PANORAMIC IMAGING SYSTEMS FOR NONDESTRUCTIVE EVALUATION

by

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Abstract

This paper reports on new developments in panoramic imaging and their application to nondestructive evaluation for aerospace requirements. The associated systems, which rely on a unique panoramic annular lens, are designed to provide new inspection capabilities for the Space Shuttle Main Engine, Space Station Freedom, and the manned expeditions projected by President Bush as part of the Space Exploration Initiative.

Introduction

Nondestructive evaluation techniques, routinely applied for decades to measure, analyze, and predict material behavior, are constantly changing in response to emerging technologies. This is particularly true in the aerospace industry where nondestructive evaluation is critical to ensure safety, reliability, maintainability, and quality assurance. Here, new inspection and quality control techniques are often required to evaluate the integrity of advanced designs, many of which consist of geometrically complex components fabricated from advanced materials using complicated manufacturing processes.

This paper describes an innovative approach to optical inspection called radial metrology and outlines steps being taken to design, build, and test prototype systems for panoramic viewing. The report includes a brief history of radial metrology, the characterization of the principles underlying the approach, examples of prototypes developed for aerospace requirements, potential applications for these systems, a brief overview of image processing techniques developed to aid in visual inspection and qualitative analysis, and directions for future research.

Radial Metrology

Radial metrology combines standard optical techniques with a panoramic lens and a computer system. The approach was conceived in 1986 when Professor Pal Greguss of the Technical University of Budapest visited the University of Alabama in Huntsville. Professor Greguss had patented a new imaging block which he called the panoramic doughnut lens.[1] The lens had remained a curiosity since its invention in 1984; prototypes were crude and few in number. While visiting the College of Engineering, Dr. Greguss was introduced to Professor Gilbert who suggested a number of potential engineering applications. As Dr. Greguss left for a VIP tour of the Alabama Space and Rocket Center, he offered to leave one of his lenses with Dr. Gilbert. During the next few hours, radial metrology was brought to practice.[2] Professors Gilbert and Greguss realized that, to produce quantifiable test results that were reliable and repeatable, it would be necessary to fully understand the underlying physical principles of the lens. This would require characterizing its optical properties and discerning the mapping function used to produce images. Dr. Gilbert was subsequently awarded a one year contract by NASA's Marshall Space Flight Center to evaluate these parameters, and worked with Dr. Greguss and Professor D.R. Matthys of Marquette University to produce refined and miniaturized prototypes. The promising results, on what has since become known as the panoramic annular lens

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(PAL), led to a follow-on award for the development of a panoramic system for cavity inspection. Subsequent work has been proposed to apply the PAL for panoramic imaging in space. These applications form the basis of this paper.

The Panoramic Annular Lens

The panoramic annular lens (PAL) consists of a single piece of glass with spherical surfaces that produces a flat annular image of the entire 360 degree surround of the optical axis of the lens. Figure 1, for example, is a photograph taken at the Alabama Space and Rocket Center with the PAL pointed toward the sky and shows the type of imaging that occurs. Clouds are imaged toward the center of the annular image while the ground appears along the circumference. Figure 2 shows some rays traced through the PAL and the location of the virtual image formed by the lens. Since the annular image is formed within the PAL itself, it must be transferred to an image capturing device using a collector lens. The most outstanding attributes of the overall system are that there are no moving parts, the area surrounding the lens can be viewed simultaneously, and the depth of focus extends from the surface of the PAL to infinity.

Figure 1. A photograph of the Alabama Space and Rocket Center taken by pointing a PAL camera toward the sky.

Prototype Development

The objective of work recently completed for NASA was to design, build, and demonstrate a prototype system for cavity inspection. A cylindrical view of the cavity interior was to be captured through a compound lens system which included a PAL. Images, acquired with a digitizing camera and stored in a desktop computer, were to be manipulated using image processing software to aid in visual inspection and qualitative analysis. The project called for the characterization of the PAL imaging system, construction of a prototype for inspecting cavities and acquiring images, the development of techniques for processing PAL images, and the demonstration of a working prototype.

