Fusion of current technologies with real-time 3D MEMS ladar for novel security & defense applications

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ABSTRACT

Through the utilization of scanning MEMS mirrors in ladar devices, a whole new range of potential military, Homeland Security, law enforcement, and civilian applications is now possible. Currently, ladar devices are typically large (>15,000 cc), heavy (>15 kg), and expensive (>$100,000) while current MEMS ladar designs are more than a magnitude less, opening up a myriad of potential new applications. One such application with current technology is a GPS integrated MEMS ladar unit, which could be used for real-time border monitoring or the creation of virtual 3D battlefields after being dropped or propelled into hostile territory. Another current technology that can be integrated into a MEMS ladar unit is digital video that can give high resolution and true color to a picture that is then enhanced with range information in a real-time display format that is easier for the user to understand and assimilate than typical gray-scale or false color images. The problem with using 2-axis MEMS mirrors in ladar devices is that in order to have a resonance frequency capable of practical real-time scanning, they must either be quite small and/or have a low maximum tilt angle. Typically, this value has been less than ≤ 10 mg-mm^2-kHz^2-degrees. We have been able to solve this problem by using angle amplification techniques that utilize a series of MEMS mirrors and/or a specialized set of optics to achieve a broad field of view. These techniques and some of their novel applications mentioned will be explained and discussed herein.

Keywords: MEMS, MEMS ladar, scanning ladar, single-point ladar, flash ladar, real-time, GPS, military.

1. INTRODUCTION

Through the utilization of newer and more rugged scanning MEMS (Micro Electro-Mechanical Systems) mirror for 3D ladar (LAser Detection And Ranging) devices, a whole new range of potential military, Homeland Security, law enforcement, and civilian applications are now possible. Like most of the current ladar units, many of the past MEMS based units were designed for benign environments and could not withstand significant shock or vibration. There is a type of scanning MEMS mirror that is designed to withstand very rugged environments with that are impact resistant to over 500g/1ms:half-sine and vibration resistant to over 10g at 55-500Hz.[1] This paper will not only compare these rugged devices to conventional units but also to other MEMS mirrors that were not designed for the rugged environments that military hardware is typically exposed to. Additionally, this paper will explore how these rugged scanning MEMS mirrors could be used in traditional as well as novel military applications.

Current ladar devices are typically large (>15,000 cc), heavy (>15 kg), slow (<1 fps), and expensive (>$100,000) while our MEMS ladar designs could potentially be more than an order of magnitude smaller (<500 cc), lighter (<0.5 kg), and cheaper (<$10,000), as well as being able to operate in real-time (≥15 frames/second), opening up a myriad of whole new markets and applications.[2] In appropriate production volumes, the majority of the device could be produced on two chips resulting in not only decreasing its size to <50cc, its weight to <50g, and cost to <$100. Such devices would have definite crossover market appeal as noted in Table 1, which should only advance the development and deployment of these devices.

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Potential New Applications for Rugged MEMS Ladar

Area of Application	Description/Advantages
Remote Surveillance (border/perimeter)	Low power consumption and small size (easier to hide/protect). Could be used to protect a border for significantly less than $1M/mile.
Reconnaissance	They could be dropped behind enemy lines for quick intel and monitoring.
Missile guidance	Real-time 3D imaging. Short-range or as an adjunct (limited to < 1km).
3-D Mapping	Real-time 3D battlefield imaging, mission planning, VR simulations, etc.
Target Acquisition/ID	x, y, z of target for soldier targeting and/or remote fire control/guidance.
Automotive	Obstacle identification & autonomous navigation under rugged conditions.
UAV	Perfect for aerial drones since it is small, lightweight, and has low power consumption.
Terrestrial Drones/Robots	Though size and weight are not as critical as with an UAV, they are still important as well as power consumption.
Medical	Laparoscopic surgery, robotic surgery, face/body 3D collection (for virtual manipulation or reconstruction prior to surgery), etc.
Manufacturing	Robotic manipulation and depth of field vision, 3D bar code reading, etc.
Civil Engineering	Real-time quality control (e.g., aggregate analysis for road beds).
Scene Archiving	Forensic, archeological, etc. (small & lightweight, can go anywhere).
Movie/Camera Industry	Concurrent range data incorporated into each pixel of the digital image for computer processing into a 3D movie (TV, video, etc. as processing becomes more mature).
Simulation/Gaming	Real-time, real-word input of 3D scenes and actions for simulations/game design.
Scientific	Application such as particle analysis and distribution, microscopy.
Other	Laser printing, etc.

