Journal of Computational Design and Engineering 6 (2019) 516–526

Contents lists available at ScienceDirect

Journal of Computational Design and Engineering

journal homepage: www.elsevier.com/locate/jcde

Maintenance in aeronautics in an Industry 4.0 context: The role of Augmented Reality and Additive Manufacturing ☆

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ARTICLE INFO

Article history:
Received 19 September 2018
Received in revised form 31 January 2019
Accepted 1 February 2019
Available online 4 February 2019

Keywords:
Industry 4.0
Augmented Reality
Additive Manufacturing
Aeronautical maintenance

ABSTRACT

The paper broadly addresses how Industry 4.0 program drivers will impact maintenance in aviation. Specifically, Industry 4.0 practices most suitable to aeronautical maintenance are selected, and a detailed exposure is provided. Advantages and open issues are widely discussed and case studies dealing with realistic scenarios are illustrated to support what has been proposed by authors. The attention has been oriented towards Augmented Reality and Additive Manufacturing technologies, which can support maintenance tasks and spare parts production, respectively. The intention is to demonstrate that Augmented Reality and Additive Manufacturing are viable tools in aviation maintenance, and while a strong effort is necessary to develop an appropriate regulatory framework, mandatory before the wide-spread introduction of these technologies in the aerospace systems maintenance process, there has been a great interest and pull from the industry sector.

1. Introduction

The German government introduced in 2011 the term "Industrie 4.0" at the Hannover Fair to describe a strategic approach to manufacturing (Zheng et al., 2018) envisaged by the politics, and based on computerization of manufacturing. In recent years the term has been extended to new trends suggesting a new revolution based on the real interaction between manufacturing robots and humans, and machine themselves. As suggested by literature (Cozmiuc & Petrisor, 2018), there are four pillars creating this fourth industrial revolution: Interoperability, Information transparency, Technical assistance, and Decentralized decisions. Interoperability means to exploit internet of thing (IoT) to network people, devices, machines and robots with the final aim of automating as much as possible manufacturing, the so called "whole automatic factory" concept. The Information transparency term is intended for the concept of Digital Twins (Miller, Alvarez, & Hartman, 2018): virtual copies of real objects and enrichment of the virtual with data extracted from real sensors. Technical assistance (Hold, Erol, Reisinger, & Sihn, 2017) is another field where Industry 4.0 focuses its attention to introduce two disruptive technologies: the support to operators with information which can be visualized when needed to solve problems in short times; the substitution of humans with cyber-physical machines to perform D3 (D-cube) operations (Dull, Dirty, Dangerous). Finally, the decentralized decisions concept (Marcon et al., 2017) proposes intelligent machines able to take decisions in an automated way, solving contradictions and complex planning problems without human intervention, where the operator becomes a supervisor instead of being in charge of solving problems. From a more practical point of view, what envisaged by Industry 4.0 (Peruzzini, Grandi, & Pellicciari, 2017) can be tackled by: introducing new technologies like Augmented Reality (AR) and Virtual Reality in companies; exploiting Additive Manufacturing (AM) to accelerate production times and allow smart structures; providing companies with software tools able to manage large amount of data, the so called Big Data problem (Santos, 2017); developing software algorithms useful to aggregate data in legible and intuitive ways, thus providing to human supervisors only the most important information, and avoiding to confuse him/her with too much data; equipping factories with high band internet connections to implement a real network between human, virtual, and real hardware machines and robots. It is opinion of the authors that Industry 4.0 concepts can be translated from an industrial to an aeronautical domain, to support design, maintenance, in-flight structural health

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☆ Selected paper from the 25th ISTE International Conference on Transdisciplinary Engineering, 3–6 July, 2018, Modena, Italy.

Peer review under responsibility of Society for Computational Design and Engineering.

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https://doi.org/10.1016/j.jcde.2019.02.001
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monitoring, and flight management, just to name but a few. Aeronautics is a complex and demanding field both from a design and maintenance (FAA, 2018) point of view: civil aviation requires logistic solutions able to provide spare parts in short times in remote areas, where complex maintenance tasks are often requested from local operators. Just to support these statements on the scientific and industrial interest, it is worth noting that the European Research Programme Clean Sky 2 has focus its attention on maintenance strategies for Large Passenger Aircraft under the ADVANCE European Union H2020 project (Lee, Shin, Tsourdos, & Skaf, 2018) and subsidiary program AIRMES (Airline Maintenance Operations implementation of an E2E Maintenance Service). Just to provide another example, the paper by French, Marin-Reyes, and Benakis (2019) addresses the problem of the introduction of Additive Manufacturing in aerospace as well. The literary review analysis suggests that concepts of the Industry 4.0 program can be applied to shorten the maintenance times and exploit new capabilities provided by technologies like AM and AR. There is already an abundance of literature dealing with these topics, but the novelty proposed here is to provide a long-term-evolution of maintenance based on concepts which will be probably introduced in factories in the next decade. The following Fig. 1 shows a timeline related to the introduction of the technologies described in this paper.

As Fig. 1 suggests, AM and AR had a long run-up to achieve the current capabilities and they reached a level of maturity that could be made available to factories and aircraft maintenance. However, legislation and certification processes associated with adoption of these technologies are currently limiting the wide application of these technologies, but the market can push the authorities towards the development of suitable rules. The impact of these technologies on maintenance schedule and activities, with implications to the aviation industry and fleets of large commercial airplanes, helicopters, and general aviation airplanes could be dramatic. The Industry 4.0 program advocates significant innovative developments in industrial engineering manufacturing processes. It suggests a massive introduction of new smart solutions like Additive Manufacturing and Augmented Reality into modern factories. The aim of this paper is to analyse the benefit of the introduction of these new technologies in aeronautical maintenance, envisaging a technology transfer from automatic factory concepts to aviation maintenance. The motivation of this work is to provide examples of how AR and AM could be used in this framework, and to discuss its potential advantages when compared to traditional maintenance processes (Fioriti, Vercella, & Viola, 2018). The attention has been focused mainly on AM and AR, and not on other aspects of Industry 4.0 strategies, because these two technologies seem to be the most suitable to support on-ground maintenance operations, while the other Industry 4.0 technologies above cited are more suitable to in-flight operations. Big Data handling strategies can be useful to implement networks of sensors and obtain in-flight real-time data; this can dramatically increase the performances of avionic systems and it can allow the implementation of failure recovery strategies and data fusion when a sensor performance is degraded. Moreover, Analytic algorithms which are now developed to the sake of Industry 4.0 can support data retrieval and fusion of data from millions of remote sensors monitoring aircraft structural health. The paper is structured as follows: the next Section 2 will describe in more detail the basic concepts lying under AM, AR, and Industry 4.0 program. Section 3 deals with aeronautical maintenance and its integration with industry 4.0, while Section 4 presents case studies where applications of AR and AM are described.