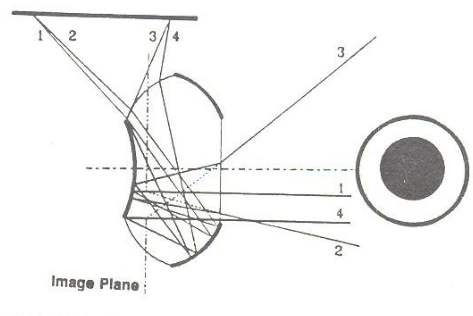

Figure 2. A ray diagram for the PAL.

To accomplish the objective and ensure the availability of the PAL for contractual research and commercial development, Dr. Gilbert founded Optechnology, Inc. The corporation subsequently licensed the patent rights to the PAL and provided a prototype lens system for use on the project. As shown in Figure 3, the system included a 38 mm-diameter PAL and an f/1.4, 25 mm focal length collector lens. The field of view extends from about -20 degrees behind the lens to about 25 degrees in front of the lens; optics were packaged with a standard "C" mount so that the system could be attached to a standard video camera.

OPTEC-II, a commercial lens design program, was acquired and adapted to obtain a detailed knowledge of the optical properties of the PAL and its associated collector lens. Application of the lens design program to the analysis of the system helped to evaluate overall performance. Tests were conducted to study aberrations, resolution, and spectral bandpass.

Problems of illumination were also addressed. Figure 4, for example, shows the prototype adapted for visual inspection. In this example, the lens system is surrounded by a ring containing a number of discrete light sources for illumination within a cavity. The PAL prototype is mounted on a standard CCD camera (Pulnix TM-845) having a resolution of 512 x 512 pixels. The hardware platform selected for acquiring and storing images was an 80386 microprocessor running on a standard AT bus under the MS-DOS operating system (Dell System 310). Images are acquired by a standard commercial frame grabber and processor (Matrox MVP-AT) and stored in the Dell 310 computer.

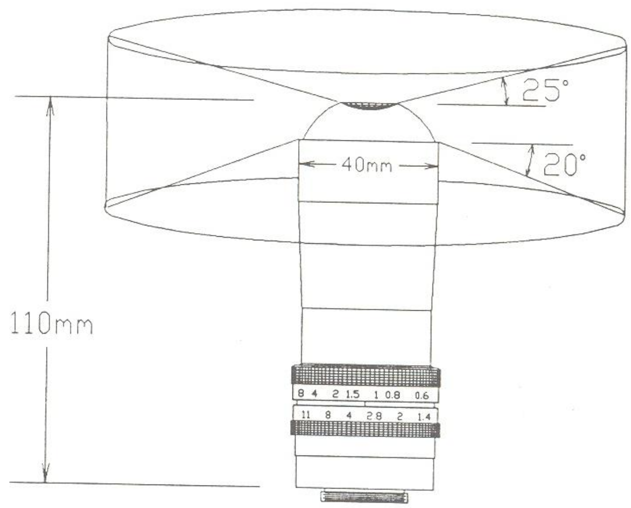

Figure 3. The dimensions and field of view a 38 mm-diameter PAL imaging system. Figure provided courtesy of Optechnology, Inc., Huntsville, Alabama.

The 386-class machine has a clock speed comparable to a main frame, yet it is designed to operate in the work area without the need for specially controlled operating environments, it is relatively inexpensive, mass storage is very cheap, parts are readily available world-wide, and the bus architecture allows for integration and intelligent control of user-supplied boards.[3] Digital image storage permits signal-to-noise enhancement algorithms to be applied to eliminate, or at least greatly reduce, undesirable signal contaminants. The computer's archival capability facilitates further analyses by several individuals and by different software algorithms, without the need for repeating the inspection. Images and their salient features can be readily compared to data recorded in other inspections, automated data analysis is possible, and independent third party evaluations can be made without relying on the expertise or subjective evaluation of a single investigator.

