Fast and High-Precision 3D Tracking and Position Measurement with MEMS Micromirrors

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Abstract - We demonstrate real-time fast-motion tracking of an object in a 3D volume, while obtaining its precise XYZ co-ordinates. Two separate scanning MEMS micromirror sub-systems track the object in a 20 kHz closed-loop. A demonstration system capable of tracking full-speed human hand motion provides position information at up to 5m distance with 16-bit precision, or <=20μm precision on the X and Y axes (up/down, left/right,) and precision on the depth (Z-axis) from 10μm to 1.5mm, depending on distance.

INTRODUCTION

Obtaining real-time 3D co-ordinates 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. However a simple and low cost solution that can provide enough precision and flexibility has not been available. Recent proliferation of low-cost inertial sensors has not addressed the problem of position tracking. Cassinelli *et al* demonstrated a scanning mirror-based tracking solution [3-4], however their system does not solve the problem of object searching/selecting and does not have adequate depth (Z-axis) measurements.

The objective of this work was to develop and demonstrate an optical-MEMS based, very low cost and versatile platform for tracking and position measurement in a variety of situations. Use of MEMS mirrors [5] with potential for use of wide-angle lenses provides the possibility of tracking in a very large volume, and very far distances. E.g. use of remote-control IR source-detector modules can provide a range of 50m or more.

MULTIPLE TRACKING OPTIONS

We have developed several beam-steering based techniques to track an object inside a conic volume, as depicted in Fig. 1a.

A. Tracking a photo-detector or a retro-reflector

As depicted in Fig. 1b, there are two laser beams scanned by two MEMS mirrors into a common volume. Both systems are pointed in a parallel direction, but are spaced a known distance *d* apart (Fig. 2a.) The devices run a spiral search pattern from origin to maximum angles until they encounter a photo-detector which synchronously relays its readings to the control FPGA. From this point forward the devices renew a search but with an updated origin at the last known position of the photo-detector. The system is therefore in a perpetual search mode, although only in a very small neighborhood of the photo-detector. Full motion tracking (Fig. 2b) was achieved with fast MEMS devices giving at least 2 kHz of motion bandwidth. Since only one device can illuminate the target at a time, we time-multiplex the sub-systems by laser modulation.

In our best-performing setup we use a quadrant photo-detector which provides additional information for tracking, specifically the needed adjustments in X and Y to get centered on the target. Here there are clearly distinct modes: search (spiraling) and tracking. Tracking is a proportional control closed-loop based on the quad-detector X and Y inputs as loop errors. We also implemented a small beam-motion dither on the MEMS scanners that allows us to measure the tilt-orientation of the quad-detector (Fig. 2c,) therefore giving us 4 DoF of the detector and allowing us to use it at any rotational position.

In a nearly identical setup, we placed 2 photo-detectors in close proximity with the MEMS mirrors. The object being searched in the 3D volume is a retro-reflector ("cats eye") or a corner-cube reflector (both were used in our experiments.) In this manner both devices can simultaneously illuminate the target and operate independently.

B. Tracking an LED

As depicted in Fig. 1c, there is a photo-detector near each one of the MEMS scanning units. An optical source such as a near-IR LED is the target object that illuminates the micromirrors. When the mirrors are properly pointed, that illumination is reflected onto each detector. Therefore no time-multiplexing or communication to the target is necessary.

3D POSITION MEASUREMENT

Both devices *X* and *Y* axes are driven by separate channels of a 16-bit FPGA system. They achieve angle (negative and positive) maxima ($-\theta_{max}$, $+\theta_{max}$) when the system sends –K to +K to its output DAC, where $K=2^{15}-1$. In most of our experiments we calibrate our devices to provide $\theta_{max}=10°$, giving a total scan angle of 20°. When device 1 successfully tracks the target, the FPGA system records the angle of the device's x-axis and y-axis in terms of the open-loop output values O_{X1} and O_{Y1}. Second device provides knowledge of its open-loop angles O_{X2} and O_{Y2}. The devices are level in *y* but spaced a known distance *d* in *x*. Therefore when both devices are tracking the object they see nearly identical Y readings O_{Y1} and O_{Y2}, but due to motion parallax the X readings are different and depend on the distance of 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:

