

Real-time 3D Tracking

The system “MEMSEye” can be used for optical 3D position and orientation measurement

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The ability to track objects in real time in a 3D environment has many real world applications, such as sensors that allow people to interact with electronic devices in very natural and intuitive ways. Controllers that can follow our hands or fingers and interpret our intentions could make human-machine interaction a more enjoyable, ergonomic and a more precise experience. Another application area is industrial automation, that heavily depends on the ability of robots to precisely locate and position objects.

To address some of these needs, whilst with a highly flexible and low-cost solution, we have developed a tracking and position measurement technology, dubbed “MEMSEye”, based on a beam steering MEMS mirror. It is capable of searching and tracking the position of a retro reflective target and providing position measurements at very fast update rates and with high resolution in a large volume. Multiple MEMSEyes can obtain 3D coordinates of the target utilizing triangulation methodologies. When multiple targets are used simultaneously, the system can obtain the orientation of an object as well as its location. A recent redesign and improvements of the system for an outdoor application resulted in a laser tracking system capable of direct sunlight operation at distances of up to approximately 150 m.

Introduction

Obtaining real-time 3D coordinates of a moving object has many applications such as gaming [1], robotics, human-machine interaction applications [2–4], industrial applications, construction, etc. Various technologies have been investigated for and used in

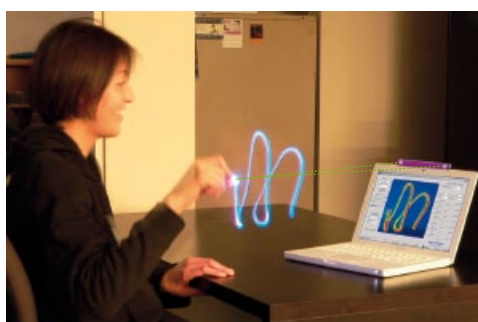


Fig. 1 Depiction of the vision of a MEMSEye sensor unit with two optical-tracking “eyes” measuring 3D position of a remote object, shown here as a small glowing blue LED or a retro-reflective marker (left). We depict various possible uses based on where we attach the small tracking targets and monitor their positions such as in robots, pens, gloves, etc. (right).

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 yet been available. The MEMSEye project at Mirrorcle Technologies has aimed for several years to utilize scanning MEMS mirrors as the technology platform for building high resolution and high speed 3D position measurement systems as depicted in Fig. 1. This technology can be used to build systems that allow users to interact with virtual and augmented reality environments in a natural and intuitive way.

The technology utilizes simple and low cost subcomponents such as consumer-market laser diodes, silicon photodiodes, scanning MEMS mirrors and it does not require any special optics. Search and acquisition of targets in a field of view of $\sim 20^\circ$ was demonstrated at up to 150 m distance using simple raster search patterns. Subsequently, targets are tracked and illuminated with the laser beam using various direction correction algorithms.

Demonstrations included hand-held target movement at different distances and speeds, tracking of targets on bicy-

cles, cars and a specially made test platform for high-velocity testing.

The tracker is geared towards high-speed, long-distance tracking. However, in the past we had demonstrated an indoor tracking system and patented a triangulation methodology for XYZ position measurement based on the use of two such trackers (two “eyes”). In indoor versions, for robotic control and other human-computer interaction applications, a wide angle lens is added to increase the field of view as necessary, and eye-safe low power laser diodes are employed. The outdoor tracking systems can also be utilized in various configurations (multiple “eyes”) if 3D information is required.

Introduction to the MEMSEye

We define the “MEMSEye” as an optical, line-of-sight sensor capable of providing real-time data on the azimuth and elevation angle position of a remote target with respect to the sensor system. Its implementation is in most cases as a laser-based continuous tracking of a remote retro-reflective marker attached to a target in test. Namely, the MEMSEye uses a laser beam (~ 1 mW average power for

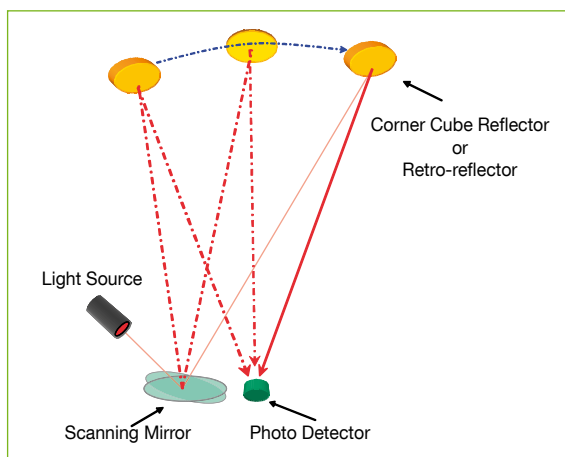


Fig. 2 Simplified schematic of the MEMSEye optical setup. MEMS mirror is directing a laser beam towards a target. Based on the retro-reflective properties of the target, a portion of the beam is returned towards the system and is in part captured by the photo detector. A control algorithm uses the detected brightness to determine any mirror adjustment needed to maintain tracking.

