Status report on next generation LADAR for driving unmanned ground vehicles[a]

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ABSTRACT

The U.S. Department of Defense has initiated plans for the deployment of autonomous robotic vehicles in various tactical military operations starting in about seven years. Most of these missions will require the vehicles to drive autonomously over open terrain and on roads which may contain traffic, obstacles, military personnel as well as pedestrians. Unmanned Ground Vehicles (UGVs) must therefore be able to detect, recognize and track objects and terrain features in very cluttered environments. Although several LADAR sensors exist today which have successfully been implemented and demonstrated to provide somewhat reliable obstacle detection and can be used for path planning and selection, they tend to be limited in performance, are effected by obscurants, and are quite large and expensive. In addition, even though considerable effort and funding has been provided by the DOD R&D community, nearly all of the development has been for target detection (ATR) and tracking from various flying platforms. Participation in the Army and DARPA sponsored UGV programs has helped NIST to identify requirement specifications for LADAR to be used for on and off-road autonomous driving. This paper describes the expected requirements for a next generation LADAR for driving UGVs and presents an overview of proposed LADAR design concepts and a status report on current developments in scannerless Focal Plane Array (FPA) LADAR and advanced scanning LADAR which may be able to achieve the stated requirements. Examples of real-time range images taken with existing LADAR prototypes will be presented.

Keywords: Unmanned Ground Vehicle (UGV); real-time 3D imaging; on & off-road autonomous driving; laser radar (LADAR); Time-of-Flight (TOF); scanning; Focal Plane Array (FPA); Field-of-View (FOV); range & range resolution.

1. INTRODUCTION

A recent NIST publication[1] included a section on Next Generation LADAR for Driving Unmanned Ground Vehicles. Most of the material in this Section and in the first part of Section 2 came from that document.

The U.S. Department of Defense has initiated plans for the deployment of autonomous robotic vehicles in various tactical operations starting in about 7 years. Several programs, including the Future Combat Systems program, have received significant funding in order for this to take place. Envisioned are manned and autonomous unmanned ground vehicles as well as manned and unmanned air vehicles performing cooperative tactical missions. Some of the tactical missions being considered for unmanned ground vehicles include: reconnaissance, active or passive surveillance, communication relay, mine detection or clearing, targeting, search and rescue, supply, terrain control/denial, forward observation, and lethal or non-lethal missions. These missions will require the vehicles to drive autonomously over open terrain and on roads which may contain traffic, obstacles, military personnel as well as pedestrians. UGVs must therefore be able to detect, recognize and track objects and terrain features in very cluttered environments.

Although several LADAR sensors exist today which have successfully been implemented and demonstrated to provide somewhat reliable obstacle detection which can be used for path planning and path selection, they tend to be limited in performance (primarily resolution and maximum range), are effected by obscurants (dust, fog, grass, foliage), and are quite large and expensive. An example of where the current technology falls short is shown in Figure 1. Although the flatness of the road is visible in the display of the 3D range image of the road the vehicle is following, it has very limited range information from the road and terrain further ahead in the scene. In addition, although the trees and brush along the sides of the road are seen as obstructions, it would be very hard to use that information for classifying or identifying what those obstructions are. Another example of current technology limitations is shown in

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Figure 2. The figure displays the range image of a scene taken in a parking lot. It is very hard to identify any detected known objects in the scene. In the future, it is expected that unmanned vehicles must be able to locate available parking spaces on their own and to be able to park autonomously.

Figure 1. (left): Digital camera image of road and trees; (right) the same scene as viewed by Demo III real-time LADAR. Where does the technology fall short? The vehicle is effectively myopic. Current LADAR is low resolution (75 mm to 150 mm accuracy) and short range (<40 m returns from horizontal surfaces). Current LADAR does not penetrate dust and smoke. Planning is not optimized for road following.

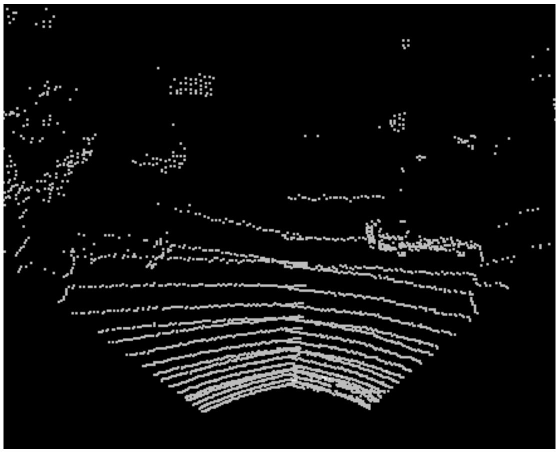

Figure 2. Typical point cloud of parking lot produced by a coarse UGV LADAR.

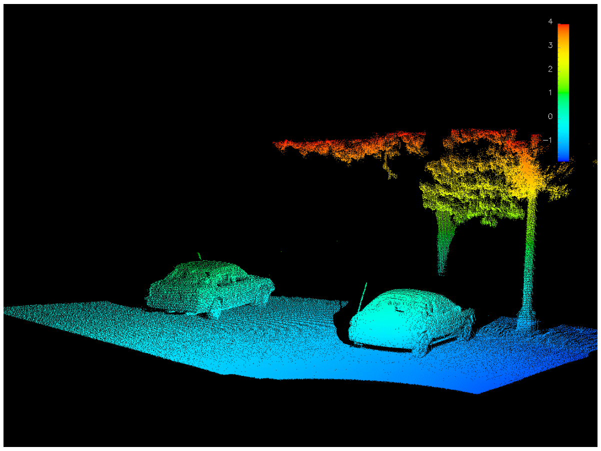

Figure 3. High resolution point cloud image of parking lot. Image is color coded in vertical (z) dimension.

What denser, high resolution range data can provide is clearly evident in the range image taken of a parking lot with a high resolution LADAR camera. This is shown in Figure 3.

