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A Handheld, Wireless 3D Laser Scanner for Shuttle Tile Inspection

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Abstract

NASA Ames engineers have developed a unique handheld instrument that increases the accuracy and reliability of Shuttle Thermal Protection System (TPS) surface flaw measurements. The device, called the Mold Impression Laser Tool (MILT), weighs only 1.16Kg and optically scans a 7.6x7.6 cm TPS area in under 2 seconds to a resolution of better than .127mm in x, y, and z. Resultant data is sent to a laptop PC via wireless transmission. A program running on the PC detects and calculates the dimensions of the flaws, and displays a 3D image in real time during the scan.

1. Introduction

Detection, measurement, and characterization of Shuttle Thermal Protection System (TPS) surface flaws is presently very time consuming and tedious manual process. NASA Ames engineers have developed a unique handheld instrument to increase the accuracy and reliability of the measurements, improve vehicle turnaround time, and maintain a historical database of the TPS surface condition. A small 3D scanning device, called the Mold Impression Laser Tool or (MILT) will be place over the TPS area to be measured, optically scan the area for flaws, and send the resultant data to a laptop PC via wireless transmission. The battery powered MILT is thus completely free of cables and allows technicians to move about the orbiter unencumbered, using the tool to measure flaws. A custom software program running on the PC locates and characterizes the flaws, identifies the TPS area under consideration, and updates the TPS database with the latest flaw information. Access to a server provides the TPS fabrication and maintenance information for each Orbiter tile, generates repair instructions, and maintains the historical database.

The MILT is capable of scanning an object at very high speeds (greater than 500,000 3D points/second) and creating high-resolution 3D surface maps. Laser triangulation is used in conjunction with a high-resolution camera, a laser diode, and processing electronics incorporated into a small sensor package that rotates from a fixed position to scan the object. Processing is done on board the instrument and the resultant 3D data is transmitted wirelessly to a PC resulting in rapid scans, with 3D images produced as the instrument is scanning.

We will begin by presenting the overall system architecture and design, followed by a description of the essential hardware components, the PC software, and finally scanner performance results.

2. System Overview and Architecture

The key design requirements for the MILT instrument were that it be small and light, fast, have high-resolution and accuracy, be portable and wireless, and be durable and reliable. The depth range requirement was from .127mm to 50.8 mm. Also required on the PC end were the capabilities to automatically detect and calculate the dimensions of surface flaws, and to view the flaws in 3D. These requirements were set to ensure that an automated, accurate, systematic, and reliable means of assessing and archiving TPS integrity be achieved, and that the maintenance technicians and engineers could effectively use the instrument around the many tight and difficult areas to reach on the orbiter.

Figure 1 shows a conceptual drawing of our sensor scanning over a target surface. Components of the instrument include a digital camera, a laser diode line generator, an electronic processing subsystem, motion control, an Ethernet communication subsystem, and an off-the-shelf wireless Ethernet bridge module using the 802.11g wireless transmission standard. 3D images are generated through a technique called laser triangulation.1, 2 As the scanner moves over the target, the camera takes frames (pictures) at even intervals of the laser line reflected off of the surface. The resulting position of the laser line on the sensor array determines the depth of the surface at each point along that cross section of the target. The electronics processing section processes laser line data, controls the laser, the motion system, and user interface and data I/O communications between the scanner and PC. During a scan, the processed data is transmitted from the instrument over wireless 802.11g standard to the host PC.

The PC software further processes this data to create and display 3D images with range points, and calculates the depth and volume of the surface automatically.

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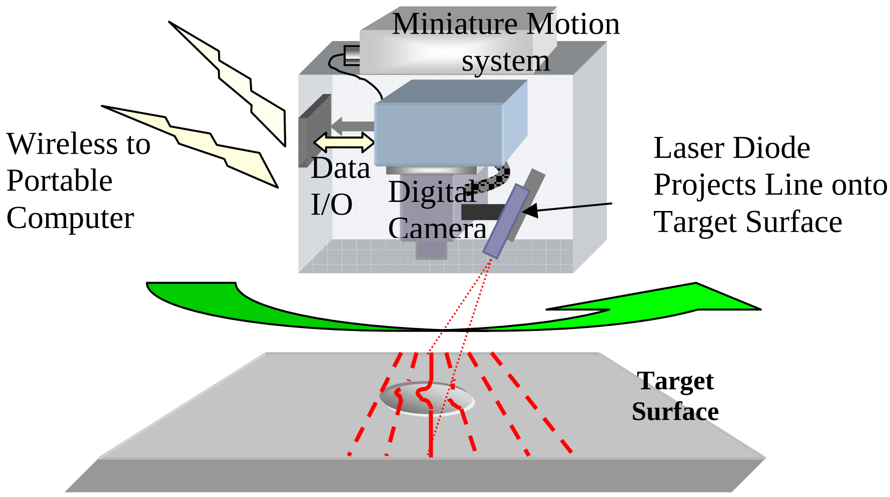

