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Scannerless Terrain Mapper

John Sackos, Bart Bradley, and Carl Diegert

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

Paul Ma, and Charles Gary

Photonics Group
NASA-Ames Research Center
Moffett Field, CA 94035

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ABSTRACT

NASA-Ames Research Center, in collaboration with Sandia National Laboratories, is developing a Scannerless Terrain Mapper (STM) for autonomous vehicle guidance through the use of virtual reality. The STM sensor is based on an innovative imaging optical radar technology that is being developed by Sandia National Laboratories. The sensor uses active flood-light scene illumination and an image intensified CCD camera receiver to rapidly produce and record very high quality range imagery of observed scenes. The STM is an all solid-state device (containing no moving parts) and offers significant size, performance, reliability, simplicity, and affordability advantages over other types of 3-D sensor technologies, such as 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, and facility surveying. This paper reviews the sensor technology, discusses NASA's terrain mapping applications, and presents results from the initial testing of the sensor at NASA's planetary landscape simulator. **Key Words:** range imaging, laser radar, LADAR, remote sensing, terrain mapping, topography, metrology, 3D geometry sensing.

1.0 INTRODUCTION

In terms of enabling a machine to accurately recognize and document the spatial extent of objects in a remotely sensed scene, active optical imaging sensors provide significant advantages over competing radio frequency (RF), millimeter wave, passive infrared (IR), and video sensors. In general, imaging sensors that operate at optical frequencies have inherently high resolution, and are particularly well suited for high fidelity, image-quality data collection. 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. The environmentally invariant geometric signature of objects in an observed scene is the key factor that an active range-imaging sensor is particularly well suited to exploit, and with the availability of high quality range imagery, the task of developing robust target discrimination, obstacle avoidance, and autonomous vehicle mobility algorithms is greatly simplified.

The need for some type of beam scanning is one of the principal problems with current LAser Detection And Ranging (LADAR) sensors systems. Current LADAR systems 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 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

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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 first collect many individual image frames, each with a different time delay between the transmitted pulse and acceptance gate of the receiver, and then combine these multiple frames through a potentially computationally intensive post-processing step. In an attempt to develop a more capable alternative to conventionally scanned and scannerless pulse-gated laser radar systems, Sandia National Laboratories undertook the development of a novel scannerless range-imaging concept[1]. The work was initially focused at developing and demonstrating an autonomous guidance sensor for improving the lethality of future DoD tactical weapon systems. The resulting engineering evaluation sensor (shown in Figure 1 while operating at NASA's the Planetary Landscape Simulation Facility), 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 that has the following key attributes:

- It can use a variety of very inexpensive, high-power light sources including such devices as:
    - semiconductor diode laser arrays,
    - diode or flashlamp pumped crystal lasers,
    - and 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 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.

Some representative SRI imagery of a military vehicle is shown in Figures 2 and 3, and illustrates the type of actively illuminated reflectance imagery that is used to produce the corresponding range imagery. Recognizing the potential for multiple uses for this technology, Sandia, through a technology transfer initiative, has also offered this technology for private industry commercialization[2]. Possible civilian applications include collision avoidance, smart highway uses, robotic navigation, inspection, facility or terrain mapping, and surveying. In addition to these applications, there are likely to be many other applications where the speed, cost, and performance of this innovative geometry profiling sensor has potentially significant advantages over other types of scene distance measuring devices. A detailed discussion of these other potential applications, as well as the history of the development of this innovative sensor technology, may be found in an earlier SPIE paper entitled "The Emerging Versatility of a Scannerless Range Imager", which was presented at the 1996 SPIE Aerospace and Remote Sensing Conference in Orlando, Florida[3]. The capabilities of the Scannerless Range Imager, as well as a discussion of NASA's terrain mapping application are the topics of this paper.

