46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-1234

THE APPLICATION OF LINE SCAN THERMOGRAPHY USING MULTIPLE COLLABORATIVE ROBOTS

K. Elliott Cramer[1], Daniel F. Perey
NASA Langley Research Center
Hampton, VA

Joshua L. Brown
Analytical Mechanics Associates
Hampton, VA

ABSTRACT

This paper will present details of a dual collaborative robotic implementation of line scan thermography for the inspection of a complex geometry, composite aircraft fuselage. Line scan thermography is an inspection technique that has proven to be a successful means of rapidly scanning large areas of aircraft fuselage. The technique involves the movement of a line heat source across the outer surface of a large structure followed by an infrared imager at a fixed distance behind the heater. Images of defects in the structure under inspection are reconstructed from measurements of the induced surface temperature variations. An overview of the line scan thermography technique along with the robotic implementation, details and inspection results will be presented.

Keywords: Thermography, robotics, composites

1. INTRODUCTION

In recent years, the aerospace community has increased the use of composites in aeronautic and space vehicles. As demonstrated by the Boeing 787's use of composites, NASA's Composite Crew Module and liquid hydrogen cryogenic tanks, there is a push toward the use of composites for primary structural components. As these composite structures become larger and more complex, nondestructive evaluation (NDE) techniques capable of quantifying and characterizing damage are needed. NASA's Advanced Composites Project (ACP) is collaborating with members of the aerospace industry to reduce the timeline to develop and certify composite structure for commercial and military aeronautic vehicles. NASA and industry have identified three focus areas, or technical challenges, as having major impact on the current certification timeline. One focus area, Technical Challenge (TC2) - Rapid Inspection, is concerned with increasing the inspection throughput by the development of quantitative and practical inspection methods, data management methods, models, and modeling tools. One of the objectives in TC2 is to develop tools for rapid quantitative characterization of defects. The adoption of composite materials in aircraft manufacturing for use in structural applications continues to increase but is still relatively new to the industry and has relatively large development and certification costs in comparison to metallic structures. Traditional methods of nondestructive evaluation (NDE) used for isotropic materials such as metals may not be adequate for composite applications and is a contributing factor to the cost and complexity of developing new structural composites. Additionally, the defects of interest in composite materials are significantly different from metals. In order to increase the rate of inspection for large, complex shaped composite structures, current research at NASA Langley Research Center is investigating the use of collaborative robots (COBOTS) for autonomous inspections.

Industrial robots have been used increasingly in production for over five decades in widely varying applications, ranging from spot welding in the manufacturing of automobiles, to the pick-and-place operations in the packaging industry. The successful deployment of millions of industrial robots has traditionally relied on a number of factors: on repeatability as a tool to achieve consistent quality, on the speed and force they make available to manufacturing processes, on the flexibility brought about by programmability, on the possibility to delegate hazardous production tasks to machines to a greater extent, and also on the reduction of the manufacturing work force. In addition, since robots as a rule are hazardous machines that require safeguarding against human intervention, investments in protective guards and safety equipment are non-negligible. The floor space use of a fenced robot installation is also associated with increasing costs for real estate [1]. Historically, the costs associated with typical industrial robots have precluded their application to NDE techniques, except in rare high volume production situations.

[1] Contact author: k.elliott.cramer@nasa.gov

On the other hand, a collaborative robot is specifically designed to be low cost and share workspace with human labor. This leads to a significant reduction in floor space and safety requirements which makes these robots more attractive for NDE applications. In most cases, robotic implementation simply replaces the manual movement of an inspection transducer or system over the structure, with an automated one. While this implementation achieves modest improvements in inspection efficiency, a collaborative and continuously moving inspection system has the potential to substantially decrease inspection times while allowing inspection processes to proceed alongside production processes, compounding the benefits to production efficiency.

2. EXPERIMENTAL APPROACH

Line scanning thermography (LST) is a dynamic thermography technique which has been successfully applied to the inspection of metallic surfaces and composites. In LST, the heat source moves across the sample's surface at a constant speed and an IR imager records the temperature changes on the surface during the heating protocol. The IR detector moves at the same surface velocity as the heat source, and the imager's field of view is adjusted to image the cool-down region behind the heat source. The temperature recorded is used to analyze the cooling behavior after heat deposition, allowing the detection of defects or material property changes. This technique is more conducive to robotic implementation, enabling rapid interrogation of very large surfaces. [2-8].

