LASER-BASED MAPPING TECHNOLOGY FOR THE INSPECTION OF ROCKET THRUSTERS

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Abstract: Each of NASA's Space Shuttles employs 38 position reaction control system (PRCS) thrusters to control attitude and position while on-orbit. If a chip occurs in its protective ceramic coating, burn-through could occur, thus creating a potentially hazardous situation. Currently, these thrusters are manually inspected using conventional visual methods. When a chip is found, a rubber replica is made and measured by hand in order to determine the depth and overall size of the feature. This process is laborious, time-consuming and subject to human error. NASA has conducted a program to significantly improve the technology by which the PRCS thrusters are inspected. The result is a fully automated, laser-based inspection system that is capable of three-dimensional mapping of the most inaccessible areas of the thrusters, the combustion chamber and throat region. The two-phase program began with the development of a miniature, precision laser-triangulation sensor. Laboratory tests confirmed the sensor to be capable of mapping features to an accuracy of better than 0.0127 mm. Phase two included the development of a robotic scanning system that provides four degrees of motion for negotiating the complex geometry of the thruster throat and combustion chamber. Each scan provides NASA with a photograph-quality image and profile map of the interior surface of the thrusters. Chips as small as 0.25 mm diameter can now be reliably located and characterized using this automated, laser-based mapping technology. This new NDT capability will allow NASA to quantitatively monitor the condition of each of its many PRCS thrusters while eliminating human error and subjectivity in this critical inspection task.

Introduction: The primary reaction control system (PRCS) thrusters on NASA's Space Shuttle (Figure 1) are subject to chipping in their protective ceramic coating. Technicians use a flashlight and mirror to inspect the combustion chamber and throat of the thruster after each flight. In the event that a chip is detected (Figure 2), measurement of flaw size is accomplished by creating a mold impression and measuring the features using an optical comparator. This visual inspection method is operator dependent and subject to human error. As part of its ongoing program to improve the inspection methods used on safety-critical Space Shuttle components, NASA recently funded a project to develop an automated, laser-based inspection system for PRCS thrusters. The objective of this program is to reduce the dependence upon the operator's visual acuity and judgment through the development of an automated, highly accurate and repeatable thruster scanning system.

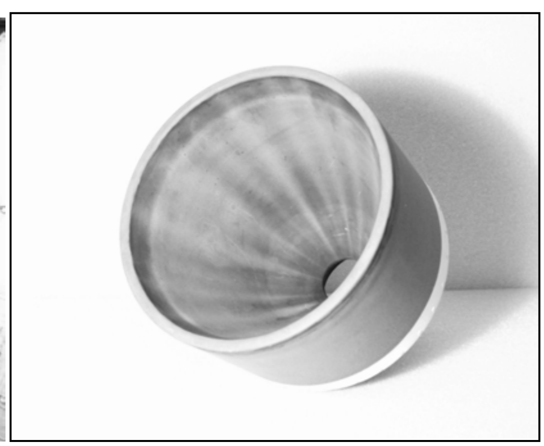

Figure 1. The Space Shuttle has 38 PRCS thrusters located around the orbiter.

Figure 2. Chip in throat of PRCS thruster.

A Proof-of-Concept study was funded by NASA for the development of a miniature, high-performance sensor that could fit through the 50 mm diameter thruster throat and operate in the tight confines of the thruster combustion chamber. A prototype laser profile sensor (Figure 3) was designed, built and demonstrated to measure features to an accuracy of better than 0.01 mm (1). The sensor was evaluated on a retired PRCS thruster and was demonstrated to be capable of negotiating its geometry and the repeatable detection of chips in the ceramic coating. The successful demonstration of the prototype sensor resulted in the funding of a Phase II program, in which a full-scale scanning system would be developed and delivered to White Sands Test Facility in New Mexico, USA.

Figure 3. Miniature laser profile sensor developed for NASA

Theory: The principle of optical triangulation (2) employs the use of a light source, imaging optics, and a photodetector (Figure 4). The light source and focusing optics are used to generate a focused laser beam that is projected onto a target surface. An imaging lens captures the scattered light and focuses it onto a lateral effect photodetector, which generates a signal that is proportional to the position of the spot in its image plane. As the distance to the target surface changes, the imaged spot shifts due to parallax. To generate a three-dimensional image of the part surface, the sensor is scanned in two dimensions, thus generating a set of distance data that represents the surface topography of the part.

