Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 16 (2014) 9 – 14

www.elsevier.com/locate/procedia

Product Services Systems and Value Creation. Proceedings of the 6th CIRP Conference on Industrial Product-Service Systems

Service knowledge capture and reuse

R. Roy*, J. Mehnen, S. Addepalli, L. Redding, L. Tinsley, C. Okoh

EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services
Manufacturing and Materials department, Cranfiled University, MK43 0AL, UK

* Corresponding author. Tel.: +44 (0)1234 758555; Fax: +44 (0)1234 758292. *E-mail address:* r.roy@cranfield.ac.uk

Abstract

The keynote will start with the need for service knowledge capture and reuse for industrial product-service systems. A novel approach to capture the service damage knowledge about individual component will be presented with experimental results. The technique uses active thermography and image processing approaches for the assessment. The paper will also give an overview of other non-destructive inspection techniques for service damage assessment. A robotic system will be described to automate the damage image capture. The keynote will then propose ways to reuse the knowledge to predict remaining life of the component and feedback to design and manufacturing.

Keywords: Service damage identification; degradation analysis; pulsed thermography; non-destructive inspection

1. Introduction

Industrial product-service systems aim to shift through-life engineering services [1] responsibility and risks to the manufacturers. Manufacturers of long life and complex engineering systems are looking to improve the design and manufacturing of their products to reduce the service cost, in order to improve their profitability. The design and manufacturing for service is becoming essential for the industrial product-service systems [2]. The most common approach is to utilize the service knowledge from similar products to improve the design and manufacture of the new products and associated services, such as maintenance. Service knowledge is defined as the processed information and experiences of the service personnel gained through their service related activities. The knowledge will include assessment of the current health of a component or system in service and the operational and service history. This paper presents an outline of the service knowledge capture approach developed within the EPSRC Centre at Cranfield University and ideas to reuse the knowledge for design and manufacturing of aerospace components.

Service knowledge capture and reuse is of significant importance especially with high-value components within the aerospace industry due to the associated high maintenance cost relating to component replacement and/or refurbishment. Thus there is constant need to collect service information to critically assess component degradation during maintenance. This keynote paper presents a novel approach to capture service damage knowledge of an individual component using thermographic inspection, automated robotic thermographic inspection and image processing which will perform root-cause analysis for the degradation identified thereby identifying new relationships between component degradation, initial system design, and manufacturing process used. The research will produce new knowledge on dependencies and will capture design and manufacturing rules to extend the life of the component.

Infrared thermography has become the condition monitoring tool gathering additional interest in the field of advanced NDT methods [3]. With faster inspection, data

doi:10.1016/j.procir.2014.03.001

processing and lower equipment costs, thermography has found its way into traditional NDT methods, however has not been fully incorporated to inspect high-value components. Currently thermography is being used to detect subsurface damages such as cracks, delaminations, disbonds, voids, inclusions or water ingress in advanced materials mainly in composites [4].

The EPSRC Centre for Through-life Engineering Services at Cranfield University is currently developing automated NDT techniques to quantify service damages occurring in high-value components that will predict the remaining life of the component. This paper presents the automatic thermography inspection using a robotic arm.

The EPSRC Centre:

The £11.15 million National EPSRC Centre (including £5.7 million from EPSRC) for Innovative Manufacturing in Through-life Engineering Services provides world-class capability in the UK to enable industry to deliver high value products with outstanding availability, predictability and reliability with the lowest life cycle cost. The EPSRC Centre vision is to provide thought leadership in through-life engineering services and be the first choice for UK manufacturing companies as a source of technological solutions, R and D capability, knowledge, skill and advice.

As a part of the center's activities, the following are the major projects being taken up by the center:

- Characterization of **in-service component feedback** for system design and manufacturing
- Reduction of **no-fault found** (NFF) through system design
- Improvement of **system design** process for whole life cost reduction
- **Self-healing technologies** for electronic and mechanical components and subsystems
- **Collaborative Autonomous Robotics for Maintenance**

2. Service knowledge capture and reuse: current research and industry practice

The role of service knowledge for product-service systems is recognized by Baxter et al. [5], Goh and McMahon [6]. Baxter et al. presented a framework to inform design with service requirements purely based on human expert assessment. Goh and McMahon argue that continuous improvement for product-service systems depend crucially upon the implementation of effective knowledge and information management systems within a dynamic learning environment across the product lifecycle. The paper does not address any automatic knowledge capture approaches for effective knowledge capture. There are other authors who focused on intelligent monitoring and algorithmic approaches for the service knowledge capture [7][8]. The knowledge obtained through the monitoring was used to optimise maintenance schedules, but did not feedback to improve the design or manufacturing.

