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Citation: Deane, S., Avdelidis, N. P., Ibarra-Castanedo, C., Maldague, X., Tsourdos, A., Williamson, A., Nezhad, H. Y. ORCID: 0000-0003-0832-3579 and Zhang, H. (2019). Autonomous Systems Imaging of Aerospace Structures. Paper presented at the 10th International Symposium on NDT in Aerospace, 24-26 Oct 2018, Dresden, Germany.

This is the published version of the paper.

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Autonomous Systems Imaging of Aerospace Structures

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Abstract. Manufacturers are constantly looking for more cost-efficient means to produce aircraft components. An effective way to do this is to reduce the weight, which results in less fuel required to power the aircraft. This has led to an increased use of composite materials. Carbon fibre reinforced polymer (CFRP) composite is used in industries where high strength and rigidity are required in relation to weight. e.g. in aviation – transport. The fibre-reinforced matrix systems are extremely strong (i.e. have excellent mechanical properties and high resistance to corrosion). However, because of the nature of the CFRP, it does not dint or bend, as aluminium would do when damaged, it makes it difficult to locate structural damage, especially subsurface. Non-Destructive Testing (NDT) is a wide group of analysis techniques used to evaluate the properties of a material, component or system without causing damage to the operator or material. Active Thermography is one of the NDT risk-free methods used successfully in the evaluation of composite materials. This approach has the ability to provide both qualitative and quantitative information about hidden defects or features in a composite structure. Aircraft must undergo routine maintenance – inspection to asses for any critical damage and thus to ensure its safety. This work aims to address the challenge of NDT automated inspection and improve the defects' detection by performing automated aerial inspection using an Unmanned Aerial Vehicle (UAV) thermographic imaging system. The concept of active thermography is discussed and presented in the inspection of aircraft's CFRP panels along with the mission planning for aerial inspection using the UAV for real time inspection. Results indicate that this inspection approach could significantly reduce the inspection time, cost, and workload, whilst potentially increasing the probability of detection.

Introduction

Technology is currently thriving in industry, therefore companies are competing with one another and are all looking for innovate ways to meet the demands of the global economy [3]. In this global economy, companies must turn out the highest quality of products in an efficient manner with minimal manpower and remain profitable [3]. For Aircraft to remain the safest way to travel the structure and parts need to be manufactured to an impeccable standard and then maintained regularly. Non-destructive testing (NDT) is a range of different inspection methods which can be used to evaluate the health of materials and components without interfering with the serviceability [1]. Infrared thermography (IRT) is a popular NDT technique that has risen due to the increased use in varied applications and the rapidly decreasing price of thermal technology in today's market. Infrared Thermography is predominately being used to detect subsurface defects in a plethora of structural elements and mechanical systems [1]. It is one of the newest non-destructive technologies and has proven to provide substantial improvements in performance as well as good cost savings, allowing more frequent maintenance with minimal manpower [16].

Airbus and Boeing are considered the most elite commercial aircraft manufacturers of the past few decades. The demand in the market is putting pressure on companies to develop new solutions for larger aircraft [12]. Since the successful release of the A380 and Boeing 787 Dreamliner, commercial Aircraft manufacturing has seen a rapid increase in the use of composites materials. In 1985, around 5 percent of the A310-300 consisted of composite materials, 18 years later and more than half (53%) of the materials used to manufacture the A350XWB consists of composites [2]. Composites are being used more and more for primary structures in many industries such as; rail, wind power and marine. Composites offer greater strength characteristics compared to the common structural metallic materials [9]. The materials of an aircraft structure have immense responsibilities, there are required to resist many intense loads repeatedly and be free from damage, delamination, fatigue and corrosion after each cycle. IRT is suitable for use on a wide range of materials, including glass and carbon fibre composites, natural fibres, ceramics and metallic materials. Due to the increased popularity in composite materials there is a demand for reliable and fast NDT methods to ensure the safety of the material.