Table 1. Those applications with crossover potential into the civilian markets are italicized.

This next-generation of MEMS ladar devices is not anticipated to replace the relatively mature current technologies initially but rather be used for new applications where current ladar devices are not appropriate because of size, weight, speed, or their inability to withstand rugged conditions. Such real-time applications include unmanned aerial vehicles (UAV), helmet mounted ladar for the individual soldier,[3] and many more as described in Table 1. As MEMS ladar technology does mature, it will likely take over current ladar applications and markets just like cell phones did to pay telephones. The comparison of MEMS ladar with cell phones, GPS, and other disruptive technologies is a good one in the sense that they were initially rather large (shoebox size or larger), very expensive (tens of thousands of dollars for the first generation) and yet they are now very small, inexpensive, and have found uses that no one had initially imagined.

2. SCANNING MEMS MIRRORS

MEMS ladar in addition to its inability to meet field specs, it had too small of a surface area for a high power beam to be collimated appropriately. One such attempt at increasing the usable surface area was to use MEMS mirror array. The DMD (digital mirror device) was such an array that consisted of 1024x768 binary mirrors each about 13µm square for a total array size of 14.0x10.5mm. Though this array has worked well in televisions, its design was not for rugged conditions and did not work well for ladar.

MEMS mirror arrays do have some advantages over larger single MEMS mirrors in that surface flatness may be more easily manufactured and that a larger surface area can be achieved without sacrificing frequency or tilt angle, but there are significant optical problems with mirror arrays. Because one can never get a 100% useable mirror surface from an array due to the gaps between the mirrors and edge conditions, there will be a loss in power above and beyond that of mirror reflectivity as some of the beam's power will be lost in these "gaps". These gaps and any pixel-to-pixel discontinuity would be expected to cause unwanted diffraction effects that could cause a higher divergence angle and degraded beam quality.

Another problem with MEMS ladar was its limited tilt angle that typically kept the field of view (FOV) to <20°, which was too narrow for most field applications. This was recently overcome by using optical amplification which consists of using a series of lenses in conjunction with the MEMS mirror to increase its tilt angle by a factor several-fold.[3] For instance, a MEMS mirror with a maximum optical tilt angle of ±3° could be increased to ±20° in this manner.[3] With the advent of electromagnetic MEMS scanning mirrors, the optical tilt angles are not only increased to ±30° but with the use of optical amplification, the FOV can be increased to over 120°.

Electromagnetic MEMS mirrors also allowed larger mirrors to be used while not sacrificing tilt angle or resonant frequency. They not only have optical tilt angles in excess of ±30° but also resonant frequencies in the kHz range with a relatively large surface area (tens of mm^2 surface area in some versions as compared to <1 mm^2 in other prior versions). By using torsion bars instead of a single support post as shown in Figure 1, the shock and vibration resistance are markedly improved. Current torsion bar electromagnetic 2-axis MEMS scanning mirrors can be designed for most military applications and to the desired specs usually without any additional protection. If there are some extreme specs that need to be met though, there are protective systems that can be used.[4]

