Actuator Design for a High-Speed Large-Range Tip-Tilt-Piston Micro-mirror Array

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INTRODUCTION
This paper presents a new method for the modeling and optimization of actuator performance in a high fill-factor (99%) micro-mirror array (10,000 1mm² mirrors). The high torque output resulting from the optimization enables the mirrors to be driven with three degrees of freedom (DOFs)—tip, tilt, and piston—over large ranges (≥±10° rotation and >±30µm translation) at high speeds (up to ≈40kHz small stepping rate), all with continuous closed-loop control. The capabilities of this new mirror array will extend the performance of a variety of high-impact technologies including: (i) optical switches, (ii) confocal microscopes, (iii) autostereoscopic display and image capture, (iv) microprojectors, (v) high speed focusable LIDAR, (vi) micro-additive fabrication approaches that utilize principles of light steering (e.g., two photon polymerization or optical tweezers), and (vii) high-powered laser steering systems for defense applications including projectile interception. A seven mirror prototype array has been built to-scale to demonstrate the design’s fabrication feasibility.

BACKGROUND
The instability due to pull-in has been extensively studied [1–5], and a range of additional effects have been considered including bearing stiffness [2] and varying comb cross-section [3]. These efforts typically focus on deducing a critical stiffness for design [1,2,4,5] and take the comb geometry as given. This work instead draws upon the kinematically designed flexures to find the comb geometry which maximizes actuation within the given design topology and geometric constraints.

We present a new method to analyze pull-in that extends beyond previous work to incorporate both fabrication errors and the compliance of the full load path loop into closed-form analytical expressions for pull-in displacement. This expression is then incorporated into a new approach to comb-drive design which uses constraint-based optimization (CBO). CBO offers several advantages when used in design, including rapid redesign, optimal performance, and the ability to study sensitivity to constraint inputs, so as to aid in design decisions.

STRUCTURE
A seven mirror array is shown in Figure 1 to illustrate the scale and components of the micromirror. Only the middle element is shown fully assembled.

The micromirror array is composed of hexagonal unit cells, each of which contains three bipolar electrostatic comb drive actuator paddles, three hexapod flexure linkages and a hexagonal mirror.

FIGURE 1. Micro-mirror array design.

FIGURE 2. Actuator paddle in detail.
The actuators are the green/blue paddles which are anchored at two corners to the red actuation plate below and are free to rotate around a single axis as shown in Fig. 2. The two comb pads on the actuation plate are electrically controlled from pads on the underside of the device, linked to the comb pads through vias. The paddle is tipped in either direction by energizing one of the comb pads.

MODEL
An analytical model was generated by calculating closed-form expressions for each of the stiffnesses in the structure, and assembling these as springs in series to mimic the summed structural displacements. These include the actuation combs, $k_p$, ground plate combs, $k_c$, and the $R1$ and $R2$ flexures that govern the paddle rotation. The paddle is able to move in two main modes, a rotation in $\theta_z$ with stiffness $k_{\theta z}$ and a translation in X with stiffness $k_{xx}$ as shown in Fig. 2. The net pull-in displacement $x_p$ is calculated as shown in Eq. (1), where $c_{tot}$ is the net load path compliance and $T$ is the 3rd order Taylor series of the nonlinear pull-in force $F_p(x_p)$ around $x_0$, which is $r_p$ fraction of the initial gap $d$, minus the fabrication max misalignment, $\delta$. The gap fraction allows the designer to choose how close they want to come to the singularity at $r_p=1/3$, where full pull-in occurs.

$$c_{tot} = k_c^{-1} + k_b^{-1} + k_{\theta z}^{-1} + k_{xx}^{-1}$$

$$x_p = c_{tot} T(F_p(x_p))\bigg|_{x_0 = r_p(d-\delta)}$$

OPTIMIZATION
The optimization is carried out by constraining $x_p$ to be at the $r_p$ limit. The three inputs, ground plate comb width $w_c$, actuation plate comb width $w_p$, and the initial gap $d$, are then adjusted to maximize the actuator torque, $\tau_{act}$ while meeting the gap constraint, as shown in Eq. (2).

$$\text{Given } x_p(w_c, w_p, d) = r_p(d-\delta)$$

$$\text{Maximize}(\tau_{act})$$

The initial gap can be made a function of the comb widths, which turn out to be equal due to symmetric conditions, leaving a single variable to scale over in this design. The torque output over a range of comb widths is shown in Fig. 3.

CONFIRMATION
The structural kinematics and elastomechanics were confirmed via FEA as shown in Fig. 4.

REFERENCES