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'In-situ' inspection technologies: Trends in degradation assessment and associated technologies

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Abstract

The advent of advanced, innovative and complex engineered systems has established new technologies that are far more superior and perform well even in harsh environments. It is well established that such next generation systems need to be maintained regularly to prevent any catastrophic failure as a result of regular wear and tear. Non-destructive and structural monitoring technologies have been supporting maintenance activities for over a century and industries still continue to rely on such technologies for effective degradation assessment. Maintenance 'in-situ' has been adopted for decades where the health of system or component needs to be inspected in its natural environment, especially those safety critical systems that need in-field inspection to determine its health. This paper presents selective case studies adopted in the area of damage assessment that qualify for both field and 'in-situ' inspection. The future directions in the applicability of traditional and advanced inspection techniques to inspect multiple materials and in the area of inaccessible area degradation assessment have also been presented as part of this study.

Keywords: 'In-situ' inspection, non-destructive testing, degradation assessment

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1. Introduction

Manufacturing in the 21st century has seen technological transformation whereby newer concepts are being adapted not just to increase production but also improve the quality of the product. With the introduction of complex technologies, the industries especially in the aerospace, automotive and locomotive sectors are now focussing on delivering next generation systems that are far superior and intuitive when compared with the age old counterparts. Concepts such as Industry 4.0 are the new drivers that control not just productivity but head to provide those factories of the future where the product quality is the top priority and the product is sold with a confidence factor to the customer, as part of their sales strategy [1] [2]. These concepts are completely data-driven; wherein much of the development has come from the digitisation of those critical manufacturing decisions that improve productivity. The high value manufacturing theme has now been embracing shift in service strategy where the responsibility of the system has fallen back to the manufacturers leading to next generation solutions such as industrial product service systems. Further, the shift in service responsibilities has led to the development of solution based approaches that monitor the whole-life cost of the product [3]. These solutions are based on those critical service decisions that accommodate the continuous and failure free operation of the system extending the life of the product. Thus maintenance is now a key aspect where end-users request for post-sales service packages as part of the sale.

With the ever increasing use of advanced materials into complex systems; the serviceability of the component has now become challenging, particularly in determining their maintenance requirements as dis-assembly and inspection is very expensive. Technologies such as non-destructive testing

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have been gaining importance over the last decade where determining the health of the component and or a system without causing further damage is vital [4]. Techniques such as thermography, ultrasonic testing and 3D x-radiographic computed tomography are gaining importance. However, the key aspect of full automation and ‘in-situ’ in field inspection (where the health of the system is determined in its natural working environment), hasn’t matured in high value manufacturing (HVM) sectors and is currently being investigated to achieve connected factory type concepts [2] [5]. This paper presents those concepts that are currently being developed to address the areas of ‘in-situ’ in field maintenance scenarios capable of monitoring areas having limited or restrictive access.

2. State-of-the-art

Manufacturing technologies have matured over the last century with tremendous progress in developing high quality and high performance products without compromising productivity. The introduction of advanced materials has helped build complex systems leading way to high value manufacturing wherein maintenance requirements are constantly being evaluated and built alongside those developments. The current drive of Industry 4.0 is being derived in the context of digitisation of various activities in traditional manufacturing thereby establishing the next phase in industrial revolution. As part of this next-gen revolution, the concepts that are aiding connected factories of the future are defined with challenges such as large data handling, use of complex analytics, the interface between operator and machine and finally the transfer of digitally developed information into a physical form [1] [2]. With all of these perspectives comes the ability to maintain these systems in field where they are continuously monitored with advanced sensors that provide not just live but also those regular safety critical information that help prevent premature system failure. These activities suggest that regular in-situ monitoring together with digital decision making advanced analytical systems would be the future. Current technologies dealing with concepts of automated and in-situ inspection with the help of robotic probes and arms could improve in-field maintenance activities by characterising the health of the system in a fast and robust manner thereby providing those repair strategy decisions completing the entire maintenance decision activities in-field saving significant inspection downtimes [6] [7] [8].

This section presents the current in-situ inspection techniques covering three industrial sectors; machine tools, materials and transport sector.