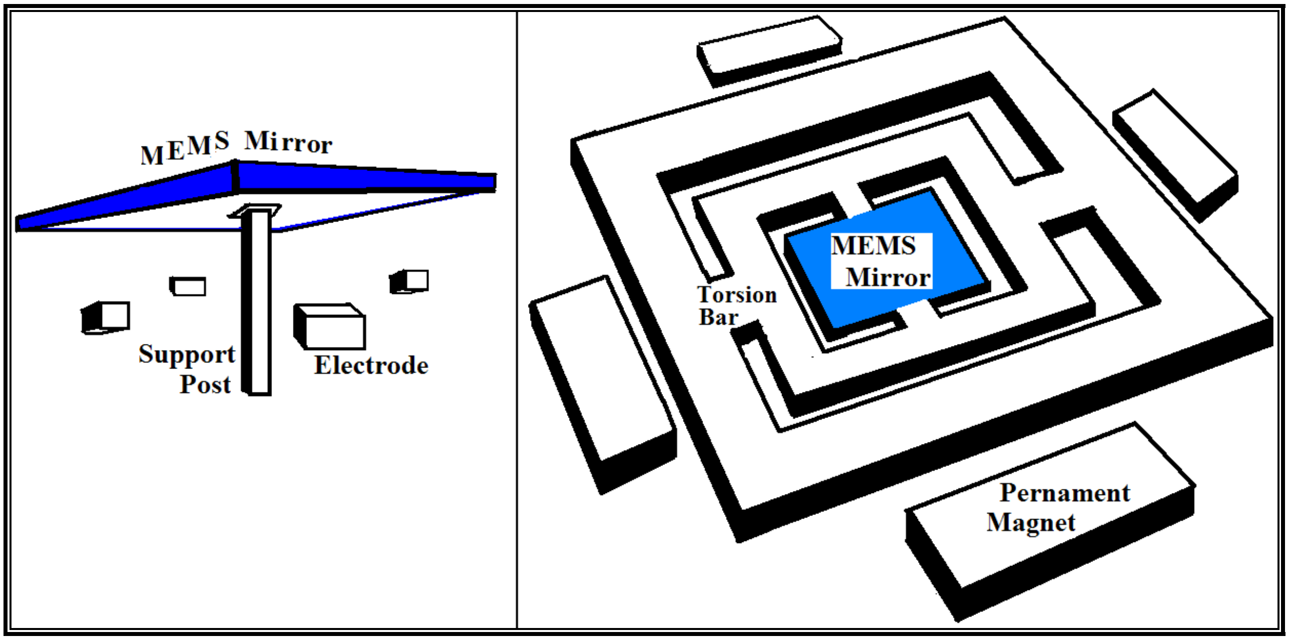

Figure 1. An example of an electrostatic support post MEMS mirror (left) and an electromagnetic torsion bar MEMS mirror (right).

These electromagnetic MEMS scanning mirrors (designated as A# in Table 2) do present a significant leap in performance when compared to electrostatic MEMS mirrors (designated as B# in Table 2) that typically have an S-value ≤ 10 mg-mm^2-kHz^2-degrees.[1] This "S-value" is derived from the fundamental relationships (see Equation 1) that limit the performance of a MEMS mirror (or a similar device). Since mass (m), radius (r) squared, and optical tilt angle ($\pm\theta$) are all inversely proportional to the resonant frequency (f) squared, we can therefore say that these factors are inversely proportional to a constant "S" and that any improvement in performance based upon design, materials, mode of operation, manufacture, etc. would therefore cause an increase in the MEMS mirror's S-value. One "S-unit" equals 1 mg-mm^2-kHz^2-degrees. These newer electromagnetic MEMS mirrors currently have S-values that is typically >500 mg-mm^2-kHz^2-degrees which is an increase of about two orders of magnitude over the electrostatic versions (see Table 2).[1]

$$S = m\, r^2 f^2 \theta \tag{1}$$

The calculation for device A3 is shown in Equation 2 as an example. This device has a mechanical maximum mechanical tilt angle of ±15° which yields a maximum optical tilt angle of ±30° (the optical angle is twice the mechanical angle) and a FOV of 60°. Because it is a 2-axis unit, the S-values for both axes are added together to get a combined S-value.

