SAND96-0906C
CONF-9604105--4

The Emerging Versatility of a Scannerless Range Imager

John Sackos, Bart Bradley, Bob Nellums, and Carl Diegert

Sandia National Laboratories,
Exploratory Systems Development and Parallel Science Computing Centers,
Albuquerque, New Mexico, 87185

ABSTRACT

Sandia National Laboratories is nearing the completion of the initial development of a unique type of range imaging sensor. This innovative imaging optical radar is based on an active flood-light scene illuminator and an image intensified CCD camera receiver. It is an all solid-state device (no moving parts) and offers significant size, performance, reliability, simplicity, and affordability advantages over other types of 3-D sensor technologies, including: scanned laser radar, stereo vision, and structured lighting. The sensor is based on low cost, commercially available hardware, and is very well suited for affordable application to a wide variety of military and commercial uses, including: munition guidance, target recognition, robotic vision, automated inspection, driver enhanced vision, collision avoidance, site security and monitoring, terrain mapping, and facility surveying. This paper reviews the sensor technology and its development for the advanced conventional munition guidance application, and discusses a few of the many other emerging applications for this new innovative sensor technology. **Key Words:** range imaging, laser radar, LADAR, remote sensing, metrology, 3D geometry sensing.

1.0 INTRODUCTION

Modern weapons must engage a growing array of targets, and must do so in ways that both reduce the risk to our service personnel, and minimize the risk of collateral damage to innocent civilians. The post "cold war" reduction of military force, along with the emergence of near instantaneous world-wide news coverage, have combined to significantly alter the warfare acceptance standards for regional conflicts. The ability to execute a precision surgical strike that accomplishes a political objective through a limited military engagement has become both a viable, and sometimes preferred option to today's world leaders. However, in order to achieve the high probability of target kill required for success in this type of 21st century warfare, "smarter" more "intelligent" weapons of the future will have to make much more accurate real-time target, guidance, and fuze decisions. This will require further improvements in precision weapon targeting capability, and require improved onboard sensors, target discrimination algorithms, and computational processing.

In terms of enabling a machine to accurately recognize and identify target objects in a remotely sensed scene, active optical imaging sensors provide significant advantages over competing radio frequency (RF), millimeter wave, passive infrared (IR), and passive video sensors. In general, sensors that operate at optical frequencies have inherently high resolution, and are particularly well suited for high fidelity, image-quality data collection. Development of robust target discrimination is also easier with range imagery from an active system. As compared to imagery from passive sensors such as Low Light Level Television (LLTV) and Forward Looking Infrared sensors (FLIR), active imagery is less affected by ambient conditions such as changes in solar illumination and background temperatures which can cause large changes in target-to-background contrast in passive sensors. Therefore, because of the environmentally invariant geometric signature of a target, active range-imaging sensors make automatic target recognition easier, and countermeasure more difficult. Compared with imaging radar, the target signature is also invariant to azimuth and elevation, allowing a single correlation template to be effective.

The need for some type of beam scanning is one of the principal problems with current **LA**ser **D**etection **A**nd **R**anging (LADAR) sensors systems. Current LADARs either use mechanical moving mirrors, acousto-optic cells, liquid crystal devices, or rely on some other form of natural body scanning that is derived from the motion of the sensor platform. As a result, these systems suffer frame rate, reliability, field-of-view, cost, and signal transmission penalties, and in some cases, require added signal processing complexity to compensate for these

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

scanner-dependent deficiencies. A scannerless system has potentially significant reliability, cost, and size advantages over LADAR systems that employ mechanical scanning techniques. Although some types of scannerless laser radar concepts have been built in the past, all required either multiple and/or gated receivers, and none provided very good range resolution due to gate bandwidth limitations. In order for scannerless pulse-gated LADAR systems to produce a single full frame of range data, they must collect many image frames, each with a different time delay between the transmitted pulse and acceptance gate of the receiver. In an attempt to develop a more capable alternative to conventionally scanned and scannerless pulse-gated laser radars, Sandia National Laboratories undertook the development of a novel scannerless range-imaging concept to demonstrate a sensor and signal processing capability that could both improve the lethality of DoD tactical weapon systems and be suitable for future integration into a DoD ordnance package. The resulting sensor (shown in Figure 1), is generically referred to as the Scannerless Range Imager (SRI). It is a compact, low cost, high resolution, high frame rate, scannerless, range-imaging optical radar, and has the following key attributes:

- It can use a variety of very inexpensive, high-power semiconductor diode laser arrays.
- It can use many forms of diode or flashlamp pumped crystal lasers, or even arrays of light emitting diodes.
- It can operate today at range image pixel rates in excess of two million pixels per second.
- It can produce very high pixel density imagery (65K pixels/image today, 16M pixels/image near term).
- It is of all solid state construction and contains no moving parts.
- It employs a differential processing scheme that minimizes the need for uniformity in either the light source or focal plane.

Figure 1: View of Scannerless Range Imager System at NASA's Lunar Landscape Simulator

Good potential for commercial dual-use of this technology exits, and Sandia's Scannerless Range Imaging (SRI) technology is now mature enough to be introduced through a Technology Transfer process into applications offering achievement of capabilities of importance to many government and commercial image based applications[1]. Possible civilian applications include collision avoidance, smart highway uses, robotic navigation, inspection, mapping, and surveying. In addition to these, there are likely to be many other additional applications where the speed, cost, and performance of this innovative geometry profiling imaging sensor has potentially significant advantages over other types of scene distance measuring devices. These unique sensor attributes, as well as a number of emerging applications for the Scannerless Range Imager are the discussion topics throughout this paper.

2.0 SYSTEM DESCRIPTION

The scannerless range imager technology is based on a concept that was originally invented at Sandia National Laboratories, and later patented by the Department of Energy in 1990[2]. This technology allows the formation of a range image over a large field of view (object plane) without the use of any type of beam steering or scanning subsystem. Sandia's Scannerless Range Imager (SRI) is a floodlight-illuminated, total field-of-view (staring) system that uses an intensity modulated light source transmitter along with an image-intensified charge coupled device (ICCD) video camera receiver. Depending on the desired operating range of the system, either a laser, or an array of eye-safe light emitting diodes (LEDs) may be used as the system transmitter (light illuminator/modulator). Continuous wave (cw), pulsed, and quasi-cw semiconductor lasers, as well as diode or flash lamp pumped crystal lasers are all suitable light source for use with the SRI technology. Both semiconductor lasers and LEDs are low in cost, and either are, or can be made eye safe through means of spatial distribution (a technique that is not practical for use with beam scanned LADAR systems), and/or spectral wavelength selection.

