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UAV-Borne LiDAR with MEMS Mirror Based Scanning Capability

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ABSTRACT

Firstly, we demonstrated a wirelessly controlled MEMS scan module with imaging and laser tracking capability which can be mounted and flown on a small UAV quadcopter. The MEMS scan module was reduced down to a small volume of <90mm x 60mm x 40mm, weighing less than 40g and consuming less than 750mW of power using a ~5mW laser. This MEMS scan module was controlled by a smartphone via Bluetooth while flying on a drone, and could project vector content, text, and perform laser based tracking. Also, a “point-and-range” LiDAR module was developed for UAV applications based on low SWaP (Size, Weight and Power) gimbal-less MEMS mirror beam-steering technology and off-the-shelf OEM LRF modules. For demonstration purposes of an integrated laser range finder module, we used a simple off-the-shelf OEM laser range finder (LRF) with a 100m range, +/-1.5mm accuracy, and 4Hz ranging capability. The LRFs receiver optics were modified to accept 20° of angle, matching the transmitter’s FoR. A relatively large (5.0mm) diameter MEMS mirror with +/-10° optical scanning angle was utilized in the demonstration to maintain the small beam divergence of the module. The complete LiDAR prototype can fit into a small volume of <70mm x 60mm x 60mm, and weigh <50g when powered by the UAV’s battery. The MEMS mirror based LiDAR system allows for on-demand ranging of points or areas within the FoR without altering the UAV’s position. Increasing the LRF ranging frequency and stabilizing the pointing of the laser beam by utilizing the onboard inertial sensors and the camera are additional goals of the next design.

Keywords: MEMS Mirrors, laser tracking, laser imaging, laser range finder, UAV, drone, LiDAR.

1. INTRODUCTION

1.1 Background

With the increased commercial availability of UAV technology, UAVs or drones have become popular as toys, development projects for hobbyists, and even tools to aid in imaging, delivery, etc. There are drones available with open-source access to the hardware and software that can allow for modifications on its control and flight. This allows for introduction of new “add-on” technologies that can aid in how the drone operates, especially in the case of autonomous flight. Since cameras have already been introduced for drones to allow for aerial filming and imaging, the simplest step would be to use the camera for 3D imaging to assist the drone as it flies. Camera based imaging can be used to try to determine 3D information within a given field of view. Camera systems are prevalent especially in the electronic gaming industry and they are used on drones to help users monitor their flight path, and they are also used in various other camera based monitoring systems. However, the use of a single camera has limitations – one is the camera’s fixed and relatively limited resolution, and the second is the difficulty of 3D information detection even with high quality imagery without any true distance information. In addition to that, a camera’s ultimate limitation is always lighting, i.e. that it cannot obtain any reliable data from a relatively or completely dark scene or object.

Laser based measurement systems are commonly used in various industries in situations where an accurate measurement in position, distance, or the azimuth and elevation of a target is required. There are various technologies that can be used to perform these measurements. One method would be time-of-flight (TOF) measurement using a laser range finder (LRF). There are many commercially available LRFs that are used in construction, sports, recreation, etc. A system such as active LiDAR can be used to obtain a cloud of 3D data. A compact system that utilizes MEMS mirrors demonstrated by Moss *et al* [4] has excellent performance parameters but is still significantly ‘overweight’ and ‘oversized’ for UAV applications, with its 8.9cm x 15.2cm x 28cm dimensions and ~2.63kg mass [4],[5]. This type of system or similar commercially available LiDAR systems with a wide field of regard are presently too big and costly even for automotive applications and require significant further development. Its power consumption of 30W [4] would also need to be significantly reduced. Due to the limitations of present camera-based and LiDAR-based systems for drone applications, a solution utilizing a laser based measurement with light and a cheap off-the-shelf system should be considered.

A possible solution for a simple and functional UAV-borne LiDAR could be to have a compact MEMS-mirror based beam steering system integrated with a pocket-sized off-the-shelf laser rangefinder (LRF) to image a “point cloud” in front of the drone's flight path – allowing the system to adjust for any objects in the way. This point cloud will be less dense compared to the image derived by LiDAR, but simplifies the payload of the drone to an LRF module, beam steering device and a controller. In fact, it is anticipated that multiple such scanning systems would be necessary or could be utilized in each drone and therefore each one should really represent a nearly negligible payload in size, weight, and power consumption (SWaP) – as well as ultimately in cost as well.

1.2 Goal of this Work

The first goal of this project is to demonstrate that it is possible to have a fully wirelessly-controllable and programmable laser beam scanning module with SWaP so low that it can be flown on a toy quad-copter. Specifically, a module consisting of a MEMS Scan Head (laser, MEMS mirror and optics), electronic Controller, and a power source (Li-Po) battery which can be operated by the drone controller or by a second user wirelessly. Therefore, our first goal is low SWaP for a laser scanning system.

The second goal is to demonstrate that with a simple addition of a sensitive photodetector, tuned for the system's own laser wavelength and modulation, we can achieve a number of additional functions with hardly any penalty on the total SWaP. We want to demonstrate imaging functions such as simple threshold-based collision avoidance, as well as tracking functions such as keeping the laser beam pointed at a marked spot on a wall while the drone is in flight.

Finally, the third goal is to combine an off-the-shelf OEM laser rangefinder with the module and obtain point clouds, arrays of distances, in the forward looking field of regard of 24° while in flight.