$$S = S_x + S_y \tag{2}$$

$$S = m\, r_x^2 f_x^2 \theta_x + m\, r_y^2 f_y^2 \theta_y$$

$$S = (3.0\text{mg})\,(2.0\text{mm})^2\,(0.43\text{kHz})^2\,(30°) + (3.0\text{mg})(1.5\text{mm})^2\,(1.5\text{kHz})^2\,(30°)$$

$$S = 522\ \text{mg-mm}^2\text{-kHz}^2\text{-degrees}$$

1-axis MEMS	**Mass: m (mg)**	**X-axis: r (mm)**	**X-axis: f (kHz)**	**X-axis: θ (degrees)**				**S-value**
A1	5.94	2.50	0.54	34				368.05
A2	4.00	2.00	4.00	12				3072.00
B1	9.00	1.50	0.045	12				0.49
B2	2.1E-07	5.0E-03	6.0E+04	12				0.23
B3	0.16	0.45	0.60	10				0.12
2-axis MEMS	**Mass: m (mg)**	**X-axis: r (mm)**	**X-axis: f (kHz)**	**X-axis: θ (degrees)**	**Y-axis: r (mm)**	**Y-axis: f (kHz)**	**Y-axis: θ (degrees)**	**S-value**
A3	3.00	2.00	0.43	30	1.50	1.50	30	522.19
A4	10.50	3.00	0.24	34	3.50	0.56	34	1556.52
A5	0.44	1.50	0.32	15	1.50	6.40	15	612.25
B4	0.56	0.75	0.84	4	0.75	0.32	6	1.02
B5	9.00	1.50	0.67	1	1.50	0.05	12	9.09
B6	0.014	0.26	1.30	6	0.26	1.80	6	0.03

Table 2. S-value for various MEMS scanning mirrors. Designations of A# are electromagnetic and of B# are electrostatic.[1]

The S-value once known can be used to redesign a MEMS unit with different characteristics, such as increasing the X-axis frequency while sacrificing the tilt angle. For instance, if the X-axis in the previous example needed to be increased to 1 kHz, then it could easily be found that the X-axis optical tilt angle would need to be decreased to ~5.5° in order to preserve the S-value.

Finally, the electromagnetic units are capable of operating at <6V and <0.15W while the electrostatic ones typically operate at >100V. They are able to do this by designing the mirror system to have a resonance that is a subharmonic of the desired scanning frequency. If a static position is desired, that can be accomplished with the electromagnetic devices but more typical voltage inputs are needed. Positioning can be accomplished through either an optical or back EMF (electromotive force). The former is accomplished by manufacturing a mirrored surface on both sides of the mirror plate and using the underside for to optically detect angular position, while the latter detects the EMF generated when the mirror's coil section passes through the magnetic field.

3. ALTERNATIVE TECHNOLOGIES

There has been much research done trying to develop "flash ladar" (single-shot ladar) using a focal plane array (FPA: a 2D array of photodiodes that are individually addressable) since it theoretically could be made without any moving parts and therefore more rugged. Unfortunately, even if it were to be more sturdy than the electromagnetic MEMS, there are some problems with basic physics that make flash ladar impractical for most uses.[5] This is because the number of photons reflected from a flash (single-pulse) ladar will be much smaller than that of a MEMS (single-point) ladar because it must illuminate the entire target area rather than just 1/65,536th of the target area (for a 256x256 pixel image) as shown in Figure 2.[5] This means that a flash ladar system would need its laser to be at least 65,536x more powerful than that of the MEMS ladar system to yield the same number of photons for the surface area of the target represented by a pixel. To make the situation even worse for flash ladar, the reflected pulse energy from the laser then needs to be distributed across the entire FPA thereby resulting in another decrease in the number of photons per detector as shown in Figure 3.[5] Assuming that the both systems have similar characteristics (pulsewidth, photodiode, optical fill rate, etc.), there would be another 65,536x decrease in the number of photons per detector which means that the flash ladar's laser would need to be at least 4,000,000,000x more powerful to equal that of the MEMS ladar's laser.