2.1. ‘In-situ’ activities in machine tools industry

‘In-situ’ is a term that is widely used to define the location of sensors as part of the system with the capability to provide functional measurements when the system is in its natural working environment. These sensors could be both rigidly placed or placed onto flexible parts that can inspect the system regularly. The measurements made are compared with a good working part so that any deviation in terms of geometry and or performance could be related to degradation and in turn help predict any impeding failure to the system. Vacharanukul and Mekid [9] reviewed various measuring techniques in the context of machine tools where both contact and non-contact methods were identified. Their study identified various limitations caused by both contact and non-contact sensors suggesting the need for an ‘in-process’ non-contact system, that is light, highly accurate, inexpensive and user friendly system.

The study on the sensors for in-process inspection classified the in-situ measurement methods into (a) contact methods and (b) non-contact methods [9]. The sensors for contact measurement are usually housed with the sensing surfaces that are in direct contact with the component. A typical example is a roller calliper measuring the diameter of the roller through friction where the accuracy of measurement is low [9]. The growth of contact based sensors has led to the introduction of highly refined probes with fine contact sensors especially in the machine tools environment where the accuracy is now dependent on the type of material leading to significant improvement in measurement accuracy [10]. Due to the limitations of accuracy and increased instrumentation, non-contact in-situ measurement sensors are being preferred.

A study on early technologies showed that the measurements of work pieces was done by photodiodes and or charge coupled devices (CCD) as early as 1984 and formed part of machine vision techniques where multiple sensors were located in fixed positions to inspect the workpiece [11]. Thus Vacharanukul and Mekid [9] further classified the non-contact methods into four categories (i) optical (ii) ultrasonic (iii) pneumatic and (iv) electrical methods (Fig. 1).

The paper reviewed a range of optical methods in conjunction with the machine vision to present the trend in in-situ measurement techniques. This classification was found to be in line with studies carried out by Yandayan and Burdekin

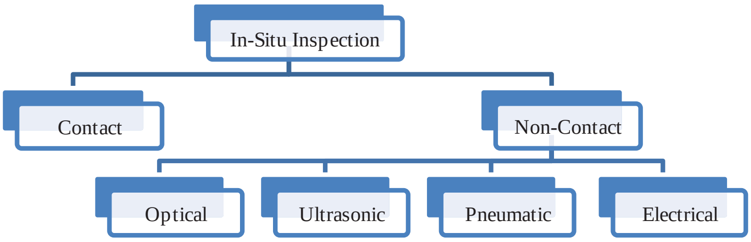

Fig. 1 Flowchart showing classification of in-situ inspection technologies in machine tools industry (based on [9])

where each of the contact and non-contact methods were further classified into direct and indirect methods [12].

2.2. 'In-situ' maintenance of composite materials

Another area which supports the need for in-field maintenance is in the aerospace industry especially with the challenge of composite repair [13]. A recent report by the US Government Accountability Office presented various safety related issues associated with composite based aircrafts [14]. The report highlighted the need for complete understanding of the behaviour of parts made from composite materials and indicated the necessity to inspect primary and secondary structures on a regular basis. A review on in-field composite repair strategies highlighted various challenges ranging from industry concerns, material behaviour, current health and degradation assessment, in-situ repair and supporting technologies that are in current practise. The study further indicated the need to use multiple non-destructive and structural monitoring methods to detect in-situ damage caused during service [13].

Garnier et al [15] studied the in-situ detection of in-service damages caused due to impact onto composite structures. Though visual inspection was used for size and reference, three non-destructive testing techniques; ultrasonic, infrared thermography and speckle shearing interferometry, were used to characterise damage. The studies indicated the suitability of multiple inspection techniques in deducing in-situ damage together with limitations of each of those techniques. On the other side, studies by Abry et al [16] indicated the need for live monitoring of in-situ damage creation with the use of AC and DC sensors that captured the electrical changes in resistance and capacitance when the composite laminates were subjected to loading. The studies concluded that the AC system was suitable to measure cracks and delaminations whereas the DC system was more suitable to identify fracture of fibres.