The SRI technology is based on classic continuous wave (cw) phase detection electromagnetic radar theory[3, 4, 5, 6]. Real-time numerical extraction of pixel range measurements from the amplitude modulated scene illumination, is made possible by predetection mixing of the return signal within an image intensifier, and subsequent extraction of the demodulated phase signal using a microprocessor based digital signal processor. Our initial laboratory implementation of the range imaging system consisted of a laser diode source, and an image-intensified analog camera receiver. The diode source and the image intensifier are synchronously modulated to produce both a sinusoidal variation in the scene illumination intensity and effective sensitivity of the camera based receiver. Because the two elements are modulated at the same frequency, a "mixing" occurs in the image intensifier which preserves the phase difference between the received laser light that is reflected back from objects in the viewed scene, and the modulated, image intensifier gain which acts as a type of injected local oscillator. The "mixing" and detection of phase occurs simultaneously for each pixel across the entire imaged scene. Because of this pre-detection mixing, the phase information can be collected and extracted using an integrating detection element such as the Charge Coupled Device (CCD). The signal processing in our system uses a minimum of two frames of target reflectance data taken with different modulation schemes. With the addition of some simple receiver image parallization, the SRI technology also offers the opportunity to capture a full-frame of range imagery with each collection of a frame of reflectance imagery. With this enhancement, the SRI concept would stand alone as the only range imager design that could allow an entire high resolution range image to be achieved with the exposure of a single image from a very inexpensive receiver.

Although operation into the X-ray and Radio Frequency spectrums are potentially feasible, the SRI technology can most easily operate within the ultraviolet, visible, or near-infrared regions of the electromagnetic spectrum. This region is defined by the bounds of available image intensifier photocathode device sensitivity and the availability of compatible light illuminators. As a result of the electromagnetic wavelength of operation, a Scannerless Range Imager has inherently high spatial resolution, and is particularly well suited for high fidelity, image-quality data collection. In addition to range imagery, an important feature or consequence of the SRI system is the automatic generation of pixel registered actively illuminated photographic imagery. This range imaging scheme also minimizes the need for stringent uniformity requirements on the illuminating light source, thereby further reducing transmitter cost, while at the same time improving system reliability.

In order to provide useful pixel throughput rates, conventional mechanical beam-steered optical range imagers typically require significant parallelism in their transmit and receive circuitry. This results in devices that are large, unreliable, complex, and expensive. By providing pixel range determination using the combination of an inexpensive focal panel array detector and signal processor (off-the-shelf devices found in commercial video cameras and home computers), Sandia's SRI system reduces cost, extends performance, and eliminates the reliability deficiencies of the more bulky conventionally scanned range imaging systems.

To date, Sandia has produced several versions of the same basic system which is designed around a commercially available digital video camera (the Dalsa CA-D1 camera). This camera is connected to a host personal computer through custom electronics that provide real-time control of the system and display of the collection reflectance and processed range images. The SRI system is operated through a graphical user software interface program that also serves to both control the SRI system and implement the various processing algorithms required to produce range images from collected reflectance images. Convenient data value interrogation, manipulation, and display of the reflectance and range images is achieved through a user friendly graphical interface and control software program. This operating environment software is referred to as the AMISRI software (Amiga Interface to Scannerless Range Imager). It is written in the C language and totals approximately 30,000 lines of source code. It provides a dual window display with pop-up push-button menus that respond to point-and-click mouse operations. The software also controls the storage, loading, and manipulation of all image data associated with the system and also includes embedded on-line documentation that allows easy access to many of the menu driven control features of the system.

From the onset of the engineering evaluation system development, the SRI instrument has been designed as a versatile stand-alone range imaging sensor suitable for both laboratory and field use. The architecture has been designed to enable the sensor to be easily reconfigured for tailoring to the requirements of a specific application, thus allowing a convenient means of rapidly and affordably evaluating the technology for any arbitrary range imaging application. A brief summary of the performance versatility of the instrument is as follows: The camera clock rate of the Dalsa CA-D1 camera is user programmable from 1 MHz to 33 MHz. Programmability is available in 1 MHz increments. This control results in the camera frame rate being adjustable from 7 to 231 frames per second, in 7 fps increments. The system architecture contains two custom arbitrary waveform generators (AWGs) that are used to produce independent analog drive signals for both the transmitter (light illuminator) and receiver (micro-channel plate) circuits. For each of these circuits, up to 16 eight bit sample values can be digitally programmed per waveform repetition cycle. The waveform repetition rate is also user programmable and can be varied from 1 to 90 MHz. Programmability of the waveform repetition rate is available in 1 MHz increments. As an example, the SRI system is typically operated at a waveform repetition rate of 66 MHz, and 12 sample values are used to generate a 5.5 MHz sinusoidal drive signal. Custom analog filtering is also used within a circuit to further enhance the quality of these synthesized drive signals. The light output level of the transmitter is controlled by the transmitter control voltage. This voltage is a periodic amplitude modulated voltage that combines with a separately controlled DC voltage. Our current SRI system architecture also contains user programmable digital controls for all aspects of the transmitter control voltage including: (1) DC bias offset level, (2) amplitude, and (3) modulation frequency. The micro channel plate DC bias offset level control is digitally programmable from 0 to 1000 Volts, in 4 Volt increments. Both the amplitude and frequency of the micro channel plate bias voltage are also user programmable. The hardware implementation for these parameters is provided by the AWG circuitry previously discussed above. The amplitude of the periodic waveform generated by the AWGs is digitally programmable from 0 to approximately 100 Volts peak-to-peak. Programmability is available in 256 discrete increments across the full scale span. Both the frequency and the phase relationship between the transmit and receive signals are also user programmable. As discussed above, the current system is capable of generating arbitrary waveforms from 1 to 90 MHz. The definition of waveforms suitable for use in the SRI system typically require several sample values for periodic wave shape definition, and therefore the useable bandwidth of the signal generator is limited to something approaching 20 MHz. The ability to accurately control the phase relationship between the transmit and receive signals is also achieved through the use of the sample value point definition, making the number of available relative phase adjustments between the transmit and receive drive signals directly related to the number of sample values employed in the generation of a particular synthesized drive signal. This functionality is particularly important in the sensor calibration phase of operation.

Common commercially available photographic camera lenses are routinely used with the system receiver. These lenses typically fill the image plane of the receiver to a standard 35 mm film format. As result, the 17 mm format of the image intensifier is overfilled, and the resultant picture angle, or the full-angle sensor field-of-view (FOV), is reduced by a factor of two as compared to the FOV in a photographic camera. In addition to serving as a convenient means for collecting the reflected light and focusing the image scene onto the active area of the image intensifier, the mechanical lens aperture adjustment also serves as one of the principal means for controlling the received light level to within the dynamic range acceptable for use by the SRI system. Additional light level control is also available through the transmitter illumination control, the gate control of the image intensifier's photocathode, and the micro channel plate bias voltage setting.