2. Augmented Reality and Additive Manufacturing

2.1. Additive Manufacturing

Additive manufacturing can be defined as the counterpart of traditional chip removal machines, like lathe or milling. Several AM techniques have been introduced in recent years (Gibson, Rosen, & Stucker, 2010). One way to classify these techniques is based upon the state of the raw material used, which can be liquid (e.g. Fused Deposition Modelling (FDM) or Stereolithography (SLA), discrete particles (typically powders, e.g. Selective Laser Sintering (SLS), or Electron Beam Melting (EBM)), or solid sheets (e.g. Laminated Object Modelling (LOM)). FDM is a cheap technique based on the deposition of a thin wire of plastic following a pre-defined path: ABS or PLA wires are melt in a nozzle which presents a relative movement in the 3D plane respect to a building table. Once extruded from the nozzle, the plastic solidifies and a solid model can be obtained. The SLA technique is based on a photo sensible liquid resin which solidifies once hit by a laser beam: also in this case, layer by layer a solid shape can be obtained by polymerizing the liquid along a path. The two techniques can be useful to obtain non-structural parts. However, when high strength materials are required, methods based on the melting of metallic powders like SLS or EBM are necessary: starting from aluminium, steel, or titanium powders (Dutta & Froes, 2017), solid parts are obtained with structural properties similar to machined or cast metals. Finally, LOM is based upon bonding adhesive-coated thin sheets of paper, plastic, or laminates up to obtaining a 3D shape stacking the single layers. But what makes it interesting AM is that complex shapes can be obtained due to the maximum freedom of shaping. Complex structures based on thin truss structures which are repeated in the

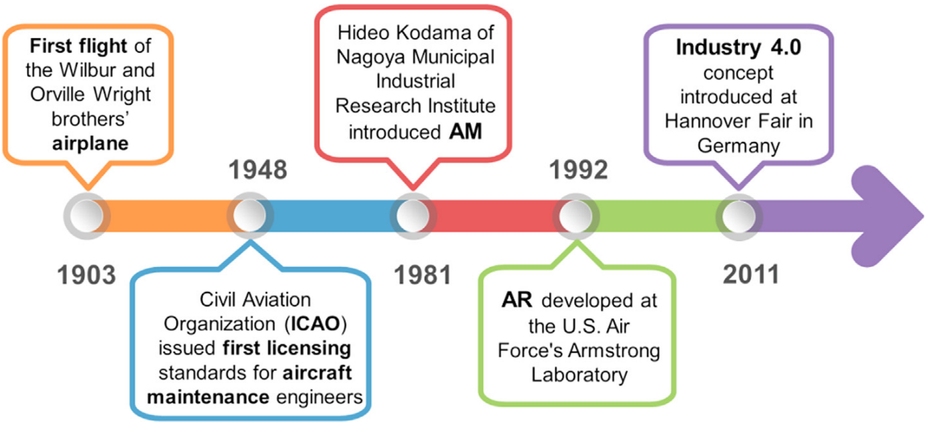

Fig. 1. Technologies timeline.

volume thousands of times (and called lattice) (Savio, Meneghello, & Concheri, 2017) can achieve a high structural efficiency where all the material presents similar values of stress. This kind of structures imitates what nature does in a very efficient way: trabecular structures are common in animal and human bones and in bird wings. Similar efficient structures (Rosen, 2007) can be found in nature where trees branches and leaves are some of the most cited examples. AM presents a wide range of geometrical structures to shape bodies in efficient way. Weight reduction can be advantageous to use less material, and to avoid to waste energy in transportation, thus reducing pollution emissions (Raymer, 1992). Three are the hottest themes from a research point of view: topological optimization (Bendsoe & Sigmund, 2004), homogenization (Vigliotti & Pasini, 2012) and lattice structures. Topological optimization means to define a control volume where the component will grow, to define points where constraints will apply, to set the points where Forces will act on the structure, and eventually to define void zones, where material isn't allowed. Fig. 2 shows an example of optimization where 4 constraint points and 1 force point have been selected and iteration by iteration the component grows along the directions assuring minimum compliance (the product of the internal forces by its displacement) of the part. In such a way high efficiency components can be obtained.

Lattice structures are parts where a dense material is replaced by a high number of elementary cells which are repeated along the three directions. Cells present high void over dense ratio: tetrahedral, cubical, hexagon structures are widely exploited. How to carry out in short time FEM analyses of lattice structures is still one of the open problems in this field. Due to the small dimensions of the beams which constitute the armour of the cell, the minimum size of the solid elements need to mesh the component is equal to the diameter of the cylinders. Due to the high dimension of the body compared with this diameter, a huge number of elements is found where analyses are carried out. This leads to computational efforts requiring high performances machines and long analysis times. Homogenization is a technique where this problem is overcome by computing an equivalent isotropic material which can be applied to a completely dense part with the same geometry of the lattice one, obtaining similar results. Through this process it is possible to significantly reduce computational time and to analyse complex structures.

2.2. Augmented Reality

Augmented Reality is nowadays a mature technique which have been introduced at first by Azuma in his seminal paper (Azuma, 1997). AR can be defined as a computer graphics technique where virtual symbols are superimposed to a real image of the external world. It presents an evolution of Virtual Reality where the user holds Head Mounted Displays or is immersed in Cave Automatic Virtual Environment (CAVE) structures. In VR there is no connection between real world and user, while in AR (Gattullo, Uva, Fiorentino, & Gabbard, 2015) there is a close contact since only CAD models, writings or symbols are added to the scene. To this aim, see-through glasses (equipped with a camera and small projectors on lenses), or mobile devices like tablets or smartphones (where the camera is used to frame the external environment and screen is used as output) can be used in AR (Di Donato, Fiorentino, Uva, Gattullo, & Monno, 2015). The virtual objects are linked to the real word so that by moving the point of view of the camera, the symbol positions respect to the external reference system does not change. This is obtained by computing the position of the camera with respect to the external environment, by either using markers (usually chessboard based symbols whose shape and dimensions are a-priori known) or without marker. In this latter case, a set of pictures of the external environment are stored in a database, so that by comparing it with what framed by the camera the recognition of the camera position in space can be possible. Makerless software packages are nowadays available in several AR packages (like ALVAR™ (Kantonen, Woodward, & Katz, 2010; Alvar, 2018) and Vuforia™ (Vuforia, 2018)), while ARtoolkit (ARToolkit, 2018; Billinghurst, Kato, & Poupyrev, 2001) can be cited as an example of tool based on markers use. Once the position of the camera has been found, it is possible to superimpose in the correct position CAD models, symbols or writings to the video stream (Ceruti, Liverani, & Bombardi, 2017). It is worth noting that AR is a real time technique so that while moving the point of view the Virtual symbols change position accordingly in the video output. A bulk of literature deals with AR and maintenance: the review paper (Palmarini, Erkoyuncua, Roy, & Torabmostaedi, 2018) shows that 17% of the selected publications deal with aeronautics, and an overall 33% papers describe assembly/disassembly tasks. The paper (Robertson, Bischof, Geyman, & Ilse, 2017) provides the outcome of a pilot study where 15 aeronautical mechanics have been interviewed about the use of wearable technology in maintenance task: the completion time for two maintenance tasks was reduced by 7.7% and 11.6%. Moreover, it is worth noting that participants appreciated the reduction in time spent traveling between the aircraft and manual, operation usually implying climbing on ladders. From a more industrial point of view, similar results can be found in literature: following Boeing and Iowa State University (Thearea, 2018), 90% improvement in