2. MEMS MIRROR BASED IMAGER AND LASER TRACKER

2.1 Gimbal-less MEMS mirrors overview

Gimbal-less MEMS mirror devices (Figure 1) are designed and optimized for point-to-point or "quasistatic" optical beam steering. This means that any steady-state analog actuation voltage results in a specific steady-state analog angle of rotation of the mirror and consequently in a specific optical beam direction. Near dc (0 Hz), there is a one-to-one correspondence of actuation voltages and resulting angles: it is highly repeatable with no measurable degradation over time. A sequence of actuation voltages results in a sequence of mirror angles for point-to-point beam-steering. These devices can be operated over a very wide bandwidth from dc (maintaining position at constant voltage with nearly zero power consumption at the device) to several thousand Hertz with mechanical tilt range of -6° to +6° on each axis or larger depending on the design [1]. At higher frequencies closer to device resonance, the full device response must be taken into account; however, it can be generally stated that this technology enables arbitrary control of laser beam position and velocity up to a certain velocity limit. Such fast and broadband capability allows nearly arbitrary waveforms such as vector graphics, constant velocity line scanning, point-to-point step scanning, and resonant-quasistatic rastering (one axis resonant, the other quasi-static) discussed more in the next section. These capabilities are utilized in established applications such as 3D scanning [2], biomedical imaging [3], free-space communication, LiDAR [4],[5], and laser tracking [6],[7].

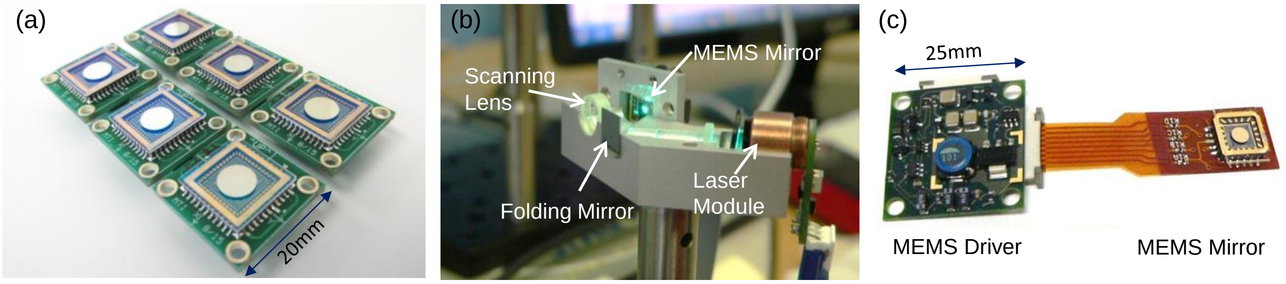

Figure 1. a) A4QQ8.3 devices with a bonded 6.4mm mirror, b) A typical MEMS scan head consisting of a laser module, a folding mirror, a MEMS mirror, and a scanning lens, c) A miniaturized MEMS driver connected to a 3.6mm mirror

2.2 Various scanning modes

Each axis of the gimbal-less two-axis MEMS mirrors [9][10] can be independently commanded to arbitrary position and velocity – in a given bandwidth of available steering movement. Hence the user has a wide range of possibilities to design scanning patterns for different applications. In Figure 2 we show some different modalities of scanning which are frequently used in applications. There are no clear distinctions between different scanning modes – in all cases there are simply different waveforms provided to each axis which can continually vary from dc to any frequency and mix of frequencies. This category is generalized as the quasi-static mode – where the mirror position responds directly to the driver commands, proportionally and with minimal phase delay. The same MEMS mirrors can also operate in the dynamic, resonant mode. When operated near the resonant frequency, devices give significantly more angle at lower operating voltages and sinusoidal motion. Furthermore there is a phase delay. Namely, the MEMS actuators utilize single-crystal silicon springs to support the micromirror and to provide restoring force during actuation. The combination of the springs and the mirror's inertia result in a 2nd order mass-spring system with a relatively high quality factor (Q) of 50-100. Therefore, in this mode, low actuation voltages at frequencies near resonance result in large bi-directional rotation angles. Resonant frequencies are in the range of several kHz.

It is possible to define three modes of operation, as described here and depicted in photos of green laser beam steering in Figure 2:

a) First mode is point-to-point mode or quasi-static mode. In this case both axes are utilizing the wide bandwidth of operation of the device from dc to some frequency, and not allowing for resonance and ringing. Therefore the mirror can hold a dc position, move at a uniform velocity, perform vector graphics, etc.

b) The second mode is a mixed mode in which one axis is used in quasi-static mode, and the other axis is used in resonant mode. A typical use case is to run one axis very fast (e.g. few kHz,) to create horizontal lines, and to run the other axis with a sawtooth-like waveform to create a raster pattern that covers a rectangular display or imaging area. Again, the axis operating at resonance should have its parameters carefully obtained, initially at low voltages and angles, to avoid exceeding maximum mechanical angles.

c) Third mode is resonant mode. In this case both axes are utilizing the narrow, high gain resonance to obtain large angles of deflection and relatively low voltages and high speeds. Motion is limited to very narrowband, sinusoidal trajectories with a phase lag to the applied voltage. It is not necessary to drive the device at the exact resonant peak as the resonant mode can be obtained within few percent of the highest gain point. Resulting 2D motion describes circles, ellipses, and various higher order Lissajous patterns and can be modulated at some rate. Devices designed for point-to-point mode, when driven near and at resonance, easily exceed safe operating angles and break. It is important to approach resonant mode of operation with very small sinusoidal driving voltages about the bias position and very carefully search for a desired operating point and angle, so as not to exceed a given device's maximum mechanical angle limit.