$$Z = \frac{d \cdot K}{\tan(\theta_{\max})} \cdot \frac{1}{(O_{X1} - O_{X2})}.$$

With *Z* known, *X* and *Y* are found from known parameters and by averaging from two devices' readings:

$$X = (O_{X2} + O_{X1}) \cdot Z \cdot \tan(\theta_{\max})/(2K) = \frac{d}{2}\frac{(O_{X2} + O_{X1})}{(O_{X1} - O_{X2})}.$$

$$Y = (O_{Y2} + O_{Y1}) \cdot Z \cdot \tan(\theta_{\max})/(2K) = \frac{d}{2}\frac{(O_{Y2} + O_{Y1})}{(O_{X1} - O_{X2})}$$

RESULTS

Our MEMS devices provided pointing precision >= the DAC's 16-bit resolution, and therefore our overall system results all demonstrated this 16-bit limitation. When target object was not moving, no single digit of X,Y,Z was changing. Movements of 1mm on an optical-bench micrometer were easily recorded at 5m distance. With the loop-gain and bandwidth capable of tracking full-speed human hand motion, the system provides position information at up to 5m distance with <=20μm precision on the X and Y axes (up, down, left, right,) and precision on the depth (Z-axis) from 10μm to 1.5mm, depending on the distance. Precision can be greatly increased with slower tracking settings and lower loop-gain in different applications.

[1] J. Brophy-Warren, "Magic Wand: How Hackers Make Use Of Their Wii-motes," The Wall Street Journal, Apr. 28th, 2007.

[2] P. Arcara, et al, "Perception of Depth Information by Means of a Wire-Actuated Haptic Interface," Proc. of 2000 IEEE Int. Conf. on Robotics and Automation, Apr. 2000.

[3] A. Cassinelli, et al, "*Smart Laser-Scanner for 3D Human-Machine Interface*," Int. Conf. on Human Factors in Computing Systems, Portland, OR, Apr. 02 - 07, 2005, pp. 1138 - 1139.

[4] S. Perrin, et al, **"**Laser-Based Finger Tracking System Suitable for MOEMS Integration**,"** Image and Vision Computing, New Zealand, 26-28 Nov. 2003, pp.131-136.

[5] V. Milanović, et al, "Gimbal-less Monolithic Silicon Actuators For Tip-Tilt-Piston Micromirror Applications," IEEE J. of Select Topics in Quantum Electronics, vol. 10(3), Jun 2004.

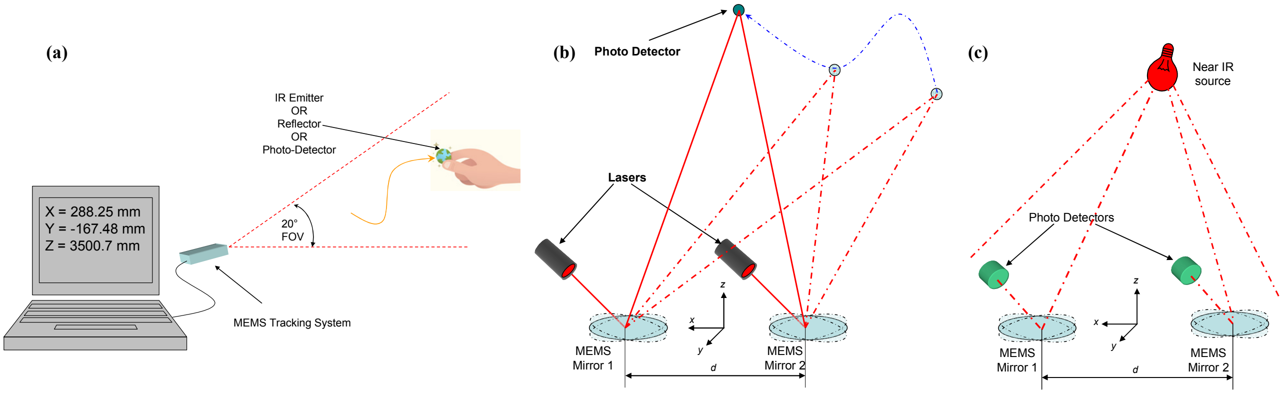

Figure 1. (a) Schematic diagram of 3D tracking of a hand-held object in a 3D volume. (b) Schematic of a 3D Tracking setup with two beam-steering MEMS mirrors aiming their laser sources onto the target. (c) Schematic diagram of 3D tracking and measurement setup with two MEMS devices steering incident light from a (near-IR) source onto their respective photo-detector.

