
High-Speed Deformable Mirror Control Using Multi-Step Actuation

Dhruv Lakhani | Joseph Boales | Steven Cornelissen

INTRODUCTION

This white paper is intended for technical and program stakeholders evaluating faster deformable mirror response for adaptive optics, free-space optical communication, and other dynamic wavefront-control systems [1]. It summarizes what BMC has measured, where the method is most useful, and what must be validated before relying on the approach in a production system.

In a development study on Multi-3.5 deformable mirrors, Boston Micromachines evaluated a multi-step actuation method that briefly applies a calibrated intermediate command before setting the requested final command. Under tested conditions, this approach substantially reduced measured 10% to 95% settling time, with approximately order-of-magnitude improvement in some cases. For customers, the practical significance is that faster settling may be achieved through calibration and drive control rather than through changes to the MEMS mechanical design [2].

The study also demonstrated that the control method can be practical to deploy. A fixed overshoot duration can be selected, while the intermediate command is determined from either a lookup table or a compact fitted calibration function. For the reported tests, a calibration generated at one location was sufficient to control other low order surface shapes on the same device. BMC subsequently implemented the method for a customer by providing calibration fits for multiple DMs at a customer-specified overshoot duration.

WHY SETTLING TIME MATTERS

Deformable mirror settling time is a critical performance parameter in applications where the optical wavefront must be corrected rapidly and repeatedly. In astronomical adaptive optics, shorter settling times allow the system to respond more quickly to atmospheric turbulence and other time varying aberrations, increasing the fraction of each control cycle available for useful correction and supporting higher closed loop bandwidths [1, 5]. In free space optical communication, rapid DM response enables faster compensation for turbulence induced wavefront distortion, beam wander, and changes in the optical propagation path, helping maintain coupling efficiency and link stability as conditions evolve [1, 3]. In both applications, reducing the time required for a DM to reach and stabilize at a commanded shape can improve the responsiveness of the overall optical system and expand the range of dynamic disturbances that can be effectively corrected [1, 5].

HOW TWO STEP DRIVE CONTROL WORKS

Boston Micromachines MEMS deformable mirror actuators behave as damped, forced, coupled mechanical systems. Their steady state surface is set electrostatically, but the transition between states is governed by actuator stiffness, effective mass, damping, facesheet coupling, and the applied voltage trajectory [2, 4-7].

Improving dynamic performance by changing stiffness, mass, or damping generally requires changes to mirror design and fabrication [5, 8]. Multi-step control takes a different approach: it changes the transient drive trajectory while leaving the mechanical design unchanged [2].

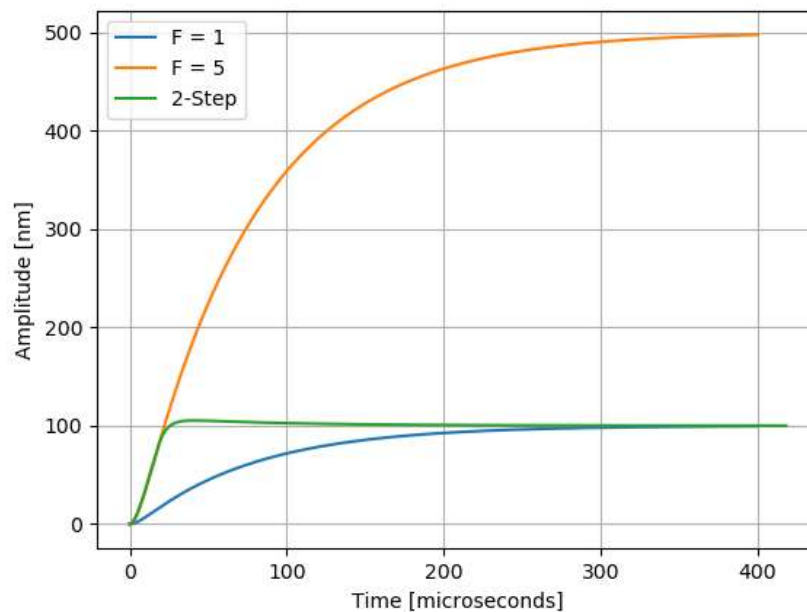
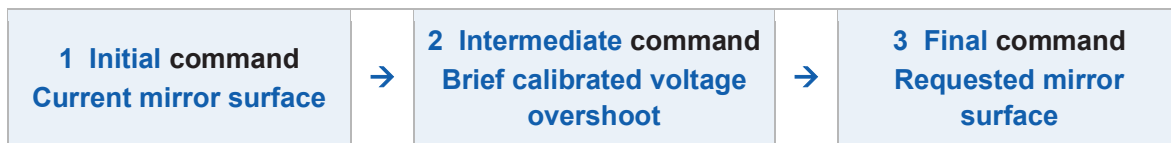


Figure 1. Theoretical example from the development study. A brief high force command followed by the final target reaches the requested position much faster than a conventional step in the simplified model. The example changes calculated settling time from 267 microseconds to 24 microseconds.

