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RESEARCH ARTICLE

The 'hangar of the future' for sustainable aviation

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Abstract
Sustainability is becoming a major strategic driver within the aviation industry, which has moved from providing primarily economic benefits to delivering the 'triple bottom line', including social and environmental impact as well as financial performance. Sustainable aviation is also being tracked by the International Civil Aviation Organisation (ICAO) Global Collation for Sustainable Aviation. Operations and Infrastructure is an important near-term opportunity to deliver sustainability benefits. Digital Technologies, Integrated Vehicle Health Management (IVHM) and Maintenance Repair and Overhaul (MRO) play a prominent role in implementing these benefits, with a particular focus on operational efficiencies. As part of this, the sustainable smart hangar of the future is a concept that is becoming more and more important in forming the future of the aviation industry. The Hangar of the Future is an excellent opportunity for innovation, combining the progress in manufacturing, materials, robotics and artificial intelligence technologies. Succeeding in developing a hangar with these characteristics will provide us with potential benefits ranging from reduced downtime and costs to improved safety and environmental impact. This work explores some of the key features related to the sustainable smart hangar of the future by discussing research that takes place in DARTeC's (Digital Aviation Research and Technology Centre) hangar led by the IVHM Centre in Cranfield. Additionally, the paper touches on some longer-term aspirations.

1.0 Introduction

The aviation industry has progressed significantly since Orville and Wilbur Wright managed to fly a distance of 120 feet in December 1903. In 2021, companies like Blue Origin and Virgin Galactic developed aircraft that are able to fly on the edge of space and offer passengers a weightless experience. In this race of evolution and technological progress, the maintenance side of aircraft cannot be left behind. Sustainability is becoming a major strategic driver within the Aviation industry, which has moved from delivering primarily economic benefit to delivering the 'triple bottom line', which includes social and environmental impact as well as financial performance [1]. The ICAO Global Collation for Sustainable Aviation is tracking and driving several major related themes, including operations and infrastructure. They recognise that this area is a 'win-win', as costs are reduced along with emissions. The promise of digital operational efficiencies in this regard is not the largest, but it is one of the most immediately available to use. It is generally accepted that approximately 10% of the opportunity derives from operations optimisation. As a case in point, the Air Transport Action Group (ATAG), in their Waypoint 2050 report, estimates that 8 to 12% of CO_2 reductions by 2050 will come from operations and infrastructure improvements [2]. Examples of actions we can consider and the resulting sustainability benefits are illustrated in Fig. 1.

The classic IVHM use case involves proactively and remotely understanding a vehicle's current and future serviceability. This is often called predictive maintenance, condition-based maintenance or aircraft health management. Through analysis, it can be possible to predict a pending equipment failure. In this case, there is an economic benefit of dealing with the issue in a scheduled manner and avoiding the

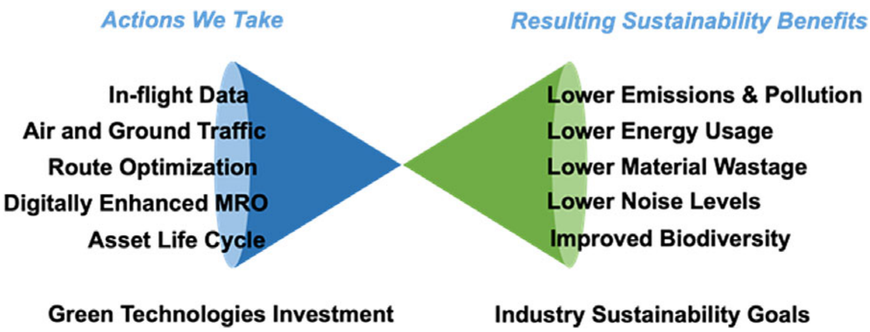

Figure 1. *Actions and the resulting sustainability benefits.*

likelihood and impact of a schedule interruption, but there are also material direct sustainability benefits. In many cases, operation with a degraded system, while safe and approved, can greatly limit operations regarding altitude or range. This results in fewer degrees of freedom in vehicle usage and lessens the likelihood of mission or schedule completion. In cases where the equipment is part of the environmental control system, such as a valve, a significant direct fuel burn penalty (up to 4%) and additional resulting CO_2 emissions may be avoided. Of course, indirect benefits follow, such as reduced stock requirements, parts shipping costs and more efficient labour utilisation.

The hangar is where all the magic happens related to maintenance, research and development activities. The hangar is a critical infrastructure for the aviation industry. People working in the MRO industry have already started to discuss and explore the features of the Hangar of the Future. In the future hangar, we will most likely meet fleets of robots performing maintenance tasks in cooperation with skilled engineers and even host local server rooms to analyse aircraft data and feed the digital twins of subcomponents. Generally, hangars must be optimised in a wide range of operations, from energy efficiency and sustainability to advanced automation and data analysis. In this article, we will lightly touch the former but analyse the latter extensively as this is where Cranfield's University IVHM Centre expertise lies. The Centre, established in 2008, leads the MRO developments and activities with expertise and capabilities in robotics, non-destructive testing (NDT) inspections, structural health monitoring (SHM) sensor monitoring, and advanced digital technologies, such as artificial intelligence (AI) and digital twins (DT), tools that could be used to synchronise, monitor, and improve all processes related to aircraft MRO. The Centre has worked on a number of research projects with partners from industry and academia, such as Boeing, Airbus, Safran, Rolls-Royce, BAE Systems, Thales and Meggitt. In the longer term, the Centre, with its core partners, has a long-term aspiration to deliver a so-called Conscious Aircraft [3]. This aims to build on the Centre's research, moving towards a zero-maintenance platform, further maximising operational efficiency and sustainability throughout the aircraft life cycle [4] (Fig. 2).

2.0 Hangar market forecast

The market for aircraft hangars is expected to experience significant growth due to a combination of factors that affect the aviation industry. This includes airport modernisation, rising commercial aircraft orders and changing aviation preferences in a globalised world. These are crucial factors that are shaping the direction of the market.

The aircraft hangar market in North America has become a major player in 2021, thanks to significant investments in airport renovation projects and the presence of established industry leaders. The United States, in particular, is expected to achieve a market worth of US$1.7 billion, highlighting the region's strong industry capabilities [5] (Fig. 3). Meanwhile, the Asia Pacific region is gearing up for substantial growth, propelled by increasing airport construction projects and rising air passenger traffic. This

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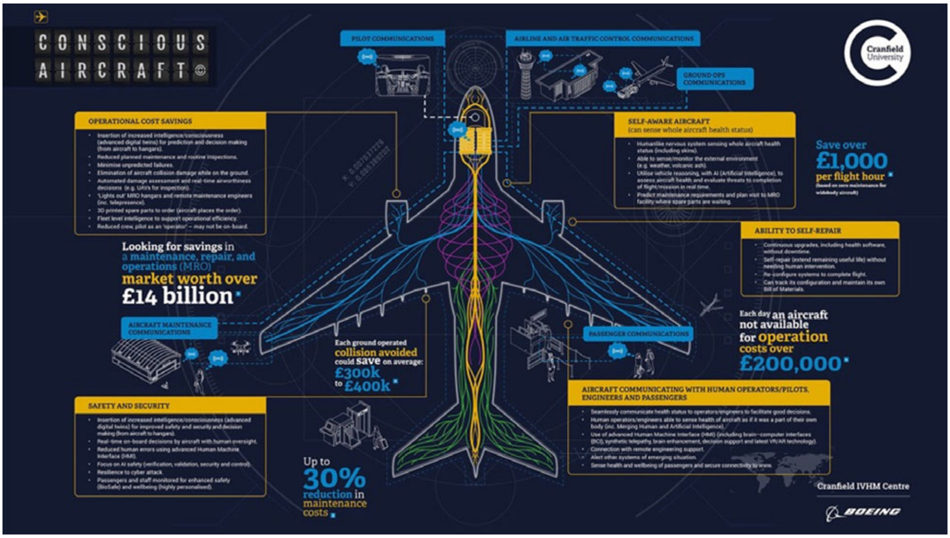

Figure 2. The Conscious Aircraft Concept (Cranfield University).

