INTEGRABLE ULTRA-COMPACT, HIGH-RESOLUTION, REAL-TIME MEMS LADAR FOR THE INDIVIDUAL SOLDIER

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ABSTRACT

Laser radar (LADAR) has many advantages over other methods of target detection and analysis, both in combat and commercial applications. Because it uses a shorter wavelength than microwave radar and has significantly greater angular resolution, it is capable of a greater degree of accuracy and more precise target resolution to a level that allows for high resolution image acquisition. The development of a next generation LADAR unit that is lightweight, ultra-compact, portable, and power-efficient real-time 3D LADAR unit would be a significant advance with many potential military and civilian applications. This paper describes a novel LADAR device that would be small, compact, field practical, eye safe, and integrable into a soldier's helmet. This would be achieved by using a 2-axis MEMS (Micro-Electro-Mechanical System) scanner with an optical system that will extend the field of view (FOV).

This next generation time-of-flight (TOF) LADAR design utilizes a novel angle amplification mechanism that uses a pre-compensating positive lens and a subsequent negative lens to overcome the small scanning range of MEMS mirrors where scan angles as small as 6° can be increased to over 40°. Also, with conventional digital zoom, a portion of an image is used to create a larger but much lower resolution image, while the LADAR zoom technology discussed in this paper will have a tighter field of view for a high resolution zoom image. Other innovation is a relatively inexpensive and compact laser driver that can generate subnanosecond pulses of varying repetition frequency.

Our analyses demonstrate that this portable LADAR device would work in close proximities as well as distances over 100 meters, could have a range resolution of less than a centimeter and a FOV greater than 40º, and be able to display 320x240 pixel real-time images at a frame rate of 15. Such a LADAR unit could be enhanced to also record and transmit range, intensity, and GPS/vector data to a remote computer. By using the same soldier for capturing LADAR images and data from multiple locations or multiple soldiers a computer program could analyze and integrate the data so as to build a 3D survey of the combat field with in-depth target information. In this potential scenario even occluded (camouflaged) targets could be revealed and identified with appropriate signal processing. Also, as the intensity (amplitude) and range (time interval) data are being quickly processed, graphically enhanced 3D images could be transmitted back to the soldiers in the field.

INTRODUCTION

Though scanning real-time LADAR has been pursued by the military for decades, only recently have the components and techniques become available for optically extending the scanning range of MEMS (Micro-Electro-Mechanical System) mirrors, making next generation LADAR possible. This next generation 3D LADAR will be highly accurate, economical, eye safe, and yet small enough to hold in one's hand. It also has the potential to meet the military objectives of a lightweight, ultra-compact, and portable real-time LADAR system that can generate high resolution images (both range and intensity), that can be carried by an individual dismounted soldier.

Today's scanning 3D LADAR can have greater angular, range, and ultimately better display resolution than alternative imaging techniques. It can also be used to "see" targets invisible by other imaging devices and has already found many practical applications. Unlike one-dimensional LADAR which is currently being used by law enforcement to catch speeders, 3D imaging LADAR is being used for target identification, terrain mapping, 3D documentation of buildings/objects, robotic navigation, and more. The major problems to the expansion of 3D real-time LADAR are that the smallest current device weighs over 15 kg and the average cost for 3D LADAR units is about $100,000.[1]

SCANNING OPTIONS

In principle, the methods by which one can achieve 3D LADAR TOF data acquisition are mainly limited to two:

(i) send out a laser pulse which is then detected by a complex photodetector array (i.e., nodding line, 2D photodetector array), or (ii) sending out sequential laser pulses in a pattern (scanning) to cover the desired FOV and then detect them by a single element detector.[2,3,4] Laser gated cameras are not an option since they can not produce real-time range images and the user must predetermine the distance window (illumination zone) for which he desires to take a "picture" and no detailed range information about the target is obtained.

