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"MEMSEYE" FOR OPTICAL 3D TRACKING AND IMAGING APPLICATIONS

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ABSTRACT

We demonstrate a compact, low-power device which combines a laser source, a MEMS mirror, and photo-sensors to enable fast-motion tracking of an object in a 3D volume while obtaining its precise XYZ coordinates, as well as high resolution laser-based imaging. Any object can be tracked which is marked by retro-reflective tape, or a corner-cube retroreflector (CCR). Two separate subsystems which we termed "MEMSEyes" track the position of the object within a ~40° field-of-view cone, allowing triangulation of the object's distance. A demonstration system running in a 40 kHz control loop is capable of human hand motion tracking and provides position information at up to 5m distance with 13-bit precision and repeatability. In another demonstration, a longer object is marked by two CCRs at its ends and the system measures its orientation in space with ~0.1° precision by locating both ends (CCRs) in a time-multiplexed manner.

When used in rastering mode, a single MEMSEye device can efficiently scan objects and 2D barcodes.

KEYWORDS

MEMS mirror, orientation sensor, micromirror, 3D tracking, laser tracking, corner-cube retroreflector, barcode scanner, laser imaging.

1. INTRODUCTION

This work aims to advance 3D position input and motion sensing in a variety of human-machine interface (HMI) and industrial robotics systems with a MEMS-mirror based optical 3D tracking approach which we termed "MEMSEye." One of the goals is to enable real time interaction with computers and robotics in ways that are more intuitive, precise and natural. Obtaining real-time 3D coordinates of a moving object has many applications such as gaming [1], robotics and human-computer interaction applications [2]-[4], industrial applications etc. Various technologies have been investigated for and used in these applications, including sensing via wire-interfaces [2], ultrasound, and laser interferometry, and others. However a simple and low-cost remote-measurement solution that can provide enough precision and flexibility is not yet available.

Optical, laser-based tracking has important uses in industry because it allows remote measurement with high accuracy, although equipment is often expensive and relatively slow (e.g. [10].) Cassinelli *et al.* demonstrated a scanning mirror-based hand tracking solution [6],[7], utilizing galvanometer scanners which are bulky and have a very high power consumption. The presented system did not demonstrate a searching mode to initiate tracking, similar to commercial laser-tracking systems which require return to tracker's 'home' position. Another potential downside in commercial applications is that their measurement of distance (Z-axis) is based on amount of returned illumination which can vary with many variables beside only distance, e.g. finger orientation and reflectivity.

We utilize fast, gimbal-less two-axis MEMS mirrors as the technology platform to build a high resolution and high speed 3D position measurement system. Previously [8], we demonstrated real-time fast-motion tracking of an object in a 3D volume, while obtaining its XYZ co-ordinates, but the system was mainly limited to tracking a photo-sensor object which communicated its readings via wire to the controller. Use of MEMS mirrors [8],[9], with the possibility for the use of wide-angle lenses provides the possibility of tracking in a very large volume, and very far distances – for example, use of remote-control IR source-detector modules can provide a range of 50m or more. We utilized two separate scanning MEMS micromirror sub-systems and a time-multiplexing scheme to track a quad-cell photodiode in a 40 kHz closed-loop.

The objective of the present work is to improve the flexibility of that methodology so that it does not require the tracked object to include a photo-sensor and synchronous communication. Namely, our goal is an optical-MEMS based, highly compact, low-cost and versatile platform for tracking and position measurement in a variety of situations, tracking objects marked with simply a light source, a corner-cube reflector, or a piece of retro reflective tape. The same platform can be utilized in laser-based imaging such as in e.g. barcode scanning which is also demonstrated in this work.

