“MEMSEye” for Optical 3D Position and Orientation Measurement

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ABSTRACT

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.” The goal is to enable real time interaction with computers and robotics in ways that are more intuitive, precise and natural. Objects can be tracked which are marked either by light sources (e.g. a near-IR LED,) corner-cube retro-reflectors (CCRs,) or with retro-reflective tape. Each "MEMSEye" unit can track the object with high speed and determine with high precision the azimuth and elevation (θ_X and θ_Y) angles of the line between the unit and the object. When two or more such units are utilized to triangulate the object, relative position can be fully determined since distance information can also be obtained. This final XYZ position information down to sub-millimeter precision can be obtained in relatively large volumes at update rates of >20 kHz. A demonstration system capable of tracking full-speed human hand motion provides position information at up to 4m distance with 13-bit precision and repeatability. In another demonstration, a vector in free space is marked by two target CCRs and the MEMSEye system measures its orientation in space with ~0.1° precision by locating both CCRs in a time-multiplexed manner.

Keywords: MEMS mirror, orientation sensor, micromirror, 3D tracking, laser tracking, corner-cube retroreflector.

1. INTRODUCTION

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. However a simple and low-cost solution that can provide enough precision and flexibility is not yet available. The MEMSEye project aims to utilize scanning MEMS mirrors as the technology platform used to build a high resolution and high speed 3D position measurement systems as depicted in Fig. 1a. This technology can be used to build systems (Fig. 1a, b) that allow users to interact with virtual and augmented reality environments in a natural and intuitive way.

Figure 1. Depiction of our project’s long-term goal – a sensor unit with two optical-tracking apertures measure 3D position of a remote object, shown here as a small glowing blue LED. In (a), the sensor unit is mounted on top of a laptop’s monitor and a user is running a 3D application. In (b), we depict various possible system uses based on where we attach the small tracking targets. For example, robot’s end effector position is monitored. (c) Mimio’s interactive electronic white board kit allows hand written materials and drawings on whiteboard to be recorded electronically in color. (d) Nintendo’s Wii remote senses the user’s motion and use it to interact with a game.

The Wii gaming system is widely considered a breakthrough in the game controller design, as it not only allows free movement for the user, but also makes use of that movement for user to interact with the virtual world[1]. The controller (Fig. 1d) tracking system utilizes a single camera-based IR position sensing system and three-axis accelerometers[5]. An IR emitter bar is placed in front of the user, emitting from two IR sources a known distance apart[5]. The hand held sensor images the sources onto a camera at standard camera rates (tens of milliseconds for update.) By calculating the distance of the IR sources as seen by the receiver, as well as the orientation - a relative, perspective-based location of the

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handheld sensor can be calculated[5]. But this is not very precise, due to both the resolution of the camera, the slow refresh rate of the system, as well as potential for ambiguity in perspective-based measurement. This can lead to errors which make such technologies inadequate for industrial applications.

Another innovative human-machine interface by Mimio (Fig 1c), makes sensor bars and accessories that provide a better interaction with the classroom white board[6]. The Mimio sensor bar uses both ultrasound and IR sensor to locate the pens, eraser and control stylus using triangulation[6]. The approach produces an audible chirp when in use. This technology is limited to two dimensions, but even with above limitations it solves an important problem in human-computer interactions and has a wide range of uses.

2. THE MEMSEYE APPROACH

2.1 Background

Cassinelli *et. al* demonstrated a scanning mirror-based tracking solution[7,8] utilizing galvanometer scanners which are bulky and have a very high power consumption. The system did not demonstrate a searching mode to initiate tracking, and measurement of distance (Z-axis) is based on amount of returned illumination which will vary with many variables beside only distance.