Detection and identification of cars, tree trunks, overhanging branches, man-made structures (light pole) and even curbs are highly possible from this kind of data. It must be pointed out, however, that the data was taken with a high resolution scanning LADAR that required several minutes to generate the range image.

2. EXPECTED REQUIREMENTS

2.1 Earlier requirements and status

Even though considerable effort and funding has been provided by the DOD R&D community, nearly all of the development has been for target detection (ATR) and tracking from various flying platforms. This includes LADAR technology development which allows for foliage penetration, permitting detection of target hidden under trees and camouflage netting. Although much of the development has contributed significantly toward furthering the performance of LADAR sensors, it has not addressed the needs for autonomous driving with unmanned ground vehicles. LADAR sensors for ground vehicles have their own particular requirements. This includes having a very broad dynamic range. This is the ability of the sensor to detect and recognize obstacles/objects/terrain features which are at very close range (<1 m) and at more than 100 m, all in a single frame of data.

Participation in the Army Demo III program has helped NIST to identify requirement specifications for LADARs to be used for on and off-road autonomous driving. NIST envisions the need for two types of LADAR range imaging sensors for this type of application. One having a wide field-of-view (40° X 90°) with a resolution of about 0.25° or better per pixel, and the second a foveal LADAR having a narrow field-of-view of approximately 1/10th of the wide field-of-view with a resolution of about 0.05° or better per pixel. The intent is to make the foveal LADAR quickly steerable to points-of-interest positions within the wide peripheral angle field-of-view LADAR at a rate of at least 3 saccades per second. Both types of LADAR sensors should have a resolution of about 5 cm or better in range, should be able to detect the ground plane out to a distance of better than 50 m and vertical surfaces out to a range of at least 100 m. Frame rates of higher than 10 Hz are required. Both types of LADAR must be eye safe and should be provided with the capability of penetrating dust, fog, grass and light foliage (either by sensing multiple returns or looking for the last return), and should be able to operate in full sunlight conditions. Small size and low cost were also emphasized as important requirements.

The initial BAA announcement, which contained details on the expected requirements, was released in June of 2002 and is included in the NIST publication[1] as Appendix B. There was a good industry response to the announcement with 15 proposals being submitted. A unanimous decision was made by the proposal reviewers to make four awards for Phase I at the end of September 2002. The four awards went to (listed in alphabetical order):

- Advanced Scientific Concepts Inc., Santa Barbara, California
- Coherent Technology Inc., Lafayette, Colorado
- Lockheed Martin Missiles and Fire Control, Dallas, Texas
- Raytheon Missile Systems, Tucson, Arizona

Synopses of some of the main features of each design were prepared by each contractor for inclusion in the NIST report[1]. A shortened version of these features is provided in Section 3 here. Because of the proprietary nature of the designs, however, the contractors desired to keep much of the proposed design information confidential. Although sponsorship and funding for the next phase of development never materialized, the need of advanced LADARs for use on UGVs still exists. Over the last year NIST received many requests for information pertaining to the status of the original BAA. Requests for additional information can be directed to the contact person or persons listed at the end of each synopsis.

2.2 More recent requirements based on analysis of autonomous on-road driving

The DARPA Mobile Autonomous Robot Software (MARS) On-Road Driving Project funded NIST to do a task analysis of autonomous on-road driving. If one looks at an on-road driving task, it is very difficult to identify the sensors and the processing required because different driving tasks have significantly different resolution, classification, and identification requirements. For the task of the vehicle driving down a road, the sensor system has to be able to identify large objects moving nearby, their direction, speed and acceleration, their position in the lanes and the state of the brake and turn signal indicator lights on other vehicles. Figure 4 shows a typical scene that a driver may encounter when driving through an intersection. The sensor processing system has to be able to identify: the position and velocity of turning cars; the position and velocity of oncoming cars; traffic signals; the position and velocity of vehicles in the direction of travel; road edges; intersection edges; lanes and the position and velocity of the driven vehicle in its lane.

The project used the NIST developed Real-time Control System (RCS, now referred to as 4D/RCS[2]) design methodology and reference architecture as the basic technique for the task analysis of autonomous on-road driving. A recent publication[3] describes how this task decomposition representation is used as the framework to further specify the world model attributes, features, and events required for proper reasoning about the driving scenario subtask activities. These world model specifications, in turn, are used as the requirements for the sensory processing system. These requirements identify those things that have to be measured in the environment, including their resolutions, accuracy tolerances, detection timing, and detection distances for each subtask. This methodology concentrates on the task behaviors explored through example scenarios to define a task decomposition tree that clearly represents the branching of tasks into layers of simpler and simpler subtask activities. There is a named branching condition/situation identified for every fork of this task tree. These become the input conditions of the "if-then" rules of the knowledge set that define how the task is to respond to input state changes. Detailed analysis of each branching condition/situation is used to identify antecedent world states and these, in turn, are further analyzed to identify all of the entities, objects, and attributes that have to be sensed to determine if any of these world states exist. An example given is the subtask activity to "PassVehicleInFront" on a two lane road. This is just one of over 170 subtask activities so far identified for on-road driving. After evaluating possible branching conditions/situations and the associated world states for this subtask, the objects that have to be observed to recognize the world states are identified along with the minimum sensing resolutions needed for each particular subtask. At a speed of 75 km per hour, the minimum passing zone is 200 m or more. In order to detect objects in this passing zone, a minimum resolution of 0.05° to 0.09° is required. This is consistent with the LADAR BAA requirement specifications mentioned earlier. At higher speeds, the passing zone will be longer and the minimum resolutions smaller, but this sets a reasonable sensor requirement for this particular subtask.

Analysis of high resolution LADAR for driving was conducted as part of the project. Figure 5 shows a LADAR range image taken with a long range, high resolution range imager of vehicles on a road and at an intersection on the NIST grounds. For this scene, cars were detected and localized for ranges out to 62 m, however, longer ranges (out to 200 m) for the detection of a road and the cars on a road were possible. The project concluded that the perception problem for on-road driving is tractable using LADAR image processing techniques.