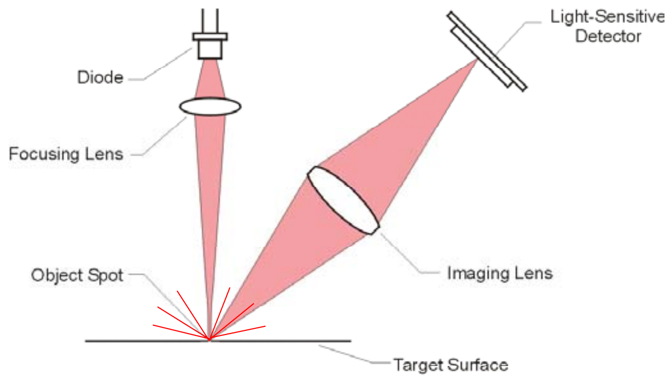

Figure 4. Principle of optical triangulation.

Laser-based profiling (LP) sensors are used to detect a variety of defects such as deformation, corrosion and pitting. In addition to generating a proximity-related signal, laser-based sensors also generate a signal that is associated with the reflectivity of the part surface. We refer to these data as the as LaserVideo™ images (LVI). By using a highly focused excitation laser and high data sampling resolution, these LVI images can take on near photographic quality. Through the process of mapping the variations in total reflected laser intensity signal, sensors can be used to detect very fine features such as small scratches, surface roughness and discoloration. LTC has developed laser-based inspection systems for a wide variety of NDE applications, including:

- Mapping denting and ovality in nuclear steam generator tubes;
- Measuring erosion in boiler tubes, heat exchangers and pipes;
- Measuring erosion and pitting in high-performance gun tubes;
- Mapping and categorizing corrosion pitting in solid rocket booster gas generators and other components.

In each of these cases, the objective was to rapidly and accurately detect and quantify potential flaws in high-value, safety-critical components. Figure 5 shows an example laser-profile mapping of pitting in a component surface

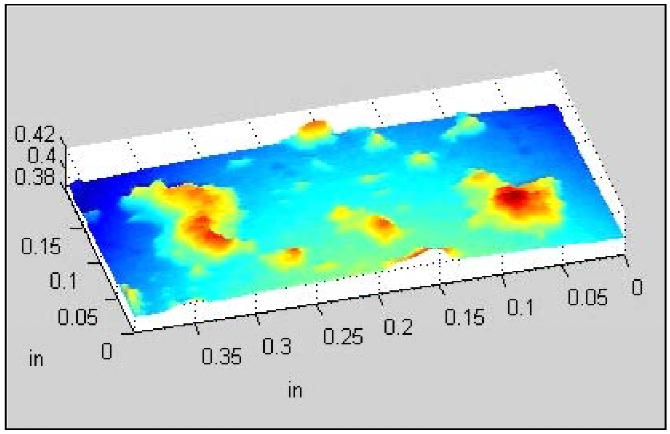

Figure 5. Laser-generated profile of corrosion on a surface.

To illustrate the near-photograph quality of LaserVideo™ image, Figure 6 shows a pair of coins that were scanned with a laser sensor. The spatial sampling resolution used for this scan was 0.025 mm (0.001 inch) with a laser spot size of approximately 0.0125 mm (0.0005 inch) diameter. The LVI images reveals very fine features such as surface scratches that might, otherwise, be undetectable using other measurement methods.

Figure 6. LaserVideo™ images of coins.

Results: Several challenges had be overcome in order to provide NASA with an inspection system. A second-generation laser profiling sensor had to be designed that could the demanding requirements imposed by NASA. This sensor was approximately one-third smaller than the prototype sensor, and had to meet the following specifications:

- Measuring Range: 4.0 mm
- Stand-off: 9.5 mm
- Laser spot size (max): 0.06 mm
- Resolution: 0.00254 mm
- Demonstrated accuracy: better than +/- 0.0127 mm

The second — and most significant — challenge was the design and development of a robotic scanning device capable of traversing the sensor over the complex shape interior surface of the thruster. A vacum locking mechanism was dveloped which can hold the sensor deliver unit

(SDU) in a “vertical-down” orientation, supporting over 70 kg (150 Lbs), which is seven times the weight of the total SDU assembly. In addition, the sensor must never contact the thruster surface, and the system was required to have several layers of fail-safe provisions to virtually eliminate the possibility of damaging a thruster. Provisions include limit switches, hard mechanical stops, extensive protective housings, teflon pads, and software range limits.
The resulting SDU included four degrees of motion for the sensor: axial, rotational, radial and tilt. In order to facilitate consistent sensor stand-off and prependicular laser transmission (to the surface), a surface following algorithm was developed to precisely control the sensor tilt as a function of axial position. In addition, the SDU included a nitrogen purge and safety interlock to minimize the possibility of scanner components interacting with any residual rocket fuel vapors. The SDU included an integrated calibration verification ring and several fail-safe features to prevent it from contacting the part surface. An illustration of the SDU as it fits in a PRCS thruster is shown in Figure 7.