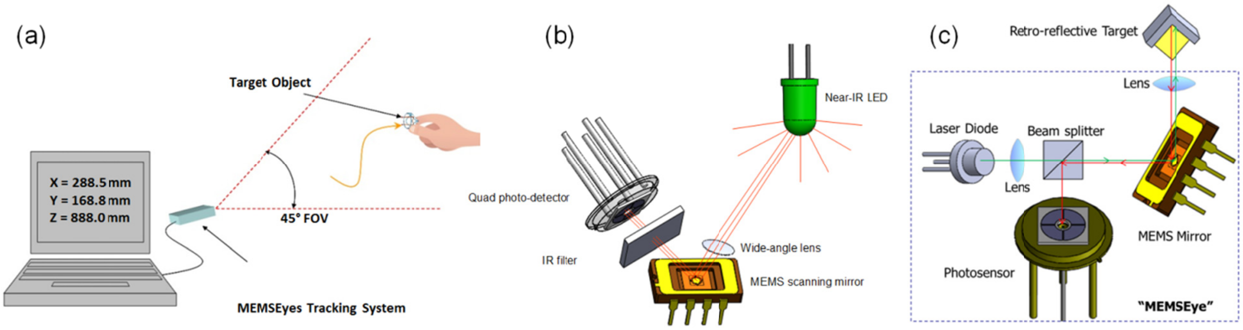


Figure 2. (a) Schematic diagram of 3D tracking of a hand-held object in a 3D volume. (b) A simplified arrangement of optics, sensors, and MEMS mirror that allows tracking of an LED. (c) A simplified arrangement of optics, a laser source, sensor, and MEMS mirror that allows 3D tracking of a retro-reflecting object such as a corner-cube retro-reflector.

Previously[9], 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[9,10] 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 20 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 provide synchronous communication. Namely, our goal as depicted in Fig. 2 is an optical-MEMS based, 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 two different MEMS-based schemes or techniques to track an object inside a conic volume are depicted in Fig. 2.

2.2 LED Tracking

As depicted in Fig. 2b, there is a photo-detector near the MEMS scanning unit. An optical source such as a near-IR LED is the target object that illuminates the micromirror. In some cases there may be a wide-angle lens ("fisheye lens") between the mirror and object which would allow a far greater field-of-view (FOV) for the unit. When the mirror is properly pointed, that illumination from the LED is imaged onto the quad photo-detector. This proper pointing would be initially found through simple search algorithms such as a spiral search. After the first signal is found, further pointing corrections are based on a closed-loop control scheme with error signals being provided by the quad photo-detector. We should also note that we envision high performance systems including adaptive lenses that allow increasing and decreasing the spot size in the far field such that e.g. search algorithm utilizes a very wide spot size and easily captures target's general position, and small spot size is used for fine and precise position measurements.

Tracking an LED light source can give the user a larger range of movement. A single LED radiates out a cone of light.

Several LEDs could be arranged such a way that all the cones of light overlap, creating a spherical light source. Such light source can be detected in all orientations as long as there is a direct line of sight between the light source and the detector. The price to pay is added complexity of the light source, which requires a battery and several LEDs.

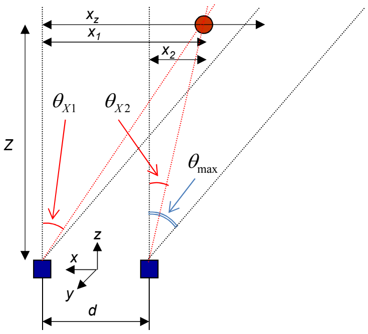
2.3 Retroreflector Tracking

As depicted in Fig. 2c, there is a collimated laser beam that is scanned by a dual-axis MEMS mirror into the space with a 45° 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 which provides additional information for tracking, specifically the needed adjustments in X and Y to get centered on the target. 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. 3mm, and in this arrangement 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. 3D POSITION MEAUREMENT BASED ON TWO "EYE" 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 Fig. 3.



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

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

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

Figure 3. 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 20 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} (Fig. 3). 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).

4. MEMS-BASED OPTICAL SCANNING

4.1 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. Devices can be made to provide optical scanning angles of up to 32° at high speeds in both axes, but typical devices such as those used in this work (Fig. 4) 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°. As seen in Fig. 4c, 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, still adequate for mobile, battery run applications.

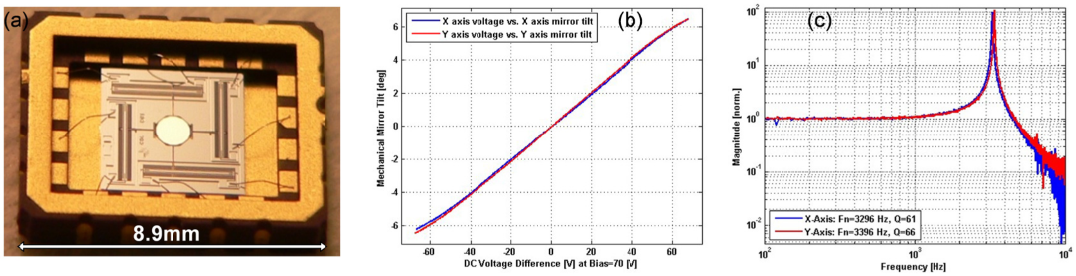


Figure 4. Gimbal-less dual-axis 4-quadrant devices used in this work: (a) typical device which reaches mechanical tilt from -6° to +6° on both axes. Device has a 1mm diameter mirror. (b) Voltage vs. Mechanical tilt angle measurements of a typical 4-quadrant device, linearized by a differential driving scheme. (c) Small-signal characteristics of such a high-speed device.