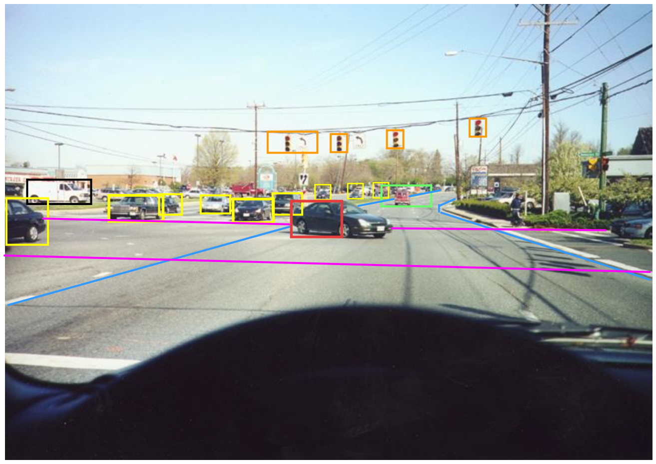

Figure 4. Perception Needed for Driving on roads.

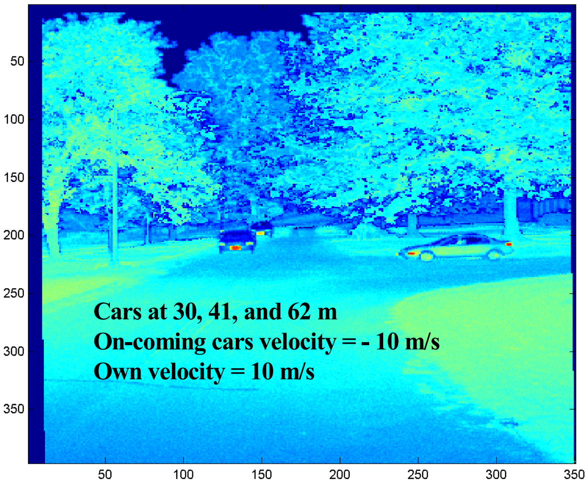

Figure 5. High resolution LADAR range image of vehicles on a road.

3. OVERVIEW OF LADAR BAA DESIGN CONCEPTS

The following are the brief technical synopses offered by the four Phase I BAA winners on their proposed designs for a next generation LADAR for Driving Unmanned Ground Vehicles.

3.1 Advanced Scientific Concepts Inc. (ASC)

Compact Unmanned Ground Vehicle LADAR (CUGVEL)

- Concept is nearly entirely based on latest technologies in development for FPA scannerless LADAR
- Concept is cost-effective since it leverages advanced sensor R&D which is sponsored by other government agencies
- An FPA sensor is desirable in military systems from the standpoint of simplicity and reliability
- Will generate two 200 X 200 array images to obtain Wide Field of View
- Concept offers a cost-effective approach of using a single sensor unit to meet WFOV and NFOV imaging requirements - this will be evaluated

- Each cell of the array can store 20 consecutive return pulse samples - this permits penetration through foliage, fog, dust, and even water
- There is ongoing work to develop and test a 128 X 128 array detector
- Will consider incorporating photocathode imaging tube technology - this could increase range resolution and reduce needed laser power by 1/10.

Figure 6 illustrates a possible camera configuration for the ASC pulse TOF WFOV design[4]. The drive and output electronic circuit boards, as well as the laser transmitter, are inside the camera housing.

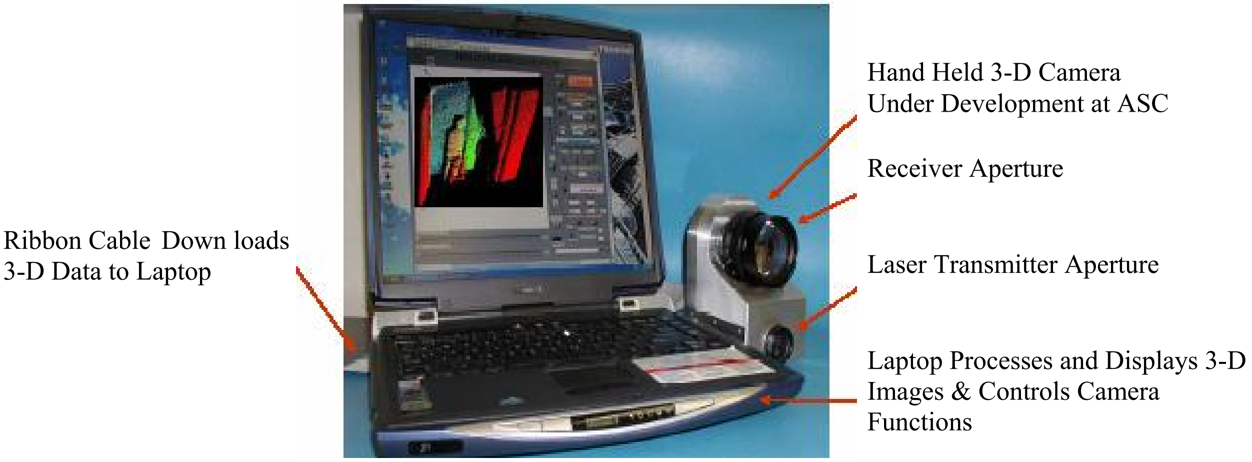

Figure 6. Possible packaged configuration for the standalone WFOV CUGVEL. Estimated weight is 1.8 kg; the COTs optics are a large fraction of the weight.

Figure 7 shows a typical ASC hybrid 3-D FPA configuration. It shows how a Readout Integrated Circuit (ROIC) is bump bonded to a solid-state detector array (such as a Silicon, InGaAs or HgCdTe PIN or APD detectors). Each unit cell, or pixel, contains circuitry which independently counts time from the emission of a laser pulse from the camera, to the detection of the reflected pulse from a surface. In this manner, each pixel captures its independent 3-D information in a scene (angle, angle, range). Additional circuitry is available in each pixel to capture temporal information from the returning pulses. Twenty sampling circuits are provided in the ASC FPA design which helps in detecting objects which are obscured by smoke, foliage, etc.