Up until March of 1996, the system was limited to a range image update rate of approximately one frame-per-second (256 x 256 pixel format), yielding a range image pixel rate of 65K pixels per second. The initial system architecture relied on the transfer of collected reflectance imagery from the camera to the computer for processing into range imagery via the parallel port of the computer (a data transfer rate that was limited to approximately 40 kilobytes per second). Today, the system has an embedded data collection and processing capability provided entirely within the camera by a custom circuit card containing a single Texas Instruments TM320C40 digital signal processor (DSP). The integration of the range processor into the camera has eliminated the parallel port data transfer bottleneck, and thereby transformed the camera size instrument into a very impressive video rate range imager capable of producing one to three inch type range resolution. With the affordable ($200) processing functionality of the TI-C40 DSP circuit card, the SRI system is capable of producing range images at a rate that can exceed 30 Hz (again, a 256 x 256 pixel format), yielding a range image pixel rate approaching 2M pixels per second. This allows scenes to be "frozen", and thereby greatly minimizing blur, by limiting the effects of temporal changes on background illumination and target albedo.

3.0 THE MUNITION TECHNOLOGY DEVELOPMENT PROJECT

The goals of the Munition Technology Development Project included the development of hardware, software, and analytical models to support both field demonstration of the SRI technology, and predict system performance for specific sensor and environmental configurations. Technical work on the project began in the 2nd quarter of FY92. Soon thereafter, a proof of concept demonstration was successfully accomplished using a crude laboratory system. In FY93, Sandia began to transition the laboratory prototype hardware into a fieldable, near real-time system. This included the integration of a higher performance digital CCD video camera and a faster personal computer for the control and display of collected range data. Throughout this period, our analytical system modeling capabilities continued to be expand and enhanced. Sensor performance models were developed to predict system operating performance for various parameters

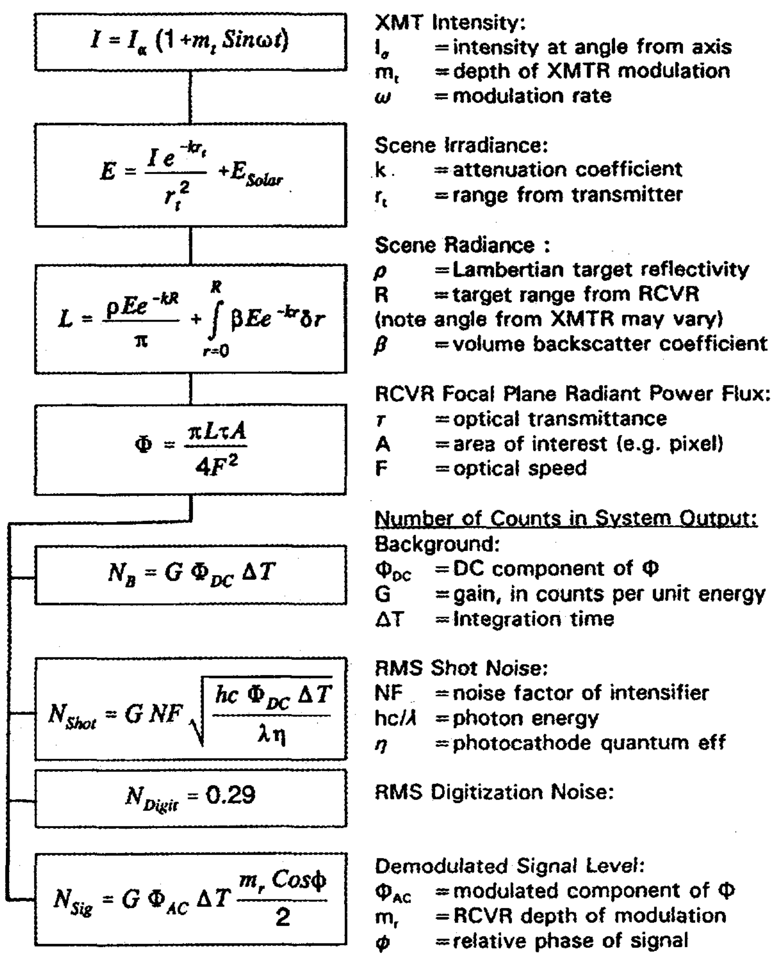

Figure 2: System Performance Model

such as receiver aperture, field of view, target characteristics, atmospheric conditions, source power, and beam illumination confinement. A summary of the equations, and variable parameters used within this analysis is shown in Figure 2.

The development of set of image processing tools to view and manipulate our experimental data was also undertaken. These tools have subsequently proven to be quite valuable in helping to understand the various subtleties of the system technology. In FY93, the design and assembly of a SRI system that was free from the electrical noise problems experienced with the earlier hardware architecture, and laboratory characterizations of the system receiver and many of its individual system subcomponents were completed. Within FY94, significant additional improvements were made on the system, in particular, the camera control and waveform generation circuitry was implemented in two custom printed circuit cards, and a non-optimized, laboratory prototype high-power laser transmitter was made fully operational.

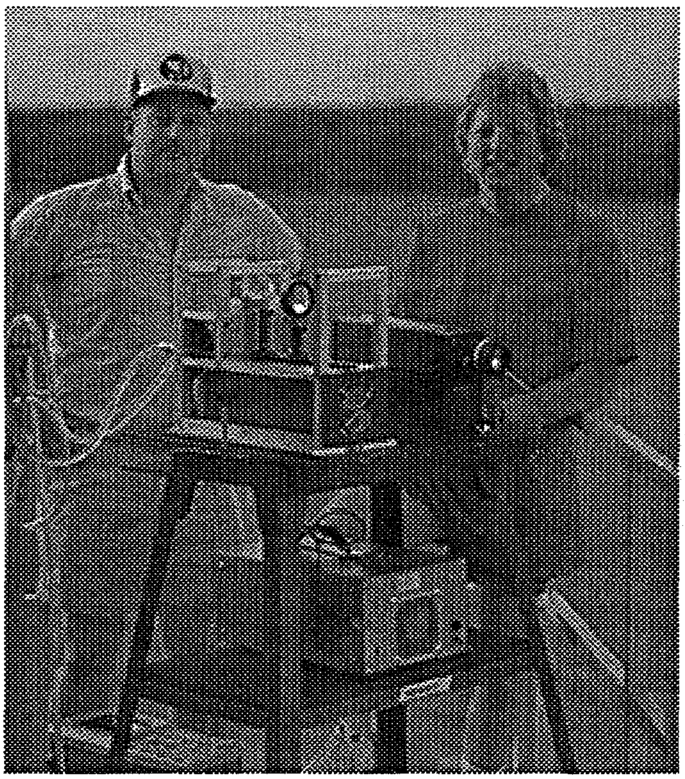

Figure 3: Experimental Configuration During Field Testing at USAF Wright Laboratory's Laser Radar Test Facility, Eglin AFB, Florida