indoor applications) that is steered towards a moving target using a Mirrorcle MEMS mirror (Fig. 2). The system can continuously track the target position in closed loop control by continually pointing the laser beam towards its location, as long as the target is within the systems field of view. The optical scan module is very compact, robust and low power, thanks to the use of MEMS mirror technology. The MEMSEye system consists of two separate modules – the Scan and Sense Module (SSM) and the Electronics Module. The SSM contains a laser diode and collimation optics, a MEMS mirror, a photosensor and a pre-amplifier for the photosensor. The Electronics Module contains the FPGA

board with analog inputs and outputs and the MEMS driver.

The MEMSEye system has two modes of operation – standalone mode and user controlled mode. The standalone mode is designed such that the MEMSEye system acts as a black box that boots up when powered, automatically searches for and acquires a target, and once acquired, starts tracking it and reporting target position (angles) to a user's analog or digital interface. In user-controlled mode, the electronics system is connected to a PC via TCP/IP, which allows the user to modify the search and track waveforms and parameters, adjusting scan angles (field of view), enable and disable the laser and MEMS driver, etc. In this mode, the target's position is reported back to the PC via TCP/IP and displayed in a LabView GUI window.

In the case where multiple sensors are utilized to obtain complete 3D position information by triangulation, the user-controlled method allows the controller to combine measurements from multiple MEMSEyes and compute XYZ coordinates and display in the GUI.

In order to address a larger volume of interest with a wider field of view than that possible by the MEMS devices alone, MEMSEye system can employ a post-scan lens such as a custom designed fisheye lens [5]. In our experiments we typically utilize an off-the-shelf negative lens element which magnifies the MEMS scan angles from approximately 20° 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. 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.

Robust tracking of both corner cube retro-reflector (CCR) targets, as well as retro-reflective tape targets has been demonstrated as shown in Fig. 3. For short-distance applications of up to 5 m, The MEMSEye system is able to track and follow the individual position of the retro-reflective tape placed on the tip of a pencil, or on the edge of a cell phone, in a wide-angle cone of ~45°. In longer distances, appropriately larger targets are utilized to improve the signal-to-noise ratio (SNR) and even more importantly to reduce the time for the initial searching and acquiring the target. Namely, a search algorithm must raster or spiral the laser beam through the entire field of view and in no area skip the location of the target. To minimize the search time and therefore reduce the number of search lines, target size must be increased. Typical sizes in our work range from 1 cm diameter marker at up to 5 m distance to 6 cm diameter marker at up to 100 m distance.

MEMS-based optical beam steering

Our 3D tracking technology is enabled by gimbal-less two-axis scanning mirror devices to provide very fast optical beam steering in two-axes. The type of devices used in this work are designed and optimized for point-to-point optical scanning mode of operation. A steady-state analog actuation voltage results in a steady-state analog angle of rotation of the micromirror. There is a one-to-one correspondence of actuation volt-

Company

Mirrorcle Technologies, Inc. (MTI)

Richmond, USA

Mirrorcle offers beam-steering MEMS mirrors and supporting hardware and software. Based on patented MEMS technology, products include the world's fastest large scan-angle two-axis mirrors capable of point-to-point, vector and other types of scanning. MTI is the only provider of tip-tilt MEMS actuators in combination with mirrors from 0.8 to 4.2 mm diameter with a variety of specifications. Plug-and-play R&D packages include three MEMS, hardware, electronics and a software development kit.

www.mirrorcletech.com



Fig. 3 Photographs of a corner-cube retro-reflector (CCR) and retro-reflective tape being tracked by the MEMSEye system. The red glow in the images is caused by the red laser beam which is directed by the MEMS mirror to track the objects. Fast hand movement in the left image and an extended exposure time of the photograph shows the trail of target and laser beam positions.