In most of the applications of LST, the camera and heat source are fixed together with a defined separation distance, and then moved by a single robot over the surface of the specimen. This configuration works well when the specimen is flat or has a constant radius of curvature. However, when the specimen has varying degrees of curvature along the scan path, attempting to perform LST in this manner can lead to several problems such as uneven or poor heating and a changing camera field of view relative to the surface. In order to better accommodate varyingly curved specimens, such as an actual aircraft fuselage, the heat source was spatially decoupled from the infrared camera using 2 COBOTS working in tandem. This allows both the heat source and the camera to follow the contours of the surface while maintaining both a constant speed of inspection and constant spatial separation with respect to the scan surface. The COBOTS used were Universal Robots model UR10 with a 10 kg payload capability. To extend the effective reach of the COBOTS they were attached to a 3.9 m long linear stage. For this demonstration the linear stage was used only to move the COBOTS to one of four fixed positions (or stations) along its length, next a LST scan was performed (keeping the linear stage stationary) and then the COBOTS were translated to the next station.

Figure 1 shows the dual COBOT system performing an inspection of a graphite epoxy composite fuselage section. The specimen is the forward fuselage of a Hawker 4000 business jet. The heat source is a Research, Inc. LineIR series (model 5194-05) 12.7 cm long, water cooled quartz lamp that uses an elliptical mirror to form a line of heat on a surface 50mm away. The lamp intensity is controllable and will produce a maximum heat flux at the surface of 78.75 W/cm. The infrared camera is a FLIR A655sc microbolometer, sensitive in the 8 – 14 µm wavelength range. The infrared camera has an array of 640 x 480 pixels, with a detector pitch of 17 µm, a maximum frame rate of 50 Hz and a noise equivalent temperature difference < 30 mK.

FIGURE 1: DUAL COLLABORATIVE ROBOTS INSPECTING A COMPOSITE AIRCRAFT FUSELAGE USING LINE SCAN THERMOGRAPHY.

In order to program the COBOTS to follow the contours of the aircraft surface, a Creaform Metrascan 750™ Elite 3D optical scanner was used to produce a 1mm resolution solid model of the specimen. This model is used to plan the scan path of the COBOTS, keeping both the heat source and the camera normal to the surface and at a fixed separation relative to the inspection surface throughout the scan. Figure 2 shows the optimized scan path for a portion of the fuselage specimen modelled from the optical scanner. This is one of four stations along the length of the linear stage.

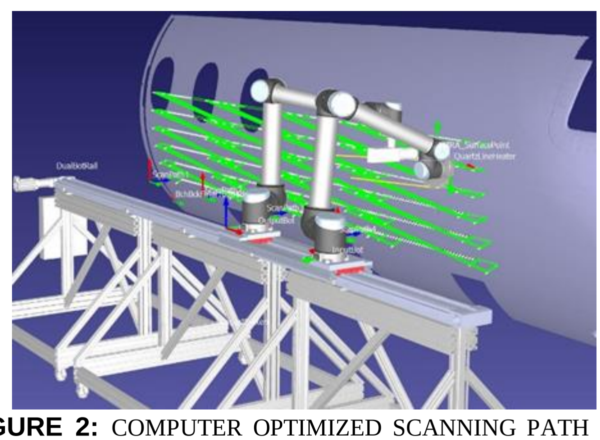


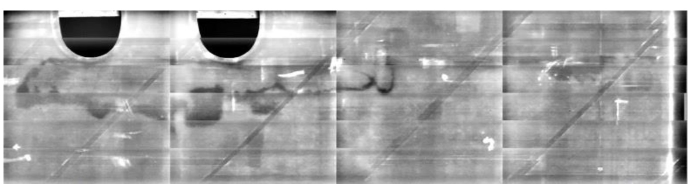
FIGURE 2: COMPUTER OPTIMIZED SCANNING PATH FOR FUSELAGE SECTION.

3. RESULTS AND DISCUSSION

The digital data from the infrared camera was acquired and stored at rates up to 50 frames-per-second using the control computer. The camera moved with the heat source, enabling data acquisition at a fixed surface distance behind the source. From a set of acquired images, a single image was then reconstructed to represent the induced temperature change at a fixed surface distance from the heat source. The reconstructed image is typically 480 pixels high and approximately 5000 pixels wide (depending on the physical length of the scan). This reconstruction is currently done either in real-time by the control computer, or as post-processing analysis of the data. All of the data presented here were collected at 50 frames/s with a scan speed of 105 mm/s and reconstructed in the manner described.