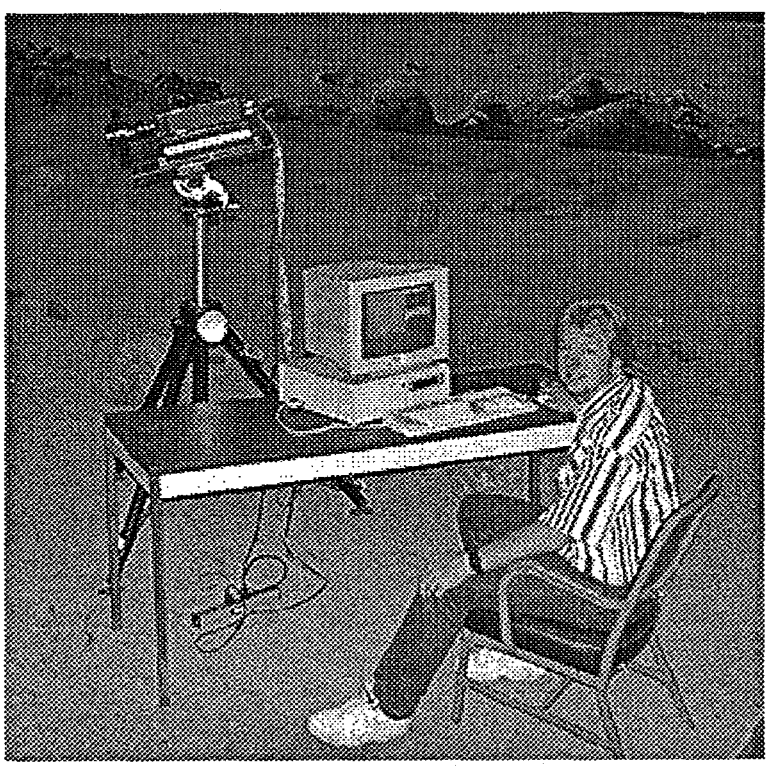

Figure 1: View of Scannerless Range Imager System at NASA's Planetary Landscape Simulator