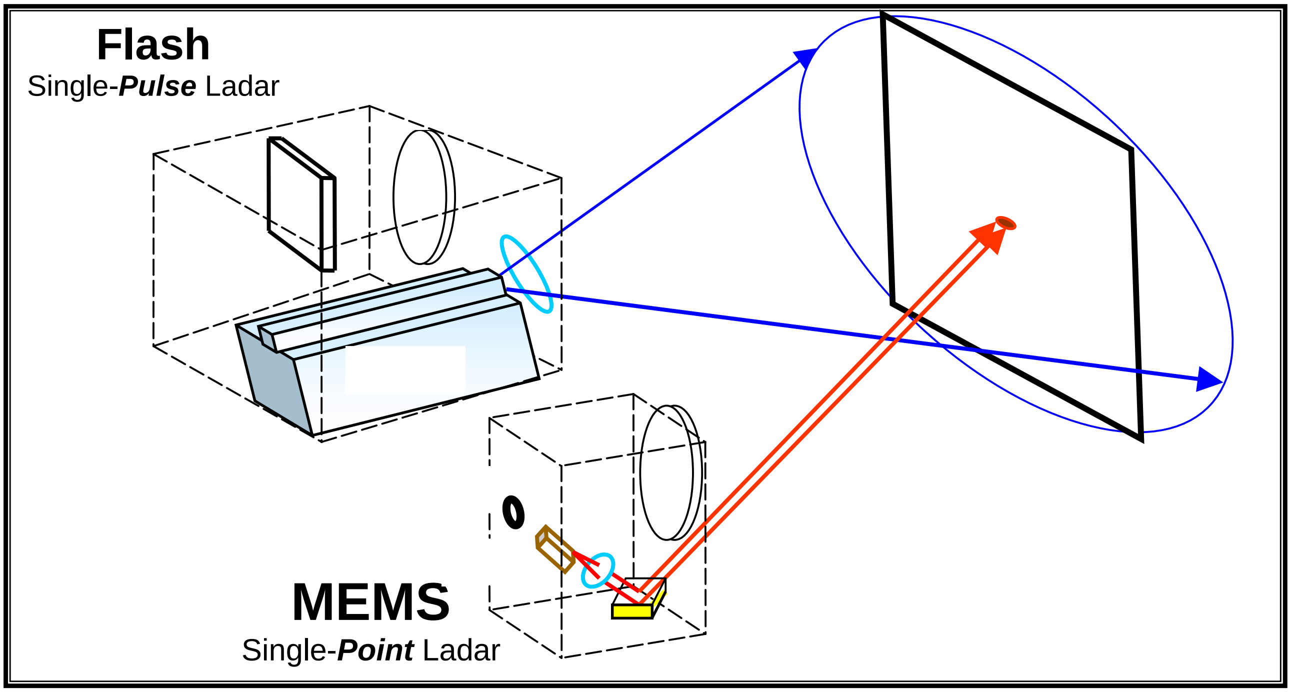

Figure 2. To yield the same energy at the target area, the pulse from the flash ladar's laser would have to be over 65,000x more powerful than that from the MEMS ladar's laser. (Assuming that both are using the same pulse duration, optical collection area, optical fill rate, photodiode (PD) characteristics, etc. to produce a 256x256 pixel image.)