Figure 1: Model of MILT 3D Scanner architecture

3. System Hardware

The MILT dimensions are 17l x 14w x 14h cm, and it weighs only 1.16kg making it very portable and easy to carry and use for long periods of time. Please refer to Figure 2 for a picture of MILT. A custom miniature lens with a 15.066mm focal length was designed and developed to allow the 7.6 x 7.6cm field of view with an optical path-length of about 12.7 cm. The laser, camera with lens, and electronic PC boards make up the sensor portion of the instrument and are integrated into one bracket that is rotated +/- 22 over the target using a miniature rotational stage. Thus, the sensor effectively scans a 7.6 x 7.6cm area (3 x 3 inches) over the target surface in about two seconds collecting 3D data. The data is processed and formatted, converted to 100/1000 Base T Ethernet, and transmitted to the laptop PC via an Asus WL-330g Ethernet Bridge 3 mounted internally. A 660nm (red), 30mw laser diode module is used which projects a straight line on to the target through a 45 fan angle lens. The laser power can be adjusted through the PC user interface allowing the instrument to effectively scan targets with a wide range of surface reflectivity.A rechargeable lithium polymer battery module is used with a 1600 milliamp-hr capacity, and will last for over 800 scans.

4. PC Computer Software and Data Flow

During normal scanner operation the host computer serves three main purposes: scanner control, surface point triangulation, and data display. The software implemented for this system is extensive, but can be divided into a series of modules consisting of functions and classes used for specific purposes.
The modules and the interaction between them are shown in figure 3 below. A brief functional description of each module is provided in the pages that follow.
The 3D Scanner Hardware receives control information from the PC (Scanner Control Module), executes the scan when the user presses the scan button, and returns raw surface information to the PC (Data Formatting Module).
The Graphical User Interface GUI allows the user to accomplish the following tasks:

- Acquire and display scan data in real time.
- Analyze the 3D surface to detect and measure defects.
- Display defect measurement results to a table with the corresponding defects highlighted in the scan image.
- Run automated calibration and verification procedures.
- Configure scan properties and save data.

This graphical user interface is the main program used by the user. It was developed with Microsoft Visual C++ 6.0 and is shown below in Figure 4.

The Real-Time Control and Communications module consists of a library of functions the GUI can call to configure the scanner, execute scans, and receive 3D data. Real-time data reception is accomplished through the use of threads that repeatedly send and receive data “in the background” while the GUI plots them three dimensionally in OpenGL.
The purpose of Data Formatting Module is to prepare the input 3D point cloud for analysis. To expedite the analysis process it is necessary to ensure that the data is evenly spaced, contains no missing points, and is relatively smooth. This is accomplished through the processes of Binning and application of a Median Filter. Binning converts the non-uniformly spaced point cloud into a uniformly spaced set of