2. MEMS-BASED OPTICAL 3D TRACKING

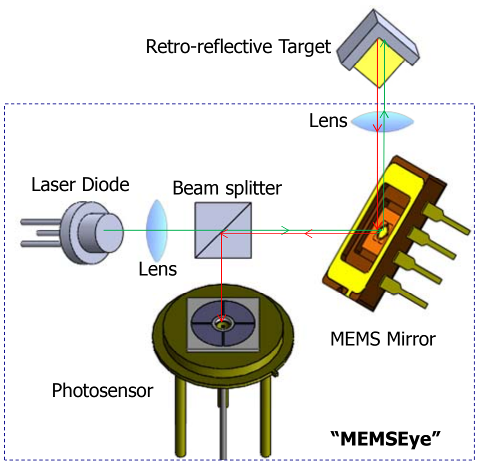


Figure 1. Schematic optical setup for laser-based 3D tracking using a scanning mirror.

As depicted in Figure 1, there is a collimated laser beam that is scanned by a dual-axis MEMS mirror into the space with a 40° field of view and of several meters in front of the unit. The MEMS device runs a spiral search pattern from origin to maximum angles until it encounters a returning retro-reflection from a corner-cube retroreflector (CCR) marked object to its photo detector. The photo detector synchronously relays its readings to the control FPGA. From this point forward the device renews the search but with an updated origin at the last known position of the object. The system performs best with the use of a quadrant photo-detector (as schematically depicted in Figure 1) which provides additional information for tracking, specifically the needed adjustments in X and Y to remain centered on the target's CCR. Therefore there are two clearly distinct modes: search (spiraling) and tracking. Tracking is a PID control closed-loop based on the quad-detector X and Y inputs as loop errors.

We also realized another type of retro-reflector tracking in which it is not possible to utilize CCR reflection offset information for quad-cell photodiode based tracking. We marked various objects such as a pencil, cell-phone, and marker with a small round section of retro reflective tape. Diameter of the spot is approx. 2-3mm, and a nutation algorithm is utilized which continuously scans small circles near the object and correlates the circles with returned light intensity which provides the X,Y vector of correction toward improved light intensity – tape's center.

3. THE MEMSEYE DESIGN

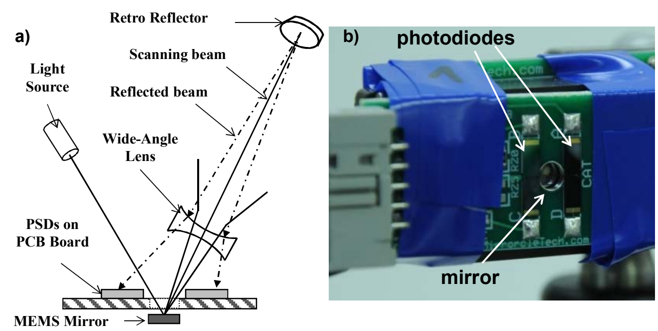


Figure 2. MEMSEye for optical 3D tracking: (a) cross-sectional schematic diagram of the methodology which eliminates the need for beam-splitters and large mirror diameters and (b) photograph of the prototype MEMSEye with a photo-sensor PCB placed in front of the scanning MEMS mirror which can be seen through a hole in the sensor PCB.

In prior methodology, the scanning system is arranged such that the outgoing beam and returning beam both pass over the mirror. Sensor and source are optically separated by a beam-splitter. This is depicted in Figure 1 where the scanning mirror is a small-diameter MEMS-based device. The disadvantage is that due to the mirror's small size, very little of the reflected light is received and conveyed to the photo detector. Further, if the mirror is small, any change of position of the reflecting beam with respect to the mirror, could be lost and result in loss of tracking. Therefore such systems should continue to utilize larger mirrors, more bulky and power consuming or slow-scanning. Another disadvantage of such typical designs is that they require beam splitters which can be inefficient and costly and require a more bulky optical system. Our aim is to use very small and fast moving mirrors (Figure 3) which can be designed to move from point to point in less than half a millisecond. Therefore we must dis-associate the size of the outgoing (scanning) aperture and the receiving (photo sensor) aperture by removing the requirement for the reflected beam to also pass the mirror before sensing. By placing four photodiodes on a PCB which sits on top of the scanning mirror package, we allow the light source and mirror to scan, but capture much of the reflected light after it diverges, as seen in the cross sectional schematic in Figure 2a. A prototype of this design was realized by placing a photo-sensor PCB with above the PCB holding the MEMS mirror device, and aligning the PCB hole to expose the mirror in its center (Figure 2b).