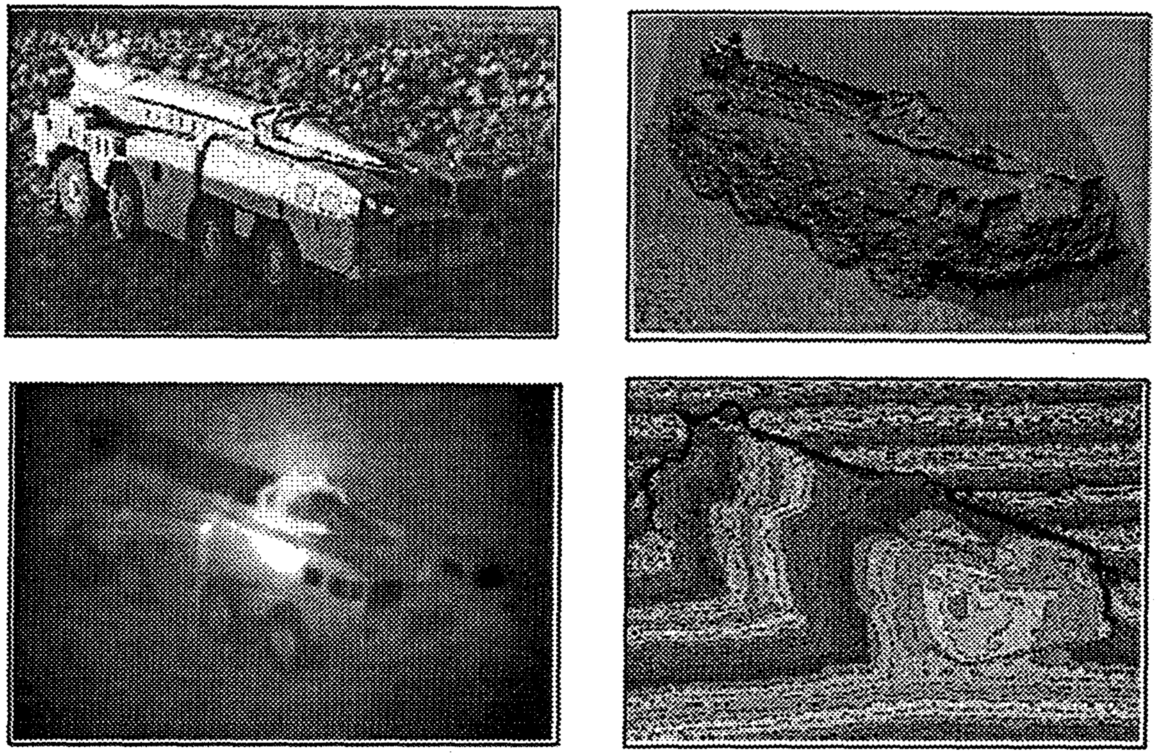

Figure 2: Representative Range and Reflectance Imagery from the Scannerless Range Imager taken at Sandia National Laboratories' Outdoor Laser Radar Test Facility, Albuquerque, New Mexico

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[1]. 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 most beam scanned LADAR systems). Operation in the 1550 nm spectral wavelength region is also possible[4], and offers another means for achieving eye-safe operation. The SRI technology is based principally on classic continuous wave (cw) phase detection electromagnetic radar theory[5, 6, 7, 8]. Real-time numerical extraction of pixel range measurements from the 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 implementation of the range imaging system consisted of a laser diode source, and an image-intensified video camera receiver. The light source and the image intensifier were 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 type of coherent "mixing" (at the waveform envelope frequency) 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,

