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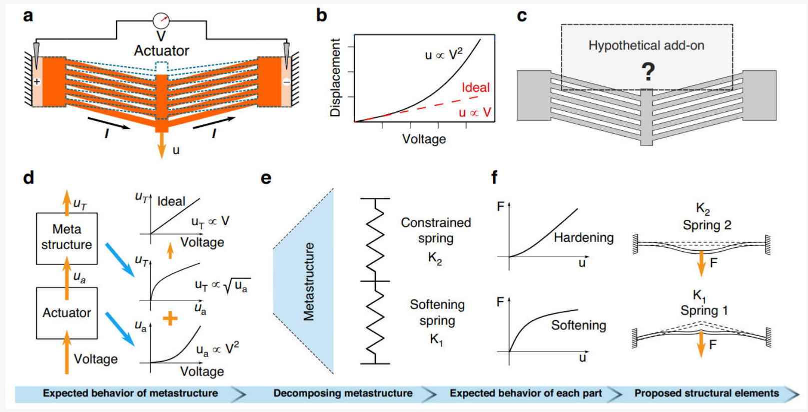
How machine learning helps MEMS actuators move in perfect lines

GA, UNITED STATES, February 4, 2026 /EINPresswire.com/ -- Achieving precise and predictable motion remains a persistent challenge for microelectromechanical systems (MEMS), where many actuators respond nonlinearly to electrical input. A new study introduces a sensor-free strategy to address this problem by embedding specially designed mechanical metastructures directly into electrothermal actuators. Instead of relying on feedback circuits or real-time sensing, the approach reshapes the actuator's mechanical response so that displacement varies almost linearly with voltage. Machine learning models guide the design of these metastructures across a vast parameter space, enabling near-linear motion through purely mechanical means. The resulting devices demonstrate markedly improved controllability while reducing system complexity, opening new possibilities for precision micro-actuation in compact and resource-constrained environments.



Concept of metastructure design.

Microelectromechanical systems (MEMS) electrothermal actuators are widely used in applications ranging from micro-optics and microfluidics to nanomaterial testing, thanks to their compact size and strong actuation capability. However, their motion typically follows a nonlinear voltage–displacement relationship, largely due to Joule heating and coupled thermo-mechanical effects. To compensate, engineers often introduce sensors and closed-loop control systems, which increase fabrication complexity, power consumption, and failure risk—especially at small scales. In many applications, fragile sensing elements also struggle to survive harsh processing conditions. Based on these challenges, there is a strong need to develop new approaches that can achieve linear actuation without relying on sensors or complex control electronics.

Researchers from McGill University and the University of Toronto report a new design strategy for MEMS electrothermal actuators in a study published (DOI: 10.1038/s41378-025-01065-4) in Microsystems & Nanoengineering on November 12, 2025. The team demonstrates that actuator nonlinearity can be corrected mechanically, by integrating machine learning–optimized metastructures into the actuator itself. These structures reshape the mechanical response so that displacement increases almost linearly with applied voltage—without sensors, feedback loops, or additional electronics—offering a simpler and more robust route to precise micro-scale motion.

The core idea behind the study is to counteract the actuator's inherent quadratic voltage–displacement behavior using a complementary mechanical response. Electrothermal actuators naturally produce displacement proportional to the square of the applied voltage. The researchers designed mechanical metastructures whose deformation follows a square-root relationship with input displacement. When combined, the two nonlinear behaviors effectively cancel each other, yielding an overall near-linear response.

To realize this concept, the team constructed metastructures using combinations of straight and inclined microbeams that exhibit hardening and softening stiffness under deformation. Because the design space spans thousands of geometric configurations, traditional trial-and-error optimization would be impractical. Instead, the researchers generated tens of thousands of finite element simulations to train neural network models capable of predicting mechanical behavior almost instantly.

These machine learning models enabled inverse design: starting from a desired linear response, the algorithm identified optimal geometric parameters for the metastructures. The optimized designs were fabricated using a standard MEMS process and experimentally tested inside a scanning electron microscope. Measurements confirmed that the integrated metastructures reduced actuator nonlinearity by about 85% compared with conventional designs, closely matching simulation predictions.

“Nonlinearity has always been treated as something to correct electronically,” said one of the study's senior authors. “What we show here is that the mechanical structure itself can be engineered to do that job.” By shifting linearization from software and sensors into geometry, the approach simplifies system architecture while preserving precision. “This opens the door to more robust MEMS devices, especially in environments where sensors are fragile, power is limited, or space is at a premium,” the researchers noted.

Sensor-free linearization could significantly expand the usability of MEMS electrothermal actuators in precision engineering. Applications such as tensile testing of two-dimensional materials, biomedical microdevices, and remote or implantable systems stand to benefit from simpler, more reliable actuation. Beyond electrothermal actuators, the design framework may be adapted to other nonlinear actuation technologies at both micro- and macro-scales. More broadly, the study highlights how machine learning can transform mechanical design, enabling intelligent structures that achieve complex functions without added electronics. As data-driven optimization becomes more integrated into engineering workflows, mechanically “smart” devices like these may become a cornerstone of next-generation microsystems.

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