Figure 3 shows a comparison of flash thermography with LST results from the scan of an area of the fuselage specimen 1m in height by 3m in length. Figure 3(A) was produced using conventional flash thermography, and is a mosaic of approximately 40 images. The flash thermography data was analyzed using Principal Component Analysis (PCA) [9-10]. Figure 3(B) is a mosaic of 24 LST scans over the same region of the aircraft fuselage. It should be noted that performing the LST inspection took a total of 8.5 minutes, 10x faster than manually performing flash thermography on the same region. Additionally, the LST inspection was more than 2x faster than using a single COBOT to robotically position the flash thermography system and inspect the same region.

(A)



(B)

FIGURE 3: COMPARISON OF FLASH THERMOGRAPHY WITH LST RESULTS FROM THE SCAN OF AN AREA OF THE FUSELAGE SPECIMEN 1M IN HEIGHT BY 3M IN LENGTH.

4. CONCLUSIONS AND FUTURE DIRECTIONS

We have demonstrated the use of multiple low-cost collaborative robots to perform rapid inspections on a composite aircraft fuselage. The demonstration included scanning a cylindrical acreage section (1m x 3m) in approx. 8.5 minutes. The results of the LST inspection qualitatively compare well with conventional flash thermography, but achieve a 10x improvement in inspection speed. Additionally, the scanning efficiency could be increased by translating the robots during the inspection period instead of moving station to station between scans. Finally, because of the positional accuracy and repeatability of the robotic system we have been able to readily map the thermography data directly to a solid model of the structure.

For this work, the data from the LST system was processed to represent the induced temperature change at a fixed surface distance from the heat source. In the future additional analysis methods that take advantage of the data acquired at multiple observation points behind the heat source should significantly improve the results and allow for quantitative analysis. One such analysis method could involve reconstructing a series of images from the data acquired, each image at a different distance from the heat source. These images could then be treated as a time series and variations in the heat propagation rates could be explored by such analysis methods as time derivatives or PCA.

ACKNOWLEDGEMENTS

This work was performed under NASA's Advanced Composites Project.

REFERENCES

[1] Fryman, Jeff, and Björn Matthias. "Safety of industrial robots: From conventional to collaborative applications." ROBOTIK 2012; 7th German Conference on Robotics. VDE, 2012.

[2] Woolard, Deonna F., and K. Elliott Cramer. "Line scan versus flash thermography: comparative study on reinforced carbon-carbon." Thermosense XXVII. Vol. 5782. International Society for Optics and Photonics, 2005.

[3] Cramer, K. Elliott, and William P. Winfree. "Thermal characterization of defects in aircraft structures via spatially controlled heat application." Thermosense XVIII: An International Conference on Thermal Sensing and Imaging Diagnostic Applications. Vol. 2766. International Society for Optics and Photonics, 1996.

[4] Peeters, Jeroen, et al. "Optimised dynamic line scan thermographic detection of CFRP inserts using FE updating and POD analysis." NDT & E International 93 (2018): 141-149.

[5] Khodayar, Fariba, et al. "Parameter optimization of robotize line scan thermography for CFRP composite inspection." Journal of Nondestructive Evaluation 37.1 (2018): 5.

[6] Ibarra-Castanedo, C., et al. "RITA-Robotized Inspection by Thermography and Advanced processing for the inspection of aeronautical components." 12th International Conference on Quantitative InfraRed Thermography. 2014.

[7] Peeters, Jeroen, et al. "Optimised dynamic line scanning thermography for aircraft structures." Quantitative infrared thermography (2018): 687-695.

[8] Ley, Obdulia, et al. "Assessing impact damage on composites using line scanning thermography." Advanced Materials & Processes 170.6 (2012): 20-25.

[9] Winfree, William P., et al. "Principal component analysis of thermographic data." Thermosense: Thermal Infrared Applications XXXVII. Vol. 9485. International Society for Optics and Photonics, 2015.

[10] Rajic, Nikolas. "Principal component thermography for flaw contrast enhancement and flaw depth characterisation

in composite structures." Composite structures 58.4 (2002): 521-528.