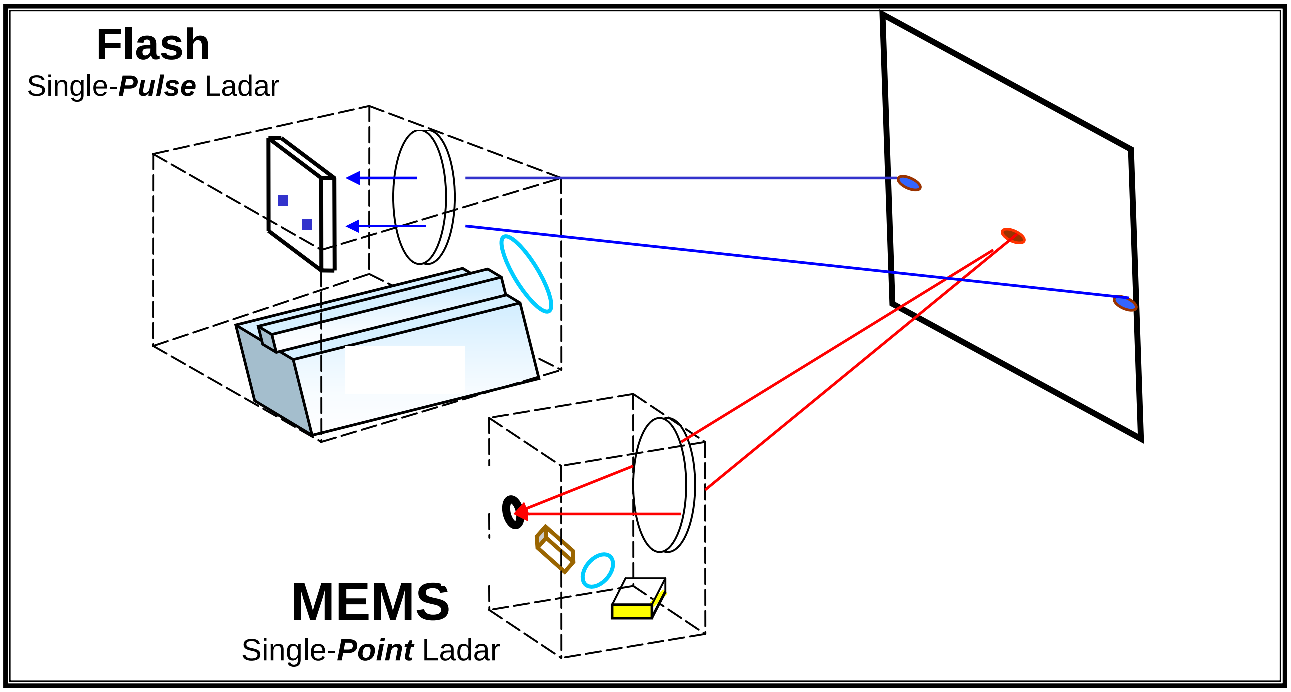

Figure 3. Because the reflected pulse is now being distributed over the entire FPA, the flash ladar's laser will now have to be at least another 65,000+ times more powerful to yield the same pulse energy per pixel as the MEMS ladar.

Flash ladar could have an advantage over the MEMS ladar when the field of view (FOV) was narrower than that which the single-point ladar was able to resolve. For instance, a single-point ladar with a 0.4 mrad beam divergence would have the same resolution as a single-shot ladar down to a 6º FOV for a 256x256 image (256 pixels x 0.4mrad = 5.9º), but less than that the single-shot ladar would have a resolution advantage. There would still be the laser power problem, and while increasing the duration of the pulse could increase the number of photons per detector, it would cause a significant loss in range resolution.[2] Although using CW ladar methodology would require less laser power, it would also make the range resolution situation worse by several orders of magnitude.[2] So it is a no win situation.

The FPA of flash ladar typically has a lower bandwidth (BW), lower optical fill rate, and slow readout rate as well as crosstalk and pixel dropout problems.[1,5] Because the low BW makes FPAs currently unacceptable for most military ladar applications, there are ongoing attempts to increase the BW by improving bonding a CMOS circuit array to the back of the FPA array so that each pixel will have its own timing circuit.[2] Whatever BW advances are made with the FPA, its specs are more than likely to be exceeded by the single PD used in single-point ladar system.[1] Though a microlens array can bring the FPA's optical fill rate close to that of a single PD (100%) and the pixel dropout rate is now typically <2% (even a 1% dropout for a 256x256 array would still mean the loss of over 500 pixels), the other problems of crosstalk/noise, and photons per detector, are still quite significant. Though an attached CMOS array could help in the high-volume of parallel processing required, flash ladar still is fairly processing intensive while single-point ladar's processing is serial rather than parallel.

There has been much work done in trying to create a FPA consisting of avalanche photodiodes (APDs) but with limited success. Even if these APDs had a 100x gain over a PIN photodiode, there is still a dramatic power discrepancy of over 40,000,000 times. Besides when a signal is amplified so is its noise, which is significantly worse than receiving a more powerful optical pulse in the first place in terms of the signal-to-noise ratio (SNR). Since the SNR dramatically affects the quality of a ladar system, these issues become critically important.