With suitable hardware in hand, field system testing began in FY94 at both Sandia National Laboratories in Albuquerque, New Mexico, and in cooperation with USAF Wright Laboratories at Eglin Air Force Base, Florida. The Eglin field testing was conducted between June 8 and June 12, 1994, and data was collect at night from a 42 foot field observation tower. The testing was conducted with a laser transmitter that consisted of a DC power supply, a radio frequency (RF) power amplifier, custom transformer coupling electronics, a Spectra Diode Laboratory 3460S 20 Watt cw GaAlAs linear array laser diode, a recirculating water chiller, and a simple two element lens configuration. Figure 3 is a picture of the actual experimental setup located on the top of the field observation tower. The laser transmitter produced about 8 Watts of average output power, and was satisfactory to image tactical mobile and fixed type targets at night out to ranges approaching one kilometer.

Two M60 tanks were used as tactical mobile targets, and several buildings and nearby observation towers were used as representative fixed type targets. A 500mm f/8 fixed focal length reflex camera lens was typically used on the receiver. The video data format was 256 horizontal pixels by 256 vertical pixels, and the reflectance frame exposure interval was about 33 milliseconds. Range images were typically produced the next day through off-line processing of the collected reflectance data using the same 25 MHz MC68040 CPU that controlled the portable personal computer which served as the principal user interface to the SRI system. The imagery was commonly viewed using pseudo-colored iso-range contours to enhance the data visualization and allow easy interpretation of the quality of the range data. In August of 1994, additional SRI image data was collected on mobile military type targets at Sandia National Laboratories. Replica Scud-B and SS-21 missile launchers, along with a few underground explosive storage bunkers, were used as test targets. The data on these targets was taken at night from a 40 foot mobile maintenance platform, and the range from the SRI sensor to the targets was approximately a few hundred meters. A photograph and some representative raw reflectance and range data images are shown in Figures 4.

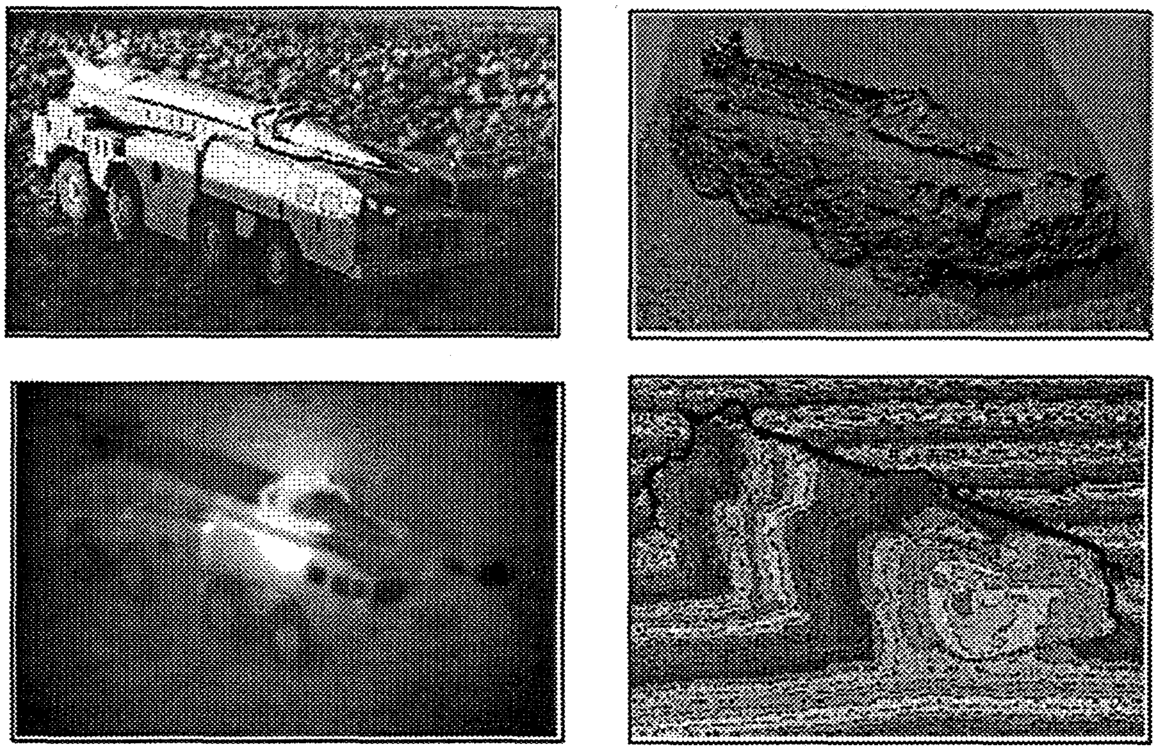

Figure 4: Representative Range and Reflectance Imagery from the Scannerless Range Imager taken at Sandia National Laboratories' Outdoor Laser Radar Test Facility, Albuquerque, New Mexico

Although high-power laser diodes are available from a number of commercial vendors, there are no commercially available drive circuits capable of driving these diodes at the high frequencies (typically 5 MHz and greater) needed for the ranging purposes of the SRI system. Laser diodes in the 20 Watt regime require 2 to 4 VDC. Threshold currents range from 3 to 12 Amps, with peak currents ranging from 12 to 36 Amps. While there are commercially available RF power amplifiers capable of driving currents at these frequencies, they are typically designed for 50Ω loads, not the 0.3Ω load presented by the laser diode. In order to meet the field testing needs and general time lines needed for the SRI system development, a near-term (non-optimized) transmitter was initially developed that took advantage of the minimum risk associated with transformer coupled technology. The non-optimized transmitter approach (previously shown in Figure 3) relied on a custom-built RF transformer. This technology served to match the output of the RF amplifier to the load of the diode, and couple the AC current to the DC current required to bias the laser diode to a point just above its output emission threshold. Although bulky, this transmitter performed very well throughout all phases of the FY94 field testing. Late in FY94, work was also begun on a longer-term (more optimized) transmitter that used high-power MOSFET transistor technology. The latter approach was intended to result in a very light-weight, power efficient transmitter, suitable for actual future weapon system use. A photograph of the initial version of this optimized laser transmitter is shown in Figure 5. It contained a 20 Watt SDL 3470 GaAlAs diode laser, a power MOSFET driver circuit, a low voltage power supply, and a recirculating thermal management system.