Through a recent study at the EPSRC Centre in Through-life Engineering Services, it was observed that the interfaces between the design and service and manufacturing and service are still not well developed in industry. It was observed that the communication between the functions is very much dependent on occasional meetings and individual initiatives. Figure 1 shows high-level communication between design, manufacturing and service functions.

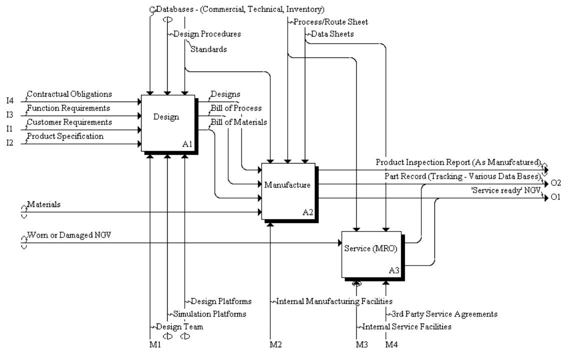

Figure 1: First Level Decomposition of IDEF0 Process Model for Design, Manufacture, & Service of an Aerospace Component

This paper presents approaches to automate the service knowledge capture using a quantitative approach and discusses opportunities to reuse the knowledge. The research is based on detailed case studies with aerospace and railway components.

3. The automated knowledge capture approach

The automated knowledge capture approach analyses the thermal images of service damage on a component and verifies the results with other non-destructive testing techniques if appropriate. An integrated system to automate the service damage capture is also developed using a robot. For inaccessible areas, a borescope is designed for railway axle internal service damage examination. From literature it has been noticed that the most common degradation mechanisms for aerospace components are wear, cracking, fatigue, and corrosion (Figure 2).

Figure 2: Image of aero-engine component exhibiting typical damage.

This project will capture component failure, damage and degradation using 3D surface scanner to identify surface features including cracks and a pulsed thermography system to detect near and sub-surface damage such as delamination, impact damage, corrosion and disbonds. In order to gain confidence in characterizing the damage, both near and sub-surface, the acquired inspection data will be compared against X-ray CT inspection data which is currently being used as a standard technique in the industry. Novel algorithms will then be used to combine data from different inspection methods which will then help identify damage features such as wear, fatigue, cracking and corrosion. Through this research, it is hoped that a link between the initial system architecture and service performance will be established which will in turn provide feedback into system design thereby providing a guidance system for better service life for the component. It should be understood that the ability to effectively and efficiently handle large volumes of complex data might be a huge undertaking as the fusion of such data for better interpretation might be a challenge in itself.

To capture the industrial requirements, a structured survey was carried out to identify key areas (see Table 1) where automated thermographic inspection could be adopted [9].

Table 1. Degradation mechanisms in aerospace components accessible to thermographic inspection [9].

Damage type	Location	Direction	Geometry
Blocked cooling channels	Surface	Area, Surface	Surface breaking
Metal thickness sizing	Sub-surface	Normal to surface	Linear
Detection of internal corrosion product	Sub-surface	Area	Volumetric
Substrate / corrosion differentiation	Sub-surface	Area	Volumetric
Surface coating thickness	Thickness	Parallel to surface	Linear
Surface coating delamination detection	Near surface	Parallel to surface	Linear
Sub-surface oxide layer detection	Near surface	Parallel to surface	Linear
Differentiation between oxide & sulphide product	Surface breaking	Area	Volumetric
Detection of cracks in substrate	Near surface	Normal to surface	Linear

It was noted that currently there are limited inspection routines that use an automated thermographic inspection system and that Thermography isn't used to carry out remaining life prediction model.