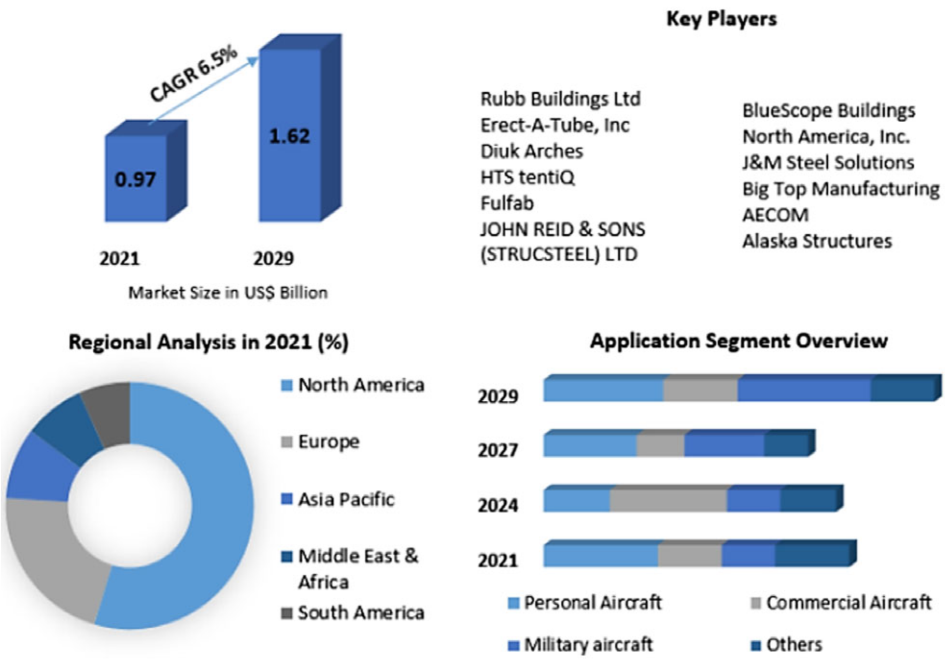

Figure 3. Aircraft hangar market forecast (image source [5]).

region's demand for commercial aircraft further supports its growth potential. In Europe, key aircraft hangar suppliers like Fulfab Inc. and Rubb Buildings Ltd. are expected to drive expansion.

According to the report [6] by Prentice et al., the MRO market is experiencing major changes. These changes are primarily due to increased aircraft retirements, leading to significant MRO costs. MRO business levels are expected to return to pre-COVID levels by 2024, with a projected annual growth rate of 2.8% in the second half of our decade prediction (Fig. 4). Eventually, MRO demand is projected to reach $118 billion in 2030.

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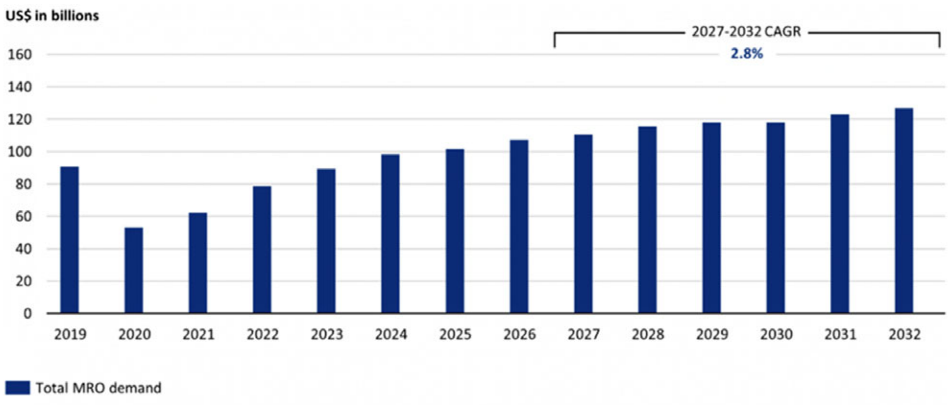

***Figure 4.** MRO market forecast in terms of compound annual growth rate (CAGR) for 2019-2033 (image source [6]).*

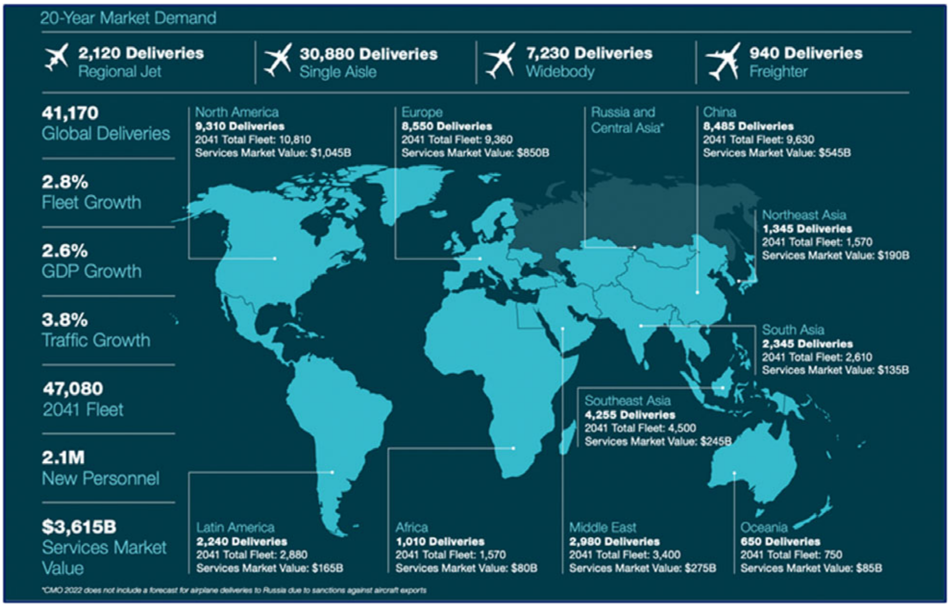

***Figure 5.** Boeing's global growth prediction for the period 2019–2041 (image source [7]).*

Boeing's Commercial Market Outlook report [7] outlines the projected growth and recovery for the aviation industry (Fig. 5). This report instils confidence in the MRO business, highlighting the impact of digital transformation. In 2019, the global aircraft base in service was around 25,900. The report predicts this number will increase to 35,400 by 2031, representing an annual growth rate of 2.6%. Looking further ahead, Boeing anticipates that the fleet size will reach approximately 47,080 aircraft by 2041, reflecting an annual growth rate of 2.8%.