The method uses a short, calibrated voltage overshoot to accelerate the mirror toward a new state. The intermediate command is applied for a prescribed duration and is then replaced by the final command.



The development effort focused on fixing the overshoot duration and calibrating the intermediate voltage. This simplifies implementation because the system does not need a different precisely controlled transition time for every actuator during every command update.

Multi-Step Control Example Response

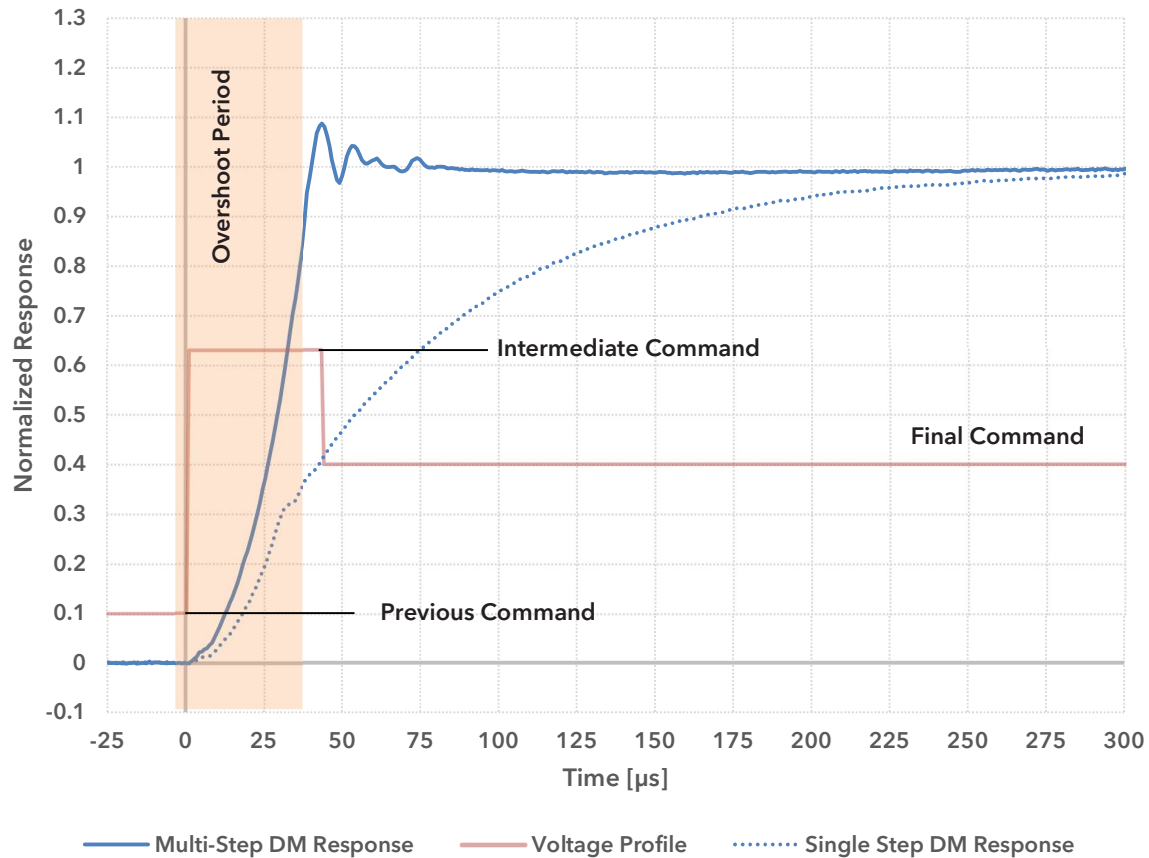


Figure 2. Example demonstration of two-step control of a DM. During the overshoot period, an intermediate voltage command greater than the final command is applied to accelerate the DM toward its target position. At the end of the prescribed overshoot duration, the voltage is reduced to the final command. The measured two step response reaches and settles near the target substantially faster than the corresponding single step response.

Overshoot Duration Sets the Performance Limits

The overshoot duration is a parameter that is selected to suit the application. Shorter overshoot durations require larger intermediate commands. These produce excellent settling behavior, but only over a limited command range. Longer overshoot durations reduce the required intermediate command and expand the range of step sizes over which the method remains effective, but lead to increased settling times.