Though FPAs seem to be application limited in terms of flash ladar, they do have other imaging uses. But even in terms of ladar, there is the novel integration of a FPA into a MEMS scanning ladar that extracts the advantages of each technology. Synergism could be achieved by using the MEMS mirror for collimated single-point scanning of the FOV in real-time while using a small FPA (e.g., 4x4, 8x8, to improve the resolution. For instance, if a 4x4 FPA and a 320x240 MEMS single-point ladar were used, the resolution of this hybrid system would increase to over 1 Megapixels; a 16-fold increase. Likewise, an 8x8 FPA would yield close to 5 Megapixels, and a 16x16 FPA would yield close to 20 Megapixels. This could also be in real-time with just a fraction of the parallel processing that would have otherwise been required for a flash ladar system. Though there would be a decrease in the number of photons per pixel compared with a pure MEMS ladar system (~1/64th with an 8x8 FPA), it would not have been able to operate in real-time with the same resolution. Likewise for a pure flash ladar system to achieve the same resolution, its laser would need to be 76800x more powerful than that of the hybrid to have an equivalent number of photons per detector.

4. NOVEL APPLICATIONS

MEMS ladar systems could be developed with 10+GHz optical and electrical components,[1] a range resolution (ΔR) of <1cm is now possible by using various algorithms and signal detection techniques above and beyond the classic range resolution formula of $\Delta R = c/(2 \times BW) = c/(2 \times 10GHz) = 1.5$ cm. But such resolution is possible for any ladar system that wishes to use these newer 10+GHz optical and electrical components that are not unique to a MEMS ladar system. The advantages of a MEMS ladar system is that it could operate in real-time, be small, lightweight, and amenable to high-volume manufacturing (HVM). This can bring its cost down to <$1000/unit thereby opening up a whole new realm of applications, some of which were outlined in Table 1. The anticipated specs for a high-volume version are shown in Table 3.

Specification	**Potential MEMS Ladar**
Wavelength	~1550nm (Class I - eyesafe)
Bandwidth	≥ 10 GHz
Frames/second	≥ 15 fps (real-time)
Field of View (FOV)	> 60°
Size	< 500cc
Weight	<< 0.5kg
Power	< 4W (avg.), <10W (max.)
Resolution	≥ 320 x 240 pixel resolution
Range	~1 to 100+m.
Cost	Dependent upon volume but could potentially be <$1K.
Options	Options: • GPS integration • Optical Angle Amplification™ • True Ladar Zoom™ • Real-time true images Range information visually integrated with gray-scale or color CCD image.

Table 3. Potential characteristics of a MEMS ladar system.[1]

It is not easy to comprehend how small such a ladar unit could be so it is illustrated in Figure 4 which shows the actual size of a current 2-axis MEMS mirror with its supporting structure/components. With appropriate front-end design a complete MEMS ladar unit could have a footprint about the size of a business card for which a simple layout is also shown in Figure 4. With a ladar this small, it could be integrated into the helmet of soldiers for their use as well as potentially transmitting the data back to command.[3] Because ladar range imaging is often confusing to someone who is not used to it, a novel integration of a CCD real-time gray-scale or color image could be accomplished by increasing the relative brightness or intensity of the corresponding CCD pixel when the pixel's target is close, and visa-versa. The integration of a global-positioning-system (GPS) into such a compact ladar system could then also allow soldiers in the field to transmit ladar data back from multiple locations that could then be used to create a 3D virtual battlefield.

