1 Introduction

Micro-electro-mechanical systems (MEMS) are small-scale machines which are generally a few millimeters to a few microns in size. They are of interest to precision engineers because of their favorable dynamic characteristics (potential for tens to 100s of kHz bandwidth), favorable thermal characteristics (small size and high thermal diffusivity materials can be used to limit thermal strain errors) and potential for low cost and small packaging that follow when machines are miniaturized. Although the technology required to make simple MEMS devices has existed for several decades; the rate at which the technology has developed solutions for small-scale, precision machines has been slow. This is due in part to the challenges that the small-scale machine designer faces: (1) Design using materials with non-isotropic material properties and which experience non-isotropic material removal rates in MEMS fabrication processes, (2) Many MEMS process rely on chemical processes with rates that may form micron-sized parts, yet the reproducibility of critical feature size and location dimensions is difficult as the sources of variation in micro-fabrication processes are chemical/diffusion-based in nature and not as easily controlled, (3) The design and integration of actuators, sensors and electronics is complicated due to the need to ensure process compatibility between the types of devices which are fabricated on the same wafer, (4) Lack of reliable, low cost metrology equipment for characterizing the multi-axis performance and stiffness of MEMS devices (although interferometer-based systems have started to appear in recent years) and (5) difficulty fabricating robust precision contact bearings and motion constraints in MEMS devices.

This is not an exhaustive list of problems and the preceding points do not represent ubiquitous problems, rather they reflect the types of challenges which the precision engineer is likely to face when adjusting their methods to adapt to the constraints which will be placed on their thinking, and therefore the machines can design, at the small-scale. This document is mean to (1) provide a collection of references on MEMS technologies which have promise for use in precision alignment equipment/manipulators with nanometer-level accuracy/precision and (2) provide a brief introduction to the technologies which show promise for practical application in small-scale precision machines. Within the 4 page limit of this document, we have decided to separate the text into roughly 2/3 explanation of the basic technologies and 1/3 references which we believe will be of interest to precision engineers.

2 Manipulators overview

Manipulators consist of actuators, power transmission systems, and sensors. Many micro-scale fabrication processes preclude the integration of sensors in most micro-manipulation devices. Thus most micro-precision machines are forced to run open-loop. These systems may be classified according to actuator species, including electrostatic, electromagnetic, thermal, piezoelectric, electro-active polymer, etc…. Devices with one to six degrees of freedom have been micro-fabricated that employ linkages, gears, hinges, and compliant mechanisms. Unfortunately, the friction, wear and fit tolerances (e.g. “slop) in these components preclude their use in small-scale precision machines which perform Nanomanipulation tasks. Flexures are often used (generally easily fabricated) as precision motion bearings/guides for practical micro-precision machines. In many cases, this limits the range of the devices to a few percent of the device size.
3 Electrostatic manipulators/actuators

The seminal paper by Tang, et al, ignited the development of MEMS electrostatic comb-drive actuators. These actuators use electrostatic force between charged electrodes to create force/motion. Comb-drive actuators (Fig. 1A) use interdigitated electrode fingers to create motion, as opposed to parallel plate actuators which utilize parallel electrodes.

![A: Electrostatic comb drive actuator][2]  

![B: Electrostatic parallel-plate actuated mirror][3]

**Figure 1: Electrostatic actuators/manipulators**

Several variations of the classic comb-drive actuators have been developed for positioning mirrors in optical switches, tuning micro-lasers, rotating gears, Nanopositioning, and data storage [2-9]. Likewise, a variety of parallel-plate configurations have been designed for positioning of memory read heads, diffraction gratings, optical switching, and inchworm-type, large-travel drives [10-16]. In addition, Hoen, et. al., have developed a unique X-Y electrostatic dipole surface drive micro-positioner capable of 50 micron travel and 4nm open-loop repeatability [17].

4 Electromagnetic manipulators/actuators

Electromagnetic actuators are commonly used in high-power switches, and valves. More recently, a high-performance macro-scale 6-axis manipulator has been developed using electromagnetic actuators [18]. However, the complexity of fabricating micro actuator magnets and coils has been a progress bottleneck at the small-scale. An overview of magnetic MEMS, including some positioning applications can be found in [19]. Despite issues with process control, researchers have been able to fabricate micro-electromagnetic manipulators for data storage, scanning probes, and optical scanning/switching [20-23]. Figure 2 shows an electromagnetic microactuator used for rotating micro mirrors (conductive paths may be seen) in an optical switch.

![A: 2-axis EM-actuated optical switch][23]  

![B: Thermally-driven chevron-beam rotary actuator][27]

**Figure 2: Electromagnetic and thermally driven Microactuators**

5 Thermally driven manipulators/actuators

Thermal actuators make use of Joule heating and subsequent thermal expansion of materials, notably silicon, to generate displacements. Silicon-based thermal actuators can be (though not always) highly repeatable due to the predictable and reversible nature of single-crystal thermal expansion. Although strains are small in silicon devices, several configurations have been implemented to amplify the strain, including the chevron beam, differentially heated beams, and bimorph beams [24-26]. Applications include mirror positioning, linear drive systems and rotary drive systems [24, 27]. Figure 2B shows a rotary actuator driven by an orthogonal pair of thermal chevron-beams. Resolution on the order of tens of nanometers is possible with fine resolution current control. Compared to electromagnetic and electrostatic devices, bandwidth is generally lower due to the difference between electromagnetic/electrostatic time constants and thermal time constants (heating/cooling time).
6 Piezoelectric manipulators/actuators

Research on the integration of piezoelectric thin films into MEMS devices has been growing steadily in recent years. Fabrication complexity and reproducibility are the main risks in applying this technology. The most common type of actuator is the simple bimorph cantilever beam (this type of design is used in some SPMs) as shown in Fig. 3A [28-30]. In addition to the bimorph beam, several devices have been made, including tunable optical gratings, linear drive systems, and rotary motors [31-35].

![Image of a piezoelectric bimorph cantilever beam](image1.jpg)  ![SEM image of an electrostatic rotary actuator driving a hinge-mounted mirror via a rack and gear system](image2.jpg)

A: Image of a piezoelectric bimorph cantilever beam [29]. B: SEM image of an electrostatic rotary actuator driving a hinge-mounted mirror via a rack and gear system [36].

Figure 3: Piezoelectric and electrostatically driven, non-planar mechanism

7 References