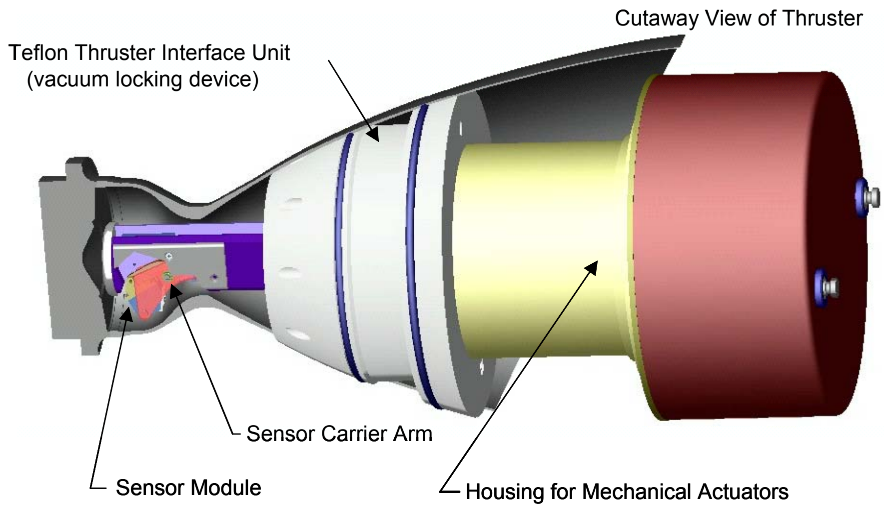

Figure 7. Cutaway image of sensor delivery unit in a thruster

The robotic scanner is controlled by a portable, computer-based data acquisition and control station. The station provides precision control of the laser power, including a remote power control mode which automatically adjusting the laser power depending on the surface reflectivity. To meet eye safety requirements, the sensor automatically shuts off if the surface is not detected. The station also provides control and position detection for the motors that move the robotic arm, and monitoring of limit and home switches. The detection signal is processed through precision amplifiers and normalization circutry, calibrated, and displayed real-time during scans.
At the conclusion of a seven month development effort a full-scale, turn-key thruster scanning system was delivered to NASA White Sands Test Facility. The system was demonstrated to be capable of scanning nearly 100% of the thruster combustion chamber, and out past the throat by approximately 35 mm. The system was successfully tested on a number of thrusters with various sizes of surface chips. Figure 8 shows an example of a full thruster scan. The data can be displayed in full color, therefore making it quite simple to visually detect any chips. However, since this manuscript is printed in black and white, the chip is shown in white, against a grey-scale background.

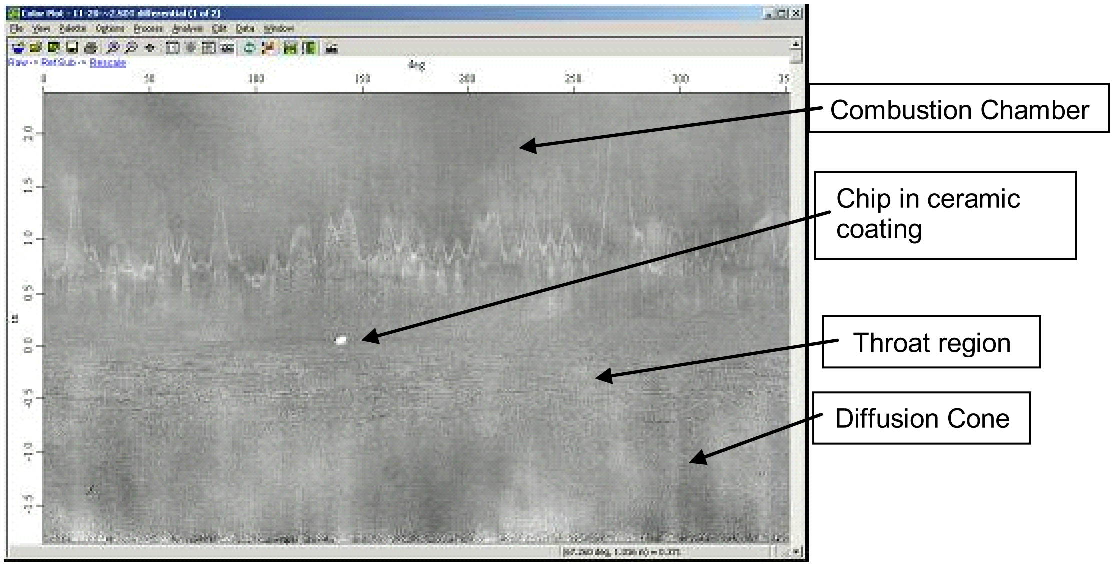

Figure 8. Full profile of thruster combustion chamber and throat area.