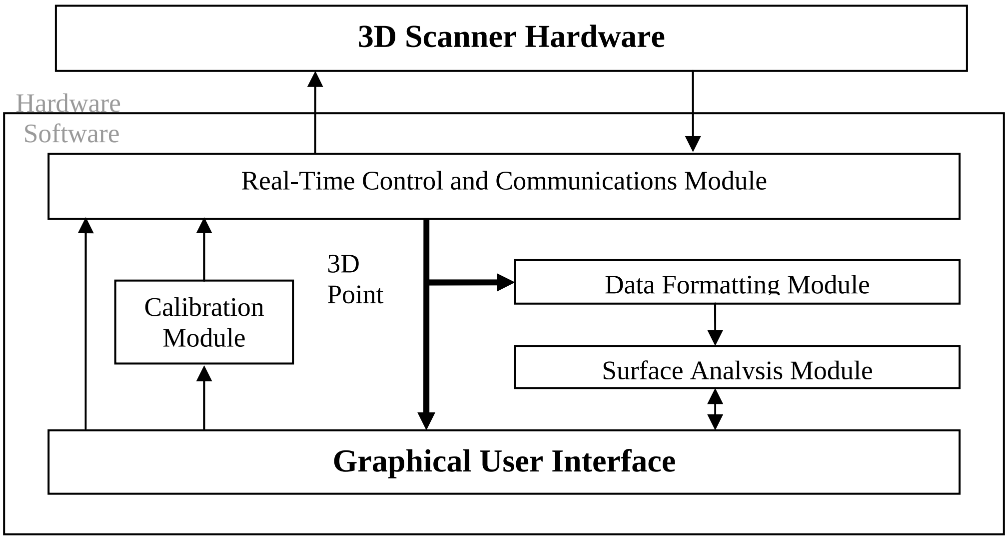

Figure 3: MILT software block diagram.

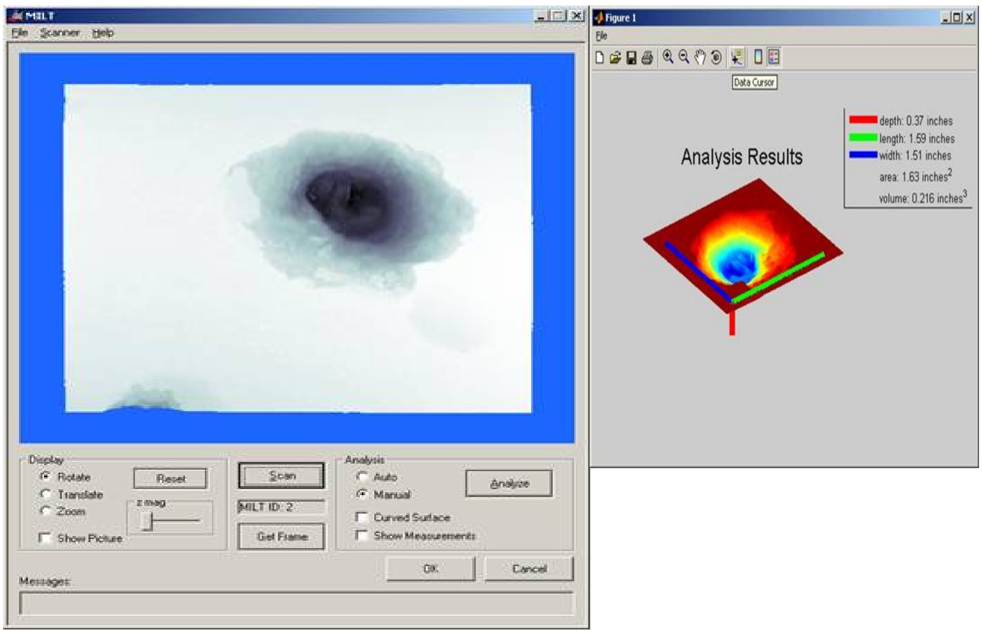

Figure 4. MILT GUI interface.

data by placing individual 3D points into bins evenly spaced in x and y. Gaps of missing data often remain after the binning process completes (although not many) and it is necessary to fill them before proceeding with the surface analysis. This is accomplished by using neighbouring points to interpolate for the missing data. Finally, a light median filter is applied to smooth sharp noise spikes from the data. For the MILT a 5 x 5 neighbourhood filter is used.

The Surface Analysis Module examines the 3D surface data output from the *data formatting* module, detects tile surface curvature, and finds and measures defects. A list of the detected defects and their measurements is created for the GUI to display in tabular form. The module also outputs a Boolean surface map indicating which points

are measured within defects (and those that are the surface). The GUI uses this result to highlight and label the defective regions on the display.
The Calibration Module consists of a set of functions used to semi-automatically determine some of the calibration parameters in an optimal way. This is accomplished by taking pictures of the laser line projected from several different known distances to the target surface. With the information from these pictures the software automatically calculates the location and orientation of each laser so as to minimize depth measurement error. The GUI guides the user through the process which involves the use of a smooth granite slab and precisely measured, NIST (National Institute of Standards and Technology, USA) traceable, gauge blocks.