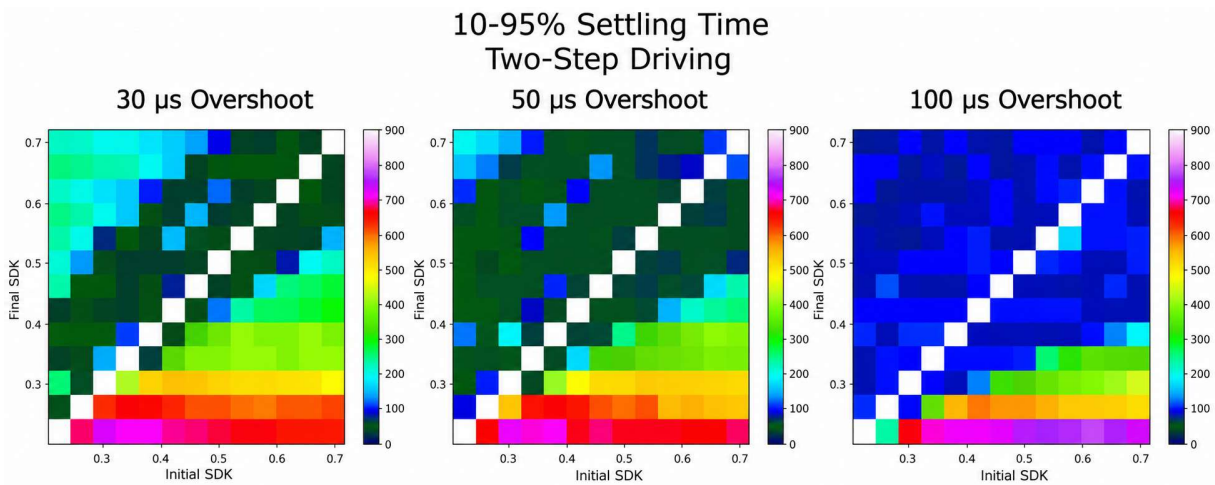


Figure 3. Measured 10% to 95% settling time for a representative Multi 3.5 DM at 30, 50, and 100 microsecond overshoot durations. Darker regions correspond to shorter settling times.

For a well-calibrated system, the overshoot duration nearly matches the settling time of the device over the calibration's useful range. The data in **Error! Reference source not found.** shows that as the overshoot duration (indicated in the subfigure titles), define this range. When the overshoot duration is short, the range over which short settling times are achieved is narrow, as indicated by the dark green band for the 30 μ s subfigures. As the overshoot duration increases, the useful range widens, but the settling time also increases.

Practical design rule from the study

The shortest overshoot duration is not the best option for all applications. Overshoot duration should be selected together with the required command range and acceptable transient position overshoot. Selecting an overshoot duration that matches the needs of the dynamic needs of the system will produce the best balance.

CALIBRATION MAKES THE METHOD PRACTICAL

The actuator force is nonlinear, and neighboring actuators are mechanically coupled through the facesheet [4, 6, 7]. Rather than relying on a detailed transient model, the study used empirical calibration. For a selected overshoot duration, the intermediate command was optimized across combinations of initial and final commands.

Two implementation formats were demonstrated: a lookup table and a compact calibration function. Across the reported calibration fits, R squared values ranged from 0.973 to 0.997.

Calibration Transfer Between Mode Shapes

For this method to be useful, it must work across different DM shapes. To evaluate this, BMC calibrated a device using tilt steps, then applied the same calibration as the DM moved through various amplitudes of oblique astigmatism. As shown in Figure 4, the measured settling behavior remained comparable, supporting the use of a single-point calibration for low-order shapes on the calibrated device.