The first option appears impractical since there are no appropriate time resolving optical receivers commercially available due to several technological issues (i.e., simultaneous signal processing problems, manufacturing issues, etc.).[5] Though some small APD (avalanche photodiode) arrays such as an HgCdTe APD 5x5 array (Raytheon) and a 4x4 APD (M.I.T. Lincoln Laboratory) have been developed, they have not yet evolved to a level sufficient for use in a 3D LADAR system in this context.[6,7,8,9] There are the rare larger arrays (e.g., Indigo, Sensors Unlimited) but they can only be used for single camera/video imaging since they do not have the bandwidth necessary for adequate range resolution and have no real-time signal processing capability for each pixel as required in 3D LADAR.[10,11]

The option selected therefore is the second one, sending out sequential laser pulses in a 2D pattern over the desired FOV with the returning scattered signal being captured by a single element detector. Although such scanning systems have existed for quite some time, even the best acousto-optic or rotating mirror scanners are too bulky, too slow, or too power hungry to be practical for LADAR system contemplated here.[2,12,13]

The goal of any real-time scanning LADAR is to be able to generate images at a rate of at least 15 fps (frames per second) which is faster than the human brain can process individually (about 12 fps) and can be increased to 30 fps (a common video rate) computationally. Therefore, our goal is to be able to generate at least 15 fps and a device scanning method that can meet that rate. In order to generate 15 fps, the scan frequency of a mirror system needs to be at least 1.8 kHz for a 320x240 pixel image. But even the fastest commercially available galvanometer/moving magnet scanners can not exceed a 1 kHz scan frequency for a 40° scan angle and are therefore not acceptable. There are some resonant scanners which although capable of 1.8 kHz scanning, require more than 10 W of power for 2-axis operation. The goal for power consumption should be less than 10 W for the entire device (0.5 W average using the LADAR unit <5% of the time) in order to make it practical for portable field use.

Although a nodding polygon mirror scanner (a rotary polygon mirror scanner with a mechanical means of changing the mirror's angle) could be constructed, many of the same problems with power consumption and size also exist. Power can be somewhat reduced by using a secondary axis mirror used in conjunction with a rotary polygonal mirror scanner, but size is still an issue and complexity increases.

The best option for laser scanning would be to use available MEMS (Micro-Electro-Mechanical Systems) technology.[12] For instance, a commercially available MEMS scanning 2-axis tilt mirror (the size of a small IC) has an inner axis scan frequency of 1.8 kHz which meets our minimum resonant rotational frequency requirement and could output 15 fps. If a 30 fps video rate is desired, the 15 fps rate could be increased to 30 fps computationally. Though MEMS scanning mirrors require a higher voltage, their power requirement is very low. We are aware of other power supplies which could be used to drive this device, one of which is <2 cm square. With supporting electronics, the power usage of this device should be less than 4 W. Another advantage of using MEMS is that it is the lowest cost solution.

There are at least two companies that manufacture MEMS scanning 2-axis tilt mirrors that could be used in our LADAR device. The usable diameter of these mirrors varies from 0.5 mm to 3 mm, their resonant frequencies vary from 1.8 kHz to 4 kHz, and the scan angles of these devices range from 6° to 16°. Though the scan angle of these MEMS devices may seem like a limiting factor since a 40° FOV or better is desirable, we have developed an optical angle amplification technique which can expand the FOV while still keeping the beam diameter to target distance ratio less than 1:1000 (e.g., <10cm at 100m). By keeping this ratio less than 1:1000, the beam diameter at the target is still smaller than that represented by a pixel in a 320x240 display. Other ratio specs can be used for higher resolution displays but the important parameter is to keep the target spot size less than that represented by an image pixel.

LADAR DESIGN

The next generation scanning 3D LADAR system will most likely utilize a pulsed time-of-flight methodology and consist of a clock, pulse generator/driver, laser, scanning MEMS mirror(s), transmitting/receiving optics, photodetector, and data acquisition electronics, as shown in Figure 1. The data obtained from the LADAR device can then be visually displayed for the user and/or wirelessly transmitted to a data collection computer for more in-depth processing. A potential example of the latter would be using multiple soldiers with GPS integrated LADAR to scan their common field of combat. These multiple input scans are then transmitted to a central computer to build 3D maps and identify targets. The key to miniaturizing and making a 3D real-time scanning LADAR affordable though, is to use innovative components and a tilting MEMS mirror in novel but practical ways.