Once a chip has been located, the operator may interrogate the data using the control and analysis software. The operator may either "manually" analyze the feature by comparing the chip depth to adjacent undisturbed areas, or employ an automatic analysis software module that locates and reports the results in tabular format. Figure 9 shows a "zoom image" of a chip that was mapped in the ceramic coating of a PRCS rocket thruster.

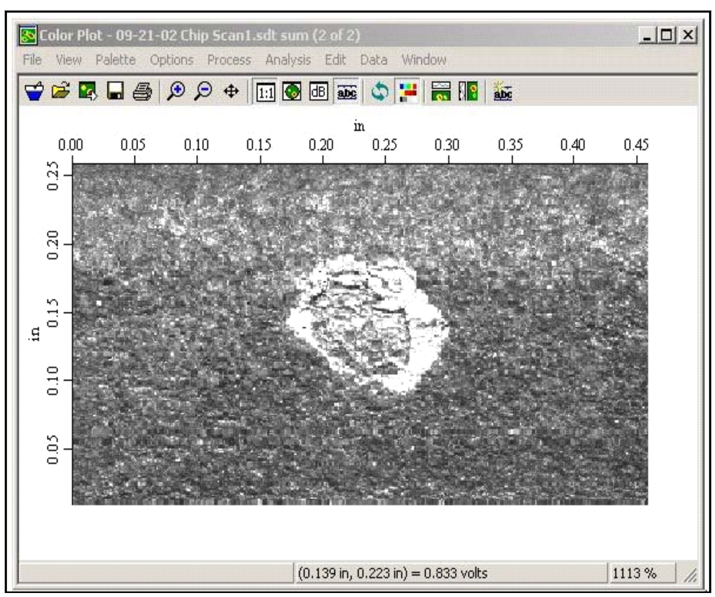

Figure 9. Zoom image of chip in thruster surface (LVI).

Discussion: Both manufacturers and end-users of high-value, safety-critical components are constantly searching for way to extend the useful life — and assure safe operation — of their products. For difficult to inspect parts, such as rocket thrusters and aircraft engine components, many organizations still rely on visual inspection methods. However, this can be a recipe for disaster. Potentially dangerous flaws can be missed by poor lighting, difficult visual access, operator inattentiveness, fatigue and low expectation to observe flaws (3). It is the objective of Laser Techniques Company to improve the quality and reliability of NDE operations by providing tools that eliminate operator subjectivity.

The successful completion of this project has led directly, and indirectly, to additional applications in the field of space propulsion. One such example is a system that was developed for mapping erosion in Hall thrusters. In this case, a miniature sensor was developed that could reach into the anular cavity of the anode and map erosion on its internal surfaces. Another laser-based system was recently used to map corrosion on flight-critical components used on the Space Shuttle solid rocket boosters.

When fully integrated into the inspection process, the laser-based inspection system for PRCS thrusters will significantly improve the quality, reliability and repeatability of Space Shuttle thrusters. It will enable technicians to not only detect and measure chips and other flaws in PRCS thrusters, but will allow these features to be documented and tracked over time.

Conclusions: Laser-based NDE methods are rapidly becoming adopted by NDE professionals for a wide variety of applications. Geometric features such as pits, deformation and erosion can be rapidly and accurately mapped using laser profiling sensors. Moreover, many non-geometric features are also detectable using LP sensors. Features that cause changes in reflectivity, including fine scratches, smears, laps and changes in surface roughness are detectable using the LaserVideo™ image process (4). The use of multiple laser sources allows for the detection of chromatic features such as overheating and Blue Acid Etch indications in titanium components (5). Laser profiling sensors are also well suited for combined use with eddy current and other NDE methods. In many cases, it is possible to replace visual inspection methods with laser-based scanning systems, thereby reducing the possibility of operator error and improving the performance and useful life of rocket thrusters and other safety-critical components.

References:

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