The team is also working towards the development of a 'Service lead Design DFMEA' system architecture. The core partner has facilitated the complete mapping of the design, manufacture, and service activities for an aerospace component as a case study, the output of which is presented in IDEF0 and IDEF3 models. The activity map was seen as an essential tool to understanding the inputs, outputs, constraints and mechanisms facilitating each stage of the process. From this the knowledge flowing through the process (model) can be assessed. This level of understanding of the 'AS-IS' condition is seen as a prerequisite for the development of the proposed system architecture and the proposed service design and support strategy.

4. Inspection of components after service

A review of the literature suggested that thermography is a fast, safe, non-intrusive, non-contact, inexpensive technique and thus differs from the current traditional NDT methods including, X-Ray CT imaging, dye penetrant testing, magnetic particle inspection and ultrasonic testing. Furthermore its ability to detect sub-surface features has helped classify thermography as an advanced NDT method. The above mentioned attributes contribute to the use of thermography for the current project.

4.1. Non-destructive testing

Non-destructive testing or NDT is a broad discipline in science that deals with the testing and evaluation of materials and/or components to determine the condition of the component without damaging it. Thus NDT may be understood as a process where a component is inspected during maintenance and is reintroduced back into its working environment without causing further damage to the component [10]. Due to the non-destructive nature, cost benefit and quick inspection results, research and industrial organisations are constantly developing and updating various techniques [11]. Visual, dye/liquid penetrant testing, magnetic particle inspection, radiography, ultrasonic testing, eddy current testing, acoustic emission, vibrational analysis are examples of most common non-destructive testing techniques currently in use [4][11]. Literature suggests that each of these techniques have their own strengths and limitations and that no single NDT technique can provide all the necessary information needed to determine the condition of the component.

4.2. Infrared Thermography

Thermography deals with the acquisition and evaluation of thermal radiation pattern or heat flow pattern which helps assess working environment, condition, performance and/or structural integrity of the component under inspection. Maldague *et al.* [12] define this study process analysing infrared images as Thermography. Literature suggests that thermography is a fast, safe, non-contact technology capable of carrying out large area inspections to detect sub-surface damages in a variety of materials and or components both metal and non-metal [12][13].

There are two major types of thermographic inspection techniques [12]:

- Passive thermography – where the thermal radiation of the component by virtue of its working condition is used to determine the condition of the component.
- Active thermography – where external heat is induced to the component under inspection and a sequence of

measurements are made to determine the condition of the component.

Active thermography techniques include pulsed thermography, lock-in thermography and vibrothermography [11]. Literature and past experiments suggest that to characterise a certain type of damage, it is important to understand the nature of damage to choose an NDT technique. For example, if the service knowledge predicts that the damage is sub-surface then pulsed thermography could help characterise the damage [3][12][13].

Pulse or pulsed thermography (PT) involves the heating up of the surface of the component under inspection with a short pulse of energy and recording the temperature decay of the component over a period of time. Thus this technique is a fast and robust technique that helps determining the condition of the component by characterising the sub-surface features from the sequence of images acquired during the inspection. It should be noted that issues such as reflections, emissivity, non-uniform heating and surface geometry could affect the quality of infrared image obtained [11][12].

5. Quantitative measurement of service damage

Mehnen et al. [9] describe a detailed case study to quantitatively measure the size and depth of service damages on aerospace components. This is the first phase of the automated damage assessment approach. This phase involves the use of pulsed thermography, thermal image processing using Matlab toolbox and then damage sizing and depth calculation. Two Xenon flash tubes provide a pulsed energy burst of around 25 kJ. The IR detector is an uncooled micro-bolometer model Xenics Gobi 384 comprised of 384x288 pixel resolution with a frame rate of ~28Hz. Through trial and error a threshold level is established, to identify the feature regions, as the upper-quartile of pixel value range from line segments intersecting interesting areas of the component. Borders of the feature regions are identified using a boundary trace algorithm [9].

One of the challenges in the image processing is to separate the structural features from the damage regions. The structural features are filtered out from the images using a musk based on prior knowledge about the component. Due to the limitations of the un-cooled thermal camera in terms of noise, a minimum feature size of 2 to 3 pixels is often recommended to classify a feature as a valid detection.