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 our devices have already passed 500G shock tests at a third-party facility, 20G vibration tests fro 20Hz to 2000Hz, and temperature cycling tests from -45° to +125°.

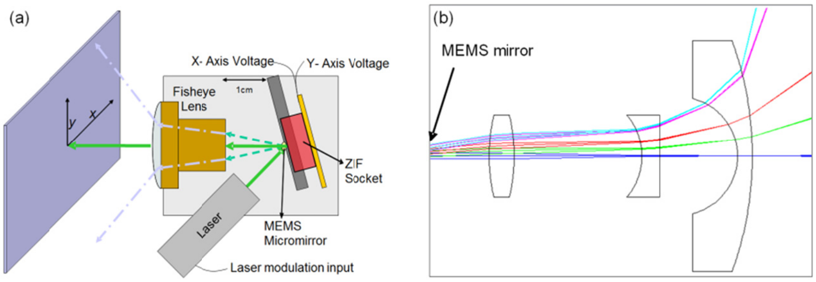


Figure 5. (a) Schematic of scanning optical beam setup with the use of a wide-angle lens increasing field of view for the MEMS mirror: laser diode points a collimated beam onto the MEMS micromirror which deflects it into the wide-angle (fisheye) lens. The lens magnifies the deflection and projects the beam into a volume of interest. (b) Example of a custom designed fisheye lens which magnifies optical scan angles to over 100° field of view.

4.2 Wide-Angle Lens

In order to address a larger volume of interest with a wider field of view than that possible by the MEMS devices alone, we employ a scan lens such as e.g. a custom designed fisheye lens shown in the example given in Fig. 5. In our experiments we typically utilize an off-the-shelf negative lens element which magnifies the MEMS scan angles from approximately 24° to approximately 45° field of view. It is important that the lens has proper anti-reflection coating which limits the amount of light scattering and erroneous detection on the photo-detectors. Additionally, the lens may include a filter or filter-type coatings to limit the amount of ambient lighting effect on the system. If any significant pin-cushion or another distortion results due to the use of such lenses, we create look-up-tables (LUT) that provides the relationship between the optical scan angle of the laser beam and MEMS driving voltage.

5. IMPROVED MEMSEYE DESIGN

In prior methodology, the scanning system is arranged such that the outgoing beam and returning beam both pass over the mirror, allowing optical system with a static beam, due to the mirror's correction, and separation of beams by a splitter. The disadvantage is that if the scanning mirror is small, very little of the reflected light is received and conveyed to the photo detector. Further, if the mirror is small, any movement of the reflected beam, i.e. 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 the overall optical system bulky. Our aim is to use very small and fast moving mirrors (Fig. 4) 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 as shown in Fig 6 where a PCB holding four photodiodes sits on top of the scanning mirror package, allowing the light source and mirror to scan, but capturing much of the reflected light after it diverges.

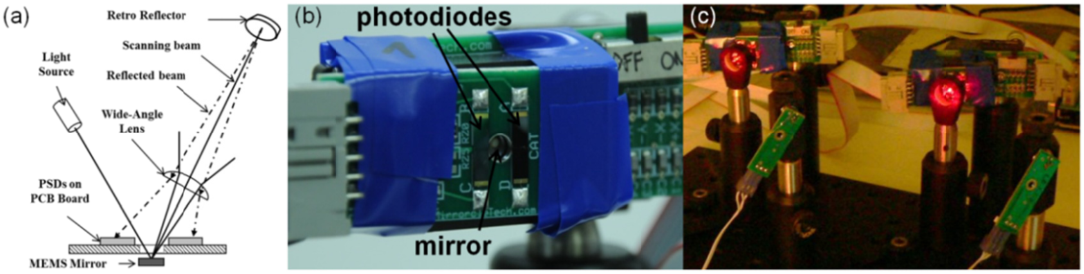


Figure 6. (a) Schematic of the new approach which eliminates the beamsplitter and increases the receiving aperture. (b) Photodiodes arranged in four quadrants on a PCB cover the MEMS package but allow mirror scanning. (c) Photograph of the current stereoscopic MEMSEye prototype setup with two units 127mm apart with a scan lens in front of each unit.

6. RESULTS

Multiple prototype arrangements were tested. LED tracking tests required the use of significantly larger mirror diameters in order to capture enough light from the LED once the LED was a significant (~1m) distance away from the sensor. With a 3.2mm mirror diameter and an aperture to block erroneous reflections to the photo sensor tracking and position measurement was demonstrated up to about 1.25m distance. Further improvements in sensitivity are filtering of ambient lighting are needed before further characterization for range, precision, etc.