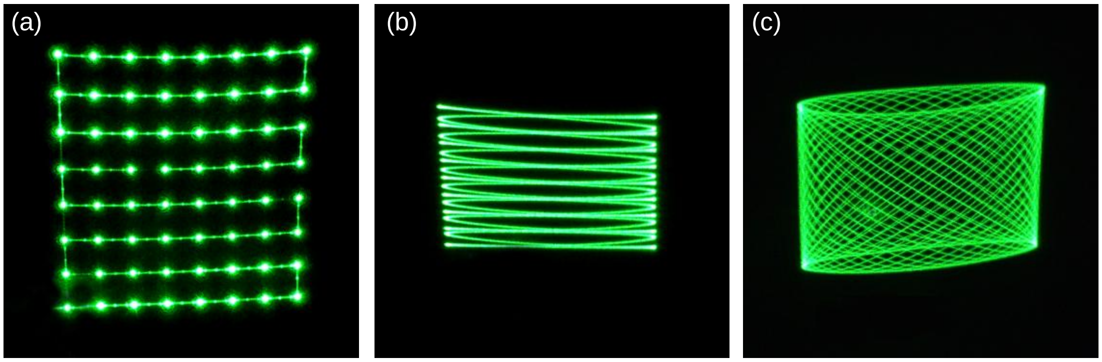

Figure 2 Photographs of examples of using Mirrorcle MEMS Mirror in (a) point-to-point scanning mode (quasi-static) on both axes with the laser beam stopping at each angle, then stepping to the next angle, (b) resonant scanning mode on the x-axis (sinusoidal beam motion) and quasi-static on the y-axis (triangle wave motion in this example), and (c) resonant scanning mode on both axes, showing a 2D resonant Lissajous pattern.

2.3 Laser Imaging with MEMS Mirrors

As mentioned above, a laser beam can be arbitrarily deflected to a desired location on a target, and can for example raster over an area on a target object. In applications such as laser marking, 3D printing, target designation or dazzling, that is sufficient. On the other hand, in some applications we wish to obtain information about the target object by receiving some feedback from the laser-illuminated point or pixel. In this laser-based imaging mode, a photodetector is arranged to receive back any retro-reflected radiation from the illuminated spot on the target. Laser imaging with this type of MEMS mirror has been implemented in several research and commercial applications, such as a handheld biomedical imaging system [3]. In the optical coherence tomography (OCT) system of [3], a laser is scanned in a raster pattern with a small MEMS mirror and the intensity of the reflection is measured to generate a volumetric scan. In fact it is very typical that a specific optical metrology method or modality such as OCT has initial applications as a single-point technique, and then in later development seeks to add two-axis beam steering to add full imaging or mapping capability that comes with that. Therefore, there are seemingly countless applications in which laser beams are used to obtain information about samples, tissue, eyes, etc., which may initially utilize only a single-point measurement or moving stages to achieve scanning – and can now utilize beam steering MEMS mirrors.

Low volume and low weight scanning and tracking applications can be achieved with simple photodiode detection. These systems work in the same manner as those used before in biomedical imaging applications. The MEMS mirror steers the laser to a certain target and the current of the photodetector is measured to determine the magnitude of laser light that is reflected back. If the current exceeds a set threshold, the object is considered detected. While not highly accurate, this technique is sufficient for certain imaging applications. For example, drone collision avoidance might be achieved by determining whether the laser is being reflecting off of a nearby wall. A security system could be devised that can trigger an alarm if a non-reflected laser is suddenly reflected by a person or object passing through the beam.

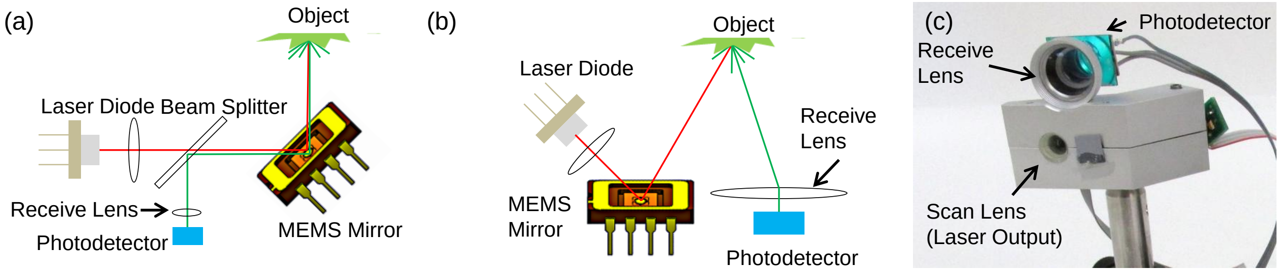

Figure 3 a) Single aperture laser imaging system using a MEMS mirror and single photo-detector; b) Dual aperture laser imaging system. The MEMS mirror can be much smaller in this system since the mirror is not responsible for handling the returning light; c) demonstration of a dual aperture imaging system with the MEMS mirror and laser in the aluminum housing and an attached photo-detector and receiving lens

It should be mentioned that a single photo-detector based imaging setup can be constructed in many ways. In Figure 3a and 3b we compare two architectures which are often used and have considerably different effects on the MEMS requirements. A single aperture system using a beam splitter – such as in [7] – can be constructed so that a laser is passed through a beam splitter to the MEMS mirror, which directs the beam towards a target (Figure 3a). Any diffuse or retro-reflected light which returns in the direction of the mirror reflects off of the MEMS mirror back through the beam splitter where it is redirected to a photo-detector. The setup has many advantages in terms of its high sensitivity for the specific target area and low sensitivity to external unwanted radiation. However its main disadvantage is that the receive aperture is limited to the size of the MEMS mirror which is typically quite small. A dual aperture system – such as in [4],[5] – is characterized by a laser beam that is steered with a MEMS mirror through one aperture towards a reflective target, while any light returning from the target is received through a proximate and larger second aperture which contains the photo-detector (Figure 3b).