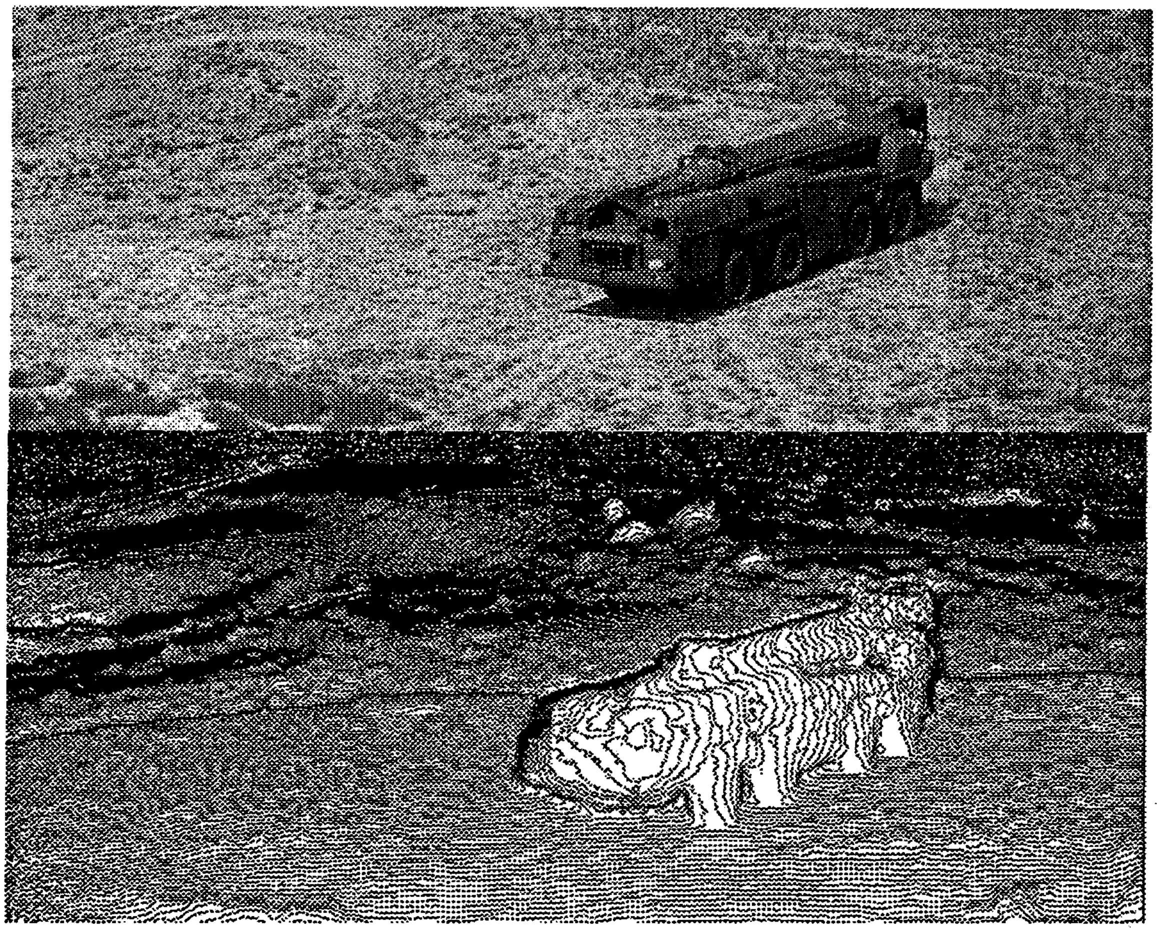

Figure 3: One foot Iso-Range Contour Plot of Ground in the Vicinity of a Mobile military Vehicle

in this process, acts as a type of injected local oscillator). The "mixing" and detection of return signal phase differences (which are proportional to target object range differences) occurs simultaneously for all pixels across the entire imaged scene. With this pre-detection mixing technique, the detected phase information can be collected in the form of subtle intensity variations using an inexpensive integrating type focal plane detection element, such as the Charge Coupled Device (CCD). The demodulation and extraction of range data is accomplished through digital signal post-processing, and 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 full-frame range imagery with each collection of a single frame of reflectance imagery. With this enhancement, the SRI concept would stand alone as the only range imager that could easily produce high resolution range imagery (greater than a 256 x 256 pixel frame format) at video camera type frame exposure rates (>30 Hz). The technology also offers a potential for providing very fast acquisition of range imagery at rates, which could greatly exceed thousands of frames per second.

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. 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 further 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 friendly 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 also achieved through the 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 that is 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 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 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 approximately 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 NASA's TERRAIN MAPPING APPLICATIONS

For unmanned space exploration operations, researchers at NASA Ames Research Center have conducted a survey of potential range imaging sensors, and concluded that that a Scannerless Terrain Mapping (STM) sensor is uniquely qualified and very attractive for use in future planetary landscape exploration. In terms of unmanned planetary exploration, the scannerless range imaging sensor could play several very important roles. It could initially aid in the landing process by which the exploration vehicle is placed on the surface of a planet. For this process, the range imaging sensor could serve to rapidly survey the surface of the planet for any obstacles and/or ground depressions that may exist within the predetermined landing zone. With feedback to the landing craft guidance system, the sensor could help guide the vehicle to a location where the effects of these hazards on vehicle stability could be minimized, and thus providing a greater degree of safety and reliability to the overall landing process.

After aiding in the safe placement of the exploration vehicle onto the surface of the planet, the STM sensor mounted on the mobile robotic exploration vehicle could then serve as an obstacle detection and avoidance sensor while the mobile exploration vehicle navigated on the planet surface. This is the principal function of the scannerless range imaging sensor for space exploration. When combined with predictive vehicle kinematics and dynamics capability, the terrain mapping feature of the STM sensor will improve an exploration vehicle's obstacle detection and assessment capability, and thus will allow it greater latitude in terms of safe, semi-autonomous vehicle mobility. For the mobile-robotic planetary exploration application, sensor reliability, size, power consumption, and dynamic functionality are the principal issues. These demanding constraints effectively prohibit the use of mechanically scanned LADAR systems. Finally, the STM sensor could also provide value by accurately mapping the viewed exploration path of the vehicle, whereby serving to record valuable scientific geological scene documentation.

For other space applications, a scannerless range imaging sensor could also be used to monitor and control maneuvers required for vehicles, such as the Space Shuttle, to dock with an orbiting space station, and/or potentially control the robotic manipulators that may, someday, be employed to help maintain and repair various types of remotely deployed space structures.