Figure 4. A ring of lights may be used to surround a PAL system for illumination within cavities.

Figure 5 illustrates a number of these attributes. It shows a reconstruction of the digital image acquired and stored when the prototype, shown in Figure 4, was positioned along the axis of a cylindrical pipe, the interior surface of which is covered with a test pattern. Even though details are recognizable, direct visual interpretation of the PAL image is often difficult for the unskilled observer. With this in mind, an algorithm was developed to allow the annular images to be linearized for viewing purposes. This was accomplished by 'rolling' the annular image along its outer circumference and moving all the pixels between the contact point and the center of the image to an appropriate location on a vertical line in the final rectangular image.[4] Figure 6 shows the result of applying the algorithm to the fourth quadrant of the image shown in Figure 5.

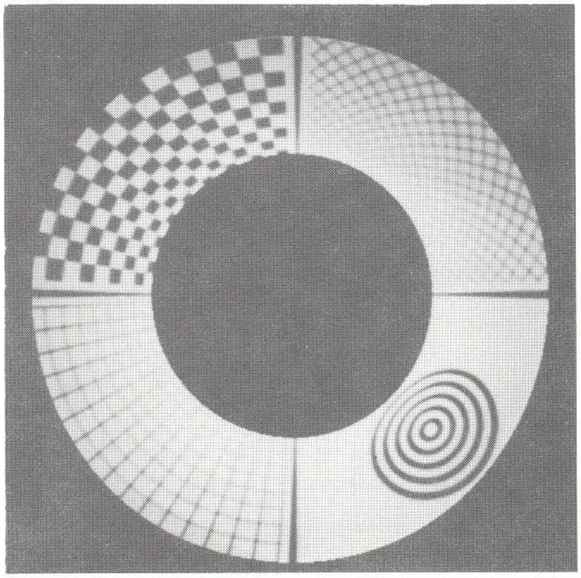

Figure 5. The image obtained when a PAL is positioned along the axis of a cylindrical pipe, the interior of which is covered with a test pattern.

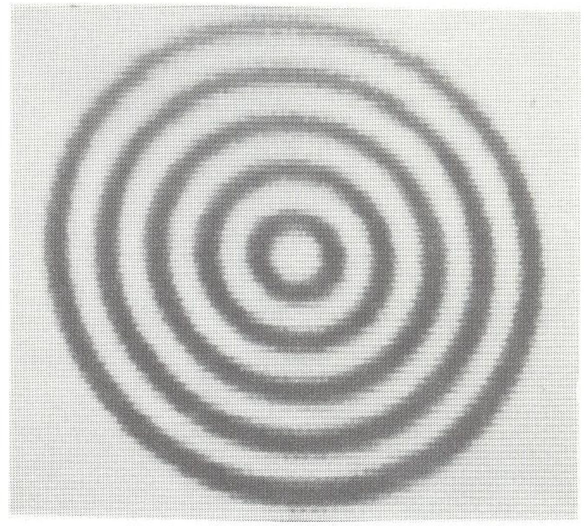

Figure 6. Linearized version of the fourth quadrant of the image shown in Figure 5.

Cavity Inspection

Potential applications of the inspection system include detection of surface and near-surface cracks in weldments, detection of seams and foldovers in castings, monitoring of wear, and detection of structural failures. These applications are typically encountered in aerospace structures and propulsion systems where many components, designed to function at high temperatures and pressures, must be periodically inspected to avoid catastrophic failures.