The idea of inspecting aircraft structures came from an ongoing project at Cranfield University in collaboration with Airbus, where a commercially available UAV is performing a non-destructive liquid penetrant test. A liquid paint substance is added to a metallic wing panel and a UAV equipped with a UV light inspected the aircraft in a dark room, the primary objective is to execute the algorithms in order to display, classify and log defects [6]. Since there is such a rise in the use of composite materials it seems necessary to discover a fast and cost-efficient inspection method. IRT is a fast-non-contact method and is well-suited for testing large areas of complex geometry [7]. Nevertheless, the traditional thermographic systems are bulky and inconvenient for use on many applications. Therefore, it is necessary to develop a more versatile thermographic system, with the help of UAV technology.

1. Composites

Composite materials have significant beneficial properties for IRT inspection, including low reflectivity (high emissivity), meaning that they absorb energy very well. Once the energy is absorbed, the material will retain the energy and release it much slower than traditional metallic materials, such as aluminium, therefore using infrared NDT is very attractive for inspecting composite materials. Composites have some limitations, perhaps the most noteworthy limitation is the poor response to impact loading [17], which can be caused easily by runway debris, a dropped tool or any other impact. It's been reported that 80% of in-service damages to composites is caused by impact strikes [18]. Composite materials are known to have poor impact resistant, the material responds differently than metals in terms of impact loading and its ability to dissipate the incident kinetic energy of the projectile [17]. For minor incident energies, metals absorb energy through elastic and plastic deformation, this will usually result in permanent structural deformation however, metals can carry the load and it results in consequences that are less-significant compared to composites. Plastic/Elastic deformation for a composite is very limited as the resultant energy is frequently absorbed in creating large areas of fracture, which will affect the performance of the material due to the reduction in both strength and stiffness [11]. During composite manufacturing, it is possible for the material to be damaged due to the complexity of the manufacturing process.

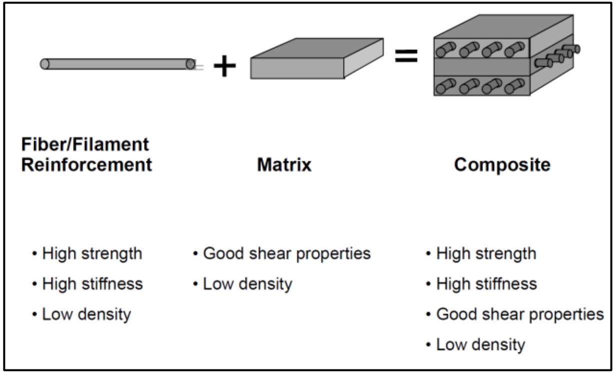


Figure 1: shows the composition of composite material [9].

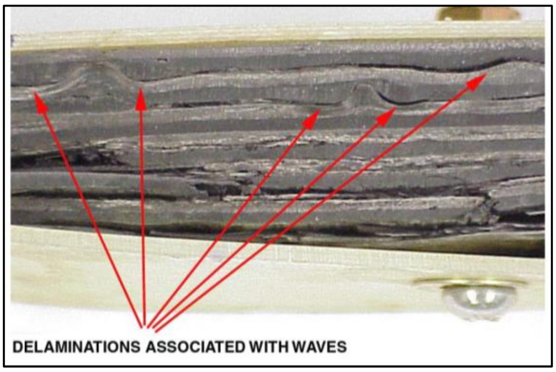


Figure 2. Composite delamination's, this is the consequence of misalignments in large aircraft structures [13].

1.1 Demand for NDT inspection on composites

Due to the increased demand of CFRP, it has subsequently caused rapid large-scale manufacturing. Airbus estimates its Carbon Fiber demand to soar to around 20,000 tons by the year 2020 (see figure 3, right) [2].