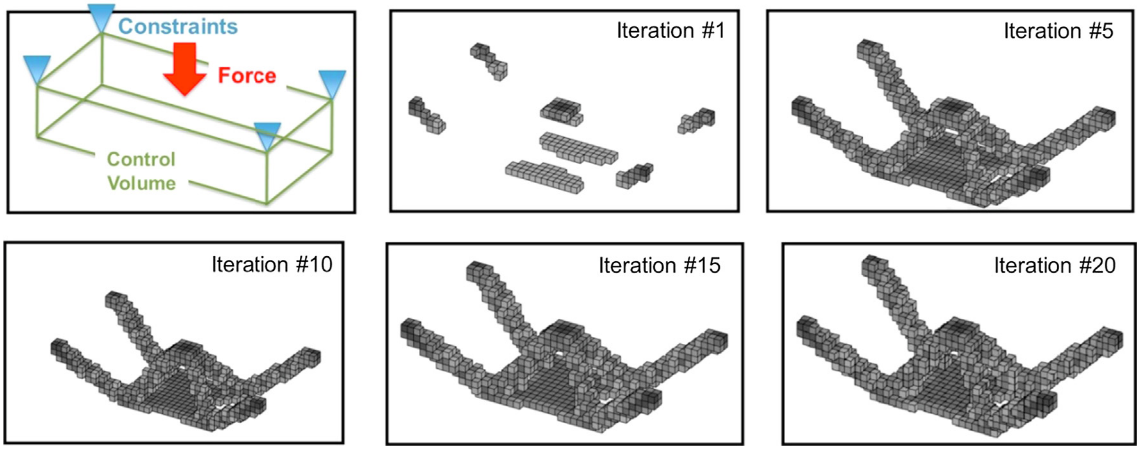

Fig. 2. Example of topological optimization.

quality and 30% in time can be achieved when technicians tasked of manufacturing a wing structure are equipped with tablets. A similar research carried out by Airbus (2018) showed a plummet of the A380 fuselage brackets inspecting time from three weeks to three days.

3. Maintenance in Aeronautics 4.0

3.1. Maintenance in Aeronautics

In aeronautical terminology, the term MRO (Maintenance, Repair and Overhaul) describes operations like: inspection, replacement of damaged or crushed parts (together with supply logistics (Regattieri, Gamberi, Gamberini, & Manzini, 2005)), replacement of sealants, fixing of coatings, refilling of lubricants or gases (e.g. in damping cylinders, hydraulic accumulators, conditioning systems). The aim of MRO is to assure the compliance of a commercial aircraft with Airworthiness Directives every time it flies. MRO is crucial for safety and it is therefore strictly regulated by aeronautical national authorities like FAA (Federal Aviation Administration) for USA, TC (Transport Canada) for Canada, EASA (European Aviation Safety Authority) for European countries. Civil Aviation Organization (ICAO) provides general guidelines to maintenance process too. FAA and EASA are in charge of certifying operators working in maintenance as well: this is motivated by the fact that maintenance is a complex and risky task which can lead to flight incidents without a specific effective training. In such a framework, it is worth citing the SHELL model (Marx & Graeber, 1993): it links 4 aspects strongly affecting the aviation system, namely software (regulations, instructions, information, organization), hardware (aircraft, material buildings), environment (weather, temperature, physical/social/political variables that can have an impact on the operators), liveware (human element: pilots, maintenance operators, ground crew). Usually, accidents arise in aeronautics due to a poor link between hardware, and liveware (e.g. poor ergonomics in tools) or software and liveware (e.g. unclear manuals and documentation in general). From a historical perspective (Khee, 2009), the maintenance was strictly related to each one of the revolution in industry and aeronautics. ICAO issued in 1948 the first maintenance personnel licensing standard: at the time, an aircraft was basically a pure mechanical object made up by an internal combustion engine, mechanical systems, and airframe. The revolutionary advances in electronics, materials and power plants led to a more deep specialization in maintenance engineers. Nowadays, a high specialization is necessary because avionics and power plants are so complex that a general purpose engineer isn't skilled enough to manage complex sets of maintenance operations, depending on the specific aircraft and system to maintain. In years, the importance of maintenance has increased so much that Licensed Aircraft Maintenance Engineer (LAME) requirements are now detailed in the EASA/FAA, Part 66 Aircraft Maintenance Personnel Licensing. Maintenance is required because aviation authorities require each commercial operator (Alitalia, Lufthansa, Qantas, United Airlines, just to name but a few) to prepare the so called Continuous Airworthiness Maintenance Program (CAMP), which has to be included in its OpSpecs (Operations Specifications). CAMP lists all the routine and detailed inspections air operator must carry out. The Airworthiness Review Certificate (ARC) is the document attesting the regular maintenance of the airplane which is requested to allow a vehicle to operate (Air Navigation Certificate). Therefore, commercial aircraft are periodically inspected following procedures developed by manufacturers and designed depending on the features of structural design and systems installed on board. Inspections can be programmed depending on flight hours (fatigue in general), number of take-off/landing cycles (where inertial loads peaks occur), or time (ageing problem). While dealing with commercial/civil aircraft, four levels of maintenance checks (from A to D) are widely adopted by operators. *Check A*: it is a light check which is carried out after 200–300 cycles. It involves checking and inspection of passenger cabin, internal and external structure, engine pylons, control surfaces, engines. *Check B*: it is light check which is carried out when 2000 flight hours are reached (usually 6–8 months for a commercial aircraft). It takes around 1–4 days to complete it. All the A checks are carried out, together with a deep inspection of engines, structural elements, all movable parts, wings, composite materials (looking for crack or delamination). *Check C*: it is a heavy maintenance process which is carried out after 3500 flight hours (18–24 months). It takes from 8 to 15 days to carry out this check, which requires the aircraft to be sheltered in the Air Carrier Company hangar (or to bring it to specialized maintenance company). Apart A and B checks, several components and groups are disassembled and carefully inspected (in particular engines and pylons). *Check D*: it is the heaviest maintenance operation which can be carried out on an aircraft and it is sometimes called overhaul. Check D starts when the aircraft reaches 18,000–26,000 flight hours, which corresponds to an average time of 9 years. The aircraft is completely disassembled: both the external and internal structure are inspected in each detail and it usually takes 60 days to complete it. A flight test 3 h long is prescribed after each Check D. From a practical point of view, MRO requires that operators follow check lists where assembly/disassembly procedures are reported in detail with illustrative pictures and list of actions to do. Components to be replaced with spare parts should be detected correctly, supplied by the maintenance logistic (Regattieri et al., 2005) chain "just in time" to avoid loss of time and a potential confusing excess of unnecessary parts on the shelves ("Lean Warehousing" concept). Aeronautical structures are quite complex and several problems can occur when maintenance is carried out in a traditional way based on paper manuals: pictures in manuals different from actual configurations, disassembly procedures complex to guess from bidimensional pictures and schemes, doubts during maintenance tasks requiring to ask for clarifications the aircraft manufacturer, excessive workload due to poor ergonomics while carrying out maintenance (narrow places where to operate with tools), difficulty in detecting components in a complex area where similar components lie, long and tiresome assembly/disassembly sequences, just to name but a few. It is opinion of the authors that the link between Software and Liveware introduced by the SHELL model (Marx & Graeber, 1993) is not sufficiently adequate with traditional maintenance manuals. The paper (Koornneef, Verhagen, & Curran, 2017) supports this statement: the use of paper-based documentation in aircraft maintenance is defined "slow, burdensome and prone to error." As already noticed, the maintenance training programs and practices evolved in parallel to evolutions in electronics, materials, and power system. Following this trend new maintenance programs are considering Industry 4.0 concepts, not just in aerospace but in several engineering fields.