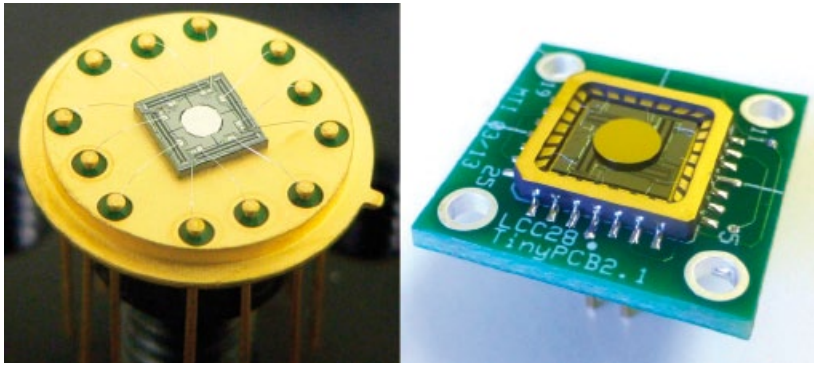


Fig. 4 Examples of MEMS Mirrors. A 1.7 mm diameter, aluminum-coated integrated mirror device (left) and a 4.2 mm diameter, gold-coated bonded mirror device (right).

ages and resulting angles: it is highly repeatable with no detectable degradation over time. This is in great part due to the electrostatic drive methodology and single-crystal silicon material selection. Positional precision of mechanical tilt in open loop driving of the mirror actuators is at least 14 bits (16384 positions) on each axis. For most devices, with mechanical tilt range of -5° to $+5^\circ$ on each axis, this tilt resolution is within 0.6 milli-degrees or within 10 micro-radians. A sequence of actuation voltages results in a sequence of angles for point-to-point scanning.

Some devices are 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 -5° to $+5^\circ$, resulting in a beam steering of approximately -10° to $+10^\circ$ or a total field-of-view (FOV) of 20° .

Both axes can be operated over a very wide bandwidth from dc (they maintain position at constant voltage with nearly zero power consumption at the device) to several hundred Hertz. Such fast and broadband capability allows nearly arbitrary waveforms such as vector graphics, constant velocity line scanning, point-to-point step scanning, object tracking, etc. The electrostatic combdrive design with ≤ 20 pF total capacitance enables very low operating power with the device consuming < 1 mW even at highest operating frequencies. Driver circuits, however, consume more. Power consumption is typically in the range of 100 – 200 mW, depending on the required bandwidth.

Our mirrors are fabricated out of single-crystal silicon wafers of the same prime grade and quality that is used for the manufacturing of integrated

circuits such as PC microprocessors. Because similar mass production processes are utilized to obtain highest manufacturing repeatability, quality and lowest cost, silicon is used as the base material. As the base material in a MEMS mirror, silicon has the optimal properties of smoothness, cleanliness and flatness. At the same time, in the MEMS actuator, silicon can be micro-machined to precise small dimensions on the order of a few microns in width, giving it excellent flexibility and range of motion for rotation and displacement. Micromachining of silicon structures with aspect ratios as high as 25 : 1 results in thin long suspensions which provide excellent elastic properties and can be very robust in shock and vibration environments.

In the final manufacturing step for optical beam steering applications, the silicon mirror must be coated for high reflectivity at required optical wavelengths. In our standard processes, we coat the silicon mirrors with a thin layer of Aluminum or Gold. In our standard processes with Al or Au coatings, we

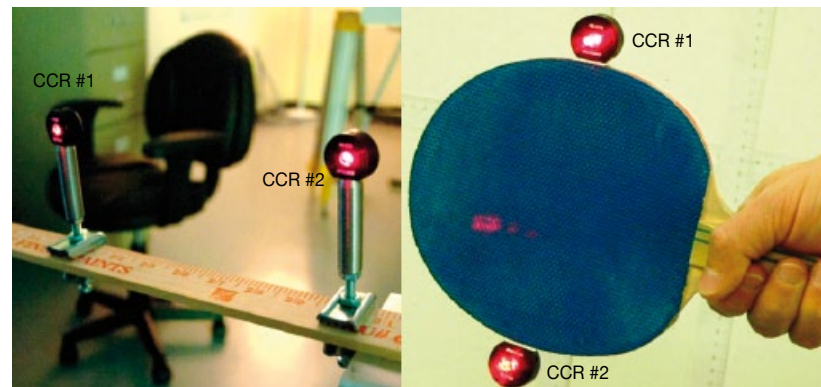


Fig. 5 Examples of 3D orientation measurement with MEMSEye. Two targets are attached to an object and tracked simultaneously (by time multiplexing the laser beam) by two MEMSEyes in order to measure orientation of two points in space.

maintain > 5 m radius of curvature in any mirror type and size.

3D position measurement 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 of light are very costly and require bulky equipment. 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, 3D position measurement was performed 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.

In the simplest case, two SSMs are spaced apart by distance d , such as having two apertures (“eyes,”) ~ 15 cm 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 >10 kHz rate.

In most of our experiments, devices were calibrated to provide $\theta_{\max} = 10^\circ$, 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} . The second mirror, spaced at a known distance d provides angles θ_{x2} and θ_{y2} . Both devices see nearly identical Y readings θ_{y1} and θ_{y2} , but due to motion parallax the X read-



Fig. 6 Scan and Sense Module (SSM) for longer range outdoor applications. A stop sign with inherent retro-reflective properties acts as a highly attractive target to the system, even at 112 m distance and is therefore illuminated by the 660 nm red laser beam.

ings are different and depend on the distance to the object. The X readings are utilized to obtain a true distance of the object to the origin (a point directly between the two micromirrors). With Z known, X and Y are found from known parameters and by averaging from two devices' readings.

