Closed-Loop Switched Operation of Piezo Actuators

Sebastian Kist, Max Bauer, Jonas Reiser

Physik Instrumente (PI) SE & Co. KG, Karlsruhe, Germany

s.kist@pi.de

Abstract

To control large arrays of piezoelectric actuators used in adaptive optics systems, high-voltage output drives are assigned to each actuator. However, scaling the size of the actuator array leads to complex, expensive and bulky driver electronics. Sequential addressing of the actuators, whereby multiple actuators share the same drive electronics, could be an alternative solution. A key enabling feature of piezoelectric actuators is their relatively large capacitance, which allows an electrically disconnected actuator to retain its displacement. This quasi-stationary behavior can be exploited to address several actuators with one drive unit. To demonstrate technical feasibility, an experimental test set-up has been developed. The experimental investigations focused, among other things, on the influence of the switch frequency and the necessary dead times for crosstalk-free addressing of several actuators. It has been demonstrated that the performance of switched piezo actuator systems is limited by the trade-off between the effective on-time available per switch cycle and the switch frequency. Failing to account for a dead time of at least 100 µs will result in crosstalk between the addressed channels.

Piezoelectric Actuators, Multiplexed Control, Deformable Mirrors

1. Introduction and State of the Art

Adaptive optics systems use deformable mirrors (DMs) to actively correct optical wavefront aberrations. Their applications range from astronomical and laser systems to biomedical imaging and industrial optics. Across these fields, there is a common trend towards systems with an increasing number of actuators, a higher bandwidth and a sufficient correction stroke, while reducing system complexity, cost, and power consumption simultaneously. Of the available DM technologies, piezoelectric deformable mirrors are a popular choice due to their relatively high stroke and mechanical robustness [1].

Traditional implementations typically use one high-voltage amplifier dedicated to each actuator channel, enabling continuous and independent control. While this approach is well established, it is hard to scale with respect to the number of actuators. In high-order systems featuring hundreds or even thousands of actuators, the resulting driver electronics are bulky, expensive, power-hungry and difficult to integrate. Alternative driving concepts have therefore been proposed to reduce the number of high-voltage amplifiers required [2]. A key enabling observation for such concepts is that piezoelectric actuators are inherently capacitive and exhibit long charge retention times. Once charged to a given voltage, an actuator maintains its displacement for a comparatively long time, when electrically disconnected, with only gradual decay due to leakage currents and creeping. This physical property forms the basis of sequential or multiplexed addressing schemes, in which a single high-voltage amplifier is shared among multiple actuators and connected to them one at a time via high-voltage switches. Previous work has demonstrated that, under the right timing and synchronization conditions, multiplexed control can achieve surface stability that is comparable to that of conventional driving schemes, while drastically reducing electronic complexity [1-3].

These developments offer promising opportunities in adjacent fields that require active surface or shape correction, beyond classical adaptive optics applications. One such field is the processing of semiconductor wafers. During processes such as laser processing, thermal treatment or thin film deposition, wafers may undergo local deformation and global warpage. Additionally, inherent wafer warpage or residual stress can restrict the achievable flatness and uniformity of the process [4].

This study focuses on finite switch-on and switch-off times, synchronization delays between control signals and electrical switching, the charge and discharge dynamics of piezoelectric actuators and potential crosstalk between channels.

2. Method

2.1. Experimental Concept

To simplify the investigation of switching behavior, timing effects and closed-loop control performance, a linear piezo-actuated stage served as the device under test (DUT). This approach preserves the essential electrical and dynamic characteristics relevant to multiplexed piezo actuation while eliminating the need for a complex multi-actuator surface deformation system. Figure 1 highlights the experimental set-up.

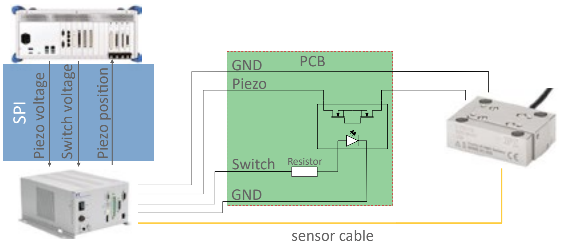

Figure 1. Layout of experimental set-up

The selected DUT was a P-753.11C LISA linear actuator and positioning stage (Physik Instrumente). The actuator provides a travel range of 15 µm and is driven by a PICMA® piezo element with an electrical capacitance of approximately 1.5 µF. Motion is measured directly at the moving platform using an integrated capacitive sensor with 0.1 nm resolution [5]. High-voltage switching was achieved using PhotoMOS relays (Panasonic AQY210EH series). These optically isolated, solid-state relays are rated for load voltages of up to 350 V DC and continuous load currents of up to 130 mA [6]. The turn-on time of the selected PhotoMOS relays was measured to be around 100–150 µs, and the turn-off time around 50 µs. All control and switching logic was executed on a Speedgoat real-time target machine running Simulink Real-Time. An E-727 controller (Physik Instrumente) was used as both a high-voltage amplifier to drive the piezo actuator and a signal conditioning and readout interface for the capacitive position sensor. Communication between real-time target machine and E-272 was established via serial peripheral interface (SPI).