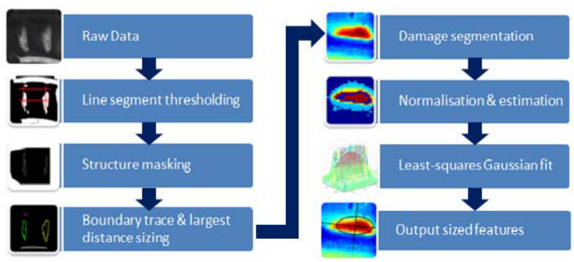

Figure 3: A flowchart for the sizing process [9].

Figure 3 describes the steps involved in the quantitative sizing of the damaged area on the component. By taking multiple images at different angles and against a reference point, damages at different parts of the component could be identified.

A 2D Gaussian surface [9] was fitted using the least-squares technique to each of the damage regions identified by the detection process. The contents of each boundary region were segmented from the parent data, with external values floored to prevent a conflict in the surface fitting. Figure 4 shows that Gaussian fitting works well and provides additional information than the single length measurement for the damaged regions.

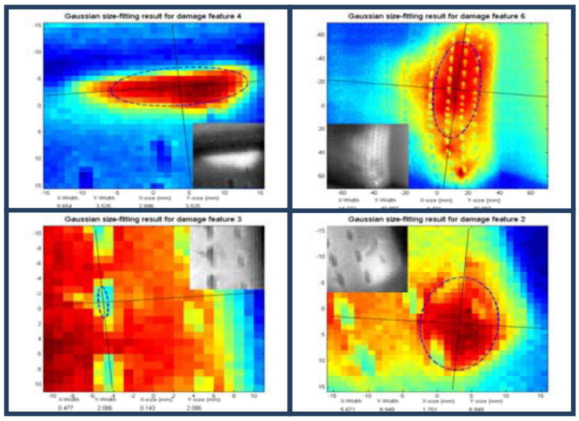

Figure 4: Four damage types auto-segmented for Gaussian fitting, with fit results plotted over the damages [9].

The service damage depth calculation can be simplified as a dependent variable on the material property as [9]:

$$z \approx \sqrt{\pi \alpha t^*}$$

where z is the depth estimation, α the substrate material property, and t* the time at which the temperature cooling curve is interrupted from linear cooling in logarithmic domain.

6. Automated thermographic inspection

The experimental setup includes a commercial Thermoscope with an IR camera to capture thermal images, and a robotic arm to present components repeatedly to the inspection system or move the camera against a stationary large component. This includes post-processing commercial software Mosaiq from TWI Inc., as well as code in Matlab Image Processing toolbox for sizing. The work being discussed in this paper is being performed with a M-20iA robotic arm from the Fanuc Europe Corporation. This setup allows for accurate, repeatable presentation of multiple components to the inspection system (Figure 5), including rapid inspection of large sample batches with high precision of presentation attitude to within 0.1 mm repeatability. For large components the camera is mounted on the robot and it is moved normal to the surface at regular intervals to capture multiple images (Figure 6). Using the commercial system the multiple images could be integrated following a 'mosaic' process.

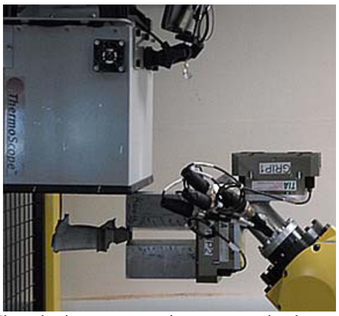

Figure 5: The robotic arm presenting a part to the thermoscope [9].

Figure 6: The robotic arm presenting the thermoscope at multiple regular positions and angle to capture images of a large component.

7. Fixed borescopic inspection

As a part of the project, based on preliminary investigation and survey data from industry, there was a requirement to design a borescopic thermographic system that is capable of inspecting damages occurring in inaccessible areas within a railway axle [14][15]. The rationale behind this project was to reduce time and cost involved to ground, strip and transport the component for inspection.