4. MEMS-BASED OPTICAL SCANNING

Gimbal-less Two-Axis MEMS Mirrors

Our 3D tracking technology uses gimbal-less two-axis scanning mirror devices to provide very fast optical beam scanning in two-axes. The type of devices used in this work are are designed and optimized for point-to-point optical beam scanning mode of operation. A steady-state analog actuation voltage results in a steady-stage analog angle of rotation of the micromirror. There is a one-to-one correspondence of actuation voltages and resulting angles that is highly repeatable with no measured degradation over time due to single-crystal silicon construction. Positional precision in open loop driving of the micromirrors is within ~1 milli-degree or within ~20 micro-radians. Typical devices such as those used in this work (Figure 3) provide mechanical tip and tilt of -6° to +6°, resulting in a deflection of approximately -12° to +12° or a total field-of-view (FOV) of 24°.

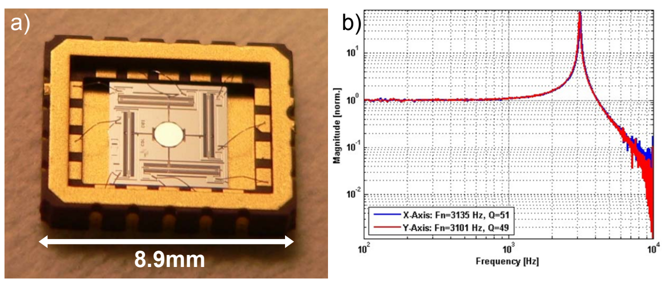
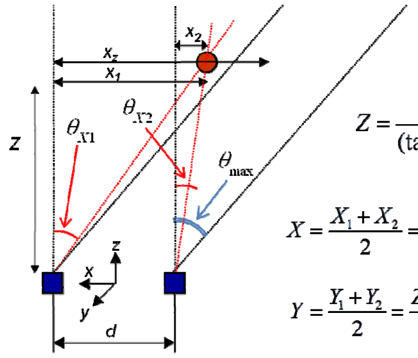


Figure 3. Gimbal-less dual-axis 4-quadrant devices used in this work: (a) typical device which reaches mechanical tilt from -6° to +6° on both axes. Device has a 1mm diameter mirror. (b) Small-signal characteristics of such a high-speed device

As seen in Figure 3b, both axes can be operated over a very wide bandwidth from dc (maintain position) to few thousand Hertz. Such broadband capability allows arbitrary waveforms such as vector graphics, constant velocity scanning, point-to-point step scanning etc. Flat, smooth mirror surfaces are coated with a thin film of metal with desired reflectivity. The electrostatic combdrive design with <=20pF total capacitance enables very-low operating power with the device consuming <1 mW even at highest operating frequencies. Amplifier circuits however consume 50mW-100mW, which we hope to further improve. Nevertheless, when compared to the large-scale galvanometer-based optical scanners, or even magnetic type MEMS actuators, our devices require multiple orders of magnitude less driving power. High-aspect ratio SOI MEMS structures used in our devices are highly resistant to shock and vibration interference, and ultra-low inertia mirror design results in overall tiny masses which further contribute to such robustness. Multiple batches of the devices passed 500G shock tests, 20G vibration tests fro 20Hz to 2000Hz, and temperature cycling tests from -45° to +125°.

5. 3D POSITION MEAUREMENT BASED ON A TWO "MEMSEYE" SYSTEM

It is possible to perform 3D position measurement with a single MEMS mirror-based tracking unit, if distance information can be obtained by time-of-flight measurement or interferometry. Time-of-flight measurements are very costly and bulky and rarely applicable outside of military and select, high-cost applications. Additionally they work best at longer distances where precision can be more reasonably obtained as light is simply "too fast." To reduce cost and complexity, we perform 3D position measurement by triangulation of two or more measurements of the target object's azimuth and elevation with respect to the scanning mirror, as long as the two or more scanning mirrors are at different locations as depicted in Figure 4.



$$Z = \frac{d}{(\tan(\theta_{X1}) - (\tan(\theta_{X2}))} \quad (1)$$

$$X = \frac{X_1 + X_2}{2} = \frac{Z \cdot (\tan(\theta_{X1}) + \tan(\theta_{X2}))}{2} \quad (2)$$

$$Y = \frac{Y_1 + Y_2}{2} = \frac{Z \cdot (\tan(\theta_{Y1}) + \tan(\theta_{Y2}))}{2} \quad (3)$$

Figure 4. Geometrical setup for two tracking sub-systems which are placed in parallel at a known distance d, and both track an object simultaneously, thereby obtaining independent azimuth information.