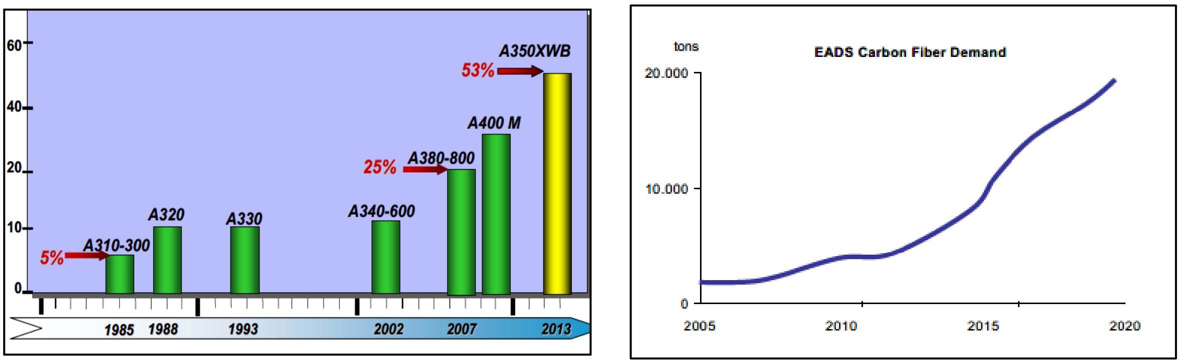


Figure 3: The graph on the left shows the use of composites in Airbus aircraft since 1985. The line graph represents the demand by tons from 2005 up to 2020 [2].

The current manufacturing and machining process are novel compared to the manufacturing of traditional metallic structures, in addition, composites have different specific mechanical properties. As a consequence, its proven difficult to control manufacturing defects, due to the complexity of the manufacturing. Composites are layered pieces of laminar with alternating orientation typically 45 or 90°. Composite impact damage can result in damage in many different forms such as matrix cracking, fibre/matric debonding, surface microbuckling, delamination and fibre breakage [11]. Such impacts can cause barely visible impact damage (BVID), this is where the damage will still exist subsurface and extend way beyond the impacted area. This can leave aircraft vulnerable by jeopardising the safety of the structure. It is clear that the damage zone of a composite is of a more complex nature and can be very difficult to characterise. The complexity of the problem multiplies due to the lack of impact damage testing techniques on a composite material [1]. This calls for an adequate way to search for defects within a composite material.

2. Methodology

The specimens were made of Carbon Fibre Reinforced polymer (CFRP) (composite laminate). Sample A4 was manufactured via manual woven and the other two samples where unidirectional. The composites consist of laying up pre-preg piles to form a laminate stack, the material is then autoclave processed at 180C and 7 bars for a few hours suitable for the thermoset resin cure, this is according to the supplier's specification (Hexcel). There were three specimens, one that was undamaged, and two that had been impacted with a force of 15J and 20J of energy.

2.1 Experiment

The infrared camera was a FLIR Phoenix, with inSb sensor material, 3-5 mm, 640x512 pixels and allows data acquisition at 50Hz.

