DOE/CE/15605-TA

FINAL REPORT

Project:
Surface Profiling System
Optimized for Inspection of Turbine Blades

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I. Introduction

The Numerical Stereo Camera System

For almost five years, DCS has assisted the Walter Reed Army Institute of Research (WRAIR) in the development of

Figure 1 - NSCS Block Diagram

the Numerical Stereo Camera System (NSCS). The NSCS is a high-speed 3-D topographical surface mapping system that projects a structured pattern of laser light onto the surface of a target object, views the projected pattern with an off-axis video camera, and calculates the 3-D profile of the surface from the apparent distortion in the pattern as it appears on the surface of the target. Figure 1 shows a block diagram of the basic NSCS mapping one side of a target.

In basic theory, the NSCS operates similarly to currently available single-line surface profiling systems. Figure 2 shows a single laser line projected onto a curved surface, viewed by an off-axis camera. If the relative positions of the laser projector and the video camera are known, the 3-D coordinates of every point on the laser line may be calculated from an image of the line, using straightforward computations.

There are two problems with this approach. First, the line must be scanned over the surface to be mapped, either through mechanical translation of the target, mechanical translation of the line projector and camera (the two must be locked together as a single unit, since the measurement depends upon precise knowledge of their relative positions), or redirection of the laser line by a calibrated moving mirror. Mechanical translation takes time and adds sources of error to the measurement. Secondly, there is the problem of detecting the line. Usually this is done by making the line very intense and simply taking every pixel in the image that is brighter than a certain threshold as belonging to the line. This can run into problems if the surface being mapped has large variations in reflectivity; it is very possible for certain portions of the line to fall below the threshold and be ignored.

Figure 2 - Single laser stripe projected onto a typical target

The NSCS improves on the single-line concept by projecting multiple parallel lines onto the target's surface simultaneously. The parallel laser lines, referred to as a "structured laser light array", are generated using a novel interferometric technique from a single laser beam. To make possible the unique identification of each line as observed on the target's surface, the laser projector passes the structured laser array through a liquid-crystal Spatial Light Modulator (SLM). The SLM allows the host computer to turn on or off any line or combination of lines.

Obviously, the system could function by projecting one line at a time. With one exposure per line, this would take N video frames to uniquely identify N laser lines.

The NSCS reduces this to $\log_2 N$ by projecting a binary sequence of patterns onto the surface of the target: one image with all lines on, one with the first half on and the second half off, one with quarter on/quarter off/quarter on/quarter off, and so forth. By correlating a complete series of such images, with the target held stationary during the sequence, the computer can determine which row in the structured light array a particular line, as observed on the surface of the target, is associated with and then solve the equations to locate any spot on the target's surface, located on that line, in 3-D space. The SLM used is capable of switching patterns during the vertical retrace time of the video camera, so patterns may be acquired in successive video frames. Given a laser array with 128 lines and a standard 30 frame/sec camera, 8 frames ($\log_2 128 +$ one image with all lines turned off) are required, for a total acquisition time of 8/30 seconds.

For the field of view covered by the laser projector and camera at one point in time, no mechanical movement of either the target, the laser projector, or the camera is necessary. All components of the laser projector and the camera are electro-optical and non-moving; thus once the system is calibrated it will retain its accuracy. In addition, the system handles non-optimal surfaces well. Since, during processing, the system effectively has images of the area illuminated by each stripe both with the stripe turned on and with it turned off, but with no other changes to the image, it can readily determine the extent of the laser line even under wide variations in target surface reflectivity.

DOE/NIST ERIP Grant

Recently DCS has begun the task of commercializing this technology. Two years ago, DCS applied for a grant from the DOE/NIST (Department of Energy/National Institute of Standards and Technology) Energy Related Inventions Program (ERIP). This program grants funds to small companies in an effort to bring to market technologies that result in energy saving or conservation. In its application, DCS proposed a variation of the NSCS optimized for the inspection of turbine blades in high-pressure steam turbines and jet engines.

In October, 1994, DCS was awarded an ERIP grant and commenced development of a demonstration prototype inspection system, based on the NSCS. Intended as a demonstrator for potential customers, the prototype is optimized for the inspection of turbine and compressor blades, and will demonstrate the increased speed and accuracy possible with the NSCS approach. The prototype uses primarily off-the-shelf components, with the exception of a DCS-developed holographic optical element, including a DisplayTech Inc. (Boulder, CO) 64-line SLM. Video images of the pattern, as projected onto the target's surface, are captured by a CCD video camera and digitized by an image processing board in the host computer (a Pentium-based PC). The system can capture one field of view, with up to 20,000 3-D data points, in less than one second. Even though processing power is limited, the captured images can be

processed into a map file in approximately one minute, for a total data throughput of approximately 700 points per second.