7.1. The Borescope - prototype

The prototype components are:

- Gold-coated mirror (50.8mm diameter, 12.0mm thickness and >96% reflectance)
- Sodium chloride window (50mm diameter, 5mm thickness and >90% transmissivity)
- Xenics camera (spectral band : 8 -14 µm, resolution: 384 x 288 pixels, pixel size : 25 µm, f/1 lens, focal length: 18 mm, horiz. field of View (HPOV) : 25.5°, NETD : =50 mK at 30° C, uncooled microbolometer)
- Detachable camera, mirror and window to allow the easy maintenance
- Cooling pipe, endoscope, lens protector, axle guides

The final prototype consists of a Xenics Gobi 384 infrared camera screwed to a hollow PVC tube of 68mm diameter and 2m length. The camera is 25mm away from the gold-coated mirror angled at 45º which is also 45º from the sodium chloride window. The mirror is supported by a piece of cork. The window protects the mirror from impurities while a lens protector slides above the camera to allow the lens to be adjusted and protected. The cooling pipe which is integrated with a freezing spray is the mean of transporting the energy excitation source (cold air). The arrangements of these components are illustrated in Figure 7 below.

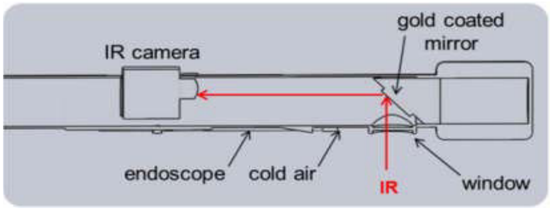

Figure 7: Cross-section of prototype.

The prototype described above was built to be integrated with commercial Mosaiq® software. The software makes it possible to infer the depth of the degradation in addition to detecting the damages in the subsurface.

7.1.1. Laboratory tests

Field visits were made to a railway maintenance site and discussions with technical representatives took place. One of the issues raised was the difficulty in inspecting hollow axles (see Figure 8).

Figure 8: A standard gauge railway axle.

These axles are made with forged steel and are 6 cm thick. Presently, the company uses the ultrasonic test method to inspect these axles. Tests are periodically performed on calibrated gauge axles with known damages to evaluate the performance of this test method. The technical representatives expressed keen interest in changing this method as they perceived its efficiency on the test piece to be random.

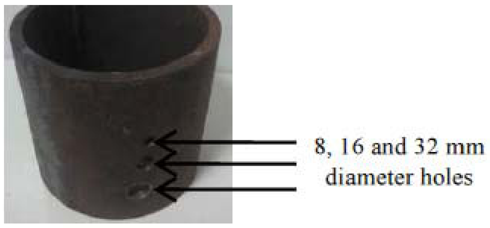

Figure 9: Forged steel round test cylinder.

In order to simulate the axle inside inspection, a 1cm thick steel cylinder was manufactured. This test piece contained holes of different diameters that were machined in the outer surface of the cylinder. The holes are at a depth of 1mm from the inside surface. Two sets of holes were made on the cylinder; one set contained no rust and another with rust. Holes with the same dimensions were made in both parts to see what influence the presence of rust had. The cylinder is shown in Figure 9. The cylinder is 10mm thick, 200mm long and is 90mm in diameter.

Tests carried out on this cylinder produced good results and can be seen in Figure 10 below.

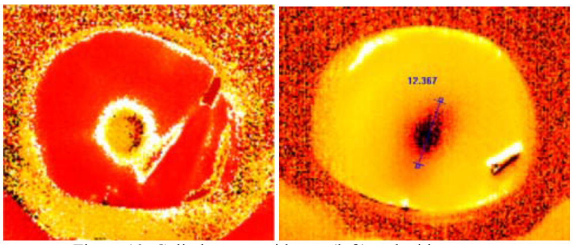

Figure 10: Cylinder tests with rust (left) and without rust.

The experiments show that the results were slightly better in the rusty area (which behaved like a coating) in comparison with the area without rust.

8. **Service Knowledge Reuse**

The automated degradation knowledge capture technique described above produces a quantitative measurement of the damage. This knowledge can be combined with ontology of the degradation and the root cause analysis results to provide a fuller description of the damage. The research proposes to reuse the knowledge, along with the material information, usage information and repair information, through a Product Lifecycle Management (PLM) environment and make it available to the designer as well as to the manufacturer. The ontology will support an intelligent search (terminology recognition) to access the knowledge within the environment. It is also proposed that the knowledge extracted from test cases could also be reused to populate a degradation database that links the material characteristics with the design and manufacturing features and the usage pattern.