2.2. Control Architecture

The control architecture follows a classical feedback structure with adaptations required for multiplexed actuation. The measured position of the actuator is continuously compared to the desired position, yielding a position error signal. This error is processed by a PI controller, which constitutes the core of the control task. A key modification to standard continuous drive operation involves how the integral term is treated. In a multiplexed system, the actuator is only electrically connected to the amplifier during defined switch cycles. If the integral of the error were to be accumulated continuously, even when the actuator is disconnected, the controller output would increase despite there being no physical effect. This could lead to excessive overshoot and potential instability once the actuator is reconnected. To prevent this behavior, the integral contribution is only accumulated when the actuator is addressed during a switch cycle. During disconnected phases, the integral state is held constant. The output of the PID controller is expressed in position-related units and is subsequently multiplied by a piezo gain, converting the control signal into a voltage command. This voltage command is passed through a saturation block to ensure that it remains within the permissible output range of the high-voltage amplifier. The resulting signal is then transmitted to the E-727 amplifier and applied to the actuator whenever the switch is closed.

2.3 Switching and Multiplexing Logic

The switching logic determines when the actuator is electrically connected to the amplifier and, thus, directly governs the effective update rate of the control loop. Two parameters are of importance:

1. Switch frequency, which defines the duration of an individual switch cycle and, thus, the time window during which the actuator can be actively addressed.
2. Inter-cycle delay, which introduces additional idle cycles between successive addressing events of the same actuator.

By inserting delays between switch cycles, the system emulates the presence of additional, virtual actuators. For example, addressing the real actuator only every tenth switch cycle corresponds to a scenario in which nine other actuators are addressed sequentially in between, all operating at the same base switching frequency. Increasing the number of virtual actuators therefore increases the effective update interval for the real actuator and leads to longer convergence and settling times.

2.4 Performance Metrics and Parameter Studies

To quantify control performance under multiplexed operation, a settling window was defined around the desired position. The settling time is defined as the time elapsed between the first switch cycle following a reference change and the moment at which the actuator position enters and remains within the settle window of ±1 % of the target position. Parameter studies were conducted to investigate the influence of controller parameters, switching frequency, and virtual actuator count on settling time and stability. Due to the inherently nonlinear behavior of piezoelectric systems, including hysteresis and creep, and the additional nonlinearity introduced by sequential addressing, analytical treatment is challenging.

2.5 Limitations of the Test Setup

The use of a single linear piezoelectric positioning stage does not capture the full mechanical coupling and spatial interactions present in a DM or active waver chuck (AWC). In surface deformation systems, actuator influence functions overlap and mechanical cross-coupling between neighboring actuators can significantly affect both static and dynamic behavior [3]. These effects are not represented in the one-degree-of-freedom set-up used here. The mapping from actuator displacement to optical surface deformation is also not addressed. As a result, the experiments focus exclusively on actuator-level performance metrics such as settling time and stability, rather than wavefront quality or surface figure error. The emulation of multiple actuators through virtual actuators captures the timing and update-rate effects of multiplexing but does not reproduce possible electrical or mechanical interactions between simultaneously connected channels in a real multi-actuator system. To partially address the limitations of the single-actuator set-up, additional experiments were conducted using two physical piezo actuators addressed through separate switching elements. These experiments were designed to validate the switching logic, dead time requirements, and isolation behavior under more realistic multiplexing conditions. In the two-actuator configuration, the switching sequence explicitly enforced non-overlapping addressing windows, including configurable dead times between successive switch events. This allowed investigation of crosstalk effects, unintended charge transfer, and current spikes that may occur when switching high-voltage piezo loads. While the two-actuator set-up still does not reproduce the full mechanical coupling of a DM or AWC, it represents an important intermediate step between the single-actuator surrogate and a true multi-actuator system.

3. Results

Figure 2 shows the measured settling time for a single 7 µm step input using a fixed and deliberately soft PI controller tuning. Measurements were performed for several switching frequencies and different numbers of inner cycle delays, corresponding to different numbers of virtual actuators.