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 1 m^3 . Precision and repeatability are better than 1 mm in distance (Z) and better than 0.1 mm 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.

Orientation measurement based on simultaneous tracking of two targets

For an orientation measurement between points in 3D space a long rod is positioned at a certain azimuth and elevation angle about 1 – 2 m from the sensor, and the sensor should be able to report those angles as the rod is moving. We used the laser tracking system, but reconfigured it to track and report on two targets. Namely, the object in 3D space (the long rod) would be marked with two displaced markers and the system would utilize two MEMSEyes to track and measure 3D position of the two markers. The XYZ position data

from each individual MEMSEye is then used to obtain a vector in space between the two tracked markers. The system demonstrated the ability to track two CCRs placed on a long rod (Fig. 5) by time-multiplexing and to compute a line vector from the measured positions and thereby provide the azimuth and the elevation angles of the rod. Accuracy and precision of the system was tested using a theodolite with arc second accuracy, which held the rod under test. A single target's position was measured to a sub millimeter precision while moving in plane with the MEMSEyes' optical breadboard. The main purpose of using a theodolite was to test the system's ability to measure the azimuth elevation of the rod under test. During the experiment, the rod was moved between 0° to 40° , orthogonal to the MEMSEyes. The system was able to track the line vector both in plane and at a different elevation angle to accuracy of around $\pm 1^\circ$. Measurements were repeatable to below 0.1° .



Fig. 7 Outdoor tracking of targets moving on a bike, and in direct sunlight. Targets are red due to the tracking laser beam centering on them. At the shown distances of $\sim 80 \text{ m}$, the beam size is nearly identical to the target size of 5 cm.

The downside of such multiplexed-target measurements is that the system is effectively tracking each individual target much slower. Due to the necessary transition of the laser beam from one target to the other, the overall update rate is approximately ten times slower than in the case of direct tracking of a single target.

Outdoor laser tracking at up to 150 m

Most recently, a new application required a significant modification of the laser tracker technology in order to allow long term outdoor operation and significantly longer distance of targets up to $\sim 100 \text{ m}$. The requirement for outdoor operation in various locations necessitates a modification of the photosensor to operate even in direct sunlight. Yet, the longer distance necessitates drastically higher photosensor sensitivity which exposes the sensor even more to the difficulties of operation in sunlight conditions. Beyond utilizing laser modulation to address ambient light and other potential interference signals and low frequency noise, significant electronic design effort was necessary to remove the effects of direct sunlight on the sensor photodiode while maintaining high sensitivity to the desired signal. Additionally, a 100 nm bandwidth optical bandpass filter centered at 650 nm was used to attenuate light at wavelengths away from the 660 nm red laser diode in the system (Fig. 6).

Our solution to the problem included a MEMS mirror size larger than one used in indoor tracking systems, in order to allow smaller beam divergence and therefore a smaller spot size at $\sim 100 \text{ m}$ distance. Experiments in

the prototype stage of the project included a gold-coated 3 mm diameter mirror, 2.4 mm diameter mirror and an aluminum coated 1.7 mm mirror. Clearly the larger mirrors could provide significantly better divergence performance and utilization of the collimated laser beam, however their lower speeds resulted in limitations for fastest possible target movements. The final design leaned toward the faster mirror (1.7 mm diameter) and traded off the spot size in the distance. The required field of view of approximately $\pm 10^\circ$ matches nicely the standard scan performance of most of our MEMS mirrors and therefore no post-scanning optics are used.

With an average laser power of about 20 mW, the system can search, acquire, and maintain track on any retro-reflective targets up to practically 150 m. The overall power consumption of the scan-and-sense module (SSM) is approximately 0.4 W, of which ~ 0.3 W drive the laser. High grade retro-reflective tape of 5 – 6 cm diameter size is the intended target for the application, however various other retro-reflective targets work nearly as well like street signs, cats eyes on car back-lights and bikes, jackets and backpacks with retro-reflective stripes, etc. At closer distances of up to 75 m, car license plates have also worked quite well (Fig. 7).

System accuracy has not yet been fully characterized due to the challenges of such long distances and fields of view, however it is presently estimated at about 1 cm at 50 m (~ 16 m range of motion), and 2.5 cm at 100m (~ 32 m range of motion). Update rate of the system is 5 ms. Targets with velocity as high as 10 m/s at 50 m are tracked without any difficulty.

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- Video of tracking demonstrations: www.youtube.com/watch?v=yGcTAi7U9hw

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