3.2. An Industry 4.0 approach to maintenance in aeronautics

The Industry 4.0 program introduces several key enabling technologies which would be disruptive for aircraft maintenance. Networking, availability of large data, capability of delocalized and personalized production, nets of micro-sensors connected each other, smart and intuitive visualization of information in remote operations, automation are examples of technologies suitable not only in factories, but also in aeronautics. Just to provide an example, big data handling efficient algorithms (Analytics) are necessary to support the real time local monitoring strategies on composite structures (Testoni, De Marchi, & Marzani, 2016) which manufacturers like Airbus and Boeing are evaluating to improve the structural health monitoring. Aim of this approach is to collect data from millions of sensors (e.g. Bragg fibres included in composite structures) to monitor the structure and detecting in the most effective way crack propagation, enabling a real "damage tolerance" strategy (Borello, Cestino, & Frulla, 2010). But technologies like AM and AR – which have been boosted by the Industry 4.0 revolution – will probably be major key player in the maintenance strategies of the future.

3.2.1. Augmented Reality

As a matter of fact, AR can be useful to obtain Augmented Maintenance Manuals and Illustrated Parts Catalogues where the position of the part to maintain is suggested to the operator in an intuitive way on the real aircraft. This is especially true in case of AR based manuals where assembly/disassembly tasks are presented to the operators through a mix of CAD models, symbols to suggest manual operations to carry out (e.g. virtual screw driver), and virtual panels where to check operations and interact with gesture tracking technologies. AM could be used for remote maintenance as well, where virtual animations could be prepared in real time to support complex procedures by centralized maintenance centres and loaded to remote operators devices if needed. This could overcome one of the problem currently limiting the use of AR in industry: the time needed to prepare animations. When dealing with a modern airliner made by millions of parts, it is straightforward to note that implementing animated virtual sequences for each of the maintenance operations which can be possible would be a time consuming operation. To prepare in a centralized office of an aircraft manufacturer a virtual assembly/disassembly sequence only when needed by remote operators could be a more affordable way to implement AR in an industrial context, as already introduced in Ceruti, Liverani, and Marzocca (2015) for aviation maintenance. Training is another task where augmented reality could soar realism and effectiveness. The AR capability to mix virtual and real parts allows to simulate complex scenarios without the need of unavailable (or bulky/dirty) parts. Overall, the impact of AR on maintenance (see Fig. 3) can be massive, especially when dealing with complex operations which cannot be clearly explained with traditional paper manuals.

Moreover, the documentation shall be in operation for several decades (the average lifespan of a commercial aircraft spans from 20 to 30 years): AR can help with keeping procedures updated respect to a paper-based maintenance approach where bulletins should be manually and periodically added to first release manuals. However, the implementation on AR of all the maintenance tasks for a commercial aircraft could be a painstakingly task: at the present, it is realistic to propose the implementation in AR of the most critical and demanding maintenance operations. The integration in CAD system of environments conceived to prepare in short time augmented scenes could reduce in a near future the time required to implement a whole maintenance manual in AR.

3.2.2. Additive Manufacturing

When the attention is focused on AM, a wide range of possible maintenance applications opens up. AM can be used to produce parts once a digital model is available. However, as already mentioned, the best results are obtained when a topological optimization is carried out, and lattice-based structures are used. In this case, complex geometries, which are unfeasible with chip removal techniques, can be produced. On the other hand, this is a visionary perspective since at the time in which this paper is written there is no regulation for structural parts produced by AM techniques, even with same geometry and material of that obtained with traditional methodologies. When and if, future regulations will allow the certification of AM metal parts numerous problems will be solved from a logistic point of view: for example, spare parts will be replaced by an AM machine and powders magazines. If the concept of "digital twin" will be extensively accepted in aeronautics, parts with different geometries could be produced to replace the original ones as well. In this case, a mass production with chip removal machines could be expected for original aircraft configuration: cracked/damaged parts could be replaced with more efficient optimized parts. In this latter case, in fact, the cost of producing a traditional part is similar to that of an optimized one. Provided that overall dimensions allows the correct functionality of the aircraft, a reduction in structural weight could be expected, with equal structural stress on components (and thus equal safety margin). Therefore, a digital twin will be necessary because of each airplane would become different from each other during lifespan due to the mix of standard parts and AM replacement parts. On the other hand, if a less visionary and more conservative approach is considered, it can be stated that AM could be a way to reduce the spare parts warehouses for non-structural parts. The widest exploitation

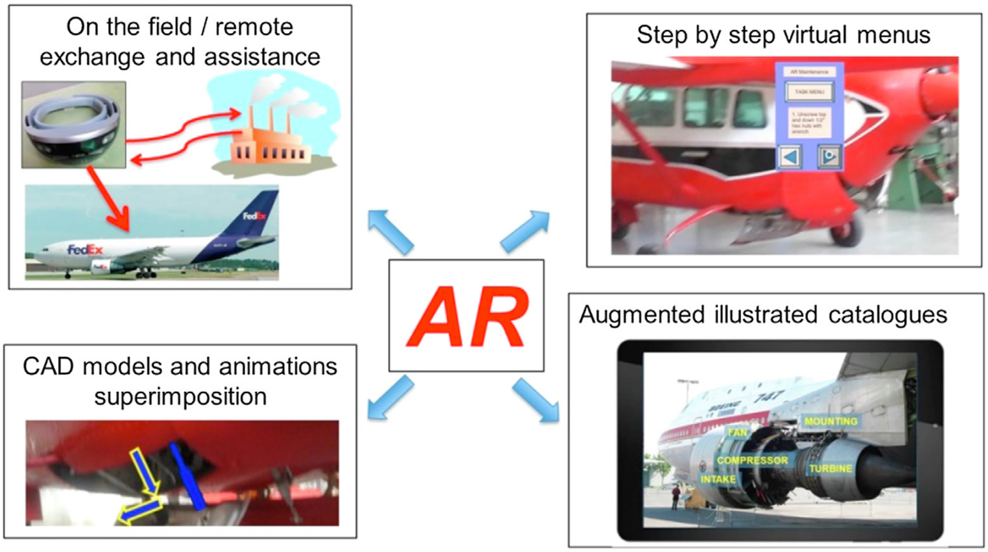

Fig. 3. AR and aeronautics.