Figure 3- DCS Turbine Blade Inspection System, Rendering

Figure 3 shows the basic configuration of the Turbine Blade Inspection System prototype. The entire system sits on a 2 foot by 3 foot optical table, for stability and ease of transportation, and comprises the laser projector, the video camera (not shown), and a 4-axis translation stage which positions the target to be mapped within the mapping volume defined by the fields of view of the laser and the video camera. The video camera, a small CCD unit, is mounted to a 3 foot post attached to a magnetic mount and may be positioned at various places on the base plate. This allows the camera's field of view to be optimized for particular targets and mapping requirements. Generally, the camera is located directly above the path of the laser array, viewing the target at a 45 degree angle, at such a distance that the laser array - as projected onto the target surface, almost fills its field of view. The lens used is a high-quality macro photographic lens, but does not have zoom capability, so repositioning the camera is required to adjust the field of view.

Also not shown, and located separately, is the host computer along with its monitor and keyboard. A Pentium PC operating in the Windows environment, the host computer contains the video digitizing and processing board and a 4-axis motor controller board. It runs the user interface, controls the overall execution of the mapping system, controls the motors in the stages, and does most of the processing of the 3-D maps as they are generated.

The 4-axis translation stages move the target around the mapping volume so that all portions of the target's surface may be measured. Generally, for turbine/compressor blades, the mapping FOV is adjusted to be approximately 1 inch x 0.5 inches (The array has an aspect ratio of approximately 2 to 1). This results in a system resolution of approximately 15 mils between stripes, and an overall system accuracy of about +/- 5 mils. A complete map of a 6 inch by 1 inch compressor blade, then, will take approximately 18 images: six image of each side, plus the leading edge, which is highly curved. Generally this can be accomplished by rotating the blade around the vertical (z) axis and moving it vertically to catch successive sections; often, however, it is also necessary to move the blade horizontally (x) so as to optimally place it within the mapping volume. Currently the y axis (towards and away from the laser) is not motorized, since it is generally used only to adjust the size of the laser array as projected onto the target (increasing or decreasing the mapping volume). It could, however, easily be motorized if the situation warrants.

The heart of the mapping system is the laser projector. Shown in the Figure without its cover, it comprises a laser, an optical fiber and chuck, the DCS Holographic Structured Light Generator (HSLG), the Spatial Light Modulator (SLM), and assorted mechanical and electrical components. The HSLG holographically generates the line array which illuminates the target; the SLM modulates the array so that the stripes may be distinguished for the mapping process. The HSLG is illuminated by the laser via an optical fiber which routes the beam and projects it onto the HSLG (allowing for a much tighter package).

Additional DCS Investment

One of the purposes of the ERIP grant is to serve as a seed for further investment. In addition to the grant funds, DCS has invested approximately \$180,000 in developing the 3-D mapping system. Some of this money was spent on the development of the mapping software, which turned out to be more complex than expected. The majority of it, however, was spent on two IR&D projects to develop improved components for the laser projector - the Holographic Structured Light Generator (HSLG) and a stabilized diode laser - and a patent application for the HSLG.

The HSLG was designed by DCS and fabricated at the University of Dayton Research Institute, in Dayton Ohio. DCS has applied for a patent on the HSLG, and expects an award in the first quarter of 1996. The four elements described above, the laser, fiber, fiber chuck, and the HSLG, replace 5 glass optical components and their mounts used in the previous WRAIR systems. They have allowed DCS to reduce the size of the laser projector from a tube approximately 4 feet long to a small box approximately 1 foot on a side, which could be reduced further if several components were to be redesigned. The HSLG increases the system's reliability and ruggedness and makes it vastly easier to align and service.

The stabilized laser diode is a system developed by the Fiber & Electro-Optics Research Center at the Virginia Polytechnic Institute to DCS' specifications. Currently, the mapping system uses a 10 mW Helium-Neon gas laser, which is contained in a 2-ft long x 2" wide cylinder (visible on the underside of the laser projector in Figure 3). HeNe lasers meets the laser projectors' stringent beam quality requirements: long coherence length, stability over time, and a Gaussian beam profile. However, due to their gas-filled laser tubes, they are fragile, large, and have a relatively short lifetime. Ideally, the laser projector would utilize a solid-state diode laser, but most such meet none of the beam quality requirements. The F&EORC took a high-quality laser diode and designed an electronic beam stabilization system to bring its output up to DCS requirements. They also coupled the laser to an optical fiber with maximum efficiency. The resulting laser will allow DCS to reduce the size of the laser projector by a factor of 2 while increasing the output power by 50%, and will also greatly increase the reliability of the system.

I. Results (as of 30 November 1995)

A. Goals Achieved

As of 30 November, DCS achieved the goal of a functional mapping system. The system will map a target, rotating it around 1 axis and translating it along 2 as required to obtain adjacent fields of view, and joining the resulting maps together into a single output file. The system calibrates itself in a semi-automatic fashion using a calibration target built into the target translation stages.

The mapping system can acquire data from a single field of view (the area on the target surface encompassed by the projected laser array and viewed by the video camera) in approximately 0.8 seconds. Computing the 3-D maps takes approximately 60 seconds per field of view. The system will translate the motion stages to the next position, so that adjacent fields of view may be tiled, while the mapping computations are taking place.