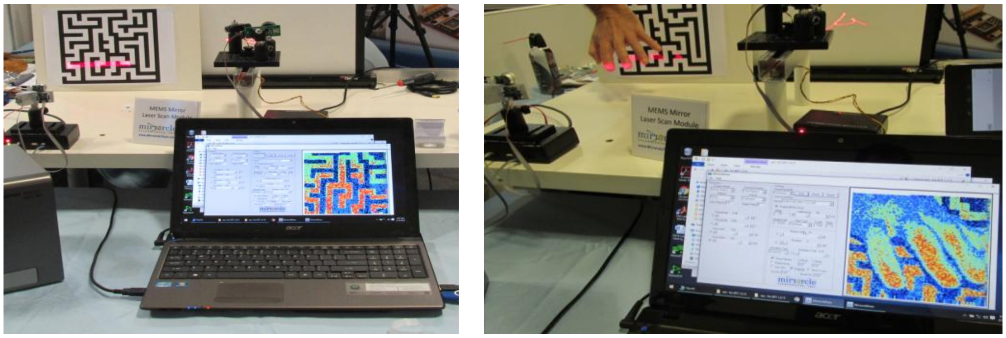

Figure 4. a) "Single pixel camera" system made from a MEMS scanning mirror and photo-detector which is able to reconstruct images from raster scanning a laser and reading the reflected light for each offset of the MEMS mirror, b) The "single pixel camera" system showing an image reconstructed by raster scanning the laser over a user's hand.

The key advantage is that the receiver can be effectively as large as desired independent of the size of the MEMS mirror. The disadvantage is that the receiver is constantly "looking" at the complete field of view and may be more susceptible to unwanted background radiation. While customers for medical applications utilize both depending on the specific requirements of the system, in general the preferred architecture with MEMS mirrors is the dual aperture style. This way the MEMS mirror size can be kept small which helps with speed and shock tolerance. At the same time receiving aperture can be independently designed, presumably of considerably larger size.

We have demonstrated a dual aperture imaging system (Figure 3c) with an aluminum housing that contains the laser, MEMS mirror and lens. The receiving lens and sensor is mounted on top of the aluminum housing. The laser and MEMS driver and processing system (not shown) is housed in a separate unit. A scanning system with a single photo-detector can in effect be used as a “single pixel” camera. By raster scanning the laser beam with the MEMS mirror, the value of the returned light can be measured for each pixel. An image constructed by using the offsets of the laser system for the pixel position. Figure 4a and Figure 4b show such as system when used to scan objects with different patterns. In particular for objects that have highly contrasting reflection patterns, a clearly defined image can be generated.

2.4 Laser Tracking with MEMS Mirrors

These laser imaging systems can be extended to provide real-time tracking of targets. One example is to place a retro-reflective tape marked object in the laser scanner’s field of view. When the laser is aimed to reflect off of the object, the photosensor reads a high current. As the object is moved, a feedback system can steer the laser to continue tracking the “high current” area and therefore the object. The advantage of course would be that the system does not need to continue to raster over the entire field of view, a full scan which may take e.g. 100ms-200ms. Instead the system only scans/rasters over a very limited ‘tracking field of view’ area taking e.g. 5ms to complete the localized search. To achieve this tracking, the laser is steered in a small, repeating pattern such as a Lissajous pattern (sinusoidal waveforms for each axis). This is depicted in Figure 5a. At the time T_{n-2}, the center of the pattern is clearly not centered over the target circle. As the pattern is drawn by the laser beam, the photo-detector values are measured so that the system can map the strength of reflected light for each sample (segment) of the pattern. In this example as the system integrates the waveform signal for each axis with the strength of the reflected light, it will find that a positive number on X and Y will result, giving the system correction values to ‘nudge’ its own center offset position toward the right and up. This feedback system can then steer the centroid of the pattern closer to the centroid of the target circle. At time T_{n-1}, another pattern is drawn sample by sample, and again at each sample measurement of retro-reflected light strength is taken. The integrals for x and y will again result in positive values, recommending another adjustment to the right and up. Finally at time T_n, the pattern is centered of the target object. In this case the integration will yield zeros for X and Y, as there are equal number of hits on all sides of the pattern. In this manner, an object can be continuously tracked and the corresponding azimuth and elevation values are provided from the MEMS mirror. A typical setup is to have an e.g. 200Hz sinusoid and a 400Hz sinusoid drawing a figure eight which is completed every 5ms. Thus, every 5ms a new integration is completed and new adjustments of the center of the figure can be made. Setting the gains and other parameters of this feedback loop as well as those exact frequencies leaves a lot of design space for the user since this is a fully programmable and flexible scheme or ‘localized imaging’.