The growth in the MRO business and the introduction of new technologies will have a positive economic and social impact. There is no separate index that isolates the new technologies' contribution to new job creation and GDB contribution, but overall, the air transport industry is expected to grow by an average of 3% per annum over the next 20 years, which is comparable with the MRO index mentioned earlier. By 2038, it is projected to contribute 13.7 million direct jobs and $1.7 trillion to the world

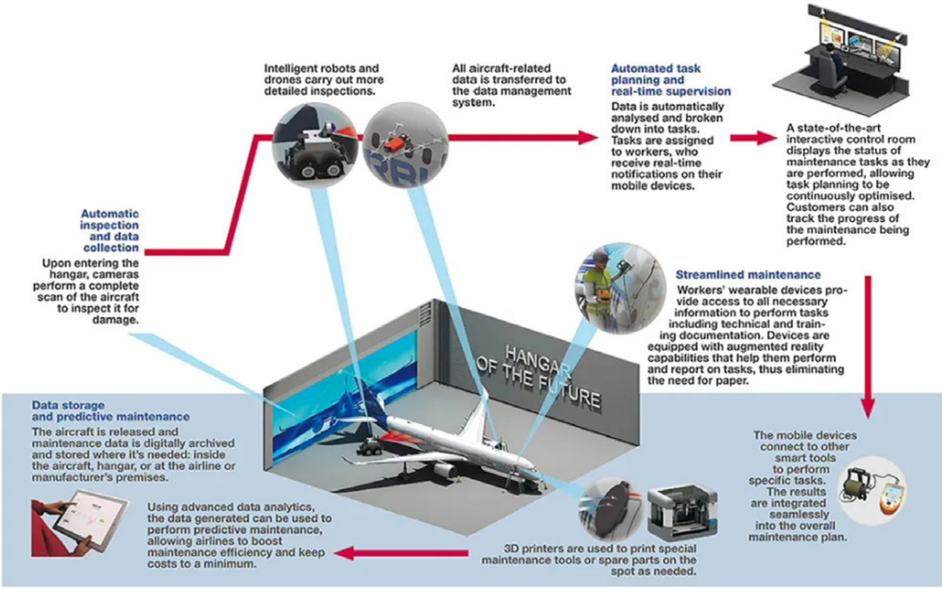

Figure 6. *Airbus's hangar of the future demonstrator (image source [9]).*

economy [8]. Including indirect and induced contributions, the industry could support 76 million jobs and $4.3 trillion in GDP by 2038. If global tourism is included, the air transport sector could contribute 143 million jobs and $6.3 trillion in GDP by 2038.

As the aviation industry continues to evolve and adapt to changing demands, the aircraft hangar market is at the forefront of innovation and growth. The interaction between modernised airports, commercial aircraft orders, and sustainable hangar solutions will define the industry's trajectory in the forecast period. With various global factors coming together, the aircraft hangar market is poised for a transformative journey, reflecting the dynamic nature of the aviation industry.

3.0 The hangar of the future

Airbus first introduced the Hangar of the Future in 2016, with the aim of revolutionising the MRO sector by integrating advanced technologies (Fig. 6). The following quantitative metrics help to understand the change, demonstrate the benefits and justify the increasing involvement of industry and academia.

- Time efficiency. Inspections are a major part of aircraft maintenance. Autonomous robotic platforms are an example of how this can be achieved. The use of drones in cooperation with ground robots [9] for aircraft inspection can reduce the time required for data capture from 2 h to just 15 min. In addition, using automated NDT allows for quicker and more accurate defect analysis and classification, reducing the time spent searching for data.
- Predictive maintenance. A game-changing approach that was introduced by IVHM is the predictive maintenance concept, which can lead to significant economic benefits by scheduling repairs before failures occur, thus avoiding schedule interruptions and reducing operational costs. For example, predictive maintenance and optimised pilot decision-making can result in fuel savings of up to 4%, leading to lower CO2 emissions [10].
- Data utilisation. The new hangar is a fully sensorised ecosystem, creating valuable data streams that can be utilised in many different ways. Internet of Things (IoT) and radio frequency identification (RFID) technologies help identify and track tools and parts, improving

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the efficiency of maintenance operations. Ultrawideband (UWB) real-time location systems can monitor assets and contribute as an additional localisation source in robotics navigation [11]. Regarding the asset of interest, the aircraft, integrating physical software, like Airbus's Skywise, can better predict future issues based on past maintenance data, leading to more efficient operations.

4.0 The digital transformation and MRO4.0

The integration of new technologies and digital transformation is not a new thing and specific to MROs. The changes were documented and started as part of Industry 4.0 (I4.0), also known as the Fourth Industrial Revolution. This term represents the trend of automation and data exchange in manufacturing technologies. It is characterised by the fusion of technologies blurring the lines between the physical, digital and biological spheres [12]. The term I4.0 was first introduced by a team of scientists developing a high-tech strategy for the German government. The phrase was later popularised by Klaus Schwab, the founder and executive chairman of the World Economic Forum, in 2016, the same year when Airbus presented the Hangar of the Future. The key technologies [13] that play a vital role in transforming a domain into I4.0 compatible are the following:

- Internet of Things: A network of physical objects embedded with sensors, software and other technologies that connect and exchange data with other devices and systems over the Internet.
- Cloud computing: The delivery of different services through the Internet, including data storage, servers, databases, networking and software.
- Artificial Intelligence and machine learning (ML): AI simulates human intelligence processes by machines, especially computer systems. ML is a type of AI that allows computers to learn and improve from experience without being explicitly programmed.
- Big data analytics: The process of examining large and varied data sets to uncover hidden patterns, unknown correlations, market trends, customer preferences and other useful information.
- Cyber-physical systems (CPS): Integrations of computation, networking and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa.
- Advanced robotics and automation: The technology dealing with the design, construction, operation and application of robots, as well as computer systems for their control, sensory feedback and information processing.
- Augmented reality/virtual reality (AR/VR): An interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information.
- Additive manufacturing (3D printing): A process of making solid objects from a digital file, usually layer by layer.
- Cybersecurity: The practice of protecting systems, networks and programmes from digital attacks.

Although the primary initial focus was on manufacturing and the application in the so-called smart factory, many fields took inspiration from I4.0 and customised the enabling technologies to their unique environments. Aircraft maintenance could not resist following the trend, and the concept of MRO 4.0 was introduced as the application of Industry 4.0 technologies to the MRO sector [14]. It involves using digital technologies to improve efficiency, reduce downtime and increase equipment lifespan. MRO 4.0 combines technologies that predict failures, create diagnoses and automate maintenance actions. It is central to condition-based maintenance (CBM), predictive analytics and decision-making support systems. As technology has advanced and become more affordable, MRO facilities in various industries, including aviation, have begun adopting digital technologies in their practices. The drive towards digitalisation in the MRO industry has been influenced by several factors, including a shortage of skilled labour, the rapid advancement of technology and increased demand for services, which are keeping costs down.

The most famous example in MRO 4.0 is the Hangar of the Future, which was introduced by Airbus in the same period. All the related industrial players and academia invest many resources to advance the technologies in a synergetic way to form the MRO4.0 ecosystem. Another relevant example [15] is the Collins Aerospace MRO facility in Singapore, where an automated vision inspection system was developed using advanced robotics and optical character recognition software to reduce the time technicians spend completing inspections. The company claims that its solution can reduce technicians' time to complete inspections from an hour to just minutes.

The general business consensus regarding the transformation is that robots and automation provide significant benefits to employees and customers. New technologies result in increased quality control, labour flexibility thanks to more efficient operations and lower costs because of the increased efficiency and reduced rework.

5.0 The humans in the centre and industry 5.0

There is no objection that I4.0 sets the foundations for digital transformation, and the enabling technologies are still valid and evolving towards the ultimate target. However, the suggested shift did not properly position the human role. An incorrect reading of the approach could even drive a new reality where robots and automated procedures replace humans. This is not the case, and to place progress in the proper context, a new industrial revolution started in a shorter interval period than any other time, showing its great importance.

The concept of Industry 5.0 (I5.0), also known as the Fifth Industrial Revolution, is a new phase of industrialisation that focuses on the integration of humans working alongside robots and IoT devices in automated industrial environments [16]. The term Industry 5.0 was first populated by the EU (European Union) in 2021 in their published report "Industry 5.0: Towards a Sustainable, Human-centric, and Resilient European Industry" [17]. Unlike Industry 4.0, which was primarily about leveraging robots and intelligent machines for maximum efficiency and high performance in manufacturing, I5.0 is centred on human impact and how the latest technologies can be leveraged to empower human work and capabilities. I5.0 places all that in the context of a greater human-centric approach [18]. It represents a shift from an economic approach to a focus on social value and well-being. It is more about collaboration between humans and machines than simply replacing human workers with machines. The key characteristics of I5.0 include:

- Human-centric approach: Industry 5.0 emphasises the importance of human interaction and collaboration.
- Resilience and sustainability: Industry 5.0 is aimed at creating sustainable products and services [19].
- Collaboration of humans and machines: The goal is to integrate humans and machines so that they work together more integratedly and collaboratively to achieve better results.
- Boost of customer experience and hyper customization: Industry 5.0 is dedicated to the customer experience, which often needs to be considered individually and personalised [20].