For example, a visual inspection of the Main Combustion Chamber (MCC) throat of the Space Shuttle Main Engine (SSME) is required during manufacture, after each test firing, and as part of refurbishment between missions. The temperature is hottest in this region and periodic inspections are performed in an attempt to detect crack initiation, to monitor crack growth, and to observe surface roughness. Current inspection techniques require an inspector to insert their head into the throat and visually examine the nozzle contour. Cracks must be at least 3.0 inches or longer before they are recorded on a map of the MCC. The application of the PAL system should allow smaller cracks to be detected and, at the same time, eliminate the hazards associated with using support personnel to physically climb up into the nozzle. Moreover, the PAL system may eliminate the need for disassembling systems for inspection of their internal components; thereby, saving time and money. The PAL system may also find practical application in the Space Exploration Initiative. The Earth to Mars propulsion system is projected to consist of space-based engines with the same thrust class as the J-2. After Earth to Orbit delivery of the propulsion system, the PAL system could be used for damage assessment of the large expansion ratio nozzle and the chamber. Both the SSME and the J-2 have been targeted for future work.

Some steps have already been taken to inspect rocket engines; Figure 7, for example, is a photograph of an RL10 engine. Built by Pratt & Whitney, the RL10 has earned its reputation as the United States' most reliable upper-stage engine and has been responsible for launching numerous satellites and spaceprobes on a variety of earth orbital and interplanetary missions. The current engine model, the RL10A-3-3A, powers the Centaur stage of the USAF's newest Expendable Launch Vehicle, the Titan IV. This system will be used to launch a number of heavy payloads for the Department of Defense during the 1990s. Figure 8 shows the panoramic image taken through a PAL system for visual inspection inside the nozzle throat.

Smaller PAL prototypes are currently being developed for use in medical applications to visually inspect internal

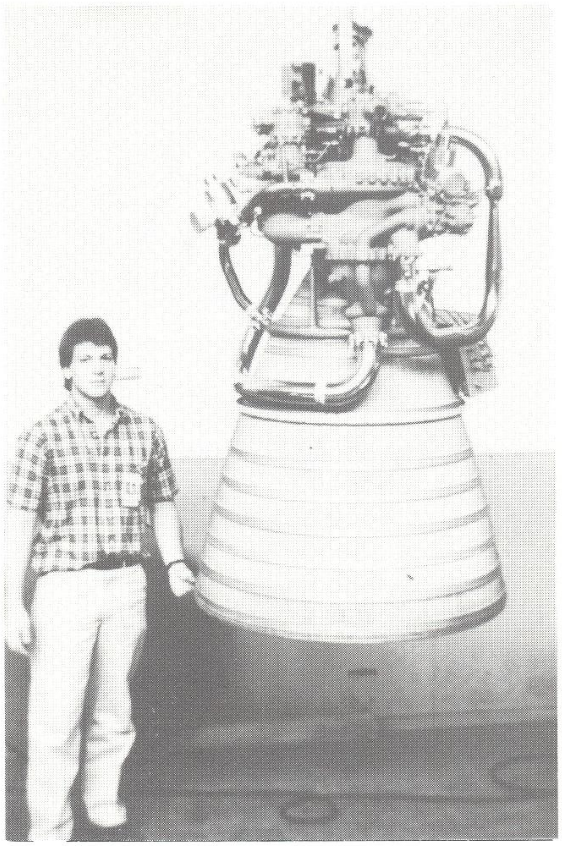

Figure 7. Photograph of an RL10 rocket engine.