In the simplest case we present here the two systems are spaced apart by distance *d*, such as having two apertures ("eyes,") ~15cm apart. Each device is run by a closed-loop control loop based on a fast FPGA computing platform which takes error information from optical sensors and provides new commands to each scanning mirror at a 40 kHz rate. In most of our experiments we calibrate our devices to provide θ_{max}=10°, giving a total scan angle of 20°. When tracking, the FPGA system records the azimuth and elevation angle of pointing of mirror 1, θ_{X1} and θ_{Y1}. θ values. Second mirror, spaced at a known distance *d* provides angles θ_{X2} and θ_{Y2} (Figure 4). Both devices see nearly identical Y readings θ_{Y1} and θ_{Y2}, but due to motion parallax the X readings are different and depend on the distance to the object. We utilize the X readings to obtain a true distance of the object to the origin (a point directly between the two micromirrors) as shown in equation (1). With *Z* known, *X* and *Y* are found from known parameters and by averaging from two devices' readings as shown in equations (2) and (3).

6. IMAGING APPLICATIONS

The same MEMSEye used for 3D position measurement can also be used for imaging applications such as e.g. scanning of 1D and 2D barcodes (Figure 5a). The same hardware is used but the methodology is somewhat different. The mirror is driven to raster the laser beam over an area of interest with a prescribed number of lines or effectively horizontal and vertical pixels. At each location the photo-sensors record the amount of reflection. In the example of barcode scanning, high contrast in the barcodes design results in easily detectable reflections when scanned, as seen in a sample scan in Figure 5b. The MEMS devices have a high repeatability and scanning resolution due to their electrostatic mechanism and single-crystal silicon construction. Therefore, images of high resolution can be obtained, although with trade-off in frame rate.

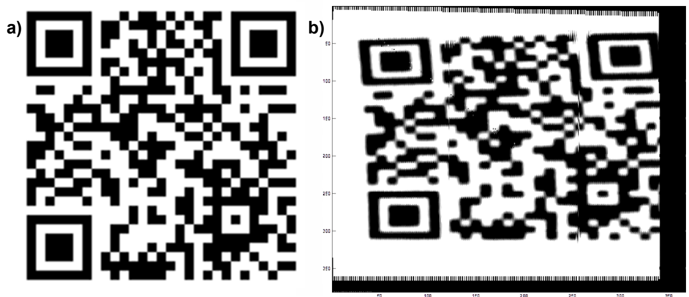


Figure 5. (a) Image of a 2D barcode used for scan tests, (b) result of the MEMSEye scan of the 2D barcode processed and mapped to a 380x380 pixel image.

The same type of line rastering over an object can also be used in 3D scanning (3D digitization of solid objects,) however in that case a remote camera sensor would be used to capture each line. The imaging MEMSEye design described above measures reflectivity of each illuminated spot but cannot measure its distance.

7. RESULTS

Multiple prototype arrangements were tested. Retroreflector tracking prototypes performed at greater distances, wide angles, and due to the use of a small mirror (1mm diameter,) significantly greater speeds of target motion were trackable. Robust tracking of both CCR targets (Figure 6 a, b), as well as retro-reflective tape (Figure 6 c, d) targets is demonstrated. The MEMSEye system was able to track and follow the individual position of the retro-reflective tape placed on the tip of a pencil (Figure 6c), or on the edge of a cell phone (Figure 6d), in a wide-angle cone of approx. 40°. After some preliminary system calibrations by approximating the angle that each MEMS mirror points to at a given voltage, the XYZ determination algorithm was tested. With preliminary calibration distances are found to be accurate within a few mm in all 3 directions, in a large volume of over 1m^3. Precision and repeatability are better than 1mm in distance (Z) and better than 0.1mm in X and Y. Therefore future improvements call for an improved calibration protocol with a complete LUT of angle vs. voltage for each MEMSEye unit.