of AM advantages would be possible if aircraft manufacturers will accept to share digital models of parts and a FAA/EASA regulation will become available for metallic parts produced from powders. In this framework, spare parts supply chain could be shortened by simply installing AM machines in maintenance hangars. Extending the Industry 4.0 concept to aviation, a tight information network between aircraft producers, airlines and maintenance operators will be required to share data. To support the previous statements, it is worth noting that nowadays several parts flying with commercial jets are made up by AM technologies: Boeing states that at least 30 additively manufactured parts are embedded in the B787 commercial aircraft (Malfitano, 2017): AM parts are used for air ducts (e.g. B787, Bell 429 helicopter), interiors/brackets (e.g. A350), propulsion (e.g. B737MAX fuel injection nozzle by General Electric), and small non-structural spare parts. The Airbus company uses more than 1000 ULTEM 9085 parts in the A350XWB. ULTEM is a FDM thermoplastic material conceived by the Stratasys Company (Stratasys, 2018) for the transport industry: it is FST (flame, smoke and toxicity) rated, its raw material and filament structural properties are certified, and its supply chain retains material traceability as required by the aerospace industry. About the use of AM for structural components, nowadays no design data databases are available. On the other hand, US FAR 25 or EASA CS-25 rules requires for commercial aircraft certification that material must be testes and fabrication must be consistent (CFR 25.603 & 25.605) and structure must be strong and analysis and tests are to be carried out in order to satisfy this requirement (CFR 25.305, 25.307 & 25.601). AM parts needs extensive studies related to consistency when used for structural applications because (only to cite an example) the same AM process can lead to parts with a high dispersion about the number/importance of defects. If controlled additive processes, certified machines and operators and FAA/EASA dedicated regulation were available, AM structural parts would be produced for maintenance purposes. In summary, a long term roadmap for introducing AM in a maintenance process can be based on (1) the use of AM to reduce the spare parts warehouses for non-structural parts; (2) on the base of gained experiences, standards, design methodologies and technological processes can be developed for structural parts if airworthiness can be assured; (3) the use of AM to produce spare parts (both structural and non-structural) identical to those to be replaced. In this scenario aircraft manufacturer can specify characteristics and standard process for AM of spare parts; maintenance organization would not be in charge of design validation, but would follow the approved process to produce third party parts from approved CAD models. In addition, the part validation would be done once by the aircraft manufacturer and would not be in charge to each maintenance organisation. (4) in the most advanced phase, AM capabilities can be exploited to develop optimised spare parts to be used during maintenance operations. In this case, the aircraft producer would provide optimized CAD model of most weight intensive spare parts to be on-site printed. In this case new technical characteristics and shapes of optimised components would require additional validation and certification with increased costs for the aircraft manufacturer.

4. Case study

4.1. AM in aeronautics

A case study has been included in this paper to show the potentials of AM concept in aeronautics: it describes how a bracket of an extension mechanisms could be replaced with a more efficient new structure, with same functionality but lower mass (or equal mass, with higher performance). The bracket in this case study could be representative of a component like the one in Fig. 4, where, for illustrative purpose, the detail of the leading edge of an Airbus A300 commercial aircraft wing is displayed.

Fig. 4. Slat extension mechanism bracket (image source: EN Wikipedia, Public Domain image).

Fig. 5 provides dimensions for the plan view shape of the bracket representative of an aircraft component: it is a curved plate (Radius 470 mm at the camber, 60° of width, 60 mm of thickness in the plan view) with three bosses (diameter Ø64 mm) and a length of around 500 mm. Each boss holds a hole with a Ø52 mm diameter.

Using a traditional manufacturing process, a component similar to the one modelled in CAD (Fig. 6(i)) can be obtained. On the other hand, a more efficient design could be based on lattice structures. As an example aiming to support this statement, the LSWM tool for FreeCAD™ (Ceruti, Ferrari, & Liverani, 2017) has been used to design a set of parts with an unconventional geometry (see Fig. 6): all these structures present the same plan-view arrangements and dimensions of the solid part, but their thickness is 20 mm, and it is based upon different geometrical arrangements which can be produced only through AM techniques. Structures (a), (b), (c), (d) are based on a conformal structure (lattice cubic elements are equally spaced along curved axis of the bracket). The cell is made by cylinders with a radius of 5 mm, and spheres with 6 mm radius placed where cylinders intersect cylinders (Structures (a), (c), (e)). Lattice based solutions (b), (d), (f) are based upon cylinders with radius of 3 mm, and spheres with 4 mm radius. Structures (c) and (d) are made up by 10 mm height cell structures, while other structures are made by 20 mm height cells. Finally, structure (g) is based upon an hexagon structure and structure (h) is made by cubic elements without spheres at the intersections. More detailed data about the shape of the geometries have been included in Table 1.

As an assumption, both the traditional dense bracket and lattice structure based are made of Aluminium with a density $\rho = 2700$ kg/m^3, an elastic module E = 71,000 N/mm^3, and a Poisson coefficient equal to 0.33; aluminium powders are available for AM machines, and AM parts present similar properties to the ones obtained from milling solid metallic blocks or cast components.

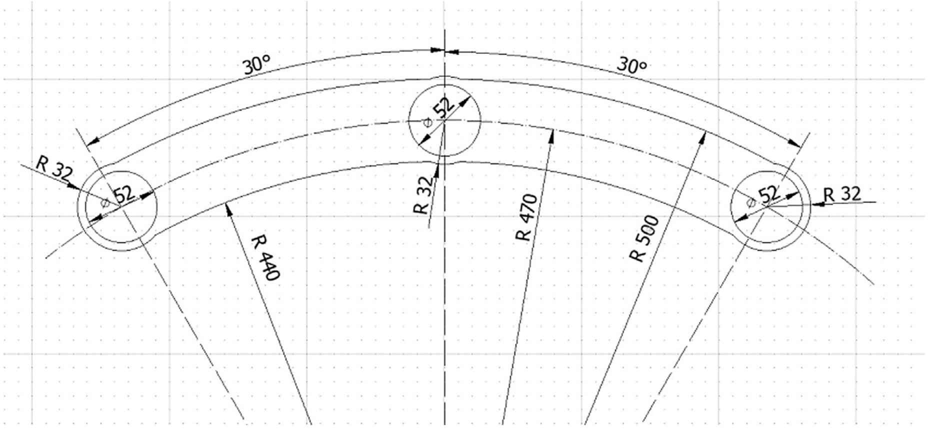

Fig. 5. SLAT extension mechanism bracket overall dimensions.