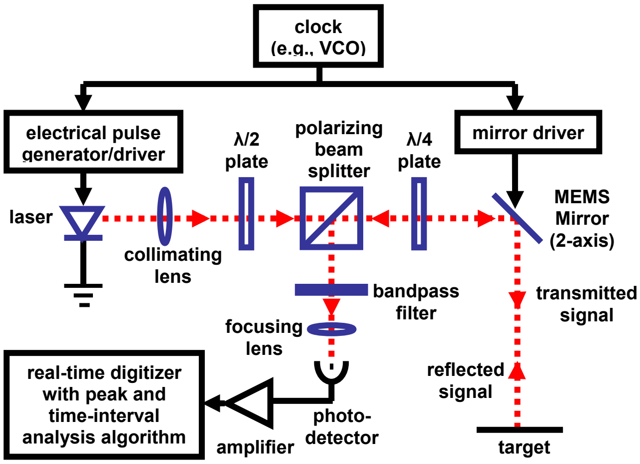
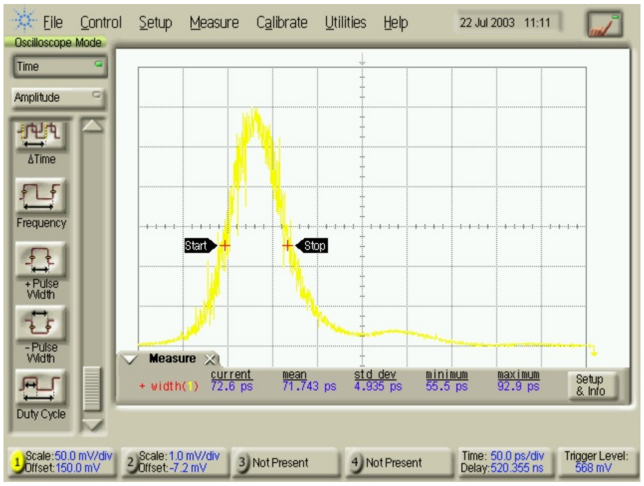


Figure 1. Simplified diagram of a next generation scanning MEMS 3D real-time LADAR device.

The pulse generator/driver and laser components for a next generation scanning 3D LADAR system need to be small and relatively inexpensive; unfortunately the two are often mutually exclusive. One small and potentially inexpensive device that has been designed by LightTime can produce optical pulse widths <75ps at any repetition rate from a single shot to 1 GHz at both 1310 and 1550nm (see Figure 2). Utilizing such a component at these wavelengths and pulse widths, along with other design factors, can result in an ANSI Class 1 eye safe LADAR device even with a peak optical pulse power of hundreds of milliwatts. Also by using a short pulse width and a GHz photodetector (typically InGaAs which has a high responsivity in the 1300-1600nm range), the range resolution (the smallest radial distance between two distinguishable targets) is about 1cm, and with advanced edge detection and algorithms, it can potentially be reduced to a few millimeters.



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          current   mean       std dev   minimum   maximum
+ width(1) 72.6 ps  71.743 ps  4.935 ps  55.5 ps   92.9 ps

1 Scale:50.0 mV/div  2 Scale:1.0 mV/div  3 Not Present  4 Not Present  Time: 50.0 ps/div    Trigger Level:
  Offset:150.0 mV      Offset:-7.2 mV                                  Delay:520.355 ns     568 mV
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Figure 2. A 72 ps optical pulse obtained from LightTime's gigahertz pulse generator using a 1310 nm laser and a 50GHz photodetector in conjunction with a 50GHz oscilloscope.

Currently, scanning LADAR devices often use dual or nodding rotating polygonal mirrors, dual galvanometric mirrors, or a 2-axis actuated mirror. All of these systems are relatively much larger and require more power than a MEMS mirror based system. A MEMS scanning system consists of either two 1-axis MEMS mirrors, which operate somewhat more efficiently, or a single 2-axis MEMS mirror, which is easier to package. The biggest limitations to the utilization of either of these MEMS mirror configurations are that their tilt angle is too small (e.g., ±8°), they are too slow for real-time imaging, or both. In order to generate a frame rate (the number of frames per second) of at least 15 for real-time imaging, the resonant frequency of a MEMS mirror system needs to be at least 1.8 kHz to generate a 320x240 pixel image.