I5.0 initiatives are increasingly being applied to the MRO industry, leveraging advanced technologies and human-centric approaches to enhance efficiency, productivity and safety. I5.0 emphasises the collaboration between humans and machines, integrating human creativity and problem-solving with the precision and efficiency of advanced technologies. In the MRO industry, this can lead to more effective

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maintenance processes where human expertise is augmented by AI and robotics to diagnose and repair issues more accurately and quickly.

A representative case study that shows the new paradigm is illustrated in [21] by Moenck et al., which describes the visual inspection for crack detection that is performed manually using a fluorescent penetrant. The areas of improvement by introducing an automated procedure could be the changing of uncomfortable working positions when the inspection is conducted in confined spaces, protection of the technicians' health due to chemicals and UV light, and improvement of their working experience when doing something repetitive that requires effort. The proposed solution is to use a robotic platform that captures high-resolution 3D scans of the surface of interest using white light interferometry (WLI). An AI-based classifier processes the generated scans to detect the presence of cracks. As usually happens, the algorithm will also generate false positives, confusing similar-looking artefacts with cracks. This is where human expertise comes and manages the procedure, deciding what is real. In addition, in the cases of true positives, the human assesses the defect and decides what needs further consideration. It is essential to mention that the human inspector does need to inspect the real part to perform the crack assessment since they can use AR/VR devices to get immersed in the 3D scan and complete the task entirely remotely. In this case study, it is clear that the human is in the centre, managing the procedure and taking ownership and responsibility.

The new paradigm represents a step in the correct direction, as it minimises the negative effects of transformation and guides innovation to preserve the world for future generations. However, achieving this goal requires effort [22]. The implementation of I5.0 technologies demands a workforce with new skill sets. Organisations must invest in training and education programmes to enhance the abilities of current employees and prepare the next generation of workers for future jobs. The increased connectivity and data exchange raises concerns about data security and privacy. Strong cybersecurity measures, encryption protocols and access controls are essential to safeguard sensitive information. The integration of diverse technologies and software solutions can lead to compatibility issues. Therefore, developing industry-compliant solutions that ensure seamless communication and interoperability between devices, machines and software platforms is crucial. Adopting AI, automation and robotics raises ethical concerns related to job displacement and algorithmic bias. It is essential for businesses to adhere to ethical guidelines and regulatory frameworks to ensure the responsible deployment of I5.0 technologies.

In summary, I5.0 initiatives are transforming the MRO industry through improved human-machine collaboration, predictive maintenance, digital twin utilisation and the integration of advanced technologies such as AR, VR and blockchain. These initiatives not only enhance efficiency and productivity but also contribute to sustainability and resource efficiency, addressing both technological and societal challenges.

6.0 Energy efficiency and sustainability

As stated earlier, sustainability is now considered in every development since environmental impact plays a crucial role in the future of every suggested solution. The Hangar of the Future concept follows the same initiatives. Hangars are large buildings containing machinery and employees working often continuously in shifts. As such, it should be aligned with the best practices, reduce the energy footprint, and utilise the different resources in an environmentally friendly way to minimise any future adverse impact (Fig. 7).

The fields that have been the most targeted in recent years are the following:

- Reduce the carbon footprint of the hangar by using energy-friendly technologies like solar panels, gas absorption heat pumps, light-emitting diode (LED) lights, advanced roofing insulation and better water management by using water reservoirs that collect rainwater [24, 25]. The industry's commitment extends to advanced heating and cooling systems, optimising energy usage and maximising comfort (Fig. 8).

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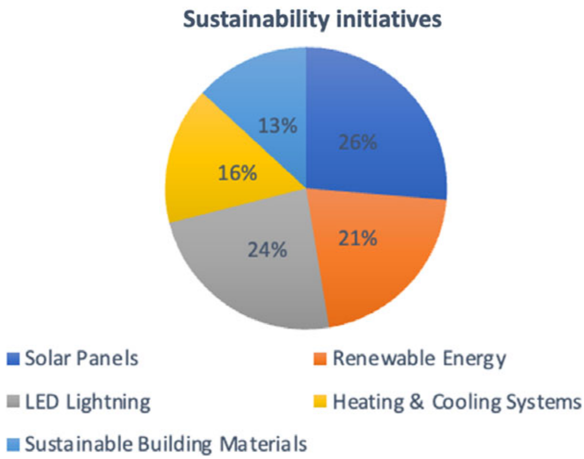

Figure 7. *Sustainability initiatives (image source [23]).*

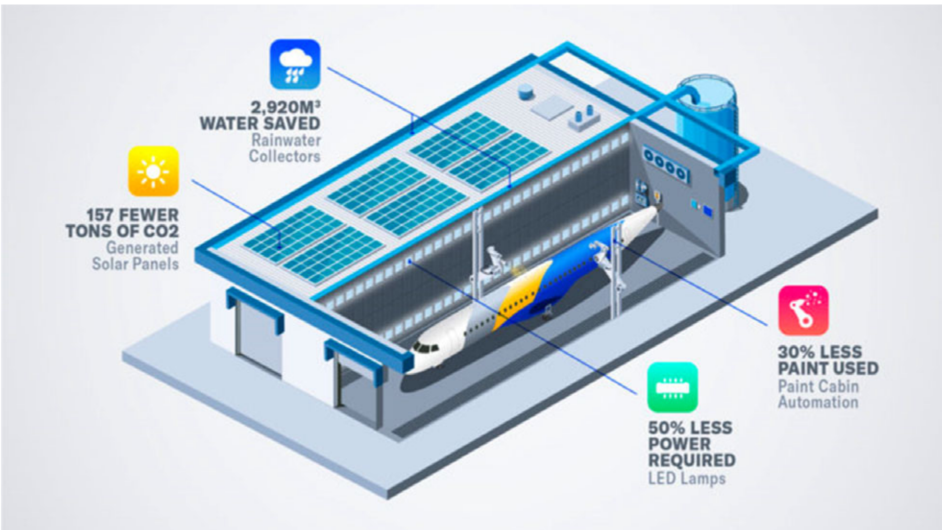

Figure 8. *Potential construction of an environmentally friendly hangar (image source [6]).*

- Use eco-friendly materials in the hangar construction, such as recycled steel and low volatile organic compounds (VOC) paints, which help to maintain longer re-coat cycles, green concrete and other green materials [26].
- Reduce waste generated during maintenance by adopting new waste treatment and disposal strategies, including hazardous materials, electronic waste and scrap metal [27].