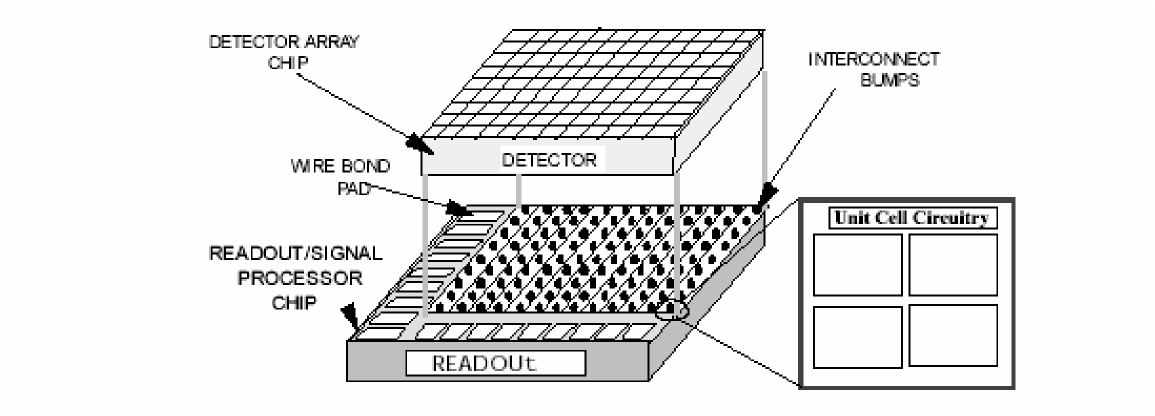

Figure 7. ASC 3-D FPA Hybrid Design. ROIC bump bonded to detector array chip

Additional information on advanced LADAR technology being developed at ASC and the BAA Phase I design for the CUGVEL can be requested from Roger Stettner (rstettner@advancedscientificconcepts.com) phone: 805-966-3331.

3.2 Coherent Technologies Inc. (CTI)

Frequency Modulated Continuous Wave (FM-CW) LADAR for an Unmanned Ground Vehicle 3-D Imaging Sensor

- Concept uses a coherent FM-CW approach to meet the desired requirements
- The FM-CW approach provides a much higher sensitivity than direct detection approaches (such as AM-CW) - this keeps the size and power of laser down
- Uses a more traditional scanning approach, but, shows that a 40° X 90° Field of View and 10 Hz can be obtained
- Uses a small aperture size, which helps to simplify scanner approach and no changes in optics are necessary when changing from WFOV to NFOV - only need to change scan pattern
- Has the potential for providing highest quality range images

Figure 8 shows a preliminary conceptual engineering drawing of the coherent FM-CW laser radar sensor.

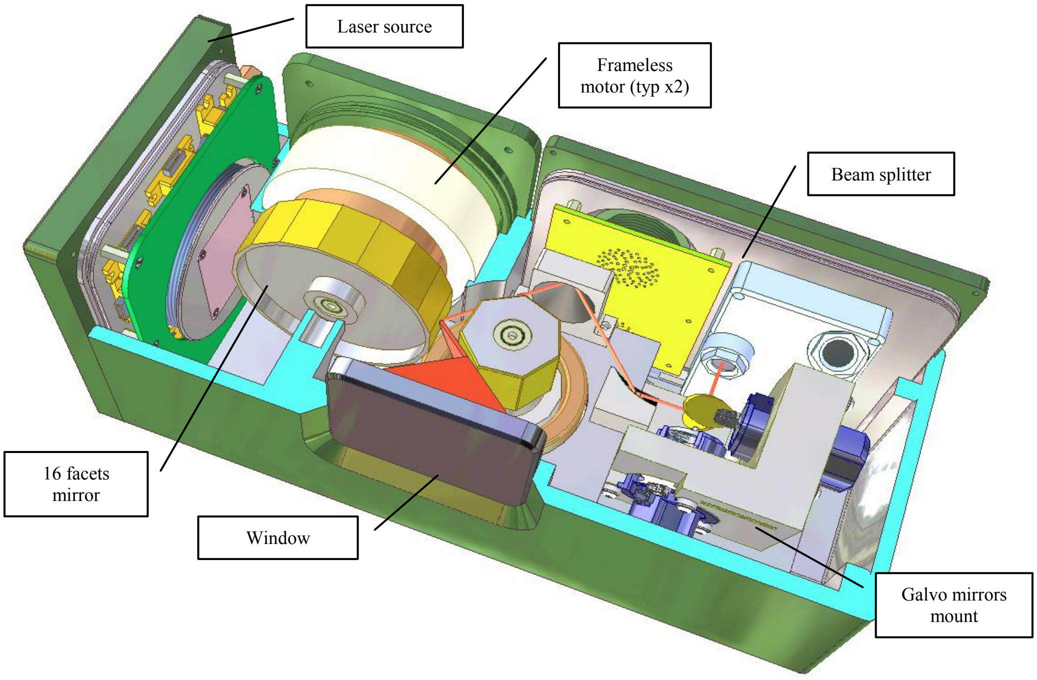

Figure 8. Mockup of Coherent Technologies Inc. FM-CW UGV LADAR

Further details on the CTI work in advanced LADAR and the concepts developed for the BAA Phase I design can be requested from the following contact person: Duane Smith (duane@ctilidar.com), phone: 303-379-3137.