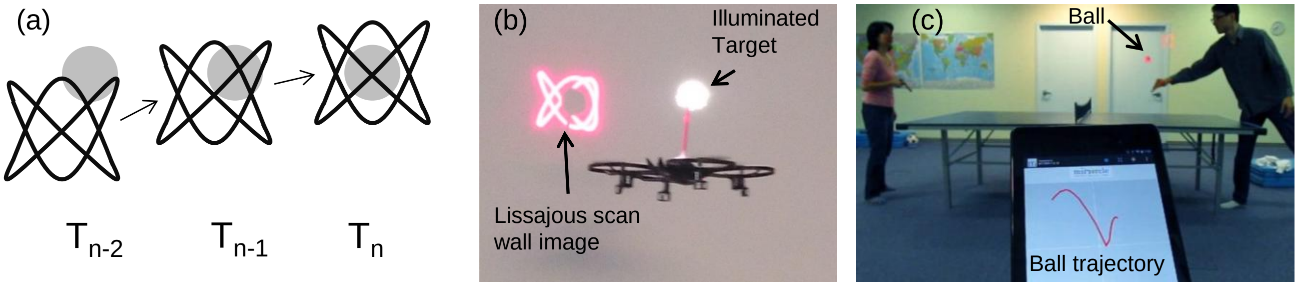

Figure 5 a) A laser tracking system functions by drawing a Lissajous pattern and reading the photo-detector value for each part of the reflected pattern. A feedback system can then move the centroid of the laser pattern to correspond to the retro-reflective object. b) A laser tracking system based on a MEMS mirror and single photo-detector is used to track a UAV with a retro-reflective object attached. c) MEMS mirror based laser tracking system is controlled by a Tablet via Bluetooth. As it tracks a Ping-Pong ball in a table-tennis game, the ball’s trajectory is plotted in the Tablet view.

We have built several test systems that utilize this real-time tracking technique. An industrial ruggedized version of the tracker has been tested outdoors in various weather conditions for three months, continuously providing tracking data. The goal of this outdoor tracker was to demonstrate being able to track a target with direct sunlight, and any other erroneous reflective surfaces seen in a daily environment. Target can be defined as highest retro-reflection part of the field of view or anything over certain threshold of retro-reflection, typically a retro-reflective tape marked object.

Another tracking development system was used for tracking the position of a UAV by placing a retro-reflective object on the UAV (Figure 5b). As the UAV moves, the feedback system of the tracking system steers the laser pattern to be drawn at the centroid of the reflective object. Similarly, the MEMS tracking system has been mounted directly on a drone and the system can track a stationary reflective object on the wall while the drone moves (Figure 5c). In this system, the offset values of the MEMS mirror are wirelessly transmitted back to a smart phone so that the values can be read and recorded. A MEMS based laser tracking system has many potential applications where a beam needs to be continually directed at a desired target, such as free space communication between moving objects.

3. DISTANCE MEASUREMENT METHODOLOGY

In the previous section we discussed how a MEMS mirror based laser scan system can obtain information about the environment in its 40° field of regard by observing the intensity of light from each chosen direction. This kind of intensity information can be very useful and can supplement e.g. camera based imagery since it is obtained with active lighting. Namely each pixel is providing its own illumination with laser power chosen to meet eye safety requirements. While the fusion of camera data and laser-imaging or laser-tracking data can provide significantly more information, it is still short of providing critical distance information to the drone.

3.1 Signal Strength Based

A rudimentary method for a coarse measurement of distance to a target with a uniform surface is measuring brightness of the light reflected back from the target surface. In a setup where the MEMS mirror illuminates a spot on a target (e.g. a wall), the received optical power from that diffuse source point source scales inversely with the square of distance [8]. If the system is calibrated to a given target reflectance, e.g. in the case of indoor navigation, it may be possible to obtain accuracy on the order of 1cm in distance measurement. However it is clear that any variations in texture, color, etc. would result in significant changes of accuracy of such a setup if it is required to provide 'multi-bit' accuracy data.

On the other hand, the system can be setup to work in a single-bit mode where it must simply decide whether the light reflected back is above a set threshold value. This value could be set or calibrated e.g. when the receiver is a given "safe" distance from the target. Any light received by the photodetector during a 2D raster by the MEMS scan head that is above that level signifies an object that is closer than that 'safe' distance at a given azimuth and elevation provided by the MEMS scan system. This methodology can be used as a simple collision detection warning system - if the MEMS imaging system mounted on a UAV approaches close to a wall or an object, it would trigger and alarm the user or the drone firmware.

3.2 Triangulation Based

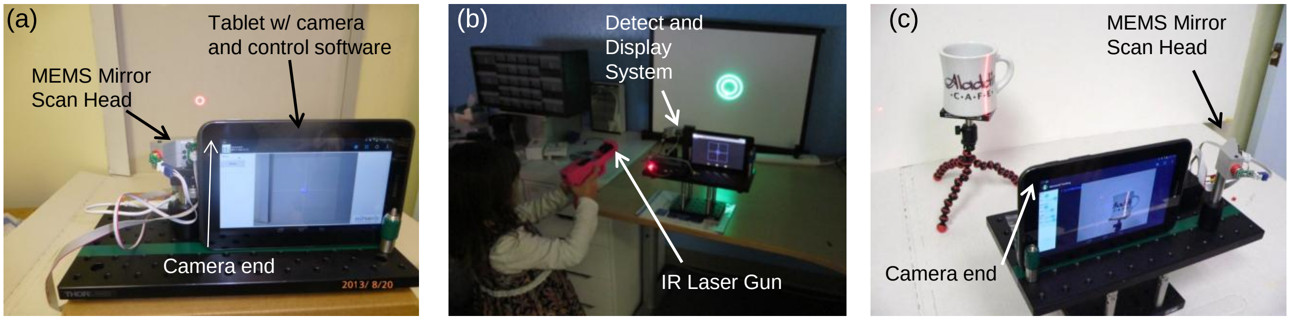

Figure 6 a) Triangulation based setup using a MEMS mirror and an Android tablet with a camera, using minimal distance between MEMS and camera for an overlapping field of view. b) The MEMS scan module displaying vector content while the detect and display system tracks the location of the IR laser gun. c) Triangulation based range finding setup using a MEMS mirror and a tablet, with known distance between the tablet camera and MEMS to image the cup, creating a 3D point cloud.