2.3. 'In-situ' monitoring in transport sector

Growth in advanced technologies globally has contributed to the rise in the application of more robust in-situ technologies such as snake robots, optical borescopes, in-situ x-ray and in-situ eddy current systems. These technologies have been developed primarily to improve and enhance maintenance activities in-situ by providing in-field diagnostics that deliver those safety critical decisions in a timely manner thereby preventing failure of the system together with reduction in huge maintenance costs [17]. The other major advantage of such technologies is the in-field serviceability of parts that may be constrained due to size, accessibility, complex dis-assembly and re-assembly and the cost incurred if they were to be transferred to the inspection facilities. A recent study by Dong et al [6] proposed a novel design of a snake robotic arm system demonstrating the improved stiffness and increased flexibility allowing simplification of cable driven systems. This unique design introduced the use of a twin actuation system to achieve the increased functionality of the snake robot.

In-situ ultrasonic and eddy current inspections techniques have been developed to inspect railroad components such as wheels and gauge corners, where damage could lead to catastrophic failure. With the introduction of high speed trains, the need for in-situ inspections has become very important. A recent study reported that a fully automated inspection vehicle, capable of assessing damage to wheels and gauge corners without having to dismantle the components and inspect them at the locomotives running speed of up to 100km/hr, was developed over a period of two years. Their studied showed clear benefits of in-situ inspection that led to the successful integration of the automated inspection vehicle as a mandatory safety system into Die Bahn AG [18].

If rail industry chose for an automated integrated vehicle system, the aerospace sector has ventured into the use of miniature multi-agent robotic systems, where research is underway to use these multiple robots to inspect and repair the modern day jet engines [19]. The research by Wong and Litt [19] presented current research at NASA Glenn Research Centre where miniature multiple robots are being conceptualised and developed to perform in-situ inspection and repair thereby enhancing the on-wing maintenance of the propulsion systems whereby early detection of damage could prevent failure of the engine. This work was further developed into 'swarm robots' primarily dealing with the design miniaturisation and algorithm refinement to generate pathways. Specific challenges with respect to miniaturisation were raised together with the need for parallel development of in-situ sensors capable of integrating with these swarm robots [20]. Studies were also taken up to perform on-wing inspection with the use of borescopes. Adair et al [21] reported the use of a blending borescope that was capable of producing live images of compressor stage blades and how they relate to a cost saving of up to $360,000.00 per inspection saving significant costs incurred from stripping the engine for inspection.

This paper presents two of those approaches where inspection could be completely automated and could be adapted for in-accessible area inspection.

3. Automated thermographic inspection

This section presents a framework that expands on those technologies that could assess degradations occurring on HVM parts. The framework (Fig. 2) shows a specific assessment process where a HVM part could be sentenced at an early stage such that the repair strategies could be decided at an early stage during maintenance thereby reducing the burden to the operator and to plan for parts availability in case the component gets scrapped. This again is an important aspect as these parts are high in value and their replacement parts aren't readily available. Thus research was taken up to develop those assessment techniques and the toolsets that help quantify these 'in-service' damages occurring in HVM parts.

The framework can be explained as follows; when a part comes for service, the maintenance system performs automated inspection using pulsed thermography where the entire process of part collection through to inspection and post-processing of data was fully automated. With the use of