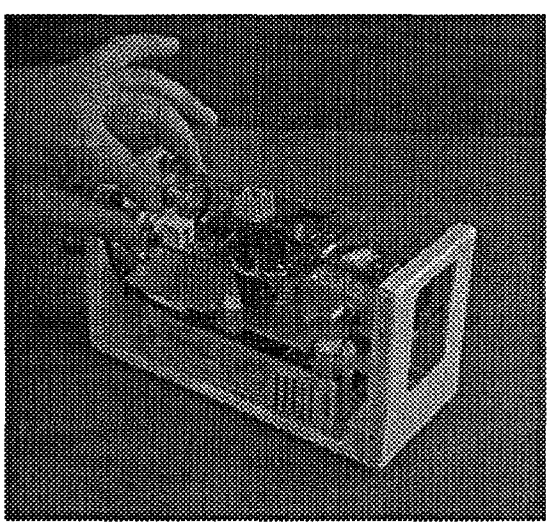

Figure 5: Miniature 20 Watt Laser Transmitter

Sandia's research is closely coordinated with other DoD service laboratory laser radar research efforts. Joint activities have been, and will continue to be initiated where appropriate, and coordination with Army, Navy and Air Force technology base managers is being conducted to ensure that duplication of work does not occur. Sandia has been proactive in seeking DoD concurrence on the topics for inclusion under this project, and Sandia will continue to monitor DoD activity to ensure that work supported by this project complements the DoD efforts and supports DoD requirements.

3.1 THE UNDERWATER APPLICATION

In FY94, the application scope for the Scannerless Ranger Imager development project was expanded to investigate the ability of this sensor to meet the operational needs of a U.S. Special Forces diver. Under this effort, we began to investigate the utility of the SRI system for underwater short range (< 20 feet), high spatial and range resolution (centimeter type accuracy). To be useful in identifying partially buried, and moored mines in shallow water or very shallow water environments, a sensor must be either hand portable or small enough to be integrated onto an underwater manned or unmanned vehicle. It must deliver high quality images in turbid coastal water, be compatible with the size and power constraints imposed by the intended deployment platform, provide day/night operation, and be able to operate in a manner that minimizes the risk of its use being detected by hostile observers on the surface.

Environmental noise sources are the principal factors that limit the performance of underwater optical imaging systems. For underwater imaging sensors, these environmental limitations include: backscatter noise, blur/glow/forward scatter noise, and attenuation. Scattering causes loss of image resolution and contrast, while attenuation refers to the loss of photon signal due to photon absorption or scattering out of the field of view of the receiver, and results in diminished signal strength at the receiver. In the course of developing underwater mine detection systems, spot systems were initially used by the various system developers, on the basis that the narrow beam could penetrate to deeper depths. However, as the evolution and maturity of laser based transmitters improve, the emphasis on mine detection systems has slowly been shifting from the spot, or narrow beam approach, to the wide area approach.

In order to address the significant backscatter problem present in turbid water environments, various hardware configurations, operating modes, and processing schemes that would optimize a floodlight system in this challenging environment needed to be investigated. Other, much larger and more mature, underwater imaging sensor projects[7, 8] have investigated laser-based imaging approaches capable of reducing the impact of environmental noise sources in order to facilitate rapid identification of mines in turbid waters at useful ranges. Two approaches in particular, the Laser Line Scan (LLS) system and the Laser Range-Gated (LRG) system, have been evaluated in detail with the objective of extending the mine identification range to five or more beam attenuation lengths. The LLS systems reduce the effects of backscatter noise and blur/glow/forward scatter noise by synchronously scanning a narrow laser beam and a narrow field-of-view across the sea bottom, while the LRG imaging system reduces the impact of backscatter by temporarily "gating-out" a portion of the backscatter. Hardware wise, the LRG system is essentially identical to that of the Sandia's Scannerless Range Imager system. Both are active light illuminated image intensified camera based systems. The LRG system employs a gated (approximately 8 nsec gate width), intensified CCD camera which generates images at standard video rates. F/.85 receiver optics with a 29.4 mm aperture are employed which gives the system an instantaneous field-of-view of 20 by 15 degrees. Laser illumination is provided by a 30 Hz, Q-switched, frequency doubled Nd:YAG laser operating at 532 nm with output power of approximately 100 mJ per 6 ns pulse.

Zoom-optics allow the output energy to be either distributed over the receiver field-of-view or concentrated near the center of the image, and gating range, camera gain, and laser zoom are all controllable from an operator console. Both approaches have demonstrated superior performance relative to conventional video imaging systems. In a head-to-head performance comparison conducted by the Navy of the LLS and LRG underwater imaging technologies, an unambiguous appraisal of their relative merits for the mine identification mission in turbid, littoral waters was conducted. Accordingly to the conclusions from the testing, the LRG system demonstrated: (a) successful detection (but not identification) of high contrast targets at relatively long range, (b) insensitivity to ambient light, and (c) insensitivity to platform motion. However, it had extreme difficulty identifying or even detecting low contrast targets even at relatively short ranges. It was found that the contrast and resolution required for the mine identification mission was severely limited by blur/glow/forward scatter noise.

Sandia was very encouraged by the favorable performance results achieved by the LRG system, and believes that further image understanding (object recognition) is possible with the simple addition of the type of range imaging capability offered by the SRI technology. Figure 6 illustrates some SRI data and synthetic imagery collected on a mock MAS-22 underwater sea mine in air, and illustrates the type of geometric data that could be generated for the underwater mine identification application. In order to exploit the full potential of a range imaging sensor, the output range data needs to be screened or interpreted to make use of the meaningful range information. In an underwater application, the images will also undoubtedly be somewhat distorted due to the scattering of light in a turbid water environment. These images may therefore require some enhancements before a human viewer or autonomous navigation system could accurately interpret a viewed scene. Laser Radar based Autonomous or Automatic Target Recognition (ATR) algorithms have been developed for other applications and are now being evaluated for use with SRI sensor data. In conducting this effort, Sandia is trying to draw upon the extensive LADAR based ATR experience that already exists within the service laboratories[9]. The USAF's Wright Laboratory has already demonstrated that 3D model based histogram matching can be used to accurately identify targets of interest. Sandia has also developed an expertise in the study of combined 3-D Synthetic Aperture Radar (SAR) and LADAR image correlation[10]. We are now working to combine these expertise, and apply them to the