7.0 Automated inspection and digital technologies

Inspections, in the context of the aviation industry, are a vital part of ensuring the airworthiness of the aircraft. Traditional aircraft inspection methods are commonly expensive, high-risk and time-consuming, with limited data capture and analysis capabilities through the use of outdated technologies (e.g. measuring tapes and cherry pickers). Additionally, relying on paper-based documentation and non-integrated systems can lead to inaccuracies in results due to transcriptional error [23]. This can result in missed

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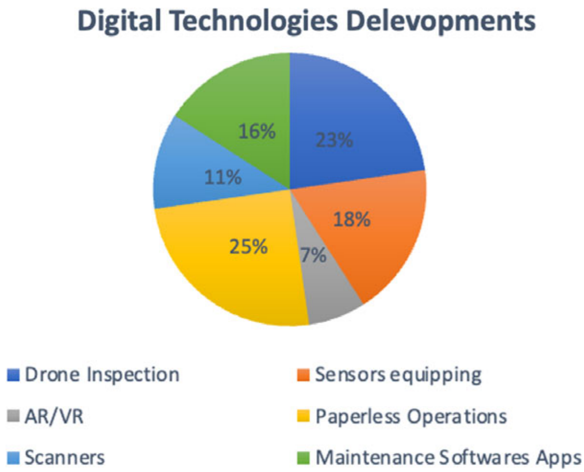

Figure 9. *Digital technologies developments (image source [23]).*

inspection points, incorrect part fittings and suboptimal performance. It's worth noting that current practices often neglect sustainability measures, resulting in wastage and higher energy consumption that contribute to the industry's carbon footprint. These factors exacerbate operational inefficiencies, ultimately impacting the reliability and quality of aircraft maintenance. Therefore, having the proper approach ensures that the operator is confident regarding safety and helps plan a better maintenance schedule.

After analysing current business trends, it was revealed that there has been a significant shift towards utilising advanced digital technologies in aircraft hangars (Fig. 9). The focus has been on incorporating drone inspections and asset tracking sensors, enabling real-time monitoring, accurate fault detection and streamlined maintenance planning. Additionally, adopting AI algorithms and digital twins has further enhanced predictive maintenance accuracy, ultimately leading to improved operational efficiency. A shift from paper-based to digital hangar processes streamlines documentation, reduces errors and speeds up decision-making.

Aircraft maintenance is quite complex and involves many intricate systems and components. Smart hangars are available to help collect real-time sensor data. This allows for predictive and condition-based maintenance, a proactive approach that can reduce unplanned downtime and minimise the chance of operational disruptions. Ultimately, this leads to higher aircraft availability and improved flight scheduling.

The current dominant maintenance activity in the aviation industry is manual visual inspection without keeping the records in a standard digital format. The way that it is performed is time-consuming and sensitive to inaccuracies. Exploration of different sensors and data processing could optimise the procedure and form a better assessment approach in examining damages and equipment degradation. In addition, equipment automation that slowly builds on more sophisticated autonomous systems can help achieve more accurate and repeatable results.

Adopting automated visual inspection provides several advantages. The inspection rate can be improved significantly, offering less downtime for an aircraft in parallel. Automated inspection will also increase the inspection's accuracy and consistency. Maintenance costs will be minimised when automated visual aircraft inspection is adopted due to the reduction of unscheduled maintenance. Finally, with the data being collected via the new technology, a more detailed analysis can be carried out and provide predictive maintenance capabilities.

IVHM research introduces tools and techniques that facilitate the digitalisation of repair and overhaul activities and improve existing approaches. The Hangar of the Future concept involves better analytical

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Figure 10. *Digital Aviation and Research Technology Centre (DARTeC) at Cranfield University (left image source cpwp.com).*

tools and advanced sensors in infrastructure, automation and robotics. On top of that, the digital records facilitate data analysis, which can act as the baseline to compare future inspections and quantify the degradation rate. Ultimately, we connect the outcomes of each procedure with existing MRO software solutions so that the adaptation of the new insights will be seamlessly integrated with existing tools and not create a gap in the skillset of the current inspection experts.

8.0 Key features of the dartec hangar of the future

The aircraft is a complex structure. The surface is uneven, and there are different levels of detail in the various parts of it. Also, some parts are concealed behind others, such as the landing gear port or the winglets. Considering these complications and the size of the aircraft body, a maintenance engineer's walk around for the pre-flight check might not be adequate to identify all critical defects and record condition data to build a detailed inspection record. This is where the Hangar of the Future provides the tools to develop strong confidence that the aircraft is ready for the next activity.

Automated inspection and analysis can be effectively implemented in smart hangars, which are specifically designed and built to accommodate these new approaches. The automation process has the potential to significantly reduce the cost and time involved in supporting aircraft operations and maintenance. A few of the benefits of adopting automated inspection approaches are the following:

- Rapid data for fast turn-around decisions.
- Reduce or eliminate unscheduled maintenance.
- Enhance flight safety with reliable inspection in all weather and base environments.
- Enhance staff safety by avoiding working from height, inside fuel tanks and congested underside.

The DARTeC hangar is built upon the concept of the smart hangar, and it aims to provide the appropriate ecosystem to automate inspection and improve aircraft operation and maintenance aspects (Fig. 10). It is equipped with technology that targets digitalising and processing data, as well as adding automation of inspection procedures. To enable a holistic approach to aircraft inspection, the hangar area is separated into three zones based on height and access difficulty (Fig. 11).

The higher zone covers the aircraft's upper part and the wing upper surfaces; this is the zone that is traditionally challenging to access. Using cherry pickers or temporary scaffolding is linked with working at heights, which is highly dangerous. Cherry pickers driven by maintenance technicians can also damage aircraft in unintentional crashes. On the hangar's roof, there is a camera system that gives real-time visual feedback in the digital MRO control room but also allows for stream recording and analysis that can be processed by the DARTeC's high-performance computing ecosystem (HILDA).

The middle zone covers the sides of the aircraft, which could be difficult to access from the roof cameras because of the view angle. In that case, the hangar has pan-tilt-zoom (PTZ) cameras with 40x

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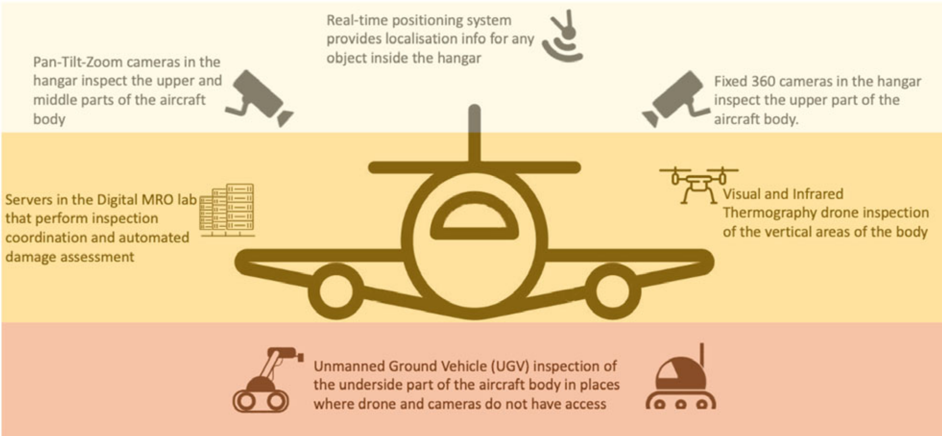

Figure 11. *The three zones of the smart hangar.*

optical zoom that can focus on the region of interest. In addition, there is the option to use unmanned aerial vehicles (UAVs) that can fly closer to the aircraft and examine the possible defect in greater detail from various angles of view [28]. The additional benefit of using UAVs is that they can carry, as payloads, more sophisticated equipment such as thermographic cameras and thermal sources, enabling advanced non-destructive imaging inspections.

The low zone covers the underside of the aircraft, which is also dangerous for potential injuries since many acute parts stand out. Ground robotics is a solution for that. Mobile robots outfitted with lights, cameras or robotic arms can inspect the lower part of the fuselage surface and localise the defects.

9.0 Visual inspections using the fixed camera system

Inspecting the higher zones of an aircraft, such as the upper fuselage, trim and the stabiliser on the tail, is not a straightforward procedure because of safety constraints. Conventionally, a maintenance technician must carefully operate a cherry picker. The personnel must drive the vehicle to the correct spots without crashing into the plane and simultaneously create the necessary clearance on the ground to avoid crashing into any valuable objects. The Hangar of the Future offers an alternative solution for this challenge. DARTeC’s hangar is equipped with a camera system that monitors an aircraft’s upper and middle zones with high-resolution resources (images, videos). Combined with ground-level techniques to cover lower zones, the system can achieve full coverage of an aircraft within the hangar area. The camera system comprises nine 360-degree and 1080HD-resolution surveillance cameras, two 180-degree and 4K PTZ cameras, and one fixed-angle panoramic camera. A desktop client has been developed to register, manage and control all cameras. The main interface is reconfigurable to cater to multiple purposes. Also, the pre-set functions allow users to set initial views in specific angles and scopes for each camera (Fig. 12).