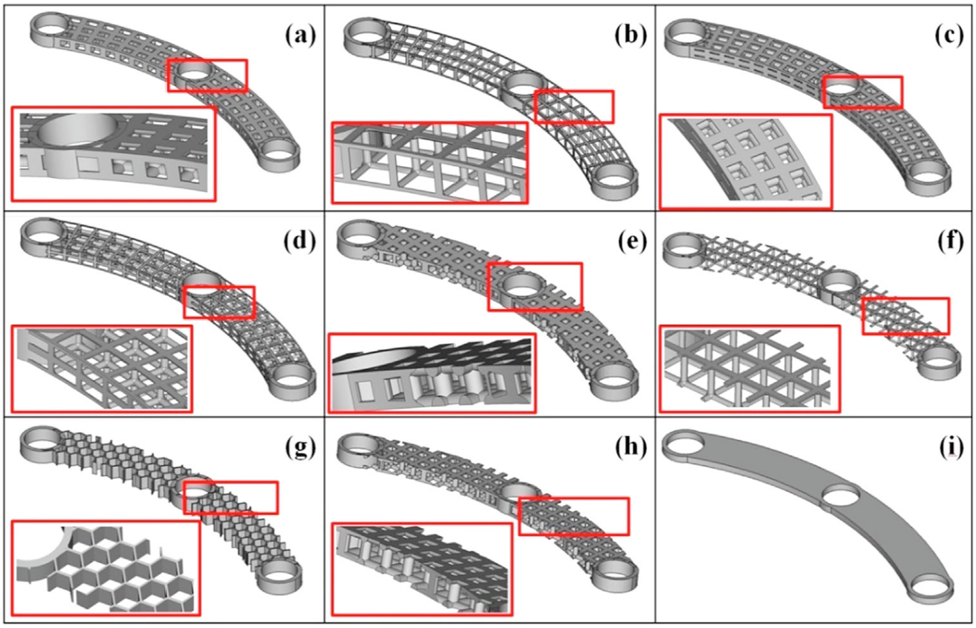

Fig. 6. Different shapes for brackets.

Table 1
FEM analysis results on AM configurations.

Additive manufactured part (see Fig. 6(a–h))								
Configuration (see Fig. 6)	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Volume [mm^3]	234,724	99,309	260,135	123,743	255,735	104,528	138,912	198,010
Mass [kg]	0.634	0.268	0.702	0.334	0.690	0.282	0.375	0.535
Cylinder radius [mm]	5	2	5	2	5	2	/	5
Number of cells in radial (or vertical) direction [–]	3	3	3	3	(3)	(3)	(3)	(3)
Total number of cells along bracket axis (or horizontal axis) [–]	16	16	18	18	(20)	(18)	(20)	(18)
Number of cells along bracket thickness [–]	1	1	2	2	1	1	1	1
Element size in Ansys Workbench® [mm]	2	2	3	3	2	2	2	2
Number of nodes in Ansys Workbench® [–]	199,134	204,606	226,318	219,156	197,503	209,122	134,293	207,431
Number of elements in Ansys Workbench® [–]	108,195	104,958	127,107	111,974	108,342	108,233	68,557	113,879
Maximum stress [N/mm^2]	432.3	42.87	320.36	425.28	31.098	41.63	200.96	194.23
Maximum displacement [mm]	0.433	4.61	0.548	2.55	0.487	8.196	15.16	0.871

As Fig. 7 shows in the left, it is assumed that the bracket is constrained in two of the three bosses, while a lateral load of 100 N acts on the internal surface of the hole third boss, parallel to its axis. Several FEM analyses have been carried out for all the structures illustrated in Fig. 6 using Ansys Workbench® tool, recording maximum stress and displacement in each case. For illustrative purposes, Fig. 7 (right) presents a zoom of the stress (right) for the (d) case study in the most loaded zone of the bracket (centre) (see Table 2).

When dealing with a generic structure, several requirements can drive the design: stress must be controlled to assure adequate

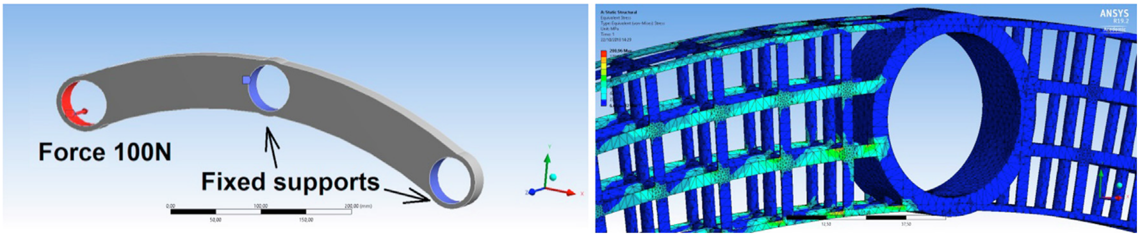

Fig. 7. Example of FEM analysis: loads and constraints (left) and stress for a case study (right).

Table 2
FEM analysis results on traditional dense part configuration.

Traditional manufactured part (Fig. 6(i))							
Thickness [mm]	2	2.5	3	4	5	10	20
Mass [Kg]	0.143	0.179	0.215	0.286	0.358	0.715	1.431
Max Displacement [mm]	150	77.0	44.6	18.8	9.69	1.20	0.16
Maximum stress [N/mm^2]	783	482	335	180	136	34.7	9.02

the life span; excessive deformations can lead to undesired contacts or blockages; natural frequencies close to exiting loads must be avoided to induce resonances, especially in helicopters design. In this case study, a design's requirement related to the displacements of the structure has been considered: maximum displacement analysis is less sensitive to mesh size and nodes number than stress analysis, so that reliable and consistent data can be obtained. Table 1 shows the outcome of the FEM analyses on structures (a-h) depicted in Fig. 6.

In the following, analyses on the traditional structure (i) have been carried out by changing the thickness of the component, with such a results set (see Table 2).

At this point, the thickness and mass of the bracket assuring similar displacements to the AM component has been computed through interpolation. Moreover, assuming an equal mass of the traditional part respect to each AM configuration (a–h), the maximum displacements have been computed. Finally, two merit indexes have been computed to evaluate the structural efficiency of the structures: the first one (MIM) is obtained by computing the ratio between the lattice structure and the traditional dense part mass assuring equal displacement, while the second one (MID) has been found by dividing the maximum displacement for an AM part and for the traditional configuration having same mass. Table 3 shows the values of MIM and MID coefficients.