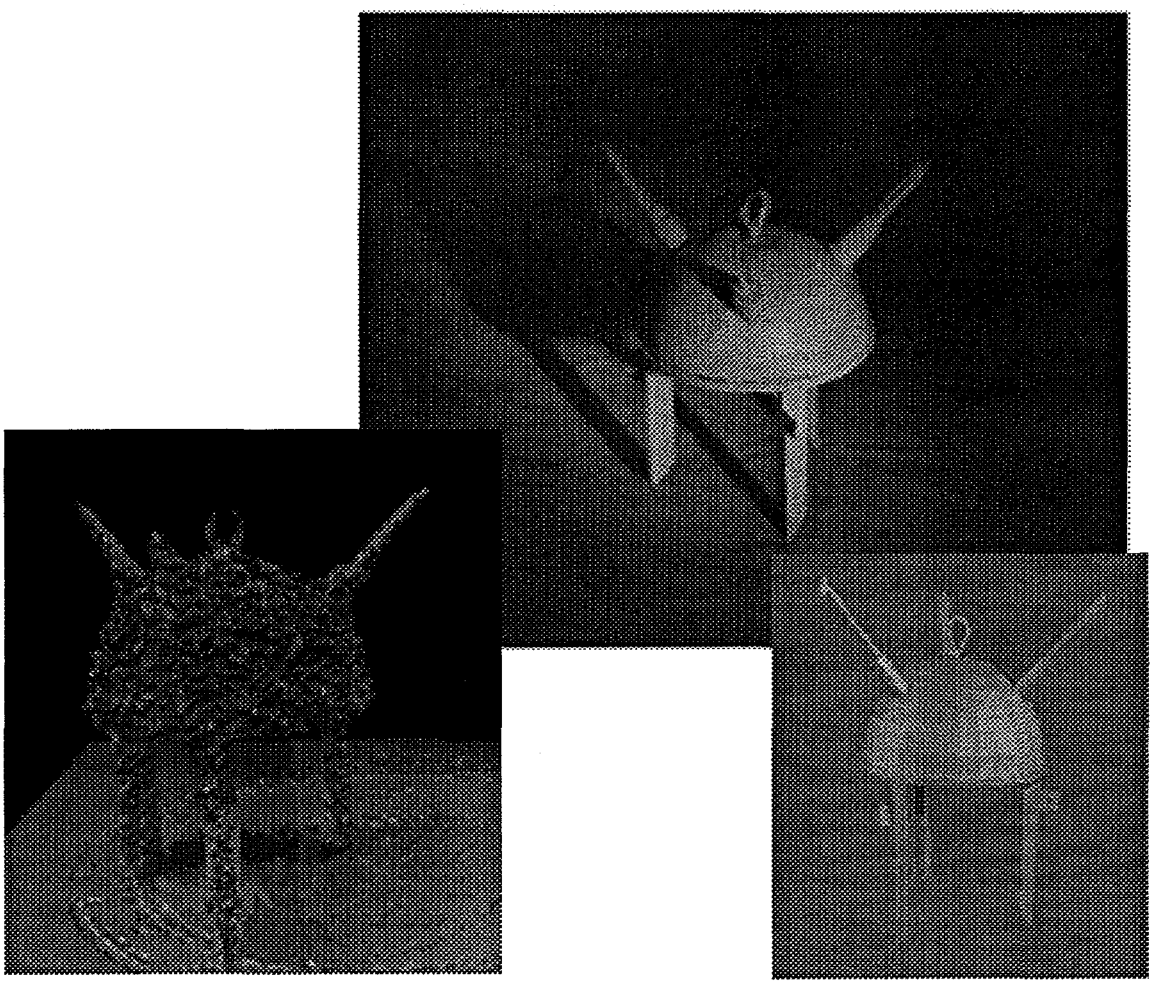

Figure 6: MAS-22 Underwater Seamine, (clockwise from top) Photograph During SRI Data Collection, Synthetic Model of Target Mine, and Actual Rendered Image of Raw SRI Data

underwater mine identification problem. Our near term project goals are to: (1) begin the experimental evaluation of the underwater version of the SRI system, including the collection of field test data on a few types of shallow water mines, (2) finish developing a predictive underwater analytical system model for the SRI sensor, validate it with an experiential data, and use the model to predict system performance in a variety of underwater environments, and (3) operate on the collected underwater range image data with an appropriate ATR algorithm to demonstrate the potential target identification performance capability enhancement offered by the SRI sensor and ATR processing system.

The underwater application emphasizes ranges out to 20 feet in turbid water. Resolution, contrast, and the ability to penetrate turbidity are priority project goals. To date, we have conducted simulations of system performance in the presence of turbidity, and assuming the transmitter and receiver can be operationally separated by a bi-static distance of one to two feet, we believe that range measurements from an SRI system could be reliably made out to 3 attenuation lengths, or about 20 feet. If necessary, further improvements in turbid water may be feasible by tailoring the waveshape of the transmitted signal and by optimizing the individual pointing directions of each of the multiple transmitter beams from the array of light emitting diodes (LEDs).

4.0 OTHER EMERGING APPLICATIONS

There is a great deal of interest in three-dimensional imaging for a variety of military and commercial uses. In these applications cost, size, reliability, and simplicity are the predominate factors that appear to have inhibited broad commercial use of range imaging sensors. Depending on performance, typical scanned laser radars that provide substantial standoff distances cost today between $50,000 and $500,000. Today, the single unit hardware cost for a basic SRI receiver is less than $15,000. Quantity commercial production would also likely reduce this cost even more. Most all of the 3D sensing techniques currently in commercial use today employ some form of triangulation to develop the third dimension, depth or range, and typically do so by only sensing a two-dimensional representation of a scene. This concept of course is well known as "stereo imaging", and is usually achieved by using two cameras separated by some distance so as to view the scene from different angles. An alternative approach to this triangulation method can be achieved by replacing one of the cameras in the stereo configuration with a structural light source, so that triangulation can be achieved between the light source, the camera and each individual pixel in the scene. While 3-D imaging with two separated cameras is perhaps the easiest to understand conceptually because it essentially mimics human vision, in a practical system it can be difficult to implement. In particular, in order to measure the displacement of features in the scenes as seen by the two cameras, it is necessary to identify and match each of the features. As scenes become more complex, the computational burden become very great. In addition, the viewing geometry, that is the position of the two cameras, the stability of the ambient light level, the spatial distribution of target reflectivity, and the aberrations in the optical system of each camera have a large impact on the performance of a structured light system. Because there is only one camera in a structured light system, there is less data to be processed as compared to a stereo system. The algorithms required to process the data are also simpler, and therefore structured light is sometimes seen as having an advantages over stereo viewing systems. The obvious disadvantages of course are the need for an active illuminator that can be accurately scanned across the scene, the need for the many line images that must be collected and processed in order to build up a single 3-D image of a viewed scene, and the need for frequent equipment registration and calibration maintenance.