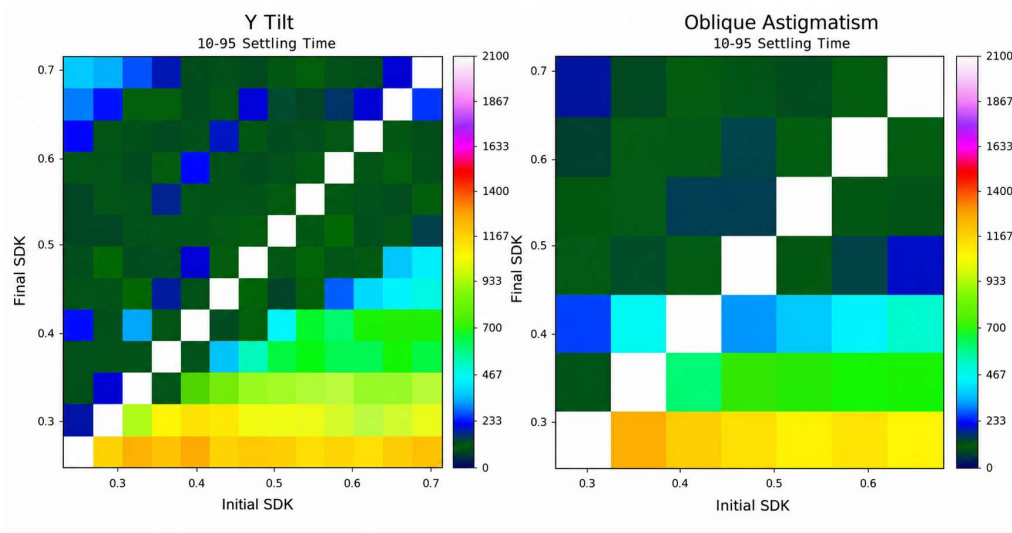


Figure 4. Two Step settling maps for Y tilt and oblique astigmatism using the same 50 microsecond calibration. The study found that the Y tilt calibration was applicable to the astigmatism test on the same device.

CUSTOMER IMPLEMENTATION

BMC has applied this calibration method in a customer implementation by generating calibration parameters for multiple DMs. Each device was characterized with a representative test shape, and a two-parameter fit was produced for the customer-specified overshoot duration. This device-specific approach aligns with the development data, which showed that calibration parameters can vary between individual DMs.

Calibration setup

In the representative example below, the calibration measured the response of a center actuator while the center 4x4 actuator array was driven through a series of command transitions. The calibration used a 43-microsecond overshoot duration.

Validation result

To validate the calibration, the device used the fitted parameters while stepping between tilt states. The calibrated Two Step drive reduced 10% to 95% settling time by 77% for voltage rise and 46% for voltage fall.

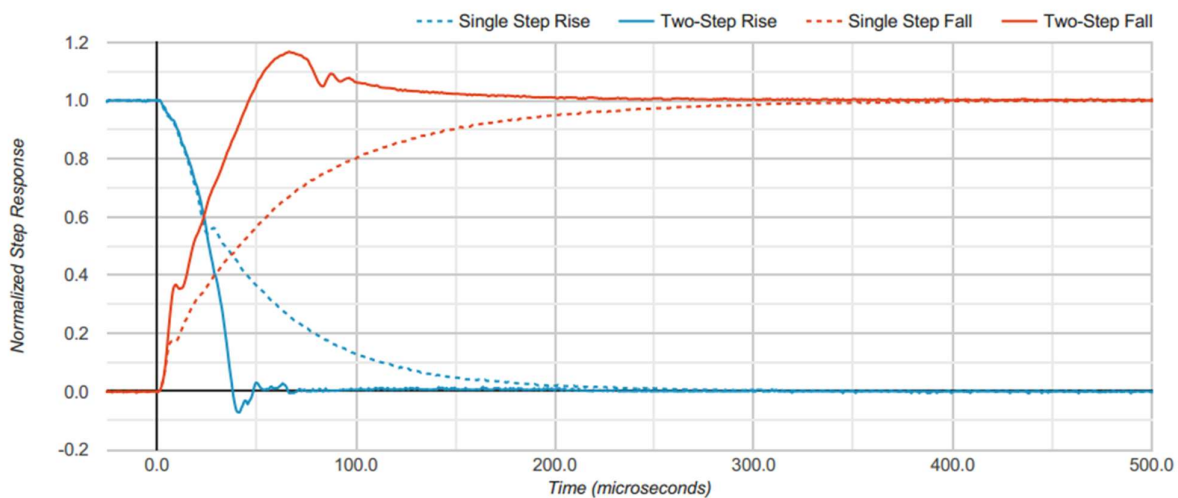


Figure 5. Representative customer calibration performance. For the Y tilt validation shown, measured 10% to 95% rise settling time changed from 138.4 microseconds with single step drive to 32.0 microseconds with Two Step drive. Fall settling time changed from 197.6 to 106.4 microseconds.

Table 1. Two-step driving performance improvement on a customer device compared with traditional single-step driving. The calibration was performed using a representative shape applied to the DM surface then validated using a different shape. This calibration produced a 46% to 77% improvement in device setting time.