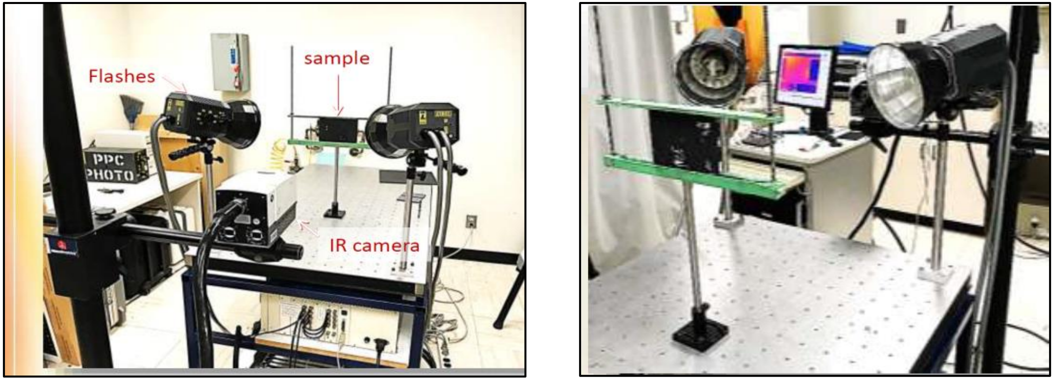


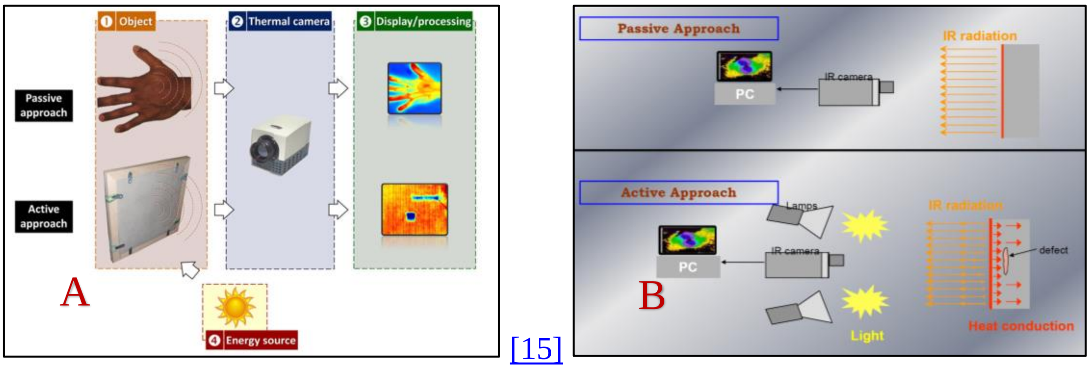
Figure 4: Images showing the NDT testing equipment and the experimental set up.

These camera needs to be cooled to 77 Kelvin (i.e. -196.15 °c) during testing. Cooled cameras work by collecting photons of infrared energy that pass through the optic. The photons are converted into electrons that are stored in an integration capacitor. After a certain period, called integration time, the charge is read out to a digital count calibrated to temperature, assigned a colour or greyscale value and then presented as a viewable infrared image [5].

The surface of the specimens where positioned parallel to the camera lens. The data was acquired for 40 seconds with a 1.5 millisecond integration time, that includes 10 frames before the flashes, plus 1990 frames during cooling a total of 2000 frames where recorded.

The software used to acquire the data was RDac from FLIR. For signal processing MATLAB and Ir_view from Visiooimage inc were employed. Two advanced processing techniques where used; PCT (principal component thermography) and PPT (pulsed phase thermography). The specimen was excited by two Balcar Xenon flash lamps, which provide 6.400 J per flash, the pulse duration was 2 ms at FWHM (full width half maximum).

The specimens were heated using the flash lamps, and then the infrared camera has captured its thermal response. There are two main types of thermography, active and passive as depicted in Figure 5. Passive thermography is an inspection without the use of an external excitation source, its commonly used for inspecting materials having a temperature naturally different than its surrounding [10]. Active thermography uses external heating dissipation to create thermal contrast, once excited the thermal waves propagate through the heated specimen, and when they reach inhomogeneities caused by a medium with different thermal properties, the diffusivity coefficient changes. These inhomogeneities could be defects, such as cracks, surface cracks, air/water/material inclusions, delaminations and debonding damages. Mathematical processing techniques are the key to gather the necessary data from the raw thermogram and help visualise the damages within the material [10].



[4] [15]

Figure 5: Show the experimental set up for both passive and active thermography.

3. Results

The figures below (Figures 6-12) are all the postprocessed results. A reflection test means that the camera and the excitation source are on the same side. Generally, reflection is more suited to detect defects closer to heated surface. PPT (pulsed phase thermography) was one of the methods used, with the acquired temperature data it varies with time and is transferred to phase data which varies with frequency, the frequencies which show adequate data are below each image in hertz. PCT (principal component thermography) was the other, method used, the data is re-ordered by variance, this method finds both time series and spatial patterns, most of the variability is contained in the first component: EOF1 (empirical orthogonal function). Usually, EOF1 shows thermal variations related to surface heating. Later EOFs are typically related to surface and subsurface damage. Comparing both techniques, for this specific data set in figure 6 it seems that the PCT technique displays the damage clearer.