A second method of measuring distance is through triangulation. We have demonstrated triangulation based distance measurement using two of the MEMS based laser tracking systems or "MEMSEyes" [6]. In that work distance could be quite accurately measured to a specific target marked with a retro-reflective tape. Both MEMSEyes lock onto the target independently and maintain lock as the target moves. But for a more general distance measurement to an unmarked surface, e.g. to a wall, methods of triangulation utilizing one MEMS based scan system and one camera are more applicable. To obtain a distance measurement using a single MEMS scanner and a camera, they are first placed a known distance apart. The MEMS scan head (Figure 1b) directs the laser beam at an object by pointing the MEMS device at the target and the light is reflected back to the sensor. The camera observes the illuminated target, and is able to image the location of the target. Using simple geometry to calculate the angle of the target from the center of the camera, comparing with the angle of the MEMS device will give very accurate results at small distances relative to the separation distance of the MEMS scan head and camera. At larger distances, the accuracy drops due to the angle changing much slower than the increase of distance. Alternately, the same system where the distance between the camera and MEMS scanner is reduced to almost zero, can be used to project a laser beam within the camera's field of view. A calibration maybe needed to overlap the scanner's FoV onto the camera's FoV. A target designated based on the camera's FoV can be transformed into the MEMS scanner's FoV, and a laser beam can be used to highlight the designated target. Figure 6b demonstrates such a system where an IR laser is used to designate a point in the camera's FoV, and the MEMS scanner highlights the point by projecting a green circle around the designated point. Since triangulation methodologies also have limitations in accuracy, dropping off with distance, the MEMs scanner's laser source and receiver can be supplemented or replaced with standard LRF module.

3.3 Laser Range Finder Based

Many LRF modules for low-cost and hand-held applications have a similar construction with a separate transmitter and receiver aperture as in the example shown in Figure 7*a.* The outgoing laser beam is chosen to have low divergence and may be visible or it may be invisible but accompanied with a visible wavelength to help aim and to improve laser safety. When a measurement is requested, the laser beam is modulated with a specific pattern of very high frequencies. The receiver in the LRF is a separate aperture of considerably larger area as seen in Figure 7*a*, designed to have a very small FOV to maximize the sensitivity for the light being reflected back from the same axis it was transmitted. The light returned is demodulated with the outgoing beam's pattern and the difference in time between the outgoing beam, and the receiver's measurements, are converted to distance. There are numerous algorithms used to obtain distance information from the phase of the received modulated light, and the specific algorithm of the units we experimented with is not known. These LRFs are constructed to be used in commercial settings, therefore are limited to eye-safe laser powers. The visible laser limits the distance and accuracy of the LRF module, or alternately, moving the laser source and receiver optics to the infrared range, which are more expensive, to maintain accuracy at larger distances. Another key limitation of the LRF is the single beam that needs to be directed by a user, or a mechanical mount for each measurement.

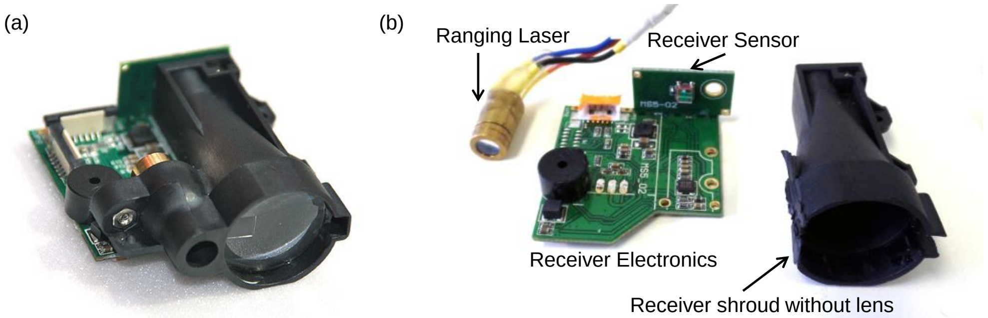

Figure 7 a) Off the shelf laser range finder module by Egismos, model: LDK-M2-RS, b) The parts that make up the laser rangefinder module - The receiver shroud and ranging laser were modified for the experiments.

4. SETUP AND REDUCTION OF SWAP FOR UAV APPLICATIONS

4.1 SWaP Driver and Optical Setup

The USB-SL MEMS Controller is a compact, USB powered controller used to drive the MEMS devices, lasers, any additional peripherals and receive analog inputs. The controller has multiple communication platforms, via USB protocol, serial COM port, or wirelessly via Bluetooth. The controller consists of an embedded MEMS driver with programmable hardware low-pass filters. The USB-SL MEMS Controller is the development platform for most environments, since it is compact and portable, and fully supported by a various operating systems such as Windows, Android, and most recently, Raspberry Pi OS. The development kit comes with SDKs in C++, Matlab, LabView, and Java-for Android. The MEMS device, laser, any beam shaping or scanning optics, and photo receivers are mounted on optical bread boarding for easy prototyping Typically, this controller connects to MEMS devices, and peripherals on an optical bench for a table top demonstration. A typical development kit weighs >500g due to the heavy aluminum optical breadboarding components. The controller itself is approximately ~140g, consuming ~1.5W, with a 5mW laser.