3.3 Lockheed Martin Missiles & Fire Control

Next Generation LADAR for Driving Unmanned Ground Vehicles

- Uses traditional scanners and pulse laser sources combined with single or linear array detectors, all off-the-shelf.
- Design will be based on an existing successful sensor built for flying platforms - hardware can be redesigned to meet all the performance requirements for Unmanned Ground Vehicle applications
- To achieve the required pixel data rates using a fixed scan (for a 0.25° per pixel resolution) LM will consider splitting the laser beam and using multiple (up to 16) detectors
- Provides a novel concept for using the scanning mechanism to build a foveal response within the 40° X 90° Field of View - software controlled
- Possible near term delivery

A core technology of the system is Lockheed Martin's existing, flight-tested, signal processing electronics to capture and analyze laser pulses. This technology is referred to as the Pulse Capture Electronics (PCE). It is a well-established direct detection approach that accurately determines relative reflectivity (scene intensity) under varying conditions of range, atmospheric attenuation, obliquity, multiple returns, and noise. Figure 9 shows the proven Lockheed sensor system architecture.

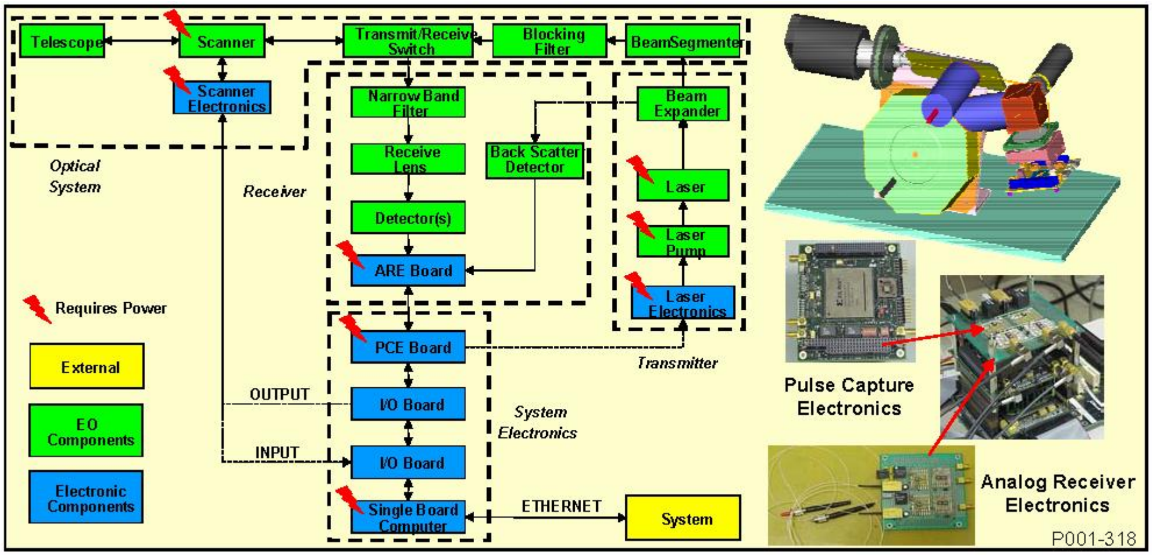

Figure 9. Lockheed LADAR concept uses proven system architecture, signal processing electronics, commercial components, and standard interfaces.

Additional information on the advanced LADAR technology being developed at Lockheed Martin and being offered in the BAA Phase I design can be requested from the following contact person: Bruno Evans (bruno.evans@lmco.com), phone: 972-603-7945.

3.4 Raytheon Missile Systems

Raytheon Flash LADAR for UGV Applications

- Uses latest advanced technology being developed - a scannerless "Flash" LADAR which uses a Focal Plane Array (FPA) detector
- Offers to leverage a large 256 X 256 HgCdTe APD FPA from an ongoing AFRL project
- The detector array is directly bonded to a Read-Out-Integrated-Circuit. Raytheon has considerable experience in this
- The concept lends itself to mass fabrication and therefore lower cost
- The concept has been proven with analytical, simulation, and experimental results
- A FPA is most convenient for use in military systems
- Multiple returns are detected and recorded - allows penetration through obscurants
- A Narrow Field of View can be achieved with the same detector architecture - by switching lenses on the tx. and rx. optics or by having two separate sensors

Figure 10 shows elements of the detector buildup as well as the final detector configuration on a leadless chip carrier.

Additional information on advanced LADAR work at Raytheon and the BAA design for UGVs using their Focal Plane Array technology can be requested from the following persons at Raytheon Missile Systems: Al Coit (coit@raytheon.com), phone: 520-545-9354 or Pat Trotta (patrotta@raytheon.com).

256 x 256 Ranging Focal Plane Array Combines Novel “Time of Arrival” Readout IC and APD Detector Array

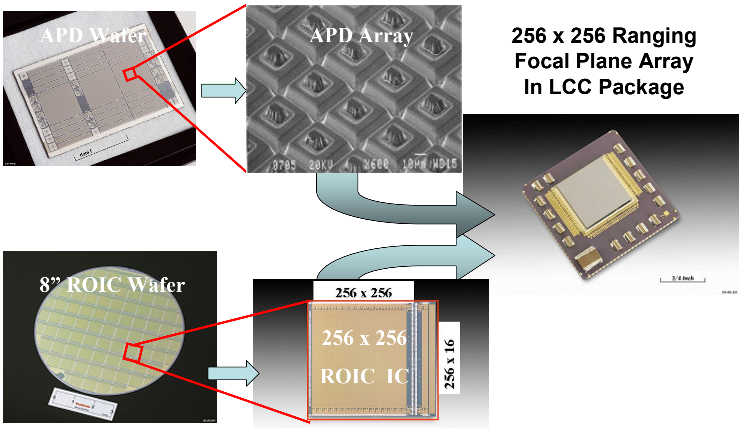

Figure 10. Raytheon FPA technology required to produce a fully functional, advanced, 256 x 256 Flash LADAR detector array.

4. EXAMPLES OF EXISTING REAL-TIME ADVANCED LADAR PROTOTYPES

This section describes several advanced LADAR prototypes (FPA and Scanning) which have been built by the developers to demonstrate use of such sensors for improving perception in autonomous and semi-autonomous vehicles for autonomous navigation, non-contact safety systems, autonomous material handling, and other industrial, commercial, transportation and military applications. Since we received a progress report from one of the Phase I BAA winners, we will begin with their report first.