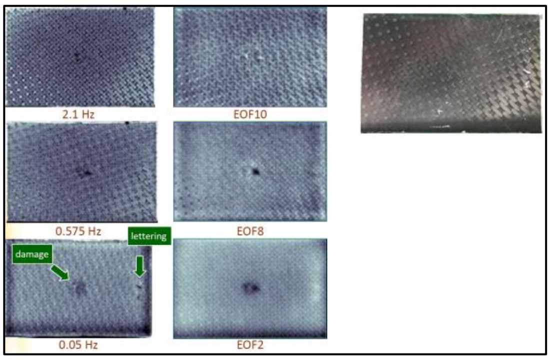


Figure 6: Sample A4 (15J woven), front face (impacted side), PPT and PCT. *The damage is barely visible in the original image of the composite (Far right image), the white marks are lettering from labelling the specimen. The 0.05Hz PPT image, shows clear subsurface damage.*

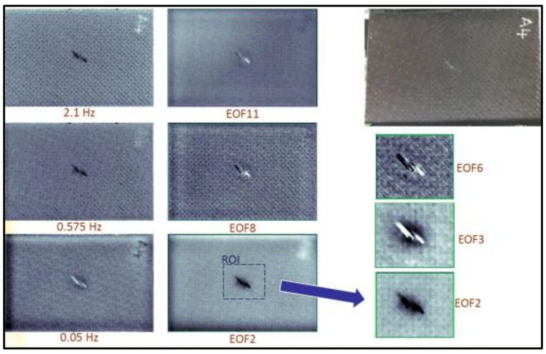


Figure 7: Sample A4 (15J), Reflection rear face PPT and PCT. *The rear surface is cracked, this is interesting because this side is significantly more damaged than the impacted side. This is a prime example of barely visible impact damage.*

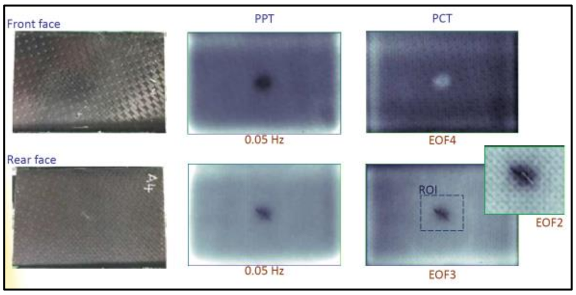


Figure 8: Sample A4 (15J). *Transmission is where the one side of the composite is excited, and the other side is observed by the camera and captures the data.*

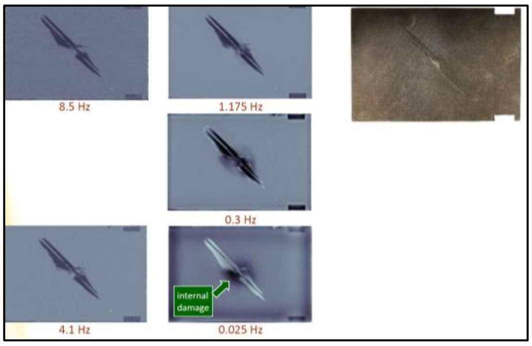


Figure 10: Sample 20J Demo, Reflection rear face*. PPT. The rear face has some substantial damage. The PPT locates the surrounding internal damage.*

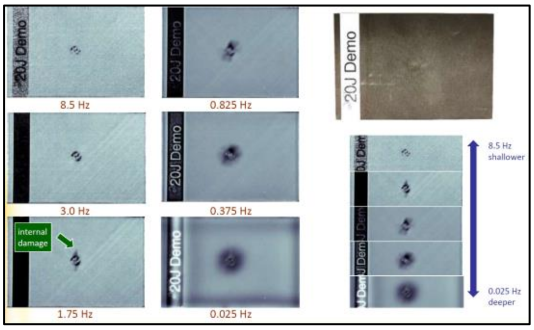


Figure 9: Sample 20J Demo, Reflection front face, PPT. *The damage is visible on the front face, how, it's clear that the damage is much worse subsurface and spreads further than the impacted area.*