By optically extending the scan angle of the MEMS mirror, it is possible to increase the field of view (FOV) of a MEMS-based LADAR from as little as 6° to over 40°. Diffractive optics and liquid crystal spatial light modulators can be used but they have had limited success. A potentially better way is to amplify the angle of the laser beam after it is reflected off the MEMS mirror (see Figure 3). When designed correctly, the diameter of the laser beam at the MEMS mirror can be ≤0.5mm, which is necessary for most 2-axis MEMS scanning mirrors that have a fast enough resonant frequency for real-time imaging.

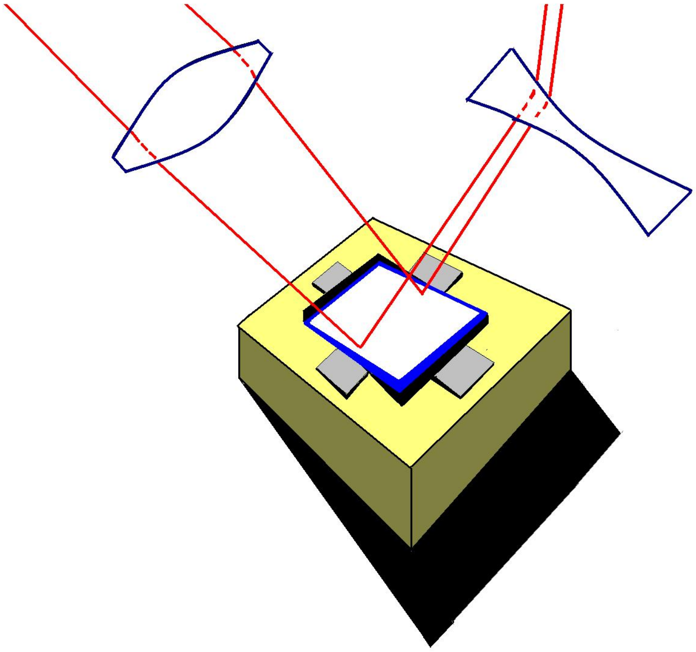

Figure 3. A collimated laser beam goes through a pre-compensating positive lens and after being reflected from the MEMS mirror passes through a negative lens which induces the desired angle amplification.

OPTICAL ANGLE AMPLIFICATION

Optical angle amplification can be accomplished by using a positive lens prior to the angularly limited 2-axis MEMS mirror and followed by a negative lens as shown in Figure 3. The purpose of the objective lens is to pre-compensate for the beam divergence resulting from the use of a negative lens for angle amplification of the collimated beam along the optical axis. The maximum divergence angle of the beam transmitted from the LADAR is determined by the desired spot diameter at the target (the objects being scanned). Through the use of this pre-MEMS positive lens in combination with a negative lens for angle amplification, spot sizes of less than 10 cm can be obtained at target distances of over 100 m which is still less than the size represented by a pixel in a 320 x 240 display.

Since a MEMS mirror may have a scan angle as small as 6˚ (±3˚ of maximum tilt from rest position), the desired FOV of the LADAR device must be achieved by an angle amplification mechanism in order to make a scanning MEMS 3D LADAR practical and useful. Attempts have been made to use diffractive optics in conjunction with MEMS based mirrors and liquid crystal spatial light modulators, but with limited success.[12] A novel angle amplification mechanism has been developed that uses a specially designed negative lens (angle amplification lens) after the MEMS mirror. With this scheme, the FOV can be increased from a scan angle as small as 6˚ to 40˚, and beyond based upon our simulations. The transmitted beam's spot size at the target determines the pixel resolution of the LADAR system. The purpose of the objective lens is to pre-compensate for the beam divergence resulting from the use of a negative lens for angle amplification (as shown in Figure 4) for a collimated beam along the optical axis. Through the use of a positive objective lens in combination with a negative lens for angle amplification, spot sizes of less than 10 cm can be obtained at target distances of 100 m.

The laser scanner section of the LADAR device depicted in Figure 1 is redrawn in Figure 4 after unfolding the optical system. The point p is the fulcrum point of the MEMS mirror around which the mirror rotates in two dimensions. The input collimated beam diameter and the beam diameter at the negative lens are denoted by D and D', respectively. The focal lengths are denoted by f_n and f_p. The subscript n refers to the negative lens while the subscript p refers to the positive lens. θ is the angle between the marginal ray and the optic axis; it is defined to be a positive quantity. The distance between the two lenses is x and it is a measure of the total size of the scanner.