As Table 3 suggests, strong improvements in terms of stiffness can be achieved with lattice based structures. Experimental analysis would be required to confirm in a precise way stress and displacements. However, from a qualitative point of view, the (a) structure seems to provide the better gain in terms of stiffness respect to a traditional part with equal mass, and displacement with same mass. This example supports the fact that AM can be a strategic way to reduce structural weights in aircraft: if a stiffness criterion is used during the design phase, the use of AM structures can half the components' weight of 50%. While dealing with stress, further studies would be required to evaluate structures behaviours with fatigue, but these preliminary results strongly show the advantage of lattice and unconventional structures. The detailed analysis of aerospace vehicle parts which could take advantage of such optimised lattice structure, the precise evaluation of the corresponding reduction in weight, are complex tasks: they involve numerous issues including material properties before and after additive production, fatigue behaviour, defects detection, and regulation. Such an analysis is beyond the scope of this paper.

Cost estimates are offered. The manufacturing cost (internal company costs, without profit) for the (a) lattice part has been evaluated to be (January 2019) 1890€ using a Direct Metal Laser Sintering (DMLS) machine and AlSi7Mg0.6 (A357) powders. It would take 18 h to manufacture the bracket. The traditional dense part providing same functionality could be produced in Aluminium AA2024 with chip removal techniques in 4 h with an internal cost (company profit excluded) around 150€. Following the FEM analysis, the mass spared (Δm) with AM part can be evaluated in 0.547 Kg (1.208 kg mass for dense part, 0.634 Kg for AM part). Assuming average lifespan of a commercial aircraft (H) 120′000 flight hours, cruise aerodynamic flight efficiency (E) 15, Thrust-specific fuel consumption (TSFC) 10 g/kN/s, CO_2 emission (COE) 2.52Kg/litres, density of Jet fuel (ρ) 0.85Kg/litres, gravity (g) 9.81 m/s^2, the difference in engine thrust (TΔT) with the AM part is:

$$\Delta T = \frac{g\ \ \Delta m}{E} = \frac{9.81\ \ 0.547}{15} = 0.358N$$

The mass of fuel (mf) necessary to obtain this thrust along the lifespan of the aircraft can be roughly approximated to (using consistent TSFC = 0.036 Kg/N/h):

$$mf = TSFC\ \ H\ \ \Delta T = 0.0358\ \ 120,000\ \ 0.36 = 1546\ \ \text{kg}$$

Table 3
Merit indexes for AM structures (a–h).

Merit index and AM /traditional part comparison								
Configuration (see Fig. 6)	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Thickness of traditional part with equal displacement [mm]	16.88	6.64	15.50	8.35	16.23	5.29	4.27	12.02
Mass of traditional part with equal displacement [kg]	1.208	0.475	1.109	0.598	1.161	0.378	0.306	0.860
Maximum displacement of traditional part with same mass [mm]	3.16	25.4	1.55	12.7	1.83	20.35	9.28	5.50
MIM merit index [–]	0.525	0.564	0.633	0.559	0.594	0.745	1.227	0.622
MID merit index [–]	0.137	0.182	0.354	0.200	0.266	0.403	1.634	0.156

The CO_2 emission saving (ΔC) using AM part along the aircraft lifespan is:

$$\Delta C = \frac{mf\ \ COE}{\rho} = \frac{1546\ \ 2.52}{0.85} = 4583\ \ \text{kg} = 4.583\ \ \text{tons}$$

Even more impressive figures can be obtained considering that a reduction in structural weight equals a higher reduction (up to 2–3 times) in maximum take-off weight (which should be considered for thrust computation), being the payload the same. It is expected that the costs of AM technology will be reduced significantly in the next years, further increasing the presented savings.

4.2. AR in aeronautics

As already said, AR can be used in aeronautics to support maintenance in several ways. AR based Illustrated Parts Catalogues, AR based Maintenance Manuals, AR based remote maintenance software tools, AR supported assembly/disassembly operations is a not inclusive list of all the operations which can benefit of Augmented Reality. AR can be useful to bridge the gap between a traditional sheet manual (Koornneef et al., 2017) where simplified bidimensional sketches represent complex components, and reality where complex 3D shapes (sometimes hidden by fairings or other components) must be detected and assembled with tools and proper handling. It is worth noting that aircraft, helicopters, ships, automatic machines can be composed by millions of parts with thousands of maintenance sequences involving several parts to assembly/disassembly: AR can be useful in these advanced engineering fields where it is complex to operate in a correct way. Following the Civil Aviation Authority (CAA, 1992), the main causes of failures in maintenance have been detected to be: (a) Incorrect installation of components; (b) Fitting of wrong parts, (c) Electrical wiring discrepancies, (d) Loose objects (tools, etc.) left in aircraft, (e) Inadequate lubrication; (f) Cowlings, access panels and fairings not secured; (g) Landing gear ground lock pins not removed before departure. Referring to the SHELL approach, all these errors can be explained with poor connection Hardware-Liveware and Software-Liveware. AR can be useful to cope with both these problems. Augmented CAD models can be useful to support the maintenance, reducing errors where parts position and type are mismatched. On the other hand, virtual menus where the operator can scroll the sequence of operations to do can help reducing the skipping of phases and operations. To evaluate the effects of the introduction of AR in aircraft maintenance, a case study has been implemented in the University of Bologna facilities where a disassembly procedure has been carried out exploiting AR capabilities. In this application, AR is used to superimpose to the external view camera streaming different kinds of information: CAD models, symbols, writings, buttons which can be pressed by the operator. A realistic 3D CAD model of the component to maintain can be projected on the video stream framing the external scenario. The hardware used in this test is composed by Hololens glasses and optionally by handheld controller. A cursor can be moved on the virtual screen and when the controller (called Hololens clicker) is pressed (or a "pinch" movement with fingers is detected by Hololens camera) an action occur: in this way it is possible to implement virtual menus which can be operated by the user pointing the head and pressing the controller with a finger. A maintenance procedure for the Cessna 337 general aviation airplane owned by the University of Bologna has been implemented: the sequence for the "5–41 Removal of Maingear wheel doors and actuators" (Cessna, 1973) has been implemented in AR. The following Fig. 8 (right) shows a picture from the original Cessna Illustrated Part Catalogue (Cessna, 1970) where parts to maintain are labelled and sketched. The left part of Fig. 8 presents a picture of the aircraft and a zoom on the left main gear door. The part called "Aft hinge" has been encircled.