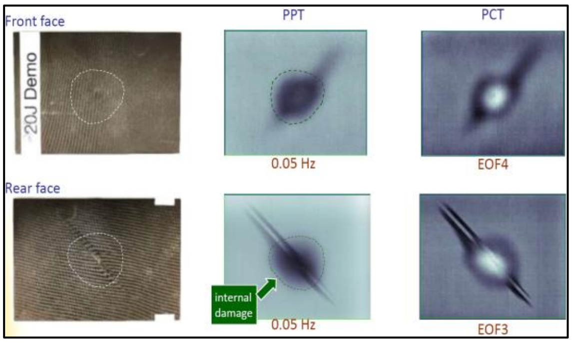


Figure 11: Sample 20J Demo, Reflection front face, Transmission. *The test has adequately located the internal damage.*

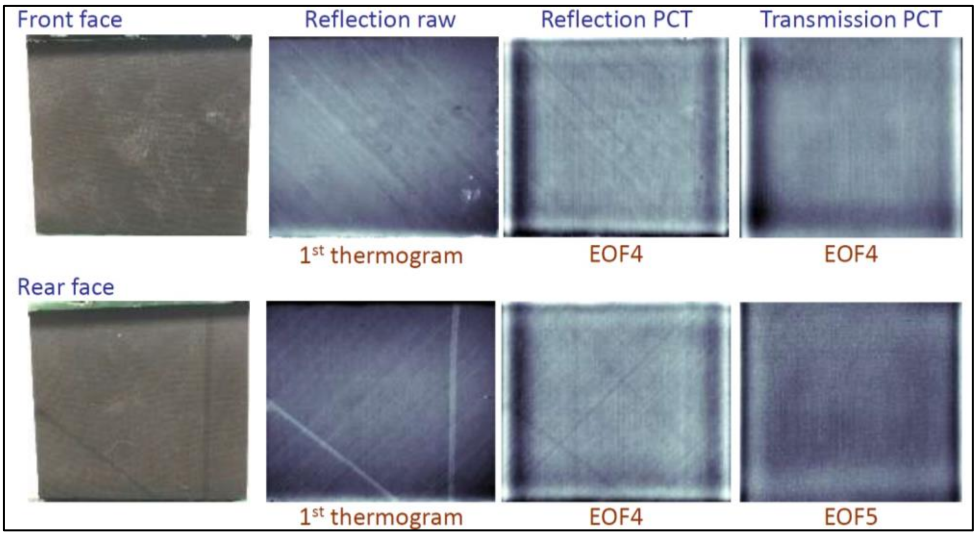


Figure 12: Sample No Name, Reflection front, back, transmission PCT. *Undamaged composite sample, which was manufactured the exact same way as the 20J sample, the different NDT test prove that this sample is damage-free.*

4. Unmanned Aerial Vehicles

4.1 Proposed UAV

Although a cooling camera was used in the beforementioned NDT test, this type of camera will not be feasible for UAV thermographic inspection. Cooling cameras usually require cryogenic cooling, which is an excess of weight. The equipment we currently have is a DJI M210, which carries an RGB and thermal camera. The thermal camera is 640 x 512 pixels which is the exact same pixels as the FLIR Phoenix that was used. It has a 13mm lens and is radiometric, therefore it uses a set of techniques to measure electromagnetic radiation, including visible light, this means that the acquired data can be extensively analysed after the survey in order to visualise and understand the data such as the temperature variations [8].

UAV dynamic inspection has the potential to provide a complete portrait of the aircraft structure much faster than static inspections. For a UAV inspection an external excitation source will be employed to heat the surface. The thickness of the composite panel may make it difficult to gather adequate results, therefore many excitation sources need to be tested other than flash lamps. For instance, halogen lamps (heating the surface for longer), Heat Blankets or a Laser. Along with the liquid penetrant NDT method, a UAV thermographic inspection was tested for civil engineering applications (see Figure 14). The UAV is equipped with a FLIR A320, this IR camera is connected to a computer via a cable, one is a power cable and the other provides real time radiometric thermal images which will reveal heat patterns and thermal anomalies [7]. Transient thermography with flash and step heating where the methods used in this inspection. An inspection took place and gathered data on difference distances between the camera and the samples (2, and 6 metres). Along with the UAV equipped with the IR camera, there was a fixed IR camera, therefore two sets of data could be acquired and compared. A thermally uniform area of a sample is delimited, and the IR cameras captured the data [7].