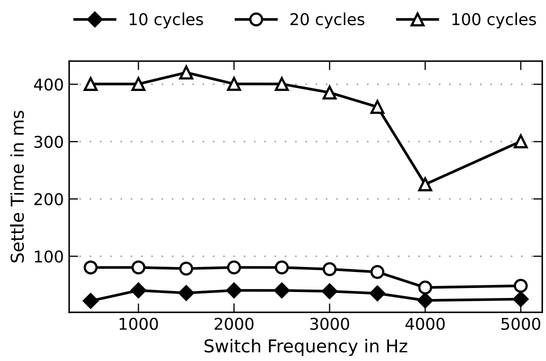

Figure 2. Comparison of settle times for a 7µm step over a range of switching frequencies for 10, 20 and 100 cycles

All three sets of measurements show a relatively constant settling time across the switching frequency. The results indicate only a weak dependence of settling time on switching frequency for this type of simple step motion. While higher switching frequencies increase the number of possible addressing events per unit time, they simultaneously reduce the effective on-time available per switch cycle for charging the actuator and applying corrective control action. As a result, the benefits of increased update rate are largely compensated by the reduced control time per cycle. Instead, the dominant factor influencing settling time is the number of inner cycle delays, the effective update interval of the actuator, which directly increases with the number of *virtual actuators.*

To investigate scaling effects beyond the single-actuator surrogate, additional experiments were conducted using a two-actuator setup with separate switching elements. These experiments focused on identifying the timing constraints required to ensure correct voltage assignment and prevent electrical crosstalk between actuators.

Figure 3 shows a single-step measurement in which actuator 1 followed a 2 µm step command and actuator 2 followed a 2.5 µm step command. The switch frequency was set to 4 kHz. Without added dead time, the voltage commands influence the other piezo channel, leading to observable oscillations in the position data. Introducing a minimum dead time between successive switching events is essential for reliable operation. The shortest dead time that sufficiently isolates the piezo channel was found to be 120 µs.

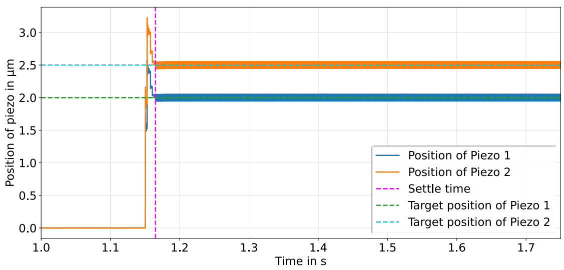

Figure 3. Crosstalk between two axes due to unaccounted-for dead times

If the dead time is too short, transient overlap during switching leads to unintended charge transfer, current spikes, and incorrect voltage levels being applied to the actuators. By enforcing sufficient dead time between addressing phases, stable and reproducible operation can be achieved, even under high switching frequencies.

5. Outlook

The experimental results demonstrate that multiplexed control of piezoelectric actuators is feasible using comparatively simple hardware, provided that switching dynamics and controller structure are carefully accounted for. Across both, single-actuator and two-actuator experiments, the dominant performance limitations were not imposed by the actuator dynamics themselves, but by the interaction between switching behavior and controller timing.

The results of this work suggest several directions for future development. From a hardware perspective, scaling multiplexed control to larger numbers of actuators will require more efficient switching architectures, potentially involving dedicated switching controllers or integrated high-voltage multiplexing electronics to reduce latency and improve synchronization.

On the control side, the strong dependence of performance on step size and operating region indicates that adaptive or gain-scheduled control strategies may be beneficial. Such approaches could allow aggressive control during large transients while automatically reducing controller gains near the target position to improve stability and settling behavior.

Furthermore, extending the experimental setup to a true multi-actuator system with mechanical coupling would enable validation of the presented concepts under conditions closer to a surface shaping application. This would allow investigation of how multiplexing-induced timing effects interact with spatial coupling and influence functions.

References

[1] Song H, Simonov A, Vdovin G 2006 Multiplexing control of a multichannel piezoelectric deformable mirror Proc. SPIE 6018, 5th International Workshop on Adaptive Optics for Industry and Medicine

[2] Vdovin G, Loktev M, Simonov A 2005 Low-cost deformable mirrors: technologies and goals Proc. SPIE 5894, Advanced Wavefront Control: Methods, Devices, and Applications III

[3] Song H, Fraanje R, Schitter G, Vdovin G, Verhaegen M 2011 Controller Design for a High-Sampling-Rate Closed-Loop Adaptive Optics System with Piezo-Driven Deformable Mirror European Journal of Control **17** 290-301

[4] Steuer M 2017 Design of an active wafer clamp for wafer machines

[5] Physik Instrumente, “LISA Linear Actuator and Positioning Stage”, 2024

[6] Panasonic Industrial Devices, “AQY210EH PhotoMOS-Relais”, 2026