Conventionally, visual inspection is widely used to perform routine maintenance checks such as pre-flight inspections, post-flight checks, light scheduled maintenance and heavy scheduled maintenance. Visual inspection is used to inspect the exterior or interior of an aircraft. The exterior material of the aircraft may be divided into metallic or composite. Visual inspection is essential to an aircraft’s safety, reliability and airworthiness [29].

Using the fixed camera network, we go beyond the manual inspection of an operator using the system dashboard to inspect the aircraft’s surface with the naked eye. Nowadays, many researchers employ deep learning, a machine learning approach based on neural networks, aiming to recognise patterns in the surface of the materials. For example, the work presented by Bouarfa et al. [30] uses a Mask Region

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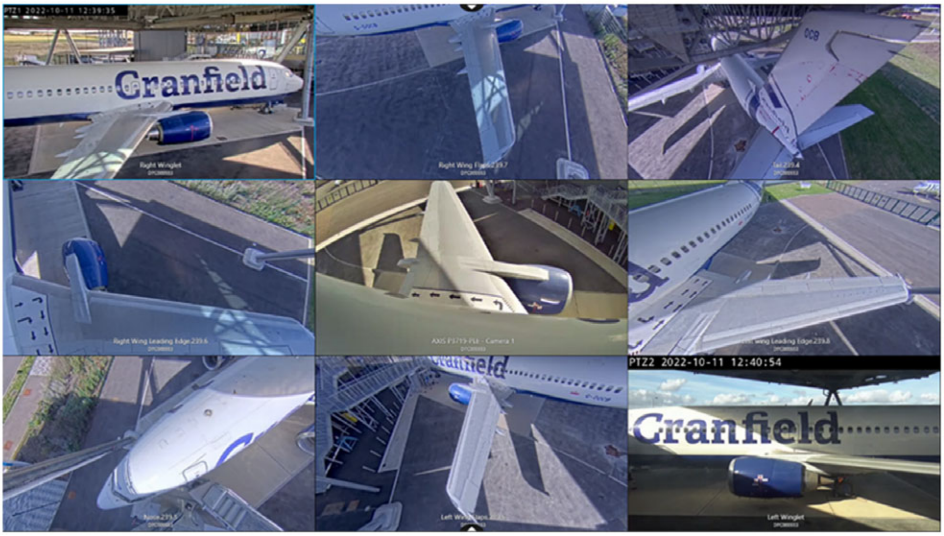

Figure 12. *Example of full coverage view in the camera's system dashboard.*

Convolutional Neural Network (Mask R-CNN) to identify a dent in an aircraft automatically. Different combinations in training for the model include the background colour of the dent, the dent's location, the dent's size, the cause of the dent, but also the source of the datasets, lighting conditions, resolution, distance and angle between the camera and the dent. However, there are challenges. Machine learning approaches require large and high-quality datasets for training, but aircraft visual inspection is niche and narrow. The research presented by Gaul et al. [31] created a damaged 3D aircraft artificial dataset to train convolutional neural networks (CNNs) for automated aircraft inspection. The datasets are generated by scriptable 3D rendering software to create images based on the accurate visual representation of the aircraft type of interest with numerous scenes and environments around the virtual aircraft.

10.0 Case study to compare existing and automated approaches in DARTeC's smart hangar

In an attempt to explore and evaluate the implementation of new technologies in the smart hangar, experiments were performed to compare different maintenance procedures. One of the Group Design Projects (GDP) teams in 2023 MSc in Aviation Digital Technology Management selected two automation technologies with high impact and low effort to implement and performed a 1A check in the Boeing 737-400 DARTeC's ground demonstrator [32]. The technologies they selected were:

- Intoware's WorkfloPlus. In this case, the team used WorkfloPlus software to digitalise the 1A inspection checks and transformed it into a compatible application that can be executed on a wearable device (Fig. 13).
- Fixed AXIS camera system. The team used the camera system to provide remote visual inspections of the aircraft, allowing for thorough assessments of its structural integrity and general condition.

In the first experiment, the team identified the 1A check tasks from Boeing's official documentation and modelled each one using the WorkFlow editor. For each task, they gave detailed instructions that were presented on the wearable device. Using voice commands, the inspector could reply immediately about the investigation. In addition, inspectors could command the device to take an image and attach it to the investigation's feedback (Fig. 14). Having the hands free and a device that supports them

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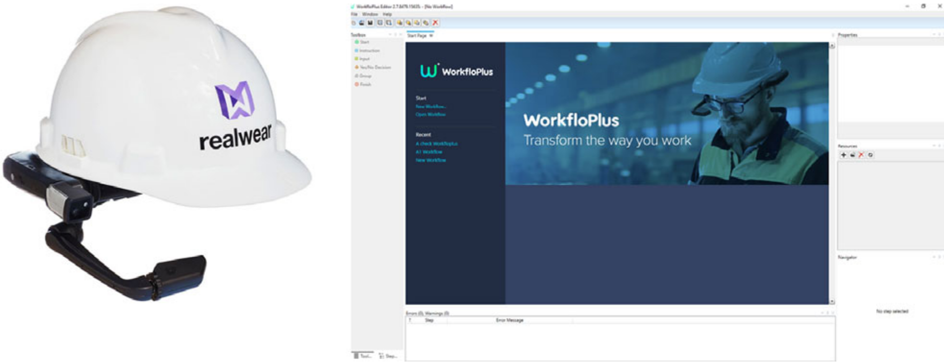

Figure 13. *(left picture) Helmet with a wearable device attached; (right picture) WorkfloPlus procedure editor interface.*

Figure 14. *(left picture) An MRO inspector is wearing the hands-free device and performing the 1A check (right picture). The dent is captured from the PTZ fixed camera that is fixed in the DARTeC smart hangar.*

continuously allows personnel to complete jobs more effectively without the possibility of forgetting or overlooking something. The beauty of the automated 1A check is that everything is gathered in a complete report where the MRO manager can evaluate and analyse the collected data, decide if something should be escalated, and ensure that everything is properly operating to continue.

Using the wearable device and the integrated software for workflow automation, the team managed to enhance the efficiency of carrying out tasks by up to 25% per task when compared to conventional methods, reducing person hours. The interface facilitates the human inspector's removal of the need to carry paperwork. The task display and instant defect documentation using the device make the inspection tasks intuitive and assist in reducing errors. The report is digitally generated and paperless and shows the data captured and the inspector's feedback throughout the 1A check, ensuring accountability, traceability and sustainability.

In the second experiment, the team used the fixed cameras using the control application from the control room of the digital MRO lab in DARTeC to perform a visual inspection of critical aircraft components and structures to complete tasks of the 1A checks (Fig. 14). In challenging areas, they used PTZ cameras and zoomed in on the region of interest. The remote visual inspection enhanced the operational efficiency by approximately 70% per task and reduced person-hours and effort by removing human walk-around and physical interaction with aircraft. In terms of fidelity, the level of detail that was captured using the system was satisfactory. In addition, cameras contribute to reducing the risk to personnel involved in inspecting areas at a certain height. The outcome of the procedure was a digital output that can be stored, accessed and analysed, promoting efficient data management practices and reducing the reliance on paperwork, enhancing sustainability.