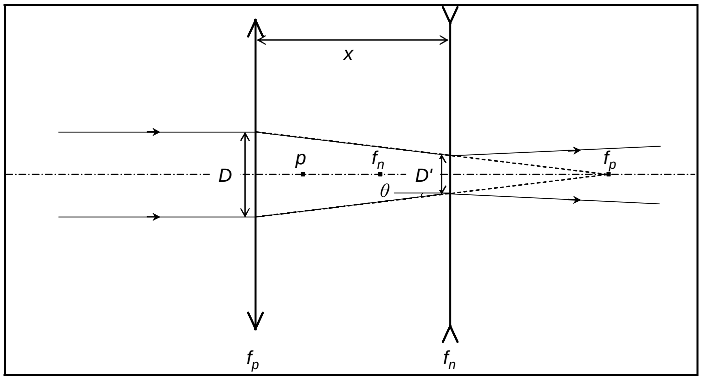

Figure 4. Unfolded MEMS mirror laser scanner setup with a collimated beam along the optic axis.

Figure 5 shows a converging beam after the objective lens with a chief ray angle θ_i with respect to the optic axis. The relation between θ_i and the output chief ray angle θ_0 can be obtained by first expressing the chief and marginal ray heights at the negative lens as functions of angles of incidence. Throughout the rest of the discussion, the paraxial approximation will be used. Figure 5 is not drawn to scale and the ray angles are exaggerated for illustration. The parameter descriptions and values for the MEMS mirror scanner are given in Table 1 along with example values for illustrative purposes. The letter "c" in parentheses denotes a parameter set as a constraint for these numerical calculations.

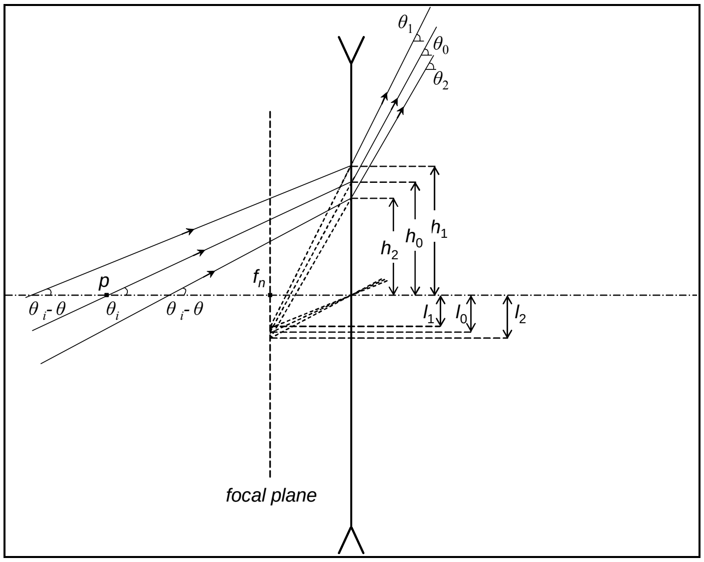

Figure 5. The angle amplification lens with a converging beam of a chief ray angle θ_i.

parameter	symbol	value
laser wavelength (c)	λ	1310 nm
scanner input max/min chief ray angle (c)	θ_i	±3˚
scanner output max/min chief ray angle (c)	θ_0	±20˚
beam divergence (c)	$\Delta\theta$	1 mrad
input beam diameter (c)	D	0.5 mm
MEMS mirror-to-negative lens distance	p	9.1 mm
positive to negative lens distance	x	33.1 mm
positive lens focal length	f_p	40 mm
negative lens focal length	f_n	-5 mm
distance to target (c)	L	100 m
spot size at target (c)	D_s	10 cm
field of view (c)	FOV	40˚

Table 1. Parameter descriptions and example values for angle amplification in a MEMS mirror scanner simulation.