With a 2" x 1" field of view, a typical setting, the system resolution is on the order of 30 mils vertical (distance between stripe centers) 5 mils horizontal, with overall system accuracy on the order of +/- 10 mils. The accuracy is limited at present by several factors, especially the machining accuracy on the calibration target and the limited error correction and filtering done in the mapping calculations.

B. Obstacles Overcome

Aside from the normal challenges of programming a complex computer system, there were three main obstacles which had to be tackled to make the mapping system function. To begin with, although the basic algorithm behind the mapping calculations is fairly well understood, the actual numerical calculations are extremely complex, especially during the calibration of the system. The process involves the least-squares solution of a very large set of over-determined equations and to write code to do this would have added months to the process. Fortunately, there are commercially available software libraries which may be utilized. Unfortunately, the first such library that we chose had not been fully tested by its creators; it did not work properly, and we spent several weeks tracing the problem and determining that it was caused by the library itself (and not our calls to it). After some further investigation, we purchased a numerical computations library published by the Numerical Algorithms Group of Downers Grove, Illinois, which proved to be most satisfactory.

The second obstacle, or set of obstacles, involved working with the two co-processor boards in the system. The video acquisition/processing board contains a Texas Instruments DSP, and does the image processing portion of the mapping calculations - relieving the host Pentium processor to do other tasks (primarily monitor and update the user interface). Similarly, the 4-axis motor control board which drives the translation stages contains an on-board processor and requires only a desired end position from the host processor to initiate a stage movement. Although both of these boards were purchased from reputable companies, they are both state-of-the-art and presented the usual difficulties. Making them work satisfactorily was mostly a matter of plowing through and thoroughly understanding the instruction manuals, obtaining several software updates from the manufacturers, and making calls to technical support.

Our final major obstacle was more of a theoretical problem, and for a while it threatened the entire project. For reasons not fully understood, but having to do with the nature of the materials used, the SLM itself introduces a certain amount of noise into the laser pattern. adjacent stripes in the laser array should pass directly through the center of the transparent stripe electrodes on the modulator, each electrode acting as an invisible window for that stripe - there should be no further optical effect. Unfortunately, where the transition from an off-stripe to an on-stripe (as the pattern is viewed on the target surface) should be very abrupt, it turns out to be smeared. When the pattern projected is one with alternate lines on and off, the pattern is smeared beyond use. A cylindrical lens placed immediately after the SLM solves this problem very well; since the noise introduced by the SLM is much closer to the lens than the origin of the pattern, the noise is spread out very thin, to the point where it is no longer visible to the camera, whereas the pattern is not. (It should be noted that WRAIR apparently has this same problem, with the same solution).

The mentioned problem appeared when we tried to map target with the lens in place. The output map contained an 'S' shaped distortion. The distortion was slight, approximately 50 mils peak-to-peak, but was a greater error than the system should have had, and was too regular to be the anticipated noise. We attempted to compensate for various errors in the system, with no success. Finally, we contacted a Dr Elisha Sacks at the Purdue University. Dr Sacks is a recognized expert in the mathematics of systems such as ours and was able to trace our problem to an unanticipated third-order distortion introduced by the cylindrical lens. He was also able to help us develop a fairly simple method for compensating for the error in software. Following implementation of this method, the mapping system yields satisfactory results.

II. Future Plans

Having developed a functional prototype capable of giving a good demonstration of the system's potential, DCS intends to improve the performance of the prototype system and to explore new technologies and techniques that will offer even better performance. Among the avenues to be explored are enhanced algorithms, to include better ways of finding the centers of the laser array lines and more powerful noise reduction; automation of the mapping process so that the computer can determine the best position of target relative to the laser array and camera and also if any portion of a complex target has been missed; the use of parallel processing to reduce the calculation time (the ultimate goal being to process the maps as fast as they are acquired); a laser projector capable of generating and modulating a larger array (we believe that a minimum of 256 lines is required for a viable commercial product, 1024 lines would be ideal); and a better Holographic Structured Light Generator, with lower noise and better efficiency.

DCS is now in the process of finding potential customers for the Areal Mapper. Due to the large number of competitors and DCS' limited experience (to date) in the commercial marketplace, we have determined that our best approach is to become a vendor and sell components of the system to existing OEM's (Original Equipment Manufacturers) for incorporation into their systems. We have discovered that this is an ideal time for this as the current technologies, single-point laser probes and laser-line scanners, have reached their limits; the market is ripe for a technology that can extend the acquisition rates of non-contact 3-D mapping.

To date, DCS has contacted two companies: Laser Design of Minneapolis, Minnesota, and Apeiron of Bloomington, Minnesota. Laser Design makes a variety of large mapping systems, mostly for the

automotive industry, but also for general reverse-engineering use. Apeiron specializes in devices for quality inspection of screw and bolt threads. Both companies have shown interest and have requested further information. By the first week of December, 1995, DCS will deliver to each of them a written description of the system, a video tape showing the prototype in operation, and example maps of a sphere and a plate. We will be attempting to similarly contact other potential OEM customers shortly.