Figure 2. The MILT

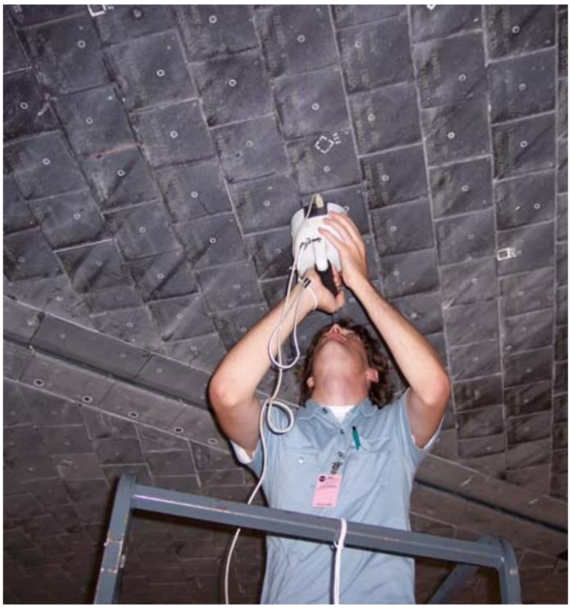

Figure 5. MILT in use on orbiter Discovery at Kennedy Space Center.

5. Conclusion

Several Wireless MILT prototype units have been built, thoroughly tested to meet specifications, and are currently in operation at NASA Kennedy Space Center. Accuracy and Repeatability tests conducted (160 samples collected) on the wireless MILT with machined and calibrated blocks from .76mm to 50.8mm in height yielded the following results:

<u>Maximum Depth Error</u>	
For depths .762mm to 12.7mm:	100% of measurements within .381mm.
For depths 12.7mm to 50.8mm:	100% of measurements within 1.52mm.
<u>Maximum Length Error</u>:	100% of measurements within .889mm.
<u>Maximum Width Error</u>:	100% of measurements within .762mm.

Maximum Volume Error: 100% of measurements within 6%.

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References and footnotes

1 Paul Besl, "Advances in Machine Vision", chapter 1 – Active optical range imaging sensors, pages 1-63. Springer-Verlag, 1989.

2 R.A. Jarvis, "A perspective on range-finding techniques for computer vision", *IEEE Trans. Pattern Analysis Mach. Intell.* 5:122-139, March 1983.

3 ASUS WL-330g Pocket Access Wireless Point + Ethernet Adaptor: http://usa.asus.com/products4.aspx?l1=12&l2=41&l3=0&model=59&modelmen

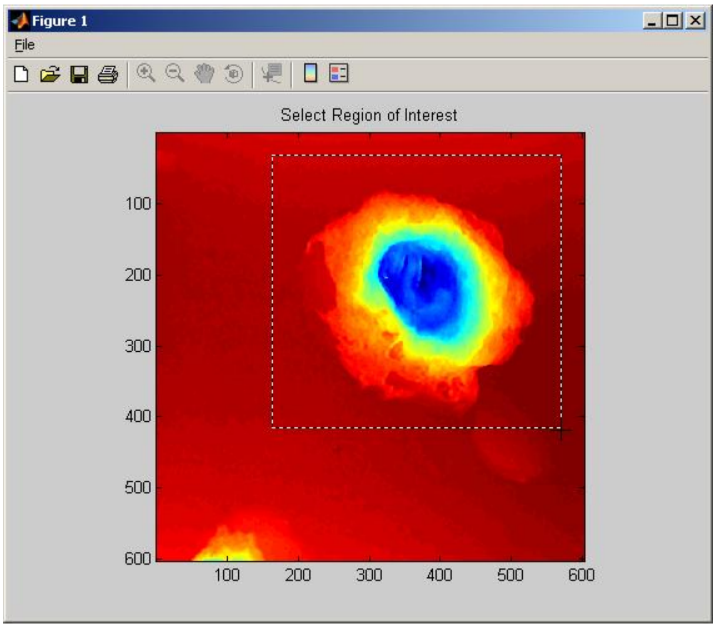

Figure 6. Flaw detection from MILT scan.