In support of the ground mapping application, Sandia has been working with researchers from the NASA-Ames Research Center, to evaluate the SRI technology for this very demanding application. In August of 1995, Sandia operated its engineering evaluation SRI system at NASA-Ames's Planetary Surface Simulation Facility and collect the first set of range image data on a simulated landscape environment that represented a Mars and Lunar planetary surface. The experimental setup is as shown in Figure 1. An example of some of the range image results that were derived from this initial experiment is illustrated in Figure 4. In this figure, a photographic image of the landscape scene is shown above a iso-range contoured plot of the resulting range image that was collected with the SRI system. The scene is comprised of a mounded sand bed with a few scattered large rocks in the foreground, and a painted mural of a Martian canyon on a flat wall in the background. For the plot in Figure 4, the data was processed and visualized using an arbitrarily selected choice of one-foot iso-range contours. Following this successful demonstration of the SRI technology, Sandia soon thereafter delivered, a fully operational SRI system to NASA to support their ongoing laboratory research with range imaging sensors for unmanned planetary exploration within a virtual reality environment.

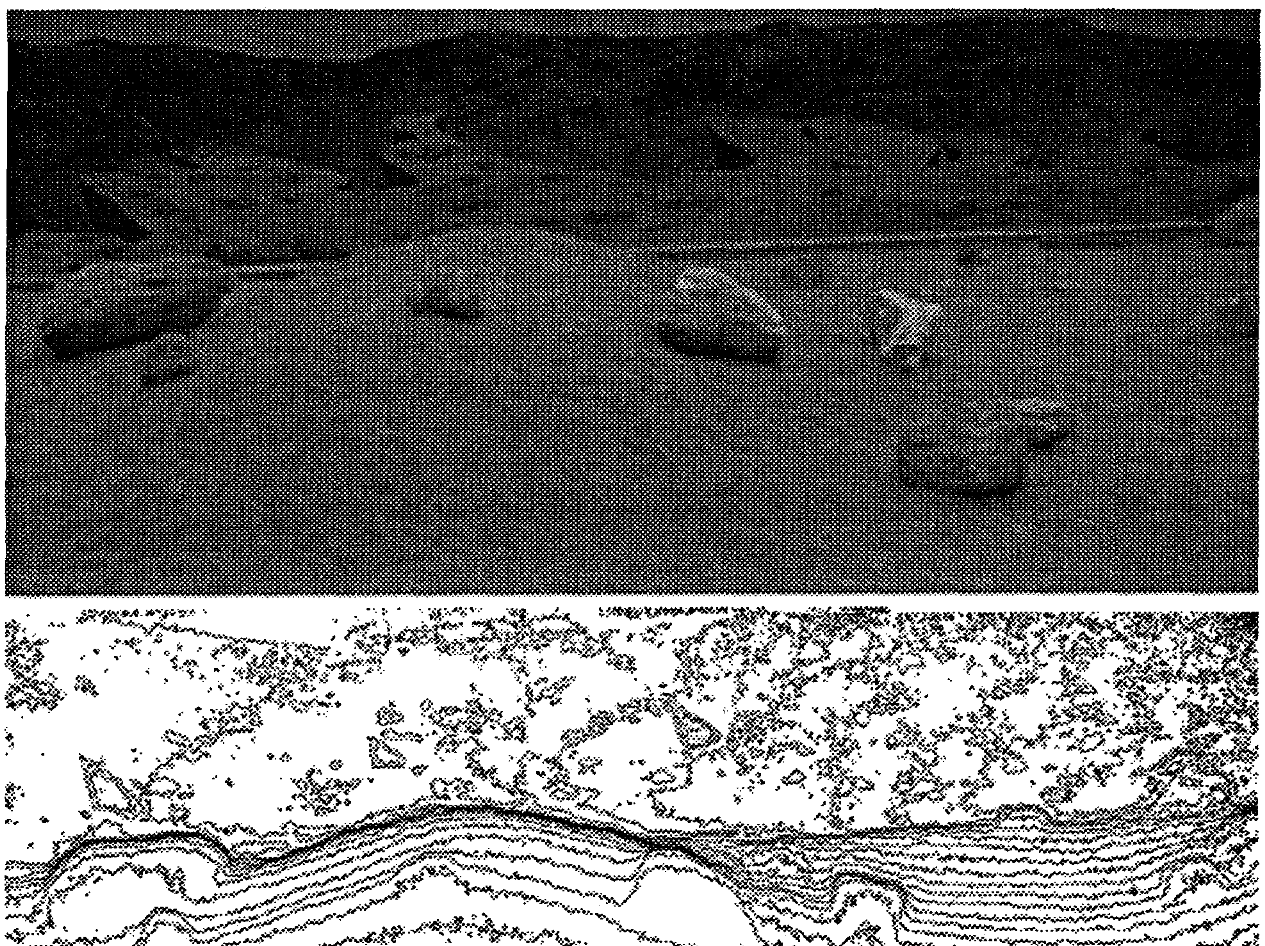

Figure 4: Photograph (top) and One-foot Iso Range Contour Plot (bottom) of Raw SRI Range Imagery within NASA's Planetary Surface Simulation Facility at NASA-Ames Research Center.

Sandia National Laboratories is also interested in independently applying SRI technology to Virtual Reality environments. Under sponsorship from Sandia's Laboratory Directed Research and Development (LDRD) program, a multi year effort entitled, "Automated Geometric Model Building Using Scannerless Range Image Data", was initiated in FY96. This effort is specifically intended to reduce the substantial quantity of multi-perspective range imagery that can be easily collected with an SRI sensor, and transform it into usable set of geometric models of the viewed objects in a scene, from which visualization and interaction can be easily and resourcefully accomplished within a virtual reality (VR) and/or commercial Computer Aided Design (CAD) software environment.

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 have inhibited the 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 the basic SRI receiver componentry is less than $15,000, and quantity procurement of these items would likely reduce the cost even more. Most of the 3D sensing techniques 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 is well known as "stereo imaging", and is usually achieved by using two cameras separated by some known baseline distance so that