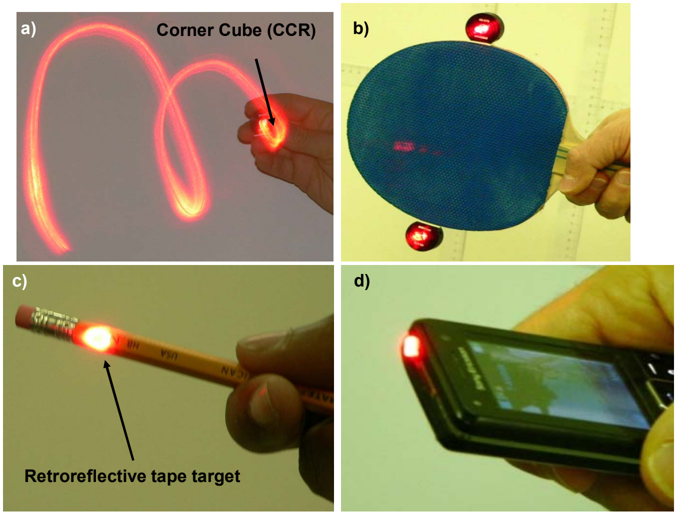


Figure 6. Examples of objects being tracked (targets are bright because the tracking system is actively pointing the laser beam onto them): (a) moving corner-cube retro-reflector, (b) a paddle-marked with two CCRs, providing orientation and position information (c) a cell-phone marked with retroreflective tape, and (d) a pencil with a retroreflective tape target.

Furthermore, the MEMSEye system was able to track two CCRs placed on a long rod while multiplexing to determine positions of both CCRs, and from the measured positions create a line vector, providing the azimuth and the elevation angles of the rod. Accuracy and precision of the MEMSEye was tested using a theodolite with arc second accuracy, which held the rod under test on a theodolite. A single target's position was measured while moving in plane with the MEMSEyes down to a sub millimeter precision (Figure 7a). The main purpose of the theodolite was to test the MEMSEye's ability to measure the azimuth elevation of the rod under test. During the experiment, the rod under test was moved between 0º to 40º, orthogonal to the MEMSEyes. The MEMSEyes were able to track the line vector both in plane and at a different elevation angle to accuracy of around +/-1º (Figure 7b). Measurements were repeatable to below 0.1° of object's orientation (azimuth.)

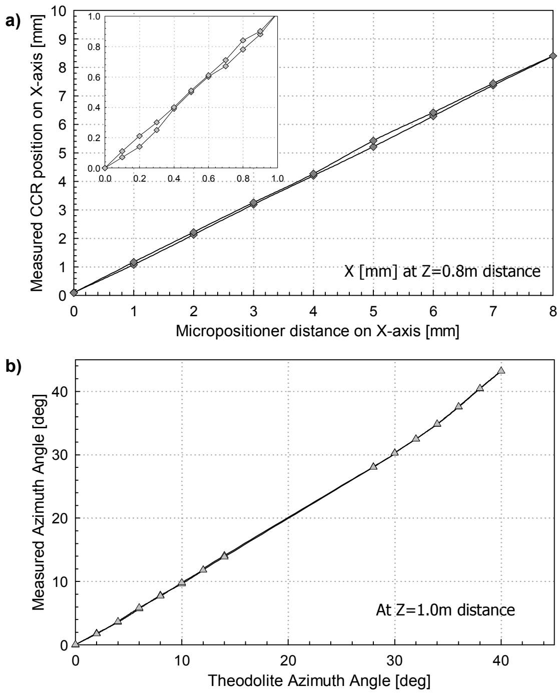


Figure 7. Results from MEMSEye system test for precision using Theodolite. (a) Measurement of precision of change in X-axis position. (b) Measurement results of change in azimuth angle, orthogonal to MEMSEye system.

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