4.1 Advanced Scientific Concepts Inc. (ASC)

ASC reports that their prototype camera, shown in Figure 6, which uses their FPA 3-D 128X128 InGaAs PIN array (operates with a 15 µJ, 1570 nm pulsed laser), has been used to take Flash range images. Several unprocessed range images are shown in Figures 11 and 12. These figures were provided by ASC. Additional details and images are provided in a recent publication[4].

4.2 MIT Lincoln Laboratory

Work at MIT Lincoln Lab has taken another approach to FPA development. In order to achieve enhanced ionization which is responsive to the arrival of a single photon, they have developed a “Geiger-mode” (GM) avalanche photodiode (APD) array that is integrated with fast CMOS time-to-digital converter circuits at each pixel[5,6]. When a photon is detected there is an explosive growth of current over a period of tens of picoseconds. This effect is achieved by reverse-biasing the APD above the breakdown voltage using a power supply that can source unlimited current. Over the last couple of years movies have been taken with a GM APD 32 X 32 FPA LADAR. However, since it is not possible to include the real-time movies in this paper, a couple of range images taken with earlier prototypes are provided. These are shown in Figures 13 and 14. These figures were provided by MIT/LL. Several different sensor cameras have been built and demonstrated over the past few years. Some of that work is described in recent SPIE conference publications[5,6]. They used solid-state Fiber-Pumped lasers (530 nm and 780 nm), operated at fast firing rates (8 to 10) kHz, required between 15 µJ and 30 µJ per pulse illumination, and used pan/tilt and scanning mechanisms to cover a larger FOV.

4.3 CSEM (Zurich, Switzerland)

Still another FPA approach has been developed by CSEM in Zurich Switzerland. Their research has concentrated on developing compact, robust, low cost, and real-time 3D image cameras, which take advantage of available custom CMOS/CCD technology. This unique combination permits the optimal use of the strengths of both CMOS and CCD technologies is terms of performance. A prototype miniature 3D Time-of-Flight (TOF) camera, the SwissRanger 2 (SR-2), has been built and is available for experimentation purposes[7]. The SR-2 is a standalone range image camera system which includes the illumination unit, a 3D optical sensor, and control electronics in a very compact unit. It is shown in Figure 15. The emitted optical signal (LED array, 870 nm) is a continuous wave signal which is modulated in amplitude.

The IR signal is modulated at a frequency of 20 MHz. This represents an ambiguity interval of 7.5 m for the range measurements. The reflected signal from the scene travels back to the camera, where the TOF is measured by recording the phase delay between the signals. The signal phase is detected by synchronously demodulating the incoming optical signal by cross correlation with the demodulation signal. Sampling response at the detector at intervals of $\Pi/2$, or four equally spaced temporal points, allow for the calculation of the phase delay. The phase delay is measured by each pixel. In other words, each pixel is able to measure the TOF. This results in a complete distance/range map at frame rates approaching 30 Hz where the spatial resolution is defined by the number of pixels in the FPA. For the SR-2, this happens to be better than 0.25° per pixel (124 X 160 pixels for a FOV of about 30°). Currently the CMOS detector is not able to suppress the effects of high intensity ambient light, therefore operation in bright sunlight is not currently possible. Pixels with ambient suppression are in the process of development by both CSEM and the German group at PMD (see below). Figure 16 is a photo of various size obstacle targets set up in a hallway at NIST. Figures 17 and 18 are the SR-2 reflectance image and range image respectively.

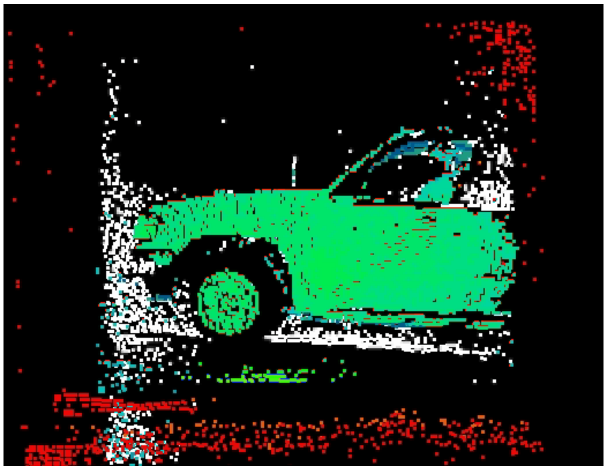

Figure 11. Car at distance of about 40 m outdoors.

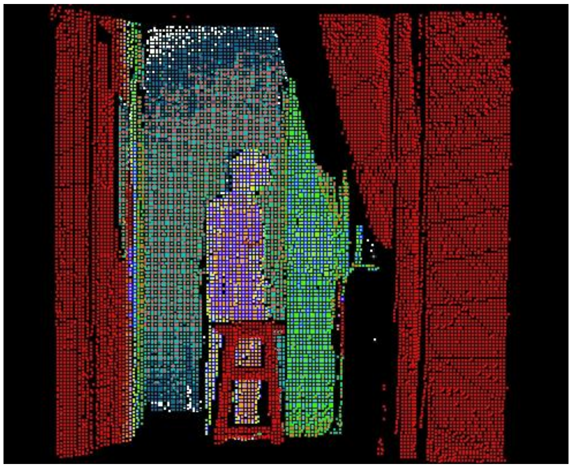

Figure 12. Person sitting on a bench (approx. 15 m)