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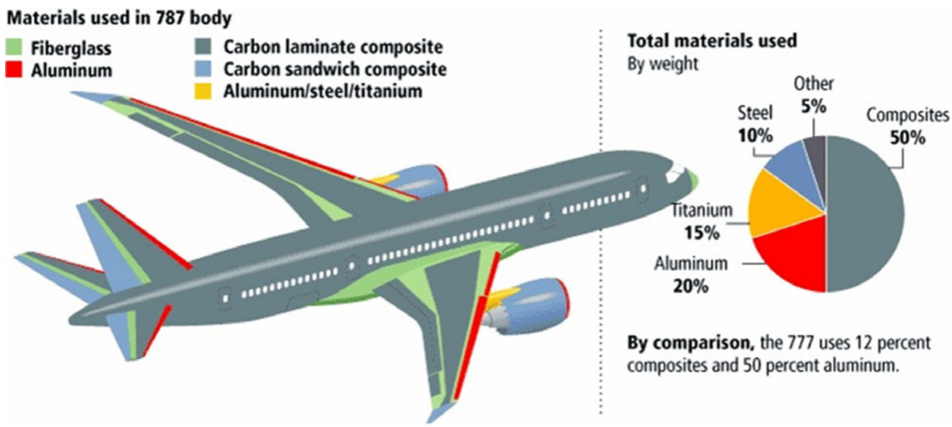

Figure 15. *Usage of various materials in the Boeing 787 Dreamliner (image source appropedia.org).*

11.0 Active thermography inspection using aerial robots

Aircraft are increasingly being made from composites due to the lower weight and fuel requirements, and airlines require minimised operating costs to be financially viable and competitive (Fig. 15). A novel inspection suitable for composites uses UAVs that can perform visual inspection combined with Active Thermography (AT). Thermography is based on measuring the emitted thermal radiation from the surface of an object of interest. This technique is commonly used for detecting defects such as cracks, voids, delamination, structural damage and corrosion by observing the component's thermal radiation patterns [33]. Miniaturisation and stabilisation of thermal infrared cameras now enable more mobile use of the technique, which is further supported by the increasing speed and capability of robots.

The concept of active thermography UAV inspection has been explored previously in a 27-month Canada-UK collaborative project (Enhanced Industrial Productivity 2019 Call) that was completed successfully in December 2021. Cranfield University (both the Autonomous and CyberPhysical Systems Centre and the IVHM Centre) was a member of this project (MultiAcT: Multiple robotic inspection of composite aircraft structures using Active Thermography), focusing on developing and optimising AT inspection on a drone for defect detection on composite structures [34]. The innovative part of this approach is that the UAV carries the excitation sources and the infrared camera (Fig. 16). During the flight, in real-time, the UAV identifies the location of a defect and transmits the thermography video stream to the central servers that perform automated defect analysis. The UAV localisation is supported by an external motion-capturing system that can provide sub-millimetre and sub-degree accuracy. Regarding the thermal excitation sources, the UAV platform is equipped with four 250 Watts optical lamps attached to the legs of the aerial platform. The UAV follows a waypoint algorithm and inspects specific points of the sample to get full coverage.

12.0 Visual inspection using ground robots

Ground robots are strong candidates for carrying out inspections in the lower zone, which could be a complex process and easily congested by trolleys, mobile tool cribs, cherry pickers and maintenance engineers. Mobile ground robots move in the environment using either wheels or tracks. The option depends on the floor surface, but as the hangars are usually indoors, both can be adapted. The most popular kinematic models used in industrial unmanned ground vehicles (UGVs) are the differential drive [35] or the skid steer [36]. The advantage of using those options is that both allow rotation in position, making them very attractive for flexibility of movement in a congested environment. As a more advanced option, in an attempt to address cluttered environments, for example, to overcome cables and obstacles

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Figure 16. *The UAV platform that performs active thermography inspection (three-day demonstration trial took place in ORE Catapult facilities in Blyth).*

on the floor, quadruped robots are a safe option to consider. However, quadrupeds usually have lower payload capabilities.

The benefit of using ground-moving robots is that they can easily carry heavy payloads compared to UAVs and are less likely to cause damage to the aircraft in case of control failure. Also, they are less sensitive to weather conditions and less frightening for humans working in close proximity. The limitation is that they are not so flexible in accessing specific points of interest because they move on the ground, although this can be remedied using robotic arms on top of them. However, robotic arms add more complex control and cost to the moving platform.

One of the biggest challenges in the robotics part of the smart hangar is the localisation of the robots. This aspect is highly critical to the automated inspection concept, mainly because of the following two reasons:

- Localisation is a vital component of navigation. Assuming the map of the hangar is known, the localisation is the algorithm that allows the robot to know where it is and guide it to the destination target. Without accurate localisation, the robot cannot go accurately and safely to the desired target.
- One of the main tasks of ground robots is to identify defects using their onboard camera. By knowing the intrinsic and extrinsic camera parameters, the robot can define the position of the defect relative to the robot frame. However, from an inspection point of view, it is meaningful to know the defect location in relation to the aircraft frame, which is linked to the hangar reference system. Therefore, uncertainty in the robot's position accumulates in defect localisation.

Initially, the Robotis TurtleBot3 robot [37] was used, which is the *de facto* academic learning platform (Fig. 17). Although the platform managed to navigate and inspect indoor structured places, the effort to achieve something similar to the hangar's ambiguous and featureless outdoor environment [38] was ineffective. The TurtleBot3 is not an ideal fit for this task. The incompatibility is due to the low-range planar lidar (2 meters range) and the difficulty of moving on the outdoor cemented surface compared to the indoor carpet. However, this is not an issue since alternative platforms on the market, such as ClearPath [39] (Fig. 18) or Husarion [40] platforms, can move and localise in outdoor environments and carry heavier payloads.

One of the substantial advantages of working in a smart hangar for robotic applications is that the hangar is outfitted with a real-time location system (Fig. 19). The system is based on UWB technology capable [41] of providing 3D locations in a space covered with sensors (antennas) mounted on the

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Figure 17. *The TurtleBot3 navigating inside the DARTeC's smart hangar.*

Figure 18. *The Clearpath's Husky navigating inside the DARTeC's smart hangar.*

hangar's roof. The positional accuracy depends on the number of antennas with a direct line of sight to the moving tag. The best accuracy reported in the open space is in the range of 0.5 to 0.9 meters. To improve the positional accuracy, we use sensor fusion [42] and utilise the UWB feedback with the onboard sensors to get a more reliable indication of the robot's position. The sensor fusion also helps us estimate the robot's heading since this information is not available in the UWB feedback, but it can be deduced using the onboard inertial measurement unit (IMU) [43].

Knowing that localisation is one of the most critical aspects of success in robotics. Alternative methods apart from the planar laser have already been investigated. Other routes that can be explored include visual feedback from onboard monocular cameras and stereo cameras [44]. Moreover, there is also the

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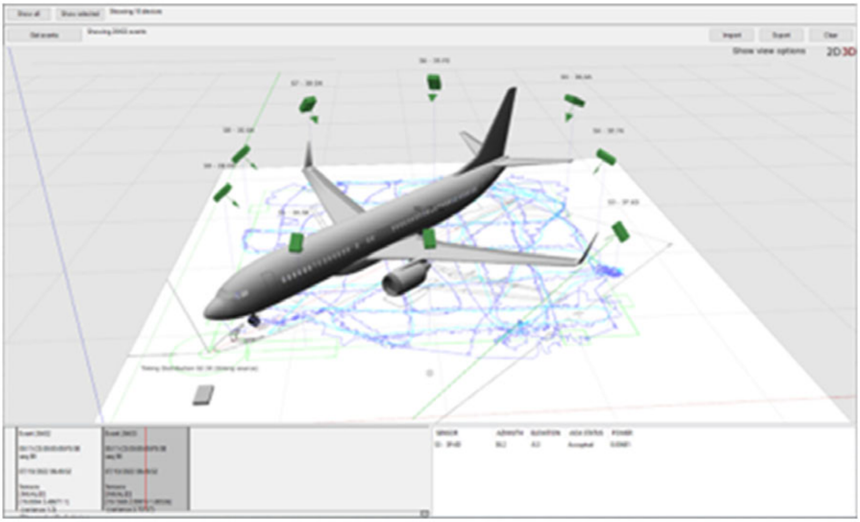