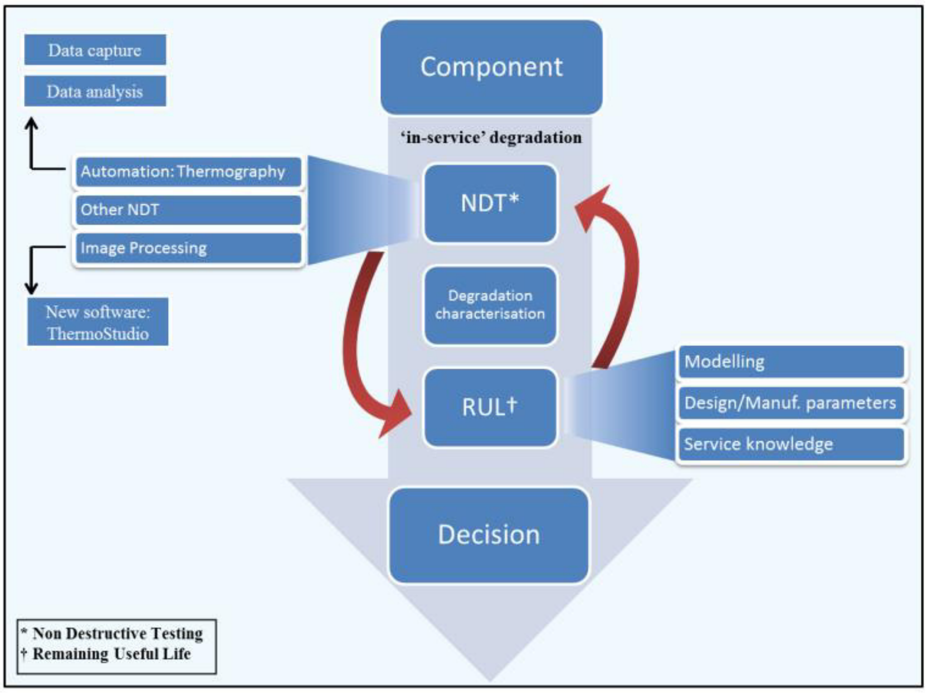

Fig. 2 Framework showing an 'in-service' maintenance system that performs damage assessment through feedback for system design and manufacture

signal and image processing algorithms, thresholds were setup to identify critical areas showing degradation beyond acceptable levels thereby reducing any operator burden to sift through the dataset. The framework for this feedback based maintenance is dependent on the data from the inspection system, existing knowledge on the history of the inspected part, and on the remaining useful life algorithms that help predict and establish time to failure with a confidence band.

As seen in the image above, a brief overview of the framework has been presented. To further understand the framework, it is important to understand the underlying principles and methods applied to this study.

3.1. Pulsed thermography

Infrared thermography, due to its robustness and adaptability, has found its way into maintenance activities in the aerospace sector. Pulsed thermography is a well-established form of active thermography technique [22] [23] [24] [25]. The working principle of this technique is as follows: the surface temperature of the component is increased briefly with the help of a uniform optical excitation source (e.g., flash pulse or hot gun). An IR camera or radiometer controlled by a computer (PC) records the response of the surface temperature due to the thermal excitation over a known period of time (Fig. 3). In a homogeneous material, the transient heat flow from the surface into the component will be uninterrupted. As soon as a thermal discontinuity appears, there is a break in the transient heat flow characteristics which shows on the surface as a hot or a cold spot indicating the presence of a foreign body in the bulk of the material.

For a homogeneous, semi-infinite sample, the heat pulse equation becomes [22],

$$T_{surf}(t) - T_{surf}(0) = \frac{Q}{\kappa \rho c \sqrt{\pi t}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where T_{surf} – surface temperature, t – time, Q – input energy per unit area, κ – thermal conductivity, ρ – density and c – specific heat capacity of the sample.

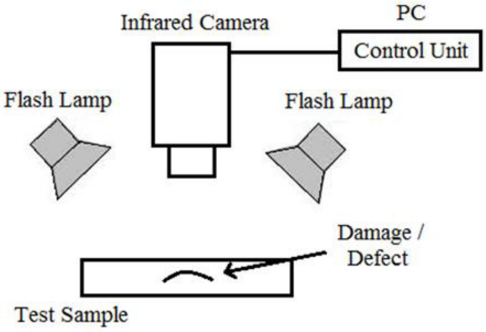

Fig. 3 Pulsed thermography experimental setup

When a natural logarithmic plot of both sides of equation (Eq. 1) (above) is plotted, a linear profile with a slope of -0.5 is obtained. As soon as there is a sub-surface discontinuity, there is a deviation from the linearity in the time temperature plot.

3.2. The automation process

The following steps explain the automation process;

1. The operator starts the industry standard robotic arm, the toolpath of which has been pre-defined by the operator.
2. The robot arm collects the part and presents it to a stationary pulsed thermographic inspection system. The inspection parameters for a component were pre-defined where the flash intensity, focus of the camera system, data acquisition parameters such as frame rate and acquisition length have all been established during preliminary tests.
3. As soon as the part is presented to the system, a trigger signal generated by the robot now instructs the pulsed thermography system to perform the inspection.
4. The data captured by the inspection system is post processed and reconstructed using image and signal processing algorithms such as Thermographic Signal Reconstruction (TSR) [22]. The data is now stored onto the legacy system and to the cloud simultaneously.
5. The data from the cloud is retrieved by a securely connected system, and with the help of the pre-installed in-house software data analysis is initiated.
6. The in-house software [24] then produces the final data in terms of various visual representations such as thermal image, log T-t plot for a pixel, fingerprint for a selected region of interest (ROI) and in the form of a scatter plot for the given ROI clearly differentiating the damage area with the sound area.

