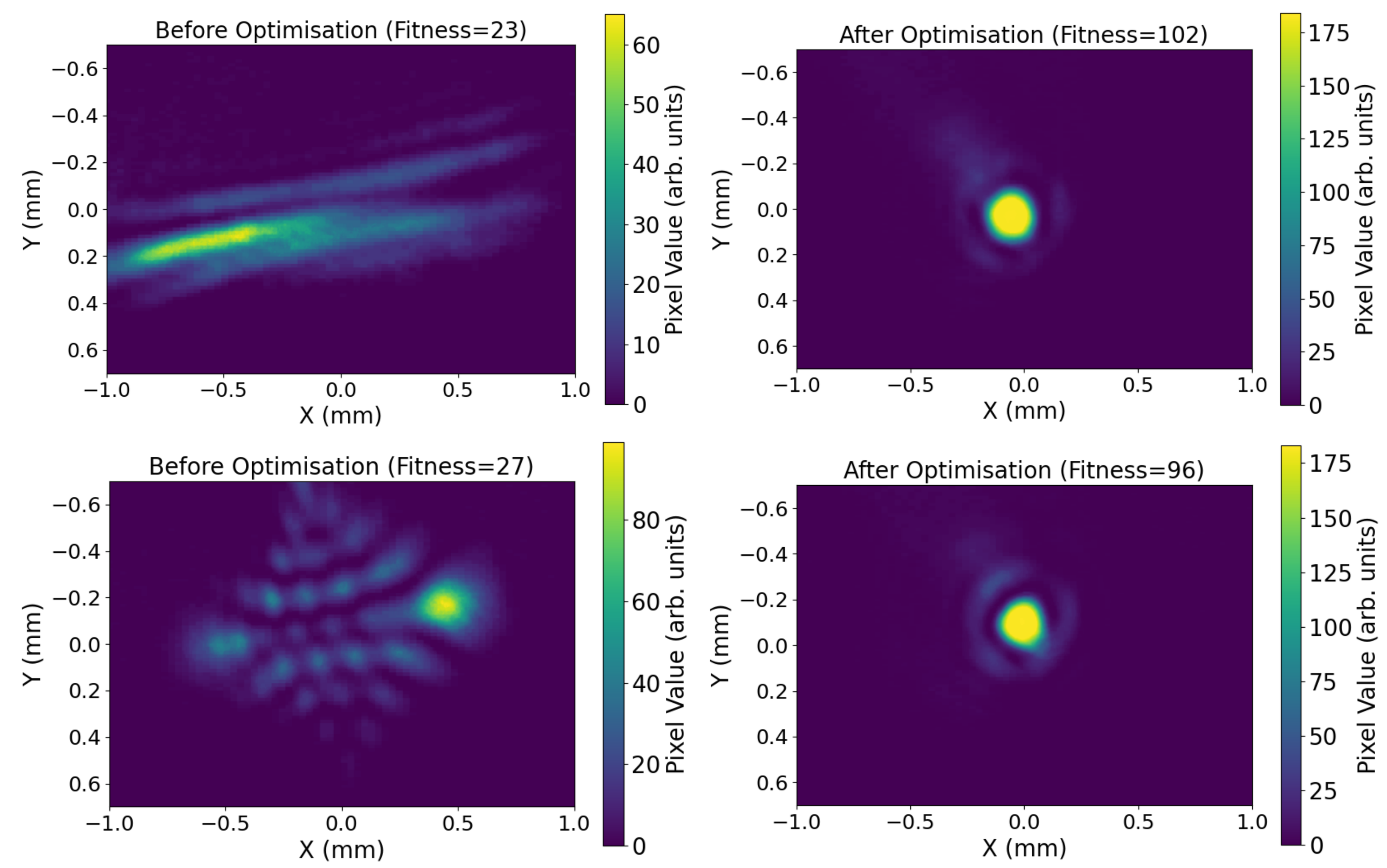

Figure 4: Focal spot of laser beam before (left) and after (right) optimisation using the adaptive optic system. The top row shows the optimisation of a cylindrically aberrated spot and the bottom row shows the optimisation of a cylindrically-defocused spot.

6. Results – II

- The GA was able to **increase the focal spot intensity (I)** on average by a **factor of 9** (Fig. 5)

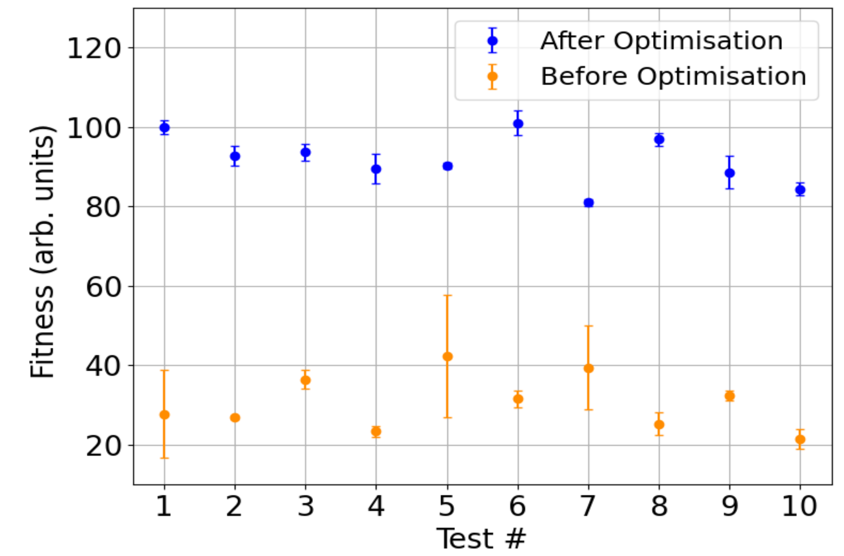

Figure 5: i) Graph of the Fitness of the focal spot before and after optimization for 10 consecutive optimization runs. The error bars represent the the standard deviation of the fitness parameter averaged over 5 images.
ii) On average factor of 3 improvement in fitness and factor of 9 increase in intensity.
$Fitness \propto Intensity^2$

7. Finite Element Analysis

- Finite element analysis (FEA) was found to be a useful tool to simulate the surface deformations of the DM by subdividing the DM into smaller parts and applying forces at the locations of the actuators.