Referring to Figure 5,

$$h_0 = p \cdot \tan\theta_i \ , \qquad (1)$$

$$h_{1,2} = p \cdot \tan\theta_i \pm \frac{D'}{2} \ , \qquad (2)$$

and

$$h_{0,1,2} + l_{0,1,2} = f_n \cdot \tan\theta_i \ . \qquad (3)$$

Also

$$l_{1,2} = f_n \cdot \tan(\theta_i \mp \theta) \qquad (4)$$

and

$$l_0 = f_n \cdot \tan\theta_i \ . \qquad (5)$$

Here, h_0 is the chief ray height and h_1 and h_2 are the marginal ray heights at the angle amplification lens. l_0, l_1, and l_2 are the distances from the optic axis to the intersection of the focal plane and the extensions of the corresponding rays after the negative lens.

From Eqn.(2) through Eqn.(4) for the beams with indices 1 and 2,

$$p \cdot \tan\theta_i \pm \frac{D'}{2} + f_n \cdot \tan(\theta_i \mp \theta) = f_n \cdot \tan\theta_{1,2} \qquad (6)$$

and

$$\tan\theta_{1,2} = \frac{p}{f_n}\tan\theta_i + \tan(\theta_i \mp \theta) \pm \frac{D'}{2f_n} \ . \qquad (7)$$

On the other hand, for the beam with index 0,

$$p \cdot \tan\theta_i + f_n \cdot \tan\theta_i = f_n \cdot \tan\theta_0 \qquad (8)$$

and

$$\tan\theta_0 = (1 + \frac{p}{f_n})\tan\theta_i \ . \qquad (9)$$

θ_0 is the angle of the chief ray while θ_1 and θ_2 are the angles of the marginal rays with respect to the optic axis after the negative lens.

Eqn.(9) determines the location of the scanning MEMS mirror with respect to the negative lens for a given focal length. Taking the scan angle of the MEMS mirror to be 6˚, for a 40˚ FOV, p needs to be approximately 6 times the magnitude of the focal length.

The maximum divergence angle of the beam transmitted from the LADAR, $\Delta\theta$, is determined by D_s, the desired spot diameter at the target located at a distance L with respect to the scanner:

$$D_s = \Delta\theta \cdot L \,. \tag{10}$$

$\Delta\theta$ is defined as

$$\Delta\theta = \theta_1 - \theta_2 \tag{11}$$

and the values of θ_1 and θ_2 can be obtained from Eqn.(7). For a spot size of 10 cm at a target 100 m from the LADAR device, $\Delta\theta$ is 1 mrad when the input beam diameter D is 0.5 mm.

The lenses with the obtained parameters are available off-the shelf. The point to note is that a FOV of 40° with a spot size of less than 10 cm is possible to achieve at a target 100 m away. These results satisfy the requirements of a compact high-resolution LADAR.

HIGH-RESOLUTION LADAR ZOOM

Another advantage of this technique is that by moving the negative lens relative to the mirror, the FOV can be increased or decreased while maintaining the same number of data points, resulting in a zoom effect without loss of image resolution as would occur with conventional digital zoom. Though a similar LADAR zoom effect could also be achieved by decreasing the scan angle while using the same number of data points, this would require additional control over the MEMS scanning mirror that some LADAR units may not be capable of. Either way, a typical 1:4 digital zoom would utilize just 4800 pixels (80x60) of a 76800 pixel (320x240) pixel image, while the LADAR zoom would still yield all 76800 pixels from their unique data points. The LADAR zoom in this example would therefore have 16x more image data points than a digital zoom. This would allow obtaining high-resolution images from a distance, which would be extremely desirable for most applications, especially for military target identification.

FUTURE OPTIONS

Though using a single laser is a practical option, by increasing the number of lasers with different wavelengths, data acquisition could be accomplished with lower bandwidth (BW) and decreased expense. Another option is to use a passively modelocked semiconductor laser with narrow pulse widths but their repetition rates are currently too fast for full data acquisition electronics. As data acquisition electronics improve, this may become an efficient and inexpensive alternative. These modelocked lasers do not need a clock and pulse generator, and produce picosecond pulsewidths that would yield a range resolution of just a fraction of a millimeter. In the design of a miniature scanning 3D real-time LADAR, all of the various components must be selected based on the optimal functioning of the LADAR device as a whole, within the desired cost and power parameters.

At LightTime, we have proposed designs for miniature 3D real-time LADAR devices with MEMS scanners that have an optical display and/or wireless transmitter being incorporated into a hat or helmet. Next generation LADAR, having at least 40º FOV, a range resolution of less than 1 cm, capability of outputting range and intensity data from over 76800 points per frame, zooming ability without loss of resolution, and a size that fits into a hand or helmet, all while using less than 4W of power, is just around the corner.