Thus the automation provides a ‘one-click’ system where the complete process of collecting the part to final analysis is completed in one go and could be easily adapted to a maintenance facility to perform in-situ inspection. This system has the capability of performing multiple inspections of the part presented in multiple angles to acquire data from complex geometry parts. Further, this system is capable of inspecting large parts and automates the entire data stitching process at the click of a button reducing significant inspection and analysis downtimes.

4. Borescopic inspection for in-accessible areas

Literature showed that medical sector had an increased use of endoscope based instrumentation and also highlighted the challenges especially in the existing design [26]. There is evidence of endoscopes being redesigned to fit industrial applications where optical inspection of inaccessible areas is key [8] [21]. There have been developments to perform pulsed thermography using a borescope to inspect the inside of a rail axle. This research considered various design approaches to identify challenges with respect to the associated instrumentation needed to build a prototype. As part of this study [8], various non-destructive testing techniques were considered and thermography was chosen as a suitable technique. Based on the in-house capabilities, a Xenics Gobi 384 camera was used to acquire the data. The following is the prototype of the borescope developed in house.

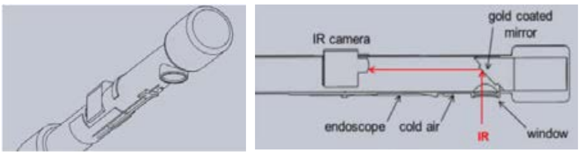

Fig. 4 Borescope design; CAD model (left) & cross-section with parts (right) [8]

Fig. 5 The prototype of the borescope [8]

As seen in Fig. 4&5, the prototype was made from a 68mm diameter PVC pipe, with a sodium chloride access window (90% transmittance) perpendicular to the line of sight of the camera. A gold coated mirror with 96% reflectivity was inserted at a 45° angle to sodium chloride window with a standoff distance to the camera set to 25mm. The full study with detailed description of specifications and results has been presented by Guillebert et al [8]. This study thus showed a specific application to inspect inaccessible area exceeding the inspection diameter of 100mm. The work was furthered by the design of a flexible borescope system. The design challenges and cost led to the development of mirror based flexible borescope system.

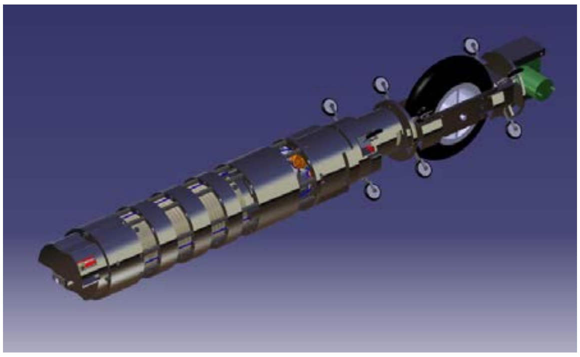

Fig. 6 CAD model of flexible borescope system

As seen in Fig. 6, a flexible borescope system capable of performing pulsed thermography was developed based on the principles of fixed borescope by Guillebert et al [8]. Through the study, various limitations were identified. The primary limitation was with the identification of a suitable heat source that was compact enough and could be integrated with the fully controlled borescope system. The other issues were the size (still at 110mm diameter), weight of the system, cabling and data transfer. The entire borescope was proposed to be made from additive layer manufacturing. Even with these limitations, the borescope had advantages of an inbuilt digital camera system for guidance, motorised movements in the x and y axes and the traverse movement of the borescope. Future work in this area would be in devising a smaller infrared sensor for inspection together with a compact heat source to perform pulsed thermography which would significantly reduce the size of the borescope.

5. Summary

The ability to inspect components and systems in-field using in-situ sensors is a challenge in itself. There are various factors that drive the applicability of such systems, which include accessibility and ability to be able to inspect without dis-assembly. Further with complex and safety critical systems, it is always better to plan for preventive maintenance for smooth and continuous functioning of the system thereby increasing life of the system. This paper presented the need for in-situ inspections with specific examples and approaches both from literature and through actual studies taken up in the area. It is the notion that these technologies would help plan robust in-field maintenance activities leading to significant reduction in both maintenance costs and inspection downtimes for complex systems across industrial sectors.

Acknowledgements

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