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# Scanning micromirror for large, quasi-static 2D-deflections based on electrostatic driven rotation of a hemisphere

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ABSTRACT

A micromirror (mirror area 3.1 mm$^2$) for laser tracking applications is presented. The mirror, which is based on a hemisphere, is designed to achieve large quasi-static deflection around two rotational axes by adapting the principle of ultrasonic motors. Here, the deflection of the mirror is achieved by a periodic momentum transfer from a stage with electrostatically driven oscillations. Due to the periodic hemisphere-stage-contact, the system has multiple degrees of freedom and is non-linear. A simple model of stage-hemisphere-interaction is presented and verified in order to identify design rules and adequate excitation regimes.

The actuator is fabricated in standard SOI-technology. The final system is excited as well in a non-resonant (2000 Hz) as in a resonant mode (2900 Hz). Thus excitation frequencies over a wide range are possible. For a resonant operation of the stage, a maximum quasi-static deflection of the mirror of up to +/−35.2° with a maximum angular velocity of 732°/s is demonstrated. In this case, the crosstalk (movement perpendicular to desired direction) is less than 22%. For the non-resonant operation the crosstalk is reduced significantly (less than 10%). In this case, a quasi-static deflection of +/−10.5° is found.



## 1. Introduction

Optical scanners have been a major topic in optical MEMS research for many years now. Recently, Holmström et al. [1] published a comprehensive review where scanners are categorized regarding the key aspects such as the driving principle, the operational mode (resonant/static) and the degree of freedom. As in other MEMS fields, electrostatic, electrothermal, electromagnetic and piezoelectric actuations are the most common. The degree of freedom (DoF) of the mirror movement can be distinguished between one (1D) and two axes (2D).

On the one hand, for imaging purposes such as microscopy, projectors and head-up displays, gimbal-mounted mirrors are often used. Benefiting from resonant actuation, they achieve high mechanical deflections above ±20° [2]. One the other hand, for tracking applications where the beam has to continuously track a moving point, the resonant actuation is not an option. For a 2D scanner with electrostatic actuation, a mechanical deflection of up to ± 15° has successfully been demonstrated[3,4]. Furthermore, for electromagnetic actuation a mechanical deflection of the mirror of 32.5° has been shown [11].

In this contribution, we focus on the requirements for quasi-static 2D micromirror as used for tracking applications [5]. It is intentionally developed for interferometric trilateration of a moving retroreflector, for instance in the tool center point (TCP) in fabrication and handling processes. For the intended application, the tool center point can move within a virtual volume of 1·1·1 m$^3$. Each movement of the TCP should take less than one second. This corresponds to a TCP velocity of 3.5 m/s and an acceleration of 7 m/s$^2$. If the micromirror is placed in a distance of 1 m with respect to the measurement volume, this results in an angular mechanical velocity and acceleration of 57°/s and 200°/s$^2$ respectively. Furthermore, a 2D tilt with high static deflection of ±27.3° is required, which enables a permanent tracking of the retroreflector. Additionally the diameter of the mirror plate should be in the millimeter range to allow long-range interferometry.

For the mirror tilt, the concept of an ultrasonic standing-wave actuator is adapted for MEMS technology. Many authors ([6–9]) present piezo-driven ultrasonic actuators with three DoF that can be used for rotating a sphere around all three axes. Piezo actuators usually generate little stroke so that mechanical amplifiers are required to enlarge the stroke by resonant oscillations. As a con-

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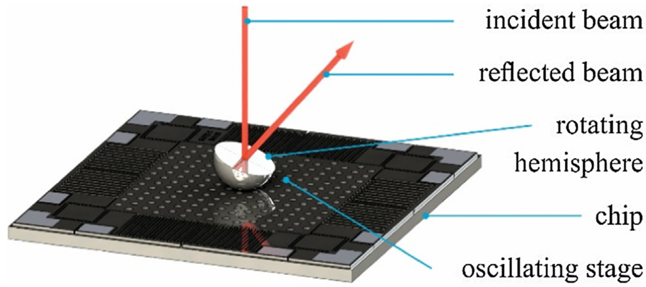


**Fig. 1.** Schematic setup for quasi-static laser beam deflection. The incident beam is reflected on the plane surface of a hemisphere, which is rotated due to the stage movement.

sequence, the precision manufacturing process is costly and the overall assembly is relatively large.

In this approach, a suspended stage with electrostatic actuation rotates a hemisphere. The plane surface of the hemisphere is used as a mirror that reflects the incident laser beam (c.f.Fig. 1). The suspended stage is fabricated by using SOI technology and electrostatic actuators for its movement in x-, y- and z-direction. The stage-hemisphere interaction allows the desired mirror tilt. Compared to piezoelectric drives, these electrostatic actuators are very compact and fully compatible to MEMS technology reducing the assembly efforts to a minimum. Furthermore, the setup presented in Fig. 1 allows scanning the entire hemispherical object space.

## 2. Design of the actuator

### 2.1. Stage-hemisphere interaction

The working principle as shown in Fig. 2 is similar to standing-wave actuators [6] The stage oscillates with a relatively high frequency in z-direction. If the acceleration of the stage is high enough (i.e. gravity acceleration if no further preload is applied), the hemisphere bounces on the stage resulting in regular contacts of the hemisphere with the stage. Additionally, the z-oscillation is superposed by an x-oscillation with a phase delay of 90° resulting in an elliptical stage movement. During each contact, a momentum in x-direction is transferred to the hemisphere. As the contact occurs well below the center of mass, it results in a torque and thus in a rotation along the y-axis. The working principle is shown in Fig. 2.