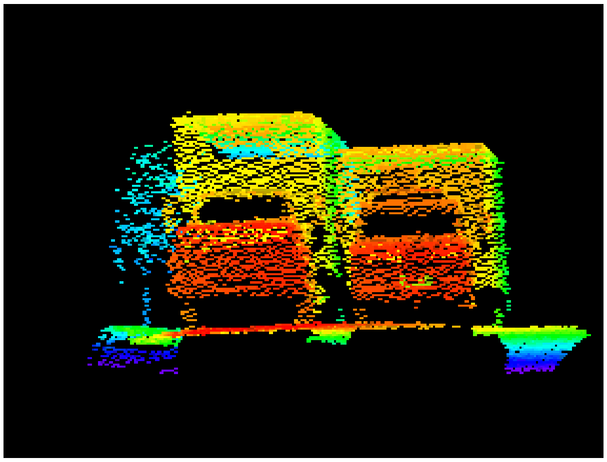

Figure 13. Two trucks at a distance of 150 m

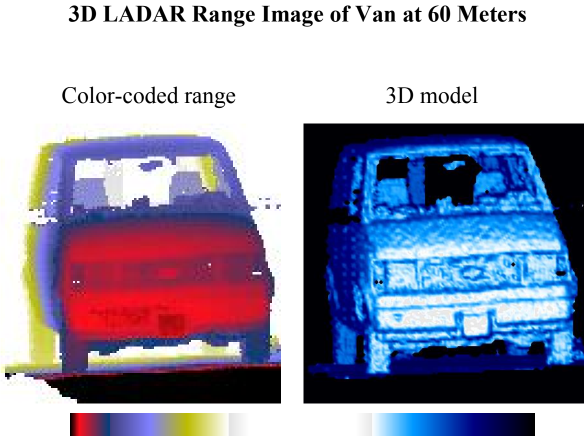

Figure 14. Chevy Van at 60 m (courtesy MIT/LL)

4.4 PMD Technologies (PMDTec) in Siegen, Germany

Another continuous wave Amplitude Modulated (AM) phase-based FPA LADAR camera is being developed by PMDTec in Germany. Similar to CSEM, it too uses CMOS technology for low cost, and, because of the single 20 MHz modulation frequency, is limited to 7.5 meter (ambiguity interval) operation. The early prototype, named “Observer 1k” is being built for interested parties. Since the process for measuring range (TOF) at each pixel is identical to that used by CSEM, it will not be further described here. There are some differences however. The available pixel array size is currently limited to 64 X 16, frame rates of up to 50 Hz are possible, and it is somewhat larger in size when compared to the CSEM SR-2. However, a key feature in the design is the addition of active Suppression of Background Intensity (SBI) circuitry at each pixel. Depending on the intensity of the illumination source and the level of ambient conditions, tests conducted by the company indicate that an SBI performance as good as 40 dB can be achieved. This implies that operation outdoors, even in sunlight, may be possible. Example images provided by PMDTec taken with the Observer 1k camera are shown in Figures 19 and 20. Figure 19 is the reflectance image and Figure 20 the 3D range image respectively.

Figure 15. CSEM SwissRanger 2 prototype camera
(Figure provided by CSEM)

Figure 16. Photo of various size obstacle targets in hallway

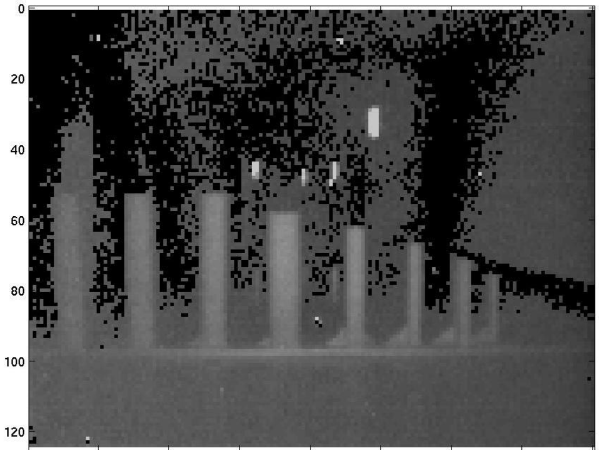

Figure 17. SR-2 active illumination reflectance image

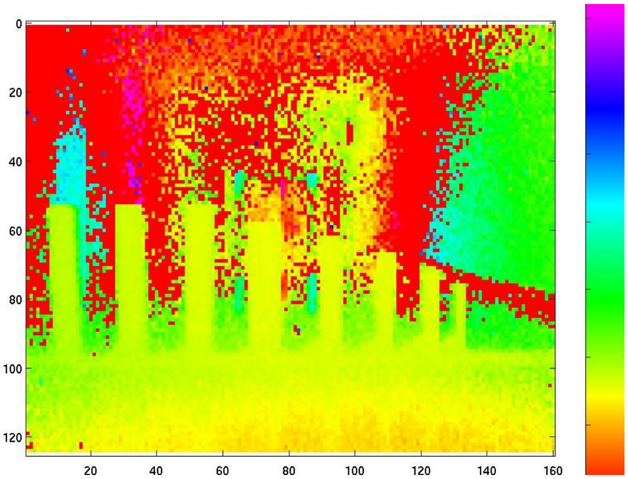

Figure 18. SR-2 processed range image – color coded in range

Figure 19. Active illumination reflectance image taken with MDTec Observer 1k prototype camera.

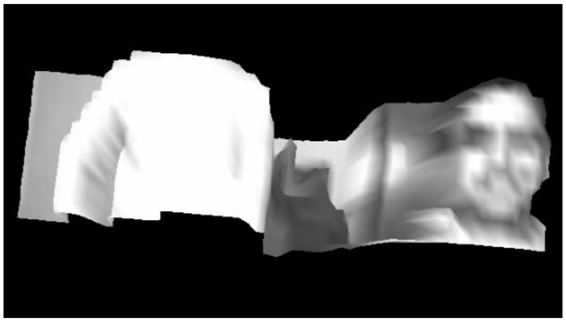

Figure 20. Processed 3D range image taken with the Observer 1k camera. Reflectance image superimposed on range image.