A "magic camera" device that can provide high speed 3-D imaging has many applications in a wide variety of fields. In the field of industrial applications (those requiring high range resolution), the metrology of machine tools which follow preprogrammed machining operations such as milling or drilling could be remotely monitored using these concepts. In other robotic operations, such as for circuit board chip placement, the orientation of piece parts, such as chip insertion pins, could also be monitored for correct orientation prior to device placement onto a receiving assembly. In-line processing and assembly could be monitored for defects. In the pursuit of applying SRI technology to these types of industrial automated quality control, inspection, and manufacturing machine vision applications, Sandia has investigated high frequency (up to 150 MHz) operation of a laboratory type scannerless range imaging setup, and have thus far successfully demonstrated millimeter type range resolution on some simple target geometry's[11]

Even with the few inch type range resolution produced by Sandia's portable SRI system, many large scale industrial assembly applications could derive some immediate benefit. Examples of such applications include ship and submarine building, where the placement of large mechanical items must be accurately located on rather large metal decks before they are welded in place. Other potential near term application examples include the monitoring of interiors of chambers, such as wells, mine shafts, and potentially dangerous excavations for dimensional accuracy, or blockage. Such a sensor would be particularly suitable for those environments that posed a particular risk to humans, such as in underground mining applications, and explosive ordinance or hazardous waste disposal applications.

In the field of transportation, a fast range imaging camera could be mounted on the front of a mass transit vehicle, such as a train, to monitor the down range track condition. Hazardous obstacles in the path of trains account for many of the most serious accidents encountered by these vehicles. Although it would likely be rather ineffective in short time line gate crossing hazard situations, it may nonetheless be very effective in other obstacle sensing situations, such as at train track switching locations. With such an onboard intelligent collision avoidance sensor, many accidents could be prevented. Use of the sensor for collision avoidance could also apply to helicopters, planes, and automobiles. The low flying helicopter obstacle avoidance application is an area of ongoing laser radar sensor development being pursued by a number of commercial and government organizations. Although plausible, the application of this technology to aircraft and personal automobiles is far less likely, primarily due to the current sensor cost benefit constraints. However, in the case of larger vehicles, such as busses and mining vehicles, the cost benefit comparison is far more attractive. In addition to possible collision avoidance applications, other transportation uses could involve "smart highway system use" where sensors are planned to be employed to classify vehicles for toll charge determination and/or toll charge compliance monitoring.

Other industrial partners are also working with Sandia to investigate the potential for the development of a Scannerless Range Imager for use as a general purpose scene documentation sensor. The realization of a low cost, handheld range imaging device for use by accident investigators would help to both improve the accuracy of accident or crash scene documentation, and automate the process making it much more time and manpower efficient. This same type of handheld range imaging sensor capability, although potentially different in terms of maximum operating range requirement, is also being investigated by Sandia for use in military forward reconnaissance applications.

In unmanned space exploration operations, SRI sensor technology could help to more effectively conduct planetary landscape exploration. For this application, the sensor could aid in helping to safely land the exploration vehicle onto the surface of the planet, serve as an obstacle detection and avoidance sensor for the mobile vehicle while traveling to explore the surface, and finally it could serve as a geological scene documentation sensor by topography mapping the viewed exploration path of the vehicle. For this application, the sensor reliability, size, power consumption, and dynamic constraints would effectively prohibit the use of any form of mechanically scanned LADAR system. In support of this application, Sandia has been working with researchers from the NASA-Ames Research Center, and in March of 1996 delivered a fully operational SRI system to NASA to support their ongoing research with range imaging sensors for unmanned planetary exploration. For other space applications, an SRI sensor could also be used to monitor and control maneuvers required for the Space Shuttle to dock with an orbiting space station, or alternatively control the robotic manipulators that may be used to help maintain the integrity of deployed space structures.

Similar to the autonomous vehicle application extending utility described above, Sandia is also beginning a cooperative effort with the Amy's Night Vision and Electro-Optics Sensors Directorate to integrate a SRI evaluation system in one of their small mobile tele-operated vehicles. The purpose of the range imaging sensor on the vehicle is to improve the obstacle detection and assessment capability of the tele-operated vehicle, allowing it greater mobility with increased safety.

The field of environmental uses is another rich area for application of this type of innovative sensor. Potential applications range from 3-D terrain mapping for use in inspecting hazardous underground storage tanks or pipes, to the sensing of agricultural target objects for optimizing the spray application of pesticides. Although the development of innovative sensors for conducting underground hazardous waste storage tank metrology is an area of ongoing DOE research, Sandia's SRI sensor is not currently included in any of these efforts. However, we do believe that this particular application would be one of the best matches for the SRI technology, particularly in its ability to be configured into a system that could easily fit within the small diameter confines of an underground tank access portal. For a similar restricted access application, we are however currently investigating the use of a SRI sensor to monitor the thickness of refractory material used to line the interior of a basic oxygen furnace used in the steel making process. We are also exploring other unique areas in the steel manufacturing process where range imaging the raw material burden could significantly improve the manufacturing process.

Under project sponsorship from the Department of Energy - Office of Safeguards and Securities, Sandia has been also working on a scannerless laser radar sensor prototype for use in the protection of high value assets, such as nuclear materials or weapon storage or manufacturing facilities. This technology is being actively developed for use in extending the detection and assessment capability of conventional video motion based intrusion detection systems.

In addition to being a potentially good solution for the difficult underwater mine ID problem, the successful achievement of a useful underwater handheld range imager would have significant utility in many others areas involved with some form of object or scene documentation, classification, identification, and/or recognition. Obvious areas of application would include search and rescue operations, off-shore oil and gas platform or pipeline monitoring and maintenance, underwater salvage operations, underwater bathemetry, submerged shoreline or breakwall monitoring, and it may ever have inspection use in such applications as municipal water system line monitoring.

Another potentially exciting application for SRI technology is in the area of Unmanned Aerial Vehicles (UAVs). UAVs are fearless, and don't require the creature comforts that pilots need (space, extra cool air, pressurization, and oxygen). They weigh less, cost less, and can pull many more Gs than manned air vehicles and offer an opportunity to out-maneuver current missile threats. Of particular importance in this era of volatile public acceptance for warfare, dead UAVs do not invoke the national sympathy that downed pilots generate. Launching and landing weapon capable UAVs routinely in an operational environment has not been done. Unlike current fighter planes that, with the aid of inflight refueling, can haul bombs very long distances for raids such as those on Libya launched from England, UAVs lack a demonstrated aerial refueling capability which limits their useful range. UAVs also lack human on board decisionmaking to limit mistakes or collateral damage in making the final decision to release the weapon. With these issues in mind, the ideal UAV would be capable of launching and landing form current runways with limited assistance and with no modifications to the airfield. The ideal UAV would be capable of aerial refueling using existing assets (current tankers). The ideal UAV would provide autonomous target identification and discrimination similar or superior to humans in combat. By being able to see and avoid power lines and towers, the ideal UAV would be able to fly low through ground based obstacles. Finally, the ideal UAV would be able to do all of this and still sustain very high G levels.