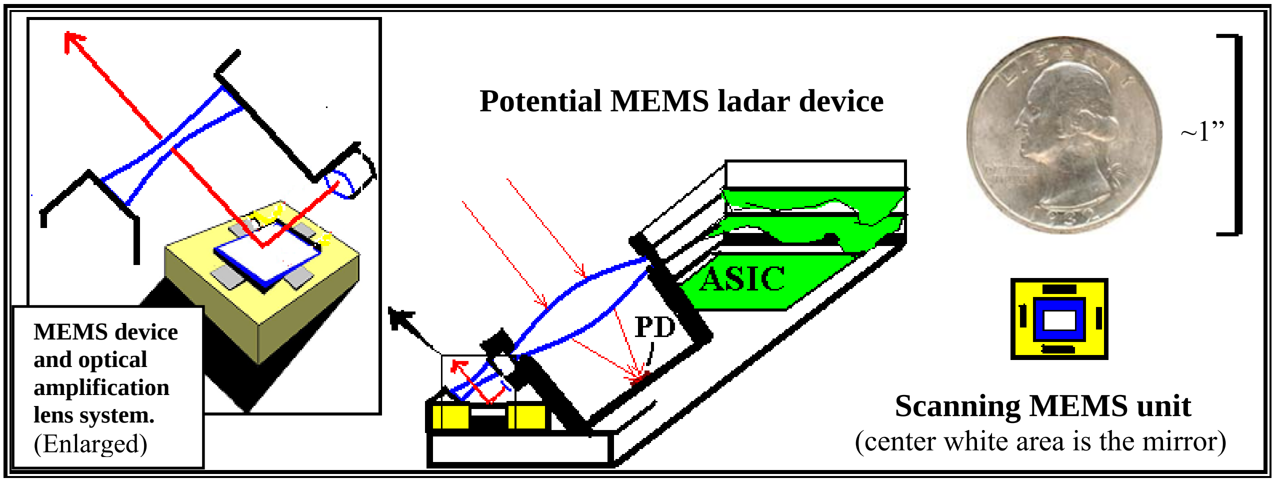

Figure 4. Size perspective of possible MEMS ladar device (center) and actual scanning MEMS unit (bottom-right).as compared to the size of quarter (which is smaller than 1"). Enlargement of laser-MEMS-lens system is shown on the left.

Other novel applications include real-time border surveillance, perimeter monitoring, imaging/targeting of hostile territory, and more by using a GPS integrated MEMS ladar which could be dropped into any of those areas en-mass because of their low cost in high-volume. These devices would be self-righting after being dropped either by parachute or an external bubble cushion that would deflate after landing. Because they would be GPS and transmitter equipped, they could be virtually integrated for complete coverage of the desired area. If enough devices are destroyed or go dark that a gap needs to be filled, then a selective drop could be done with new units. These units could be solar powered with battery backup since their power usage is so low. These devices would be self-installing thereby decreasing cost of implementation as well as minimizing human risk.

5. CONCLUSION

The limitations to scanning MEMS mirror technology have been overcome recently, such that MEMS ladar is not only viable but should be the preferred gateway towards the development of the next-generation of ladar. MEMS ladar is not expected to take the place of current ladar markets in its first-generation but rather it will open up new markets where compact, lightweight, low-power, and/or real-time ladar are needed. Being a single-point ladar system, its processing is linear (serial) thereby reducing its complexity and cost but even more important is its SNR advantage over flash ladar. There is also the potential of creating a hybrid system that would utilize a small FPA (4x4 to 16x16) in order to increase the resolution while still offering real-time imaging. Though such a hybrid would be a decrease in pulse power to the pixel, it would still have more than 76800x advantage over flash ladar.

MEMS ladar offers new opportunities to the military and paramilitary markets especially in real-time 3D imaging of borders and hostile territories. It could also be used in conjunction with a CCD camera, so that the field soldier would intuitively know the range of the object in his FOV by their relative brightness, which would be accomplished by pixel correlation and algorithmic modification of displayed image. Modern MEMS units can be designed to withstand rugged field conditions as demonstrated by some of their impact and vibration specs. Because these units could be produced at a low cost in large volumes, they could be deployed en-mass for applications where installation would be difficult or expensive. With GPS and transceiver capabilities they could be networked either as cells or virtually at a command center for a myriad of applications. The number of potential uses that are known is quite staggering but even more impressive is that there are probably many more novel applications that have not yet been considered.

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