Figure 19. *Real-time location system feedback in the digital MRO lab.*

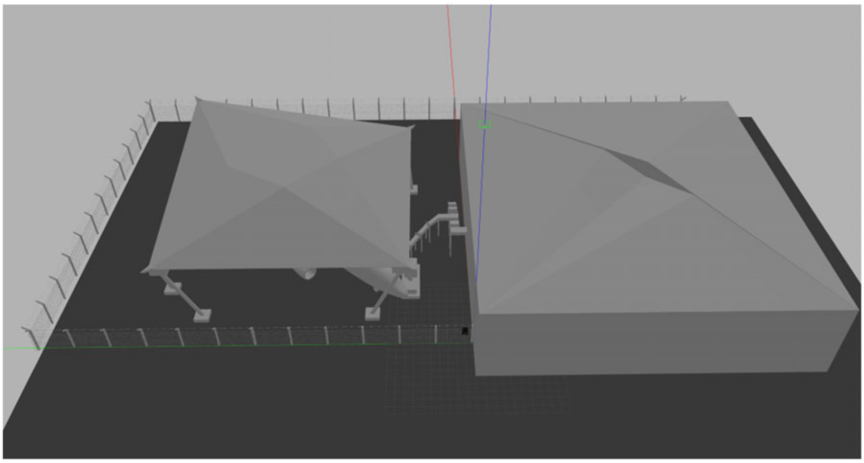

Figure 20. *The 3D model of the hangar in DARTeC.*

option of experimenting with fiducial markers [45]. However, the camera system must be calibrated to compute intrinsic parameters such as the lens and perspective distortion.

As in any robotics project, working with real robots is essential, but having tried the concept, a representative simulation is necessary. Therefore, we have designed and developed a 3D model for DARTeC's hangar (Fig. 20). The benefits of using a simulation are that it provides a platform for experimentation and enables us to develop and refine robotic technologies effectively and efficiently. The 3D model has been built in the Gazebo simulator, which is the *de facto* library that comes with the Robot Operating System (ROS) [46]. We have optimised the models, reducing the meshes' vertices and triangles, allowing faster simulation setups and smoother transitions. In addition, we have set up the hangar's innovative equipment, such as the UWB system and the fixed camera network, in a fully customisable way to enable different experiments in robotic navigation development.

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13.0 Challenges in moving towards the smart hangar ecosystem

Transitioning to smart hangars presents challenges that require careful consideration to successfully integrate advanced technologies into traditional aircraft maintenance practices. These challenges include workforce demographics, technical and logistical aspects, and more, making implementing smart hangar solutions complex.

One major challenge is the ageing workforce and shortage of skilled workers in the aviation industry. Embracing smart hangar technologies requires reskilling and upskilling the existing workforce to operate, maintain and troubleshoot these advanced systems effectively. Investing in training programs, mentorship initiatives and partnerships with educational institutions is necessary to foster a new generation of professionals adept in modern technologies.

Transitioning to digital workflows presents technical and cultural challenges, as the change can be met with resistance from a workforce accustomed to traditional methods. Hence, there is a need to establish confidence and assurance with a new system. Change management programs and comprehensive training and education initiatives are vital to ensure a smooth transition and widespread adoption of digital solutions.

Older aircraft models may lack built-in sensors or connectivity features, hindering data collection and real-time monitoring. Retrofitting such aircraft with necessary sensors and communication systems can be complex and resource intensive. Collaboration with aircraft manufacturers is essential to establish data-sharing protocols and facilitate the integration of smart hangar solutions into existing fleets.

Security and cybersecurity are paramount challenges in the digital age. Robust cybersecurity measures, including encryption, firewalls, intrusion detection systems and regular audits, are imperative to safeguard sensitive data and digital infrastructure.

14.0 Smart hangar and IVHM

The concepts of the smart hangar and IVHM are closely related as they both aim to improve the efficiency, reliability and sustainability of aircraft MRO-related processes by utilising advanced technologies. IVHM has evolved from conventional methods to DTs, driven by advancements in sensor technology, data processing and artificial intelligence. The concept of IVHM was first seen in the aerospace sector by the National Aeronautics Space Administration (NASA) in 1992, based on CBM practices [47]. Early IVHM systems mainly focused on using sensors to monitor the health of vehicle components and predict failures before they occurred. Over time, IVHM systems became more integrated, combining data from various subsystems to provide a comprehensive picture of vehicle health. A DT is a virtual representation of a physical system that can simulate its performance and predict future states based on real-time sensor data. This concept has been integrated into IVHM to enhance its predictive and diagnostic capabilities. DTs allow for the virtual rerun of events and simulation of future performance, providing a more detailed and accurate assessment of vehicle health [48].

The common denominator in both concepts is the extensive use of data. Both of them rely heavily on data analytics to enhance decision-making processes. By integrating data from various sensors and systems, they can provide a comprehensive picture of an aircraft's health, enabling more informed and timely maintenance decisions. Smart hangar is not only outfitted with its own set of sensors and wearable devices that technicians may use in maintenance, but it also provides access to computing resources to manage, store and process the data and support the DTs for diagnostics and prognostics. For example, DARTeC's smart hangar is equipped with a dense, ultra-fast WiFi-6 (IEEE 802.11ax) wireless network in combination with a wired infrastructure. On top of that, it has a dedicated data centre called HILDA (Hypercomputing Integrated Layer for Digital Aviation) composed of graphic processing units (GPUs) and multicore central processing units (CPUs), which include 4,576 computing cores, 110,592 compute unified device architecture (CUDA) cores, and 6,912 TensorFlow cores to support machine learning and any data related modelling. The future smart hangar should have local equipment, cloud or hybrid infrastructure to support new technologies.

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The aim of the smart hangar is to increase operational efficiency by automating and digitalising maintenance tasks, reducing the time and effort required for inspections and repairs. The IVHM concepts contribute to this goal by providing continuous monitoring and analysis of vehicle health, which helps in planning and executing maintenance activities more efficiently. In terms of supporting the sustainability aspect, IVHM helps reduce unnecessary maintenance and avoid unscheduled repairs, leading to lower energy consumption and reduced material waste. In a similar way, smart hangars support these sustainability goals by implementing lean management practices and using digital tools to minimise environmental impact.

15.0 Conclusions

The sustainable smart hangar of the future represents a significant step forward for the aviation industry. As we continue to develop new technologies and push the boundaries of what is possible in flight, it is essential that we also focus on improving the maintenance, research and development activities that take place in hangars. By implementing energy-efficient technologies, advanced automation and data analysis tools, we can create a more sustainable and efficient aviation industry that benefits everyone. The Hangar of the Future will likely feature fleets of robots working alongside skilled engineers to perform maintenance tasks and a computer centre to analyse aircraft data, leading to the possibility of lights-out operations. All these advancements will enable us to identify potential issues before they become significant problems, reducing downtime and improving safety. Optimising hangars for energy efficiency and sustainability can reduce our environmental impact while saving money on operating costs.

Overall, the sustainable smart hangar of the future represents an exciting opportunity for innovation in the aviation industry that has the potential to benefit everyone involved, ultimately supporting the achievement of aviation's 2050 targets for both climate change and biodiversity. In addition, it will support the IVHM Centre's longer-term ambition to develop a conscious aircraft – perhaps we will see a conscious hangar communicating with a conscious aircraft.

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