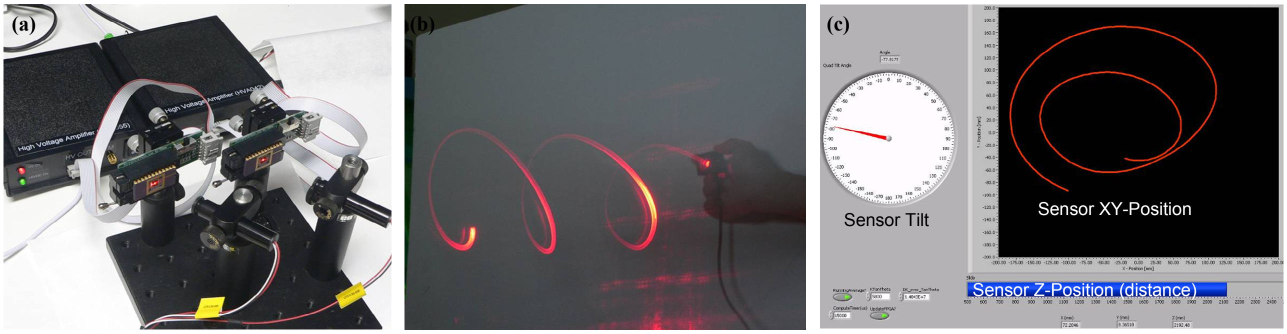

Figure 2. (a)Photograph of the two MEMS scanners and amplifiers. The devices are d=75mm apart and aimed in the same direction. Each amplifier in the background is driven by the FPGA closed-loop controller. (b) A 2s long exposure photograph of quad-detector tracking. Both laser spots are on the detector, and both devices successfully track the target. (c) GUI screen capture showing the measured 4 DoF of the detector: position X [mm], position Y [mm], position Z [mm], and tilt of the quad-detector [deg.]

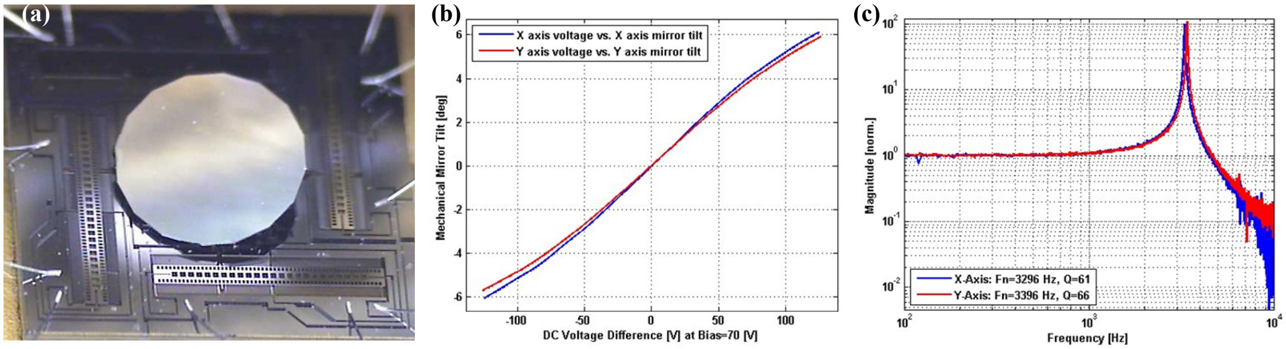

Figure 3. Gimbal-less dual-axis 4-quadrant devices used in this work: (a) typical device which reaches mechanical tilt from -8° to +8° on both axes. Device has a 2mm mirror, this larger aperture being more suitable for the setup of Fig. 1c. (b) Voltage vs. Mechanical tilt angle measurements of a typical 4-quadrant device, linearized by our 4-channel amplifier driving scheme. (c) Small-signal characteristics of fast devices with 0.8mm mirror used in the setup of Fig. 1b, where larger aperture size is not required.