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Author(s)	Govdeli, Yunus; Wong, Zhuo Wei; Kayacan, Erdal
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ADDITIVE MANUFACTURING OF UNMANNED AERIAL VEHICLES: CURRENT STATUS, RECENT ADVANCES, AND FUTURE PERSPECTIVES

YUNUS GOVDELI