These next generation LADAR devices could be built using current technology at a cost that is at least an order of magnitude less than the large and heavy units in service today. Next generation devices could be used to give the blind a form of 3D tactile/neural 'vision' or by sports such as baseball to determine strikes. A nearer term major application will be real-time 3D imaging LADAR in the field of robotics, especially for unmanned aircraft and terrestrial vehicles (other military applications examples are listed in Table 2). With its small size, high-resolution, and low cost, an optically extended scanning MEMS LADAR for real-time 3D imaging is the next generation of LADAR systems, with a market potential that is only limited by imagination.

Potential U.S. Military Markets

MARKET SEGMENT	**MARKET SUB-SEGMENTS**
Target Detection	Detection and Human Recognition of occluded targets
Target Recognition	Autonomous recognition of predetermined shapes, sizes, and movement
Target Acquisition	x,y,z of target for soldier fire and/or remote fire control/guidance
Remote Surveillance	*Aerial* – Battlefield deployed, inexpensive, 1-Meter Drone *Terrestrial* - Remote Operated Vehicles (ROVs)
IFF (Identification Friend-or-Foe)	*Passive* – Reflective Signature *Active* – Tunable and/or Encrypted Transmission
3-D Mapping	Mission Planning, VR Simulations

Table 2. Examples of military market applications for a miniature real-time 3D LADAR device.

REFERENCES

1. W. C. Stone et al., Performance Analysis of Next-Generation LADAR for Manufacturing, Construction and Mobility, NISTIR 7117: www.bfrl.nist.gov/bfrlnews/NISTIR_7117_Final_Complete.pdf.
2. C. Ye, Borenstein J., “Characterization of a 2-D Laser Scanner for Mobile Robot Obstacle Negotiation”, Proc. of the 2002 IEEE International Conference on Robotics and Automation, 10-17 May 2002, pp. 2512-8.
3. R. Richmond, R. Stettner, J. Glessner, “Eye safe laser radar focal plane array for three-dimensional imaging”, *Laser Radar Technology and Applications V*, Proc. of SPIE Vol. 4035, 2000, pp. 172-8.
4. V. Delaye, P. Labeye, “High-resolution eye safe time of flight laser range finding”, *Laser Radar Technology and Applications V*, Proc. of SPIE Vol. 4035, 2000, pp. 216-225.
5. M.R. Stevens, M. Snorrason, V. Ablavsky, S. Amphay, “ATA algorithm suite for co-boresighted PMMW and LADAR imagery”, Presented at the 15th Annual AeroSense, Proc. of SPIE Vol. 4373, 20 April 2001.
6. C. Anderson et al., “High Density HgCdTe Avalanche Photodiode Array Performance”, DTIC AD#: A390368, August 1999.
7. M. Albota, “Three-dimensional imaging laser radar with photon-counting avalanche photodiode array and microchip laser”, Applied Optics, Vol. 41, No.36, Dec. 2002.
8. M. Browder et al., “Three Dimensional Imaging Sensors Program”, *Laser Radar Technology and Applications VI*, Proc. of SPIE Vol. 4377, 2001, pp. 73-83.
9. R.M. Heinrichs et al., “Three-Dimensional Laser Radar with APD Arrays”, *Laser Radar Technology and Applications VI*, Proc. of SPIE Vol. 4377, 2001, pp. 106-117.
10. A. Richards, “Near-IR focal-plane arrays improve camera performance”, Compound Semiconductor, March 2003.
11. E.A. Watson, M.P. Dierking, R.D. Richmond, “Laser Radar Systems for Multi-Dimensional Imaging and Information Gathering, Lasers and Electro-Optics Society Annual Meeting, Vol. 2, 1998, pp. 269 -270.
12. B. Hammond, T. J. Suleski, E.G. Johnson, C. Koehler, J. Childers, “Diffractive Optics Based Micro-mirror Scanning System”, *Optical Scanning: Design and Application*, Proc. of SPIE Vol. 3787, p. 96-104, July 1999.
13. M. Greer et al., “Scanner Development”, DTIC AD#: A066902, July 1978.