For certain applications where the size, weight and power of the controller and the optical scan head are critical, the electronics hardware and optical hardware are simplified to meet the needs of the application. The optical scan head can be reduced from the bread boarding mounted parts to a simplified opto-mechanical cell, with a diode laser, beam reducing optics, the MEMS device in compact packaging, and finally a scan lens to increase the field of view. The lenses for this optical cell can be scaled down in size from the typical ½" or 1" lenses used for breadboarding, down to 3mm-6mm diameters. Additionally, with the availability of 3D printing tools, it is easy to prototype light-weight optical scan heads (Figure 8a) as plastic parts for small quantities, and transfer to injection molded plastic housing for mass production.

The components of the USB-SL MEMS controller that allow for flexibility or controlling multiple peripherals, is simplified to a processor, a communication protocol via Bluetooth, an efficient power management system designed to run from a single cell, 3.7V Li-Polymer battery, and a simplified MEMS driver without the hardware low-pass filters. The new reduced design is called the Playzer Controller (Figure 8b). The overall footprint of the controller has been reduced from 90mm x 60mm x 22mm for the USB-SL Controller to 60mm x 26mm x 15mm for the Playzer, while maintaining the same processor and memory, and in turn the same firmware, driving a simplified controller. This reduced controller still contains an analog input channel to connect a photosensor (Figure 8c) for any imaging or tracking applications, and contains a laser driver circuit capable of driving up to 100mA of current to the laser and modulate at >50kHz rates. Finally, the Playzer can be assembled together into a single package with a battery to make a compact, portable laser scanner. The reduced Playzer MEMS controller with integrated optical scan head weighs ~50g without a battery, consuming less than 1W of power, driving a 10mW laser diode, and powering a wireless Bluetooth transceiver with ~30ft range.

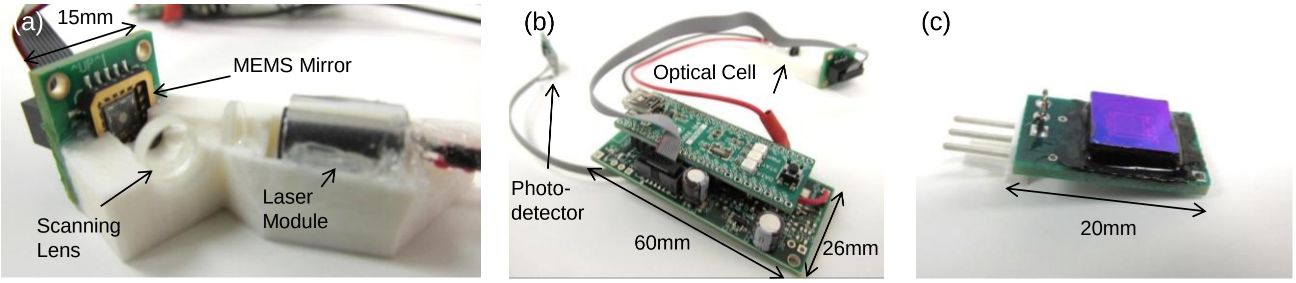

Figure 8 a) A 3D printed optical cell consisting of a laser module, the MEMS mirror, and a scanning lens b) Playzer controller to drive the MEMS and track c) A single photodiode for tracking

4.2 Drone Mount

In order to mount the Playzer onto a drone, they need to meet the weight restrictions on how much the drone can carry. For larger drones such as the DJI Phantom II, the weight limit is ~400g, well above the weight of the Playzer. However, to demonstrate the Playzer mounted on smaller (less than 50cm in length/width) drones that can be flown indoors, the weight limit can get challenging. Typically the medium sized indoor drones have the capability of carrying <100g. In order to meet these requirements, the Playzer's outer casing was dismantled, with just the controller and scan head mounted onto the drone. Another reduction of weight comes from removing Playzer's battery, and operating directly from the drone's 3.7V Li-Polymer batter. This reduces the overall flight time of the drone, but allows the concept of a laser based tracker on a drone demonstrable (Figure 9).

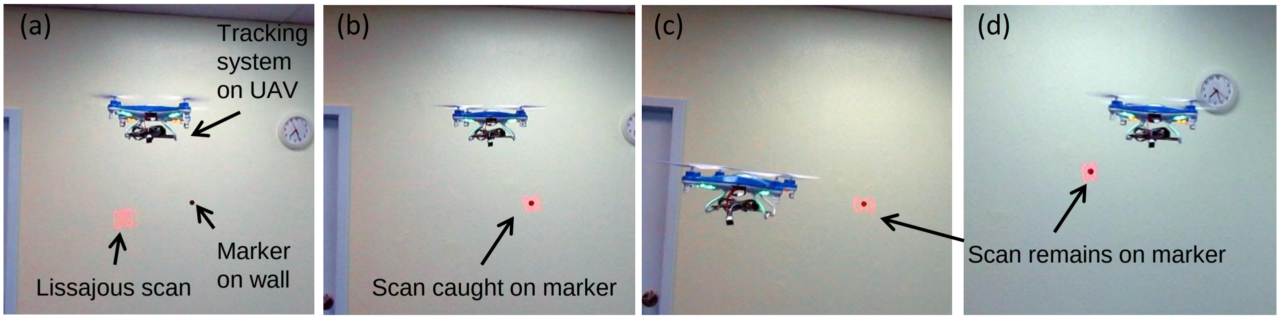

Figure 9 a) A complete UAV tracking system using a Lissajous pattern to scan for the marker. b) The tracking system found the marker and sticks to it. c)and d) UAV flies in various directions while maintaining a lock on the target.