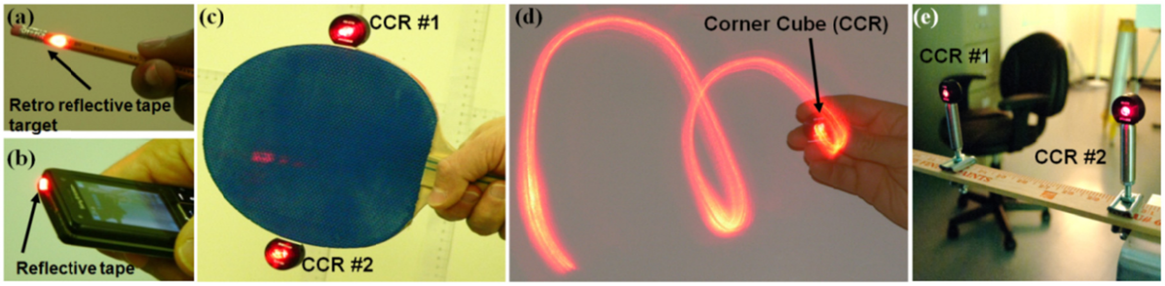


Figure 7. (a), (b) Retro-reflective tape on various objects tracked by the MEMSEye system – tape markers are glowing because they are illuminated by the tracking system. (c) MEMSEye system tracking two corner-cube reflectors at a fixed distance on a paddle, allowing measurement of orientation. (d) Photograph showing a CCR being tracked while in motion. (e) Two CCRs clamped on top of the rod under test, being moved by a Theodolite below. Glowing red because simultaneously illuminated by lasers.

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 corner cube retro-reflector (CCR) targets (Fig 7c,d,e), as well as retro-reflective tape (Fig. 7a,b) 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 (Fig 7a), or on the edge of a cell phone (Fig 7b), in a wide-angle cone of approx. 45°. 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.

Furthermore, the MEMSEye system was able to track two CCRs placed on a long rod (Fig 7e) 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,. A single target's position was measured while moving in plane with the MEMSEyes down to a sub millimeter precision (Fig 8a). 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 (Fig 8b). Measurements were repeatable to below 0.1°.

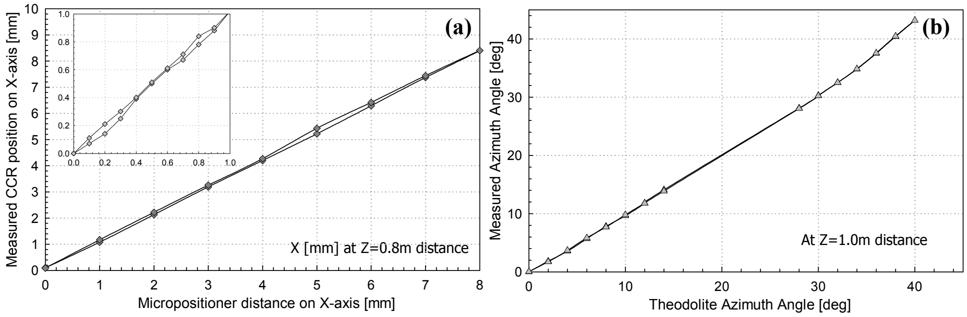


Figure 8. Results from MEMSEye system test for precision using Theodolite. (a) Measurement of precision of change in X-axis position. (b) Measurement results of change in azimuth angle, orthogonal to MEMSEye system.

REFERENCES

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

[2] Arcara, P., 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] Aoyagi, S., et al. "Measurement of 3-D Position and Orientation of a ROBT using Ultrasonic waves", CH2976-9/91/0000-2466, IEEE 1991.

[4] Bebek, O., Cavusoglu, M.C., "Whisker Sensor Design for Three Dimensional Position Measurement in Robotic Assisted Beating Heart Surgery" 2007 IEEE Int. Conf. on Robotics and Automation, April 10-14 2007 Roma, Italy

[5] http://en.wikipedia.org/wiki/Wii_Remote

[6] http://us.mimio.com/en-US.aspx

[7] Cassinelli, A., 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.

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

[9] Milanović, V., Lo, W.K., "Fast and High-Precision 3D Tracking and Position Measurement with MEMS Micromirrors," 2008 IEEE/LEOS Optical MEMS and Their Applications Conf., Freiburg, Germany, Aug. 12, 2008.

[10] Milanović, V., "Linearized Gimbal-less Two-Axis MEMS Mirrors," 2009 Optical Fiber Communication Conference and Exposition (OFC'09), San Diego, CA, Mar. 25, 2009.