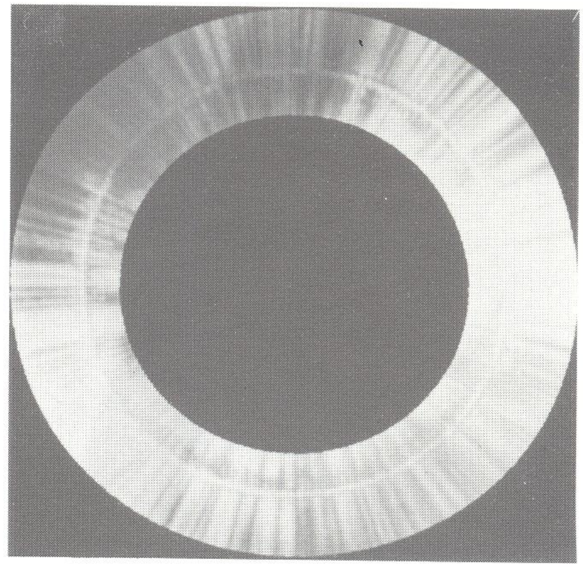

Figure 8. A PAL photograph taken inside the nozzle of an RL10. Photograph provided courtesy of Optechnology, Inc., Huntsville, Alabama.

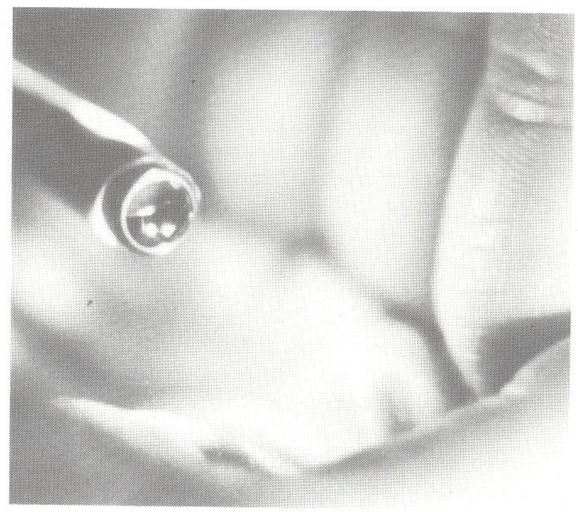

Figure 9. A 6.3 mm-diameter prototype.

organs. Figure 9, for example, shows that a 6.3 mm diameter PAL can be attached to the distal end of a cystoscope. These smaller systems should find widespread applications for nondestructive evaluation of aerospace components. In addition to those mentioned earlier, many of the critical components of the SSME are located in regions that are difficult to reach and inspect. A typical example is the LOX heat exchanger, which contains four tubing welds. Flaws may result from lack of penetration in the original weld, and cracks may be induced in these locations by forming, or by low cycle fatigue during service.[5] The most difficult weld to access is located approximately 30.6 in. (0.78 m) from the inlet, through tubing 0.190 in. (4.83 mm) ID, past a 90 degree, 0.69 in. (18 mm) radius bend, and approximately halfway around a loop 16.5 in. (42 cm) diameter. Efforts to miniaturize the PAL and adapt it to a flexible boroscope may ultimately lead to the development of a practical working instrument for inspecting these components in the field through existing ports with minimal inspection effort.

Panoramic Imaging

In addition to ground based monitoring and performance evaluations of aerospace components, PAL systems are being targeted for use in the space operating environment. Figure 10 illustrates a preliminary design for a panoramic

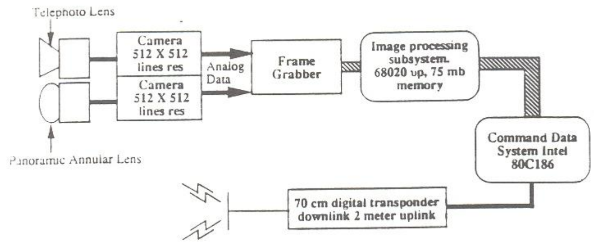

Figure 10. Schematic diagram of SEASIS.