Once the hardware and optics are onto the drone, the user flying the drone can connect to the Playzer using an android device via Bluetooth. This allows the drone to fly as needed, and display vector content such as text, symbols, etc, or use some of the photosensor based features such as laser-based imaging to image what is in front of the drone, or laser based tracking to track retro-reflective objects within the drone's field of view.

5. UAV-BORNE LIDAR

5.1 Integration of an OEM LRF with the MEMS mirror

As we described above, the OEM LRF in Figure 7 was altered to prepare for experimentation with a MEMS mirror based scanning system by removing the receive lens which strongly limited its FoV and by removing the laser such that it can be directed freely (Figure 7b). The ranging laser could then be pointed at a MEMS mirror such that its beam could be re-directed at different targets. The receiver's FoV has to be increased to accommodate the field of regard addressed by the MEMS scanner. This increase in FoV automatically reduces the sensitivity of the sensor and would ultimately significantly limit the distance the LRF can range, but the reduction in range from 100s of meters, to 10s of meters is enough distance away from the drone to find an object that is in the way, and adjust its flight path accordingly.

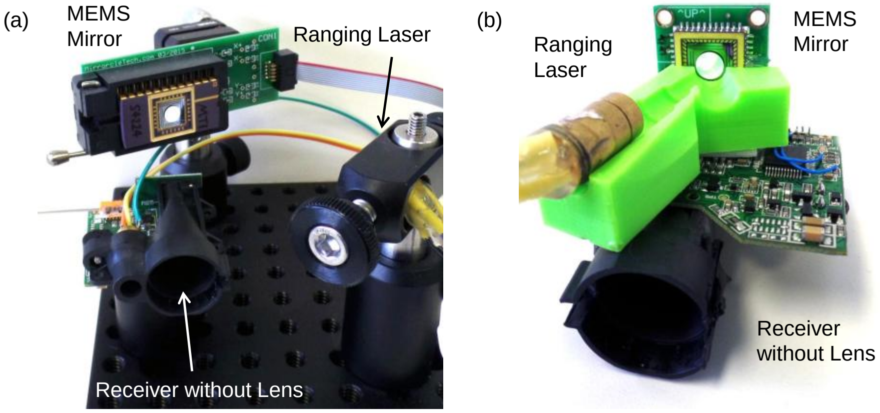

Figure 10 a) An optical breadboard based demonstration of concept of the LRF module integrated with a MEMS device, b) The kit is reduced in size by replacing the optical breadboarding with a 3D-printed optical cell.

For this study, an off-the-shelf LRF module by Egismos was used in demonstrating ranging. As mentioned above, we separated the laser from the original packaged and directed the outgoing laser beam onto a MEMS scanner as shown in Figure 10, such that the MEMS mirror's FoV is the same as the receiver's aperture. This was demonstrated to point the MEMS device within a +/-2° FoV of the receiver for accurate ranging measurements up to ~5m. Any larger angles from the MEMS device was out of the receiver's FoV.

The final demonstration of concept (Figure 10a) was to integrate the laser into a MEMS scan head to reduce any other losses in the outgoing laser beam, and to remove the receiver's lens which was limiting the FoV. The removal of the receiver's lens dramatically reduces the distance measurement range of the receiver, but increases the FoV. This system demonstrated accurate distance measurements of ~2m, with a +/-8° FoV. The system included the modified Egismos LRF module combined with the MEMS scan system as described above and a USB SL MEMS Controller connected to a host PC. A Matlab script was used which moved the MEMS device through positions, and at each position requested and received a ranging measurement from the LRF module. The placement/aim of the receiver was important in this demonstration since the shroud around the receiver was still used to limit the light returning to the sensor, even though the lens in the shroud was removed. The refresh rate of the LRF module was another limiting factor since each measurement takes approximately ~0.5s to 1s.

5.2 Miniaturization for UAV Application

The optical breadboard-based concept in the previous section demonstrated the LRF can be integrated with the MEMS device, and used together to point and range over a field of regard. The next step is to reduce the size and weight of the optics and electronics to a compact module, capable of flying on a drone. The optical breadboarding is replaced by a 3D printed cell to mount the MEMS device and the ranging laser. The development MEMS controller is replaced by the Playzer controller to drive the MEMS device, and interface with a host. The LRF module communicates with the Playzer controller, such that it can range, and return the measured value back to the Playzer. The LRF ranged values are available for the host to access from the Playzer controller through additional API commands for this application. The fully miniaturized unit (Figure 10b) is reduced down to ~23g for the MEMS scan head and LRF module, and an additional ~20g for the Playzer electronics.

6. CONCLUSIONS

We have demonstrated a MEMS laser scan and track module which addresses a 40° field of regard with an eye-safe laser beam and can be used to display and annotate, image, and track targets. The module is less than 40g in weight, fits in a volume of <90mm x 60mm x 40mm, and consumes less than 750mW of power. This MEMS scan module has been mounted onto a toy drone with very minimal or no payload capability, and successfully used to display text and vector content on walls. Furthermore it was successfully used to track retro-reflective targets while the drone was in flight, and could therefore maintain the laser beam pointed at a marked spot on the wall while the drone was erratically moving.

The MEMS based LRF module has been prepared, weighing ~45g in weight, fitting in a volume of <70mm x 60mm x 60mm, consuming less than 1W of power in normal operation. This final version of the LRF module has not been flown on a UAV and demonstrated ranging yet. The results of the LRF module's flight will be presented at the conference talk.

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