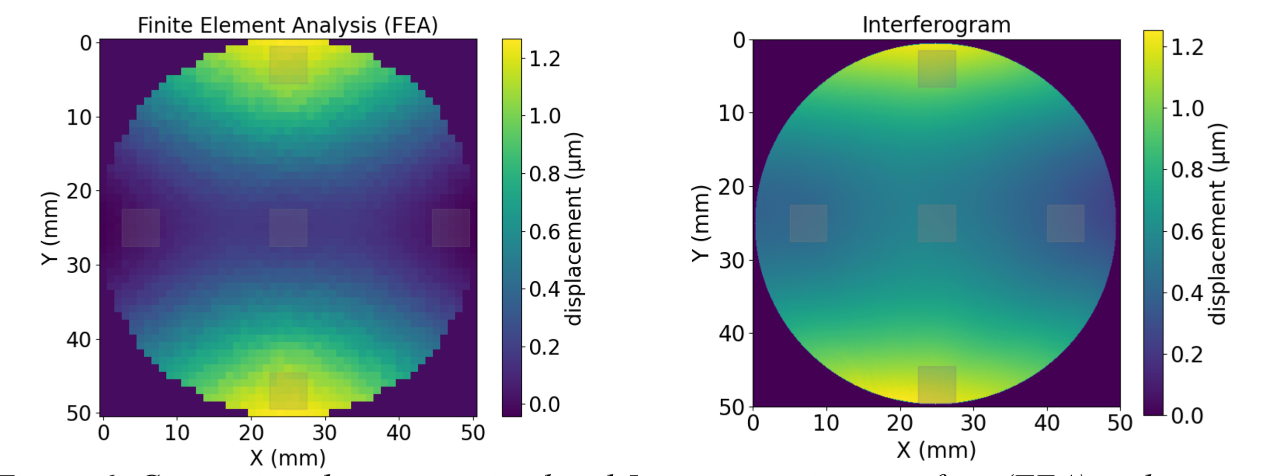

Figure 6: Comparison between a simulated 5-actuator mirror surface (FEA) and an interferogram of the actual 5-actuator mirror surface. In both cases the top and bottom actuators are pushed out to the maximum value.

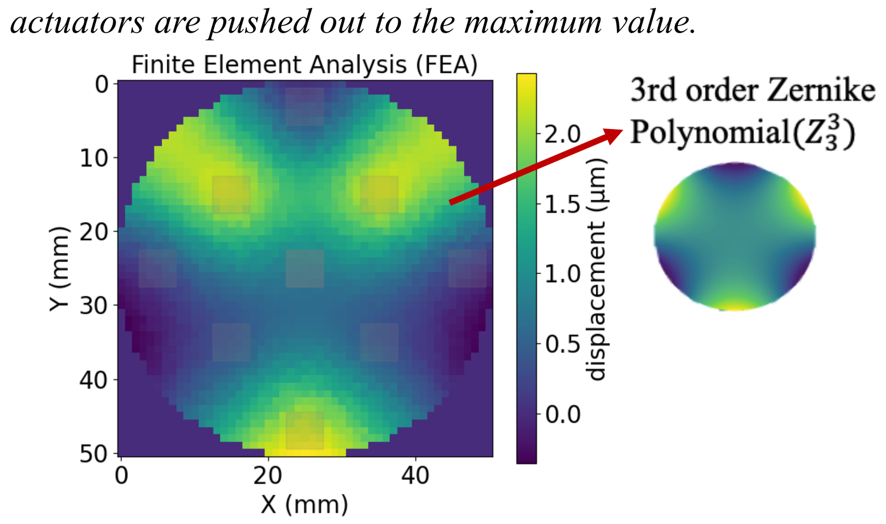

Figure 7: FEA simulation of a 9-actuator mirror surface. The next step is to build a 9-actuator DM. Using FEA it was seen that a 9-actuator mirror can correct for 3rd order Zernike Terms. This was not possible using a 5-actuator mirror. This means it can further correct for higher-order aberrations in the optical system.

8. Conclusion

- The adaptive optics system consisting of a DIY DM, a focal spot camera and a GA was successfully able to **optimise the focal spot** and **increase the intensity at the target by a factor of 9**.
- The GA is customisable and can easily be used to optimise the mirror surface of DMs with a higher number of actuators in the future.
- The next step is to build DMs with a higher number of actuators (Example: 9 actuators). FEA can be used to simulate these mirrors before they are built to test their effectiveness.

9. References

[1] J. Ma et al. 'Influence of secondary converse piezoelectric effect on deflection of fully covered PZT actuators', Sensor. Actuator. A-Phys., vol. 175, pp. 132-138, 2012.
[2] Thorlabs, https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5056, Online, accessed: 28th February 2021.
[3] Imagine Optics, https://axiomoptics.com/dmaos/ilao-dm/, Online, accessed: 28th February 2021.