4.5 IBEO Automobile Sensor GmbH, Hamburg, Germany

A LADAR product for automotive safety applications has been recently announced. The IBEO "Alasca" sensor uses multi-return pulsed TOF range measurements which are scanned across the horizontal FOV. The sensor utilizes a four–layer/plane approach where the returns from the four layers are processed in parallel as the mirror scans the scene horizontally. Although the sensor does not use FPA technology, the sensor can produce a wide 240° horizontal FOV (using two sensors in front) at a resolution of 0.25°, 0.5° or 1.0°, and a 3.2° vertical FOV at a resolution of 0.8° at a 10 to 40 Hz frame rate. Distance range measurements can be resolved to 1 cm and range accuracy can vary as much as ± 5 cm. The multi-target return detection capability was incorporated in the design to allow for the detection of objects on the road even in heavy rain. The current model sensor utilizes a 905 nm laser which has a range of 0.3 to 80 m. A 200 m sensor is expected to be released in 2005. A recent publication[8] titled: "Laser Sensor Technologies for Preventive Safety Functions" was presented at the ATA EL 2004 conference in Parma, Italy. The short term objectives for this sensor is to introduce preventive safety features/functions in automobiles to assist drivers in unsafe driving conditions. The long term objective is to provide vehicles with full automated collision avoidance capabilities. The current Alasca Gen 1 model is limited to 80 m range operation but has been tested and evaluated for automated stop&go driving, automated emergency braking, pedestrian detection, pre-crash detection - collision warning, and for other applications such as automated intersection crossing assistance, turning assist, parking assist and blind spot monitoring. The Alasca Gen 2 model, which is expected in 2005, will increase detection range to 230 m, will provide fog detection and measurements in fog, will provide for automatic detection and tracking of lane markings and road edges, and provide full ACC capability for stop&go driving at speeds of 0 to 180 km/hr. Figure 21 shows how LADARs (like the the Alasca) can be used for a variety of automotive safety and driver assist applications. In the illustration the vehicle is fitted with a single sensor (150° opening angle) and 230 m range detection. Figure 22 shows how a test vehicle was instrumented with a multi-layer laserscanner for analyzing the performance of the sensor under realistic driving conditions.

Additional information on the automotive sensors available from IBEO can be obtained from www.ibeo-as.de.

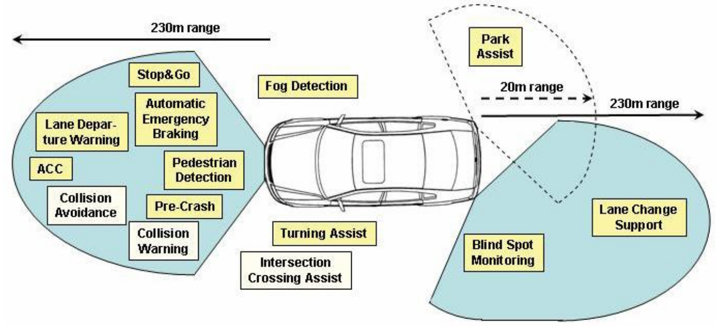

Figure 21. Use of LADARs for a variety of automotive safety and driver assist applications (figure from IBEO Automotive Sensor GmbH).

Figure 22. IBEO test vehicle fitted with an Alasca LADAR.

5. CONCLUSIONS

Based on the analysis of autonomous on-road driving conducted by NIST for the MARS project, we can make some conclusions on LADAR based sensing requirements. The required sensor resolutions will vary depending on which subtask activity is analyzed and on the speeds of the vehicles involved. This work is continuing in an attempt to identify the sensing requirements for all of the on-road driving subtask activities and the resulting required sensor resolutions. Additionally, off-road military tactical behavior driving tasks are now being analyzed to determine their sensing needs. This work will aid in identifying those sensor capabilities that are most important for both near-term and long-term future development of autonomous driving systems.

Since the release of the original BAA LADAR requirements specification in June of 2002, NIST has not seen the announcement of any new LADAR products that can meet all of the stated requirements. However, as reported in this publication, prototype advanced LADAR cameras are becoming available for experimentation which have the potential for a variety of ground vehicle mobility applications in the near future. NIST intends to continue encouraging and tracking these and other new developments, and working with other government agencies and industry to measure LADAR performance and investigate potential new applications.

REFERENCES

1. W.C. Stone, M. Juberts, N. Dagalakis, J. Stone, J. Gorman, “Performance Analysis of Next Generation LADAR for Manufacturing, Construction, and Mobility”, National Institute of Standards and Technology, NISTIR 7117, May 2004.

2. J.S. Albus, et.al., “4D/RCS: A Reference Model Architecture for Unmanned Vehicle Systems, Version 2.0”, National Institute of Standards and Technology, NISTIR 6910, Aug. 2002.

3. A. Barbera, J. Horst, C. Schelenoff, E. Wallace, D. Aha, “Developing world model data specifications as metrics for sensory processing for on-road driving tasks”, in: Proceedings of the 2003 PerMIS Workshop, NIST Special Publication 990, Gaithersburg, MD, 2003.

4. R. Stettner, et.al., “Eye-safe laser radar 3-D imaging”, Proceedings SPIE, Defense & Security, Volume 5412, April, 2004, Orlando, Florida.

5. R. Marino, et.al., “A Compact 3D Imaging Laser Radar System Using Geiger-Mode APD Arrays: System and Measurements”, Proceedings SPIE, Aerosense, Volume 5086, April, 2003, Orlando, Florida.

6. R.W. Cannata, et.al., “Obscuration measurements of tree canopy structure using a 3D imaging ladar system”, Proceedings SPIE, Defense & Security, Volume 5412, April, 2004, Orlando, Florida.

7. R. Lange, et.al., “Demodulation Pixels in CCD and CMOS Technologies for Time-of-Flight Ranging”, Proceedings of the SPIE, Volume 3965A, pp.177-188, San Jose, (2000).

8. T. Oggier, et al., “An all-solid-state optical range camera for 3D real-time imaging with sub-centimeter depth resolution (SwissRangerTM)”, Proceedings of the SPIE, Vol. 5249 No. 65, 2003.

9. U. Lages, “Laser Sensor Technologies for Preventive Safety Functions”, 12th International Symposium ATA EL 2004, June 2004, Parma, Italy.

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