Driving	10-95% Rise, μs	10-95% Fall, μs
Single Step	138.4	197.6
Two Step	32.0	106.4

PERFORMANCE DEPENDENCIES

Several variables changed the size of the performance improvement and the range over which it could be used effectively.

Table 2. The calibration performance is dependent on the device properties and how it is being used. This table summarizes how different parameters can affect the overall performance for a given device or application.

Parameter	Observed behavior in the study	Engineering implication
Overshoot duration	Shorter durations can reduce settling time for smaller steps, but require larger intermediate commands and produce a smaller effective operating range.	Select duration around the command range that matters most.
Mirror and coating	Calibration parameters differed between devices, and faster mirror designs showed a larger range where Two Step control was effective.	Calibrate the intended DM configuration rather than assuming a universal calibration.
Surface shape	Low order shapes transferred well within a calibrated device. The speed will still, however, be shape dependent	Validate representative surface shapes when high spatial frequency content is important.
Positional overshoot	More aggressive command overshoot can create larger position overshoot before settling.	Balance transition speed, transient excursion, and operating range.

Device specific calibration matters

When a calibration generated for one Multi 3.5 DM was applied to another DM of the same general design and coating family, the second device performed well over part of the range but required different best fit calibration parameters. The study linked this difference to the devices having different voltages to deflection behavior.

What the Data Suggests for System Design

- Characterize the intended DM configuration rather than assuming calibration transfers between devices.
- Choose overshoot duration based on the command step sizes and required speeds that dominate the application.
- Validate representative low order and high spatial frequency shapes when both are used.

CONCLUSION

A development study at BMC demonstrated that calibrated multi-step drive control can reduce the mechanical settling time of Boston Micromachines deformable mirrors without requiring a change to the mirror mechanical design. Under the tested conditions, the measured 10% to 95% settling time improved substantially and reached approximately an order of magnitude improvement in some cases.

The method is attractive because it can be implemented as a calibrated command transformation rather than a new actuator architecture. A fixed overshoot duration, combined with either a lookup table or fitted calibration, reduces the timing complexity of deployment while retaining a useful degree of control over the speed versus operating range trade space.

Calibration is device dependent, higher spatial frequency shapes can respond differently from low order shapes [4, 7], aggressive settings can create position overshoot [2], and low pressure operation can increase ringing [8]. For practical use, the calibration and validation should therefore be performed on the intended DM configuration and operating environment.

Faster settling through control, not redesign

Two Step drive control adds a new tuning lever for systems where DM transition time is a limiting requirement. The laboratory results show the potential performance gain, while the calibration data identifies the operating boundaries that need to be engineered for a production implementation.

REFERENCES

- [1] Wang, Y., Xu, H., Li, D., Wang, R., Jin, C., Yin, X., Gao, S., Mu, Q., Xuan, L., & Cao, Z. "Performance analysis of an adaptive optics system for free-space optics communication through atmospheric turbulence." *Scientific Reports*, 8, 1124 (2018).
- [2] Hou, J., Li, H., Qian, L., Yu, H., & Shen, W. "Control of a Micro-Electro-Mechanical System Fast Steering Mirror with an Input Shaping Algorithm." *Micromachines*, 15(10), 1215 (2024).
- [3] Chen, M., Liu, C., & Xian, H. "Experimental demonstration of single-mode fiber coupling over relatively strong turbulence with adaptive optics." *Applied Optics*, 54(29), 8722–8726 (2015).
- [4] Vogel, C. R., & Yang, Q. "Modeling, simulation, and open-loop control of a continuous facesheet MEMS deformable mirror." *Journal of the Optical Society of America A*, 23(5), 1074–1081 (2006).
- [5] Ravensbergen, S. K., Hamelinck, R. F. M. M., Rosielle, P. C. J. N., & Steinbuch, M. "Deformable mirrors: design fundamentals for force actuation of continuous facesheets." In *Advanced Wavefront Control: Methods, Devices, and Applications VII, Proceedings of SPIE*, 7466, 74660G (2009).
- [6] Zhang, W.-M., Meng, G., & Chen, D. "Stability, Nonlinearity and Reliability of Electrostatically Actuated MEMS Devices." *Sensors*, 7(5), 760–796 (2007).
- [7] González-Núñez, H., Béchet, C., Ayancán, B., Neichel, B., & Guesalaga, A. "Effect of the influence function of deformable mirrors on laser beam shaping." *Applied Optics*, 56(6), 1637–1646 (2017).
- [8] Ahmad, M., & Bahri, M. "MEMS Micromirror Actuation Techniques: A Comprehensive Review of Trends, Innovations, and Future Prospects." *Micromachines*, 15(10), 1233 (2024).