FIGURE 13 A: DJI M210 equipped with thermal camera [8]. FIGURE 13 B: UAV equipped with thermal camera [7]. FIGURE 13 C: Comparison of front face temperature responses to flash heating in the case of a large uniform irradiation with a fixed camera and a stabilized camera with UAV at two distances (2 m and 6 m) [7].

4.2 Performing an NDT inspection

The purpose of this paper is to prove that active thermography can locate defects within composite materials, then to propose the integration of this methodology into a UAV. There are several things that need to be taken into consideration. The idea is to inspect composite panels for aircraft structures straight from the manufacturing line, to verify their worthiness and quality assurance. There are some limitations for this proposed idea. Due to the fact the inspection is inside it could provide problems for the UAVs GPS system, which will result in an unstable flight and affect the data as seen. There are a few ways to combat this issue, one of them is to set up a localisation scheme by distributing some ultrasonic sensors around a specific geographic area, the UAV communicates with these sensors to understand its location therefore which will result in stabilisation. Once the flight is ready, due to the size of aircraft parts, the subject will need to be segregated into separate regions of interest, and separated images will be taken and then stitched together as a mosaic image, this segregation will ensure the subject is excited uniformly. Once the data is acquired it will then need to be postprocessed to improve results, when post processing a lot of properties need to be considered;

- Thermal Properties: conductivity, diffusivity, effusivity, specific heat
- Spectral Properties: emissivity, absorption, reflection, transmission
- Material's properties-characteristics: density, porosity, thickness, geometry [10].

With these properties understood, data process can be performed, for instance; when a material presents voids or pores in its structure, then its thermal conductivity and density decreases, its thermal diffusivity is altered and so the conduction of heat transfer within the material is affected. For instance, materials with low-effusivity values will present higher temperatures. With all this information taken into consideration, a better damage assessment can be done [10].

5. Conclusion

This study contributes to reducing the time and cost of NDT composite inspections. The research shows that NDT is an effective inspection method, whilst using PPT and PCT allows to visualise the extent of the damage and the surrounding areas. When acquiring data, the value of each pixel will represent the temperature at a specific point. The temperature profile of the point corresponding to the healthy area is different from that of the point corresponding to the defective area. Using digital image processing it is possible to enhance the images to reveal the location and geometry of the defects [1]. These methods can potentially become beneficial to the aerospace industry if integrated onto a UAV. The raw data that is acquired often contains noise caused by the environment, the reflections, the emissivity variations of the specimen or if the heating was non-uniform, it is important to take this into consideration and to employ specific algorithms for image processing in order to produce accurate results. The results from the UAV inspection indicate an excess of noise from the UAV, since this flight was done without the use of GPS, this affected the results and the noise was due to the stabilisation problem. It is necessary to perform pixel by pixel treatment in addition to the standard average signal study [7]. To do this the IR camera needs to be as static as possible, GPS or other localisation techniques can be used to compensate for any stability problems. The data acquired has shown that different techniques are better suited for different defects. Pulsed thermography can accurately locate delamination's. Delamination is where the material fails due to the layers separating which result in significant loss of mechanical toughness. In the future, a UAV inspection will be performed, and the fidelity and performance of the image processing algorithms will be further evaluated. An excitation source that is small, light and produces enough energy to penetrate the material, can also be equipped on the UAV soon, which will offer an all in one inspection product and minimise time as there will be no need to set up an external excitation source. There are a few halogen lamps on the market which offer sufficient weight to energy ratio.

This research was part supported by the British Engineering and Physics Sciences Research Council.

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