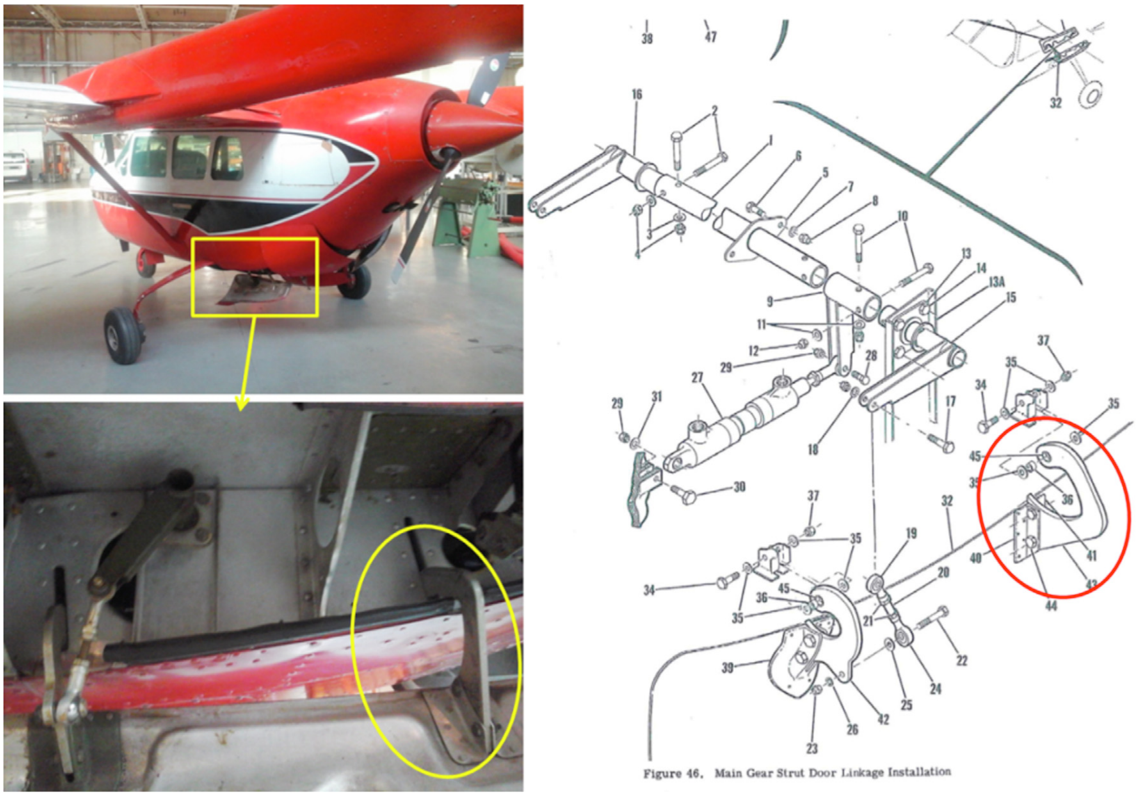

Fig. 8. Cessna 337 and particular of the main gear door (left); Cessna illustrated part catalogue (Cessna, 1970) of the Main Gear Door (right), "aft hinge" part encircled.

AR has been exploited in two ways. An interactive menu showing the index of the maintenance manual sections (from "1-General" to "18-Wiring diagrams") and task 5–41 phases (from a to i) has been implemented. Moreover, when a task deals with a specific part, its CAD model is superimposed to the real time video stream from the Hololens camera to help the maintenance manager in the detection of parts. Fig. 9 shows in the right the implementation of the section 1–3 of the Cessna 337 maintenance manual, while in the right the sequences 4–6 are displayed.

All the sections names can be scrolled by pressing the right and left triangle buttons at the bottom of the menu. By pressing one of the buttons describing the section, a second level menu shows a list of the tasks listed in the section: also in this case by pressing the right and left triangle buttons the tasks can be scrolled. Once a specific maintenance task has been selected (e.g. 5–41), the list of phases to carry out (e.g. 5–41-a 5–41-i) is listed on the menu: the M central button opens the 1–3 section list and can be used to set other task to carry out belonging to different sections. A button labelled with the number and name of the section (e.g Section 5 START) points to the list of first tasks of the section. When a phase of a tasks requires to operate on a specific part, virtual labels, CAD models and arrows are superimposed to the scene to support the user in detecting the components and suggesting correct ways to operate on. Fig. 10 presents an augmented scene where the task 5–41-h is displayed. A CAD model of the Aft Hinge has been superimposed to the external video stream framing the aircraft to immediately detect the part to operate on.

The workload of the maintenance operator is significantly reduced when compared with the one using a paper manual, with significant benefit in the accuracy of operations and in time saving to carry out the task. This gain can be even more dramatic for large commercial aircraft/helicopters, where complex operations are required, and many components (sometimes hardly recognizable in a paper manual) must be managed in a correct order in assembly/disassembly procedures. To support the usefulness of AR in aeronautical maintenance and provide data, in this paper an evaluation of the time required to find a specific maintenance task has been carried out. A set of 10 people skilled in aeronautics have been asked to find the procedure 5–41 in the paper Cessna 337 maintenance manual at first: the manual includes A4 and A3 sheets for a total of over 800 pages. In the following, after a short briefing where the Hololens working procedures has been described, glasses were held by the users and the required procedure has been retrieved by using the virtual menus implemented to this aim. The average time required to find the 5–41 task with the paper manual has been 26.5 s, while using Hololens glasses (and clicker controller) the average time was reduced to 19.4 s, with a drop of around 27% in time.

5. Conclusion

This paper suggests possible integration of Industry 4.0 technologies with the aeronautical maintenance. New technologies like Augmented Reality and Additive Manufacturing can provide better way to carry out maintenance operations respect to a traditional approach. Additive manufacturing can be useful to avoid large warehouses and cut the logistic chain: a part can be manufactured in metals like Aluminium or Titanium provided that a suitable AM machine and powders are available. Moreover, if a redesign of the part is possible, reduction of weight could be possible using opti-

Fig. 9. Menus implementing Cessna 337 Maintenance Manual from section 1 to section 3 and from 4 to 6.


Cessna 337

Section 5 START

h. Support door and remove bolts through forward and aft hinge brackets. Remove door from aircraft.

Fig. 10. Task 5–42-h menu and augmented scene.

mized lattice structures. AR can support the operators with user-friendly manuals where virtual models and instructions are mixed with real world. In this case, a reduction of workload and time required to complete tasks, and an increase in reliability can be expected, consequence of the reduction of errors which are made using AR augmented maintenance manuals. AM could be also combined with AR: a practitioner could identify a failed part or parts using AR, then the part could be virtually extracted using reverse engineering techniques, and finally sent to AM to print. Afterwards, the operator could be instructed on how to install the new part. Two case studies support the previous statements by evaluating advantages which can be obtained using AR and AM in an aeronautics domain. The main limit of this approach is due to the lack of regulations by aeronautical authorities which should start addressing the problems related to the introduction of this new technology to allow its wide spreading in the aeronautical field. Another problem is related to the necessity to develop powerful ergonomic hardware devices to support AR, and software tools able to cope with problems related to different lighting conditions, objects occlusion, video stream real time capabilities with good image resolution. Given current AM costs, it is not realistic to apply AM technology for all spare parts: considerations on availability of the spare parts, criticality of the component, manufacturing feasibility, regulations including initial and continuing airworthiness are critical factors and should be considered before moving from a traditional to an AM production process.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgments

Authors wish to thank Mr. Andrea Pasquali and ZARE Company, Italy for helping in the assessment of the machining costs of the bracket used as a case study in this paper.

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