the scene is viewed from different, known 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, 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 (1) the need for an active illuminator that can be accurately scanned across the scene, (2) 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 (3) the need for frequent equipment registration and calibration maintenance. Clearly, a high speed 3-D imaging "magic camera" which like the SRI, can directly measure the distance to all objects in an observed scene is the best way to produce range imagery. We are very excited about the many applications, in a wide variety of fields, where this technology will benefit our society.

Within various image understanding research communities, there exists substantial advocacy for both laser radar (LADAR) and its associated image analysis techniques to provide one of the most convenient and accurate means of interpreting observed scenes. However, the performance, size, cost, and reliability of previous range imaging sensors have prevented a more rapid introduction and broader acceptance. The low cost, high resolution, and ease of operation of the SRI sensor can 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 sensor technology, it is practical to put range imaging sensor hardware in the hands of the individual LADAR based image understanding researcher, and Sandia National Laboratories pleased to have started this process with NASA-Ames.

4.0 FUTURE DIRECTION

Sandia's Scannerless Range Imager sensor development efforts have focused on applying this technology to military munition guidance and fuzing applications. 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 demonstrated better than one foot range resolution for target distances approaching one kilometer, using an inexpensive, 8-bit, image intensified video camera system. Under our current sensor development efforts, 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 to provide a unique range imaging sensor capability for enhanced, remote scene sensing image understanding uses. 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, and

(6) generation of range imagery using alternative focal plane detector arrays, such as a semiconductor (CMOS) active pixel sensor[9].

We have identified 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 will have immediate applicability to many ongoing and emerging efforts of commercial and military importance. They will have particular application to those areas where fast, dense, pixel registered single or multi-spectral video and LADAR imagery, in either eye-safe and/or "out-of-band" detection regions of the electromagnetic spectrum, is required, and we look forward to the opportunity to be able to pursue these innovative range imaging sensor enhancements.

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