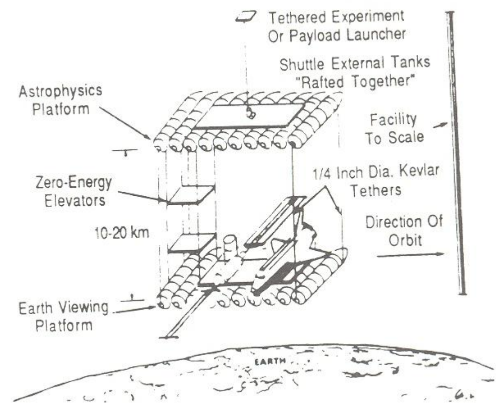

Figure 11. A space platform showing various tether applications.

imaging system called SEASIS. The imaging system will be contained in an endmass to be deployed via NASA's Small Expendable Deployer System (SEDS) from the second stage of a Delta II launch vehicle via a 40 km-long tether.[6,7] The panoramic images recorded during the mission will be incorporated with data gathered from a three-axis accelerometer to study tether dynamics. This information will be valuable, since tethered systems will be used in many space based applications including the construction and use of relatively large tethered platforms. Figure 11, for example, shows a configuration which utilizes Shuttle external tanks in a raft format to form a structure in space.[8] In this example, tethers are used as structural elements in an evolving Space Station and for links (power, data transfer, etc.) between different platforms designed for various science and applications purposes. Some of the platforms would take advantage of the facilities of the station for maintenance and repair while being isolated from contamination and mechanical disturbances. Others could be used to facilitate storage of liquid propellants and dangerous fluids, to provide a variable/controlled gravity environment for materials processing, or to study long-term effects on humans. In the future, PAL systems may be used to establish accurate frames of reference for such space based construction.

PAL systems may also be valuable for in-space inspection of space-assembled structures, deployed structures, and manned systems. A typical monitoring sequence may include characterization of defects or alignment of subsystems appropriate with mission requirements. The parameters to be monitored may include dimensional precision, and the stiffness or strength of truss members, joints, beams and structural supports. Inspections may be performed to look for cracks or deformation, externally-induced damage occurring as a result of impact from space debris or meteorites, or internally-induced damage such as fatigue or creep resulting from changes in frequency, stiffness, or temperature.

Other applications may include detection or characterization of flaws in composite materials, detection of inhomogeneities in metal castings, determination or verification of internal geometry, assessment of internal configuration and failure analysis support, detection of materials anomalies, determination of structural integrity, development of acceptance criteria for critical components, and impact damage tolerance studies.

A formidable challenge for the future will be to apply radial metrology in space to detect potential major and minor failures of structures and structural elements, leaks, and degradation of systems and subsystems over time and under conditions with which there is a very limited experience base. This challenge is magnified by the constraints imposed by the space environment such as operating in a vacuum and under micro-gravity conditions. Factors influencing the choice of instrumentation will include costs of development, installation, operation, portability, and transportability. The ease of operation, weight, size, sensitivity, reliability, power requirements, and the need for human intervention must also be considered.

Conclusions

New panoramic imaging systems have been designed for nondestructive evaluation of aerospace components. They rely on a unique panoramic annular lens (PAL) which produces a flat annular image of the entire 360 degree surround of its optical axis. The most outstanding attributes of a PAL system are that there are no moving parts, the area surrounding the lens can be viewed simultaneously, and the depth of focus extends from the surface of the PAL to infinity. The annular image may also be linearized for improved human viewing.

PAL systems are currently providing a new inspection capability for the SSME program and are expected to be applied for cavity inspection to verify the condition of space hardware after manufacturing, to perform inservice inspections following ground test engine firings, and to predict potential failure sites during refurbishment between shuttle flights. Current work to evaluate the potential for identifying and locating internal flaws, measuring the depth of surface cracks, comparing design contours to actual part contours, performing automated dimensional inspections, and imaging the relationship of the details in a complex assembly will be of tremendous importance to the space program.

With their unique imaging capabilities, PAL systems may also become an integral part of the Space Station Program and the manned expeditions projected by President Bush as part of the Space Exploration Initiative. As we look to the near-term future in space, they may be used for applications ranging from preforming on-orbit nondestructive evaluation to guiding rovers over the lunar surface.

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