The SRI sensor offers the potential for a UAV to achieve all of these desirable attributes. The 3D range image provides both depth perception and angular information with a single camera as well as critical target identification data. More exactly, it can serve to keep the UAV on the taxiway and runway for launch. It can be used to maneuver the UAV in close proximity to the tanker for aerial refueling. It can be used for low level obstacle avoidance with the capability to see power lines. In the target area it can serve as an additional sensor for target identification and fire control. It is assumed that other sensors like GPS, FLIR, and SAR will be used together with the SRI to achieve the high confidence necessary to allow an unmanned vehicle to deliver weapons autonomously. Finally, it could aid in the landing and taxi back. With its range and reflectance images the SRI is a potentially perfect replacement for human binocular vision, a critical sensor required to build a UAV with operational utility very similar to current manned fighter operations. Unlike current scanning LADAR systems, the SRI has no moving parts, and thus has the opportunity to operate in high G environments.

Within various image understanding research communities, there exists substantial advocacy for both laser radar (ladar) and its associated image analysis techniques. However, it appears that these technologies have only been developing at rather modest rates, and are only now beginning to be introduced into important military and commercial applications. This slow rate of development is particularly perplexing, since the vast majority of image understanding experts have long realized that ladar imagery provides one of the most convenient and accurate means of interpreting observed scenes. One can only speculate that the shortcomings have resulted from limited access to ladar systems and data. The low cost, high resolution, and ease of operation of the SRI sensor could immediately enhance ongoing and emerging work in many research areas currently involved with any form of 3-D object description from multiple range images. With the SRI technology, it is now practical to put a ladar system in the hands of individual ladar based image understanding researchers.

Finally, under sponsorship from Sandia's Laboratory Directed Research and Development (LDRD) program, a multi year effort was initiated in FY96, and is entitled "Automated Geometric Model Building Using Scannerless Range Image Data". This effort is specifically intended to reduce the substantial quantity of multi-perspective range imagery collected from the SRI sensor, into usable geometric models of the viewed object which would be compatible with virtual reality and/or Computer Aided Design (CAD) software.

5.0 FUTURE DIRECTION

Sandia's Scannerless Range Imager sensor development efforts have been principally focused on applying this technology to military munition guidance and fuzing applications. As such, we have successfully achieved state of the art ladar performance in many areas, most notably in range resolution, image acquisition rate, and image pixel density. We have already demonstrated better than one foot range resolution out to target distances approaching one kilometer, using an inexpensive, 8-bit, image intensified video camera system. Under the Munition Technology Development Program, the maturity of this innovative range imaging sensor technology has been developed to a point where it can now be logically and affordably taken in a number of different directions, each offering a unique range imaging sensor capability for enhanced remote sensing image understanding. These potential sensor innovations include:

(1) generation of pixel registered range and multi-color (multi-spectral) video imagery,

(2) the acquisition of very high range resolution imagery (millimeter type range accuracy).

(3) generation of image frame pixel densities in excess of 2K x 2K,

(4) snap-shot (freeze-frame) range image capture,

(5) laser based eye-safe operation in the 1.5 μm wavelength region[12], and

(6) generation of range imagery using alternative focal plane detector arrays, such as a semiconductor (CMOS) active pixel sensor[13].

We have well developed and practical engineering approaches to achieve these possible sensor improvement development objectives, and are actively seeking opportunities to pursue these challenging engineering efforts. The range imaging sensor capability enhancements described above would have immediate applicability to many ongoing and emerging efforts of national commercial and military importance, and would have particular application to those areas where fast, dense, pixel registered single or multi-spectral video and ladar imagery in eye-safe and/or "out-of-band" detection regions of the electromagnetic spectrum was required.

6.0 ACKNOWLEDGMENTS

Special thanks to Maritza Muguira for her significant contributions to the advancement of the Scannerless Range Imager technology, and to Randy Williams and Linda Doren for their respective contributions. Thanks also to the Department of Defense - Office of Munitions, for providing the project support that served to transform this innovative scannerless range imaging sensor concept into a versatile, proven, and usable field evaluation sensor.

We would also like to thank both the past and present members of our Army, Air Force, and Navy tri-service oversight group, who have provided valuable comments and recommendations regarding the development direction for this new sensor technology.

7.0 REFERENCES

1. Sandia National Laboratories, *Technology Transfer Opportunity - Scannerless Range Imaging System*, Commerce Business Daily, September 30, 1994.

2. M. W. Scott, *Range Imaging Laser Radar*, U.S. Patent 4,935,616, June 19, 1990.

3. J. P. Anthes, P. Garcia, et al., *Non-scanned LADAR Imaging and Applications*, Applied Laser Radar Technology, Proceedings of SPIE, Vol 1936, 1993.

4. P. Garcia, J. P. Anthes, et al., *Characterization of a Scannerless LADAR System*, Applied Laser Radar Technology, Proceedings of SPIE, Vol 1936, 1993.

5. M. M. Lecavalier, et al., *Scannerless Range Imaging with a Square Wave*, Guidance and Navigation - Applied Laser Radar Technology II, Proceedings of SPIE, 1995.

6. Ken Frazier, *Innovative Range Imager Sees How Targets Measure Up*, Sandia Laboratory News, Vol. 46, No. 19, September 16, 1994.

7. M. L. DeLong, T. J. Kulp, *Underwater Laser Imaging System (UWLIS)*, Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium, p 6-103, April, 1995.

8. M.P. Stand, *Underwater Eectro-Optical System for Mine Identification*, Proceedings of the Autonomous Vehicles in Mine Countermeasures Symposium, p 6-238, April, 1995.

9. USAF Wright Laboratories - Eglin AFB, Florida, *LRTAG ATA Algorithm Suite*, 1996.

10. D. H. Cress and M. M. Lecavalier, *Fusion of LADAR with SAR for Precision Strike*, Proceedings from the Eighth National Symposium on Sensor Fusion, 1995.

11. R. Schmitt, T. Fischer, Laser Radar Technology for High-Performance, *Cost-Effective, 3-D Imaging in Industrial Applications*, Sandia Cooperative Research and Development Agreement (CRADA) with Perceptron, Inc. - SC94/01340S, 1994.

12. K.A. Costello, V.W. Aebi, G.A. Davis, R. La Rue, and R.E. Weiss, *Transferred Electron Photocahode with Greater than 20% Quantum Efficiency Beyond 1 micron*, SPIE Proceedings Vol. 2550, (1995).

13. E. R. Fossum, *Low Power Camera-on-a-Chip Using CMOS Active pixel Sensor Technology*, 1995 Symposium on Low Power Electronics, Oct. 9-10, 1995.

DISCLAIMER