9. **Concluding Remarks**

Service knowledge capture and reuse has become more important within the context of industrial product-service systems. It is observed that there is a lack of research trying to understand the nature of the service knowledge and how it could be made available to the designers and manufacturers. This paper presents a quantitative approach to capture the service damage knowledge for a component after service. The knowledge capture uses thermography as a non-destructive inspection technique and image processing for a quantitative assessment of the damage. Automation of the image capture is achieved with a robot and that provides the necessary positional repeatability for multiple images of the same component from different angles. The damage within inaccessible areas can be investigated using a borescope capable of pulsed active thermography. There is a need to design a more flexible and smaller diameter borescope. It is proposed the service damage knowledge can be fed back to the designer and manufacturer using the PLM environment and an advanced search based tool that will allow access to relevant knowledge. Further research is necessary to establish the effectiveness of the knowledge reuse approaches at the design and manufacturing stages.

Acknowledgements

The authors acknowledge the EPSRC and industry partner funding to the EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services. The EPSRC Centre is hosted by Cranfield University and Durham University. Additionally, the support of colleagues in the Manufacturing and Materials Department at Cranfield University is acknowledged.

References

[1] Roy, R., Shaw, A., Erkoyuncu, J. A. and Redding, L. (2013). Through-life Engineering Services. Measurement and Control, vol. 46 (6), 172-175.

[2] Meier, H., Roy, R. and Seliger, G. (2010). Industrial product-service systems – IPS2. CIRP Annals – Manufacturing Technology, vol. 59(2), 607–27.

[3] Maldague, X. (1999, May). *Infrared Thermography and Nondestructive Evaluation*. Retrieved January 26, 2014, from NDT.net: http://www.ndt.net/article/v04n05/irtnde/irtnde1.htm

[4] Widjanarko, T., Tinsley, L., Roy, R., & Mehnen, J. (2012). Characterisation and Performance assessment of a Pulsed-thermography Camera System for component degradation inspection. Proceedings of the 1st International Conference on Through-life Engineering Services, Cranfield, 297-308.

[5] Baxter, D., Roy, R., Doultsinou, A., Gao, J. and Kalta, M. (2009). A knowledge management framework to support product-service systems design. Int. Journal of Computer Integrated Manufacturing, vol. 22 (12), 1073–1088.

[6] Goh, Y. M. and McMahon, C. (2009). Improving reuse of in-service information capture and feedback. Journal of Manufacturing Technology Management, vol. 20 iss: 5, 626 – 639.

[7] Yao, J. and Warren, S. (2005). Applying the ISO/IEEE 11073 standards to wearable home health monitoring systems. Journal of Clinical Monitoring and Computing, 19 (6), 427–436.

[8] Lee, J., et al. (2006). Intelligent prognostics tools and e-maintenance. Computers in Industry, vol. 57 (6), 476–489.

[9] Mehnen, J., Tinsley, L. and Roy, R. (2014). Automated in-service damage identification. Accepted for publication in the CIRP Annals – Manufacturing Technology, vol. 1.

[10] ASNT.org. (n.d.). Introduction to nondestructive testing. Retrieved January 26, 2014, from The American Society for Nondestructive Testing: https://www.asnt.org/MajorSiteSections/NDT-Resource-Center/Introduction%20to%20Nondestructive%20Testing

[11] Ibarra-Castanedo, C., Piau, J., Guilbert, S., Avdelidis, N., Genest, M., Bendada, A., et al. (2009). Comparative study of active thermography techniques for the nondestructive evaluation of honeycomb structures. Research in Nondestructive Evaluation, vol. 20(1), 1-31.

[12] Maldague, X. P. (2002). Introduction to NDT by active infrared thermography. Materials Evaluation, vol. 60(9), 1060-1073.

[13] Minkina, W., and Dudzik, S. (2009). Infrared Thermography, Errors and Uncertainties. Chichester, UK: John Wiley & Sons, Ltd.

[14] Guillebert, V. et al. (2013). Development of a Thermographic NDI System for Service Damage Identification in Inaccessible Areas. Procedia CIRP, vol. 11, 124-129.

[15] Seibel, E. J., Johnston, R. S. and David Melville, C. (2006), A full-color scanning fiber endoscope. Optical Fibers and Sensors for Medical Diagnostics and Treatment Applications VI, vol. 6083, 21 January 2006 through 22 January 2006, San Jose, CA.