### 2.2. Modelling the periodic actuator movement

As compared to state-of-the-art piezo-driven ultrasonic actuators, the stiffness and mass of the moving stage are much lower in this approach. Therefore, the hemisphere interacts with the actuator in a much stronger way. Furthermore, the bouncing ball system is well-known as a chaotic system [12]. Nevertheless, a well-defined, periodic movement of the hemisphere is advantageous for the application as optical scanning. So the design and excitation are chosen based on the following analytical derivations in order to enable simple and periodic movements as shown in Fig. 3.

The assumptions used for the following model are:

- Movement of the stage and the hemisphere only in z-direction (i.e. 1-dimensional).
- Perfectly elastic behavior of the bounce.
- Infinitesimal short bounce.
- Undamped movement of the stage and the hemisphere.
- Stage and hemisphere assumed as point-masses.

The hemisphere movement in z-direction $z_h(t)$ is parabolic due to gravity as shown in Fig. 3. Hence between one bounce $\left(\text{at}\, t_b = t_0 - \frac{1}{2}T_g\right)$ and the following one $\left(\text{at}\, t_0 + \frac{1}{2}T_g\right)$, the movement is:

$$z_h(t) = -\frac{g}{2}\left(t - t_0 + \frac{1}{2}T_g\right)^2 + \dot{z}_{h,0}\left(t - t_0 + \frac{1}{2}T_g\right) + z_{h,0} \tag{1}$$

where $g$ is acceleration due to gravity, $T_g$ the time between two bounces as well as the speed $\dot{z}_{h,0}$ and the z-position $z_{h,0}$ of the hemisphere after the bounce. To enable a periodic movement with the period $T_g$, the $z$-position has to be identical at each impact resulting in $z_h(t_0 - \frac{1}{2}T_g) = z_h(t_0 + \frac{1}{2}T_g) = z_{h,0}$. As a consequence, the absolute value of the speed before the bounce must be equal to the value after the bounce. Hence, the period can be calculated as:

$$T_g = \frac{2\dot{z}_{h,0}}{g} = \frac{1}{f_g} \tag{2}$$

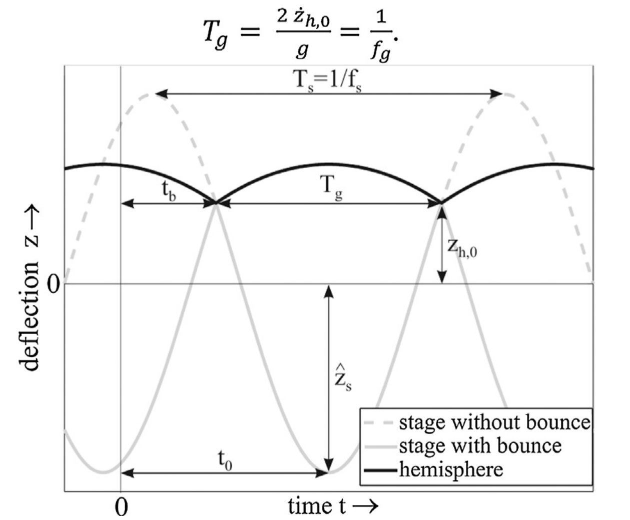


**Fig. 3.** Desired movement of the stage (grey solid line) and the hemisphere (black solid line) for $f_s/f_g$ = 3/5 in comparison to the stage oscillation without bounces (grey dashed line).

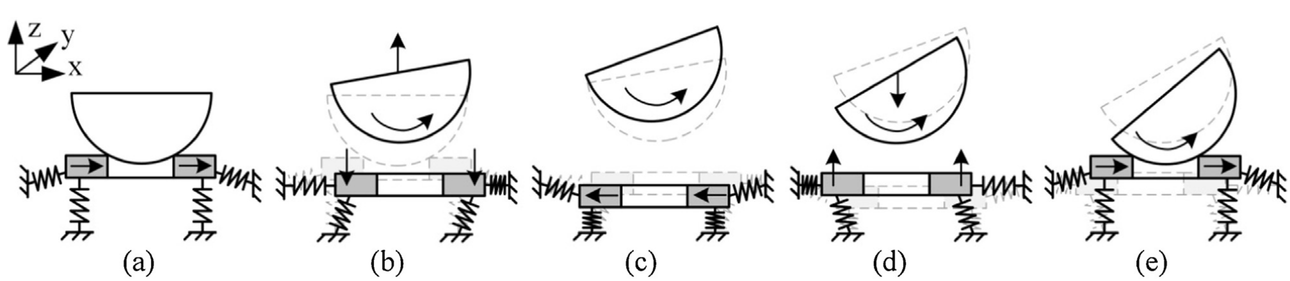


**Fig. 2.** Stage-hemisphere interaction for a rotation around the y-axis. The stage oscillates elliptically clockwise and hits the hemisphere at its highest position. The momentum transfer results in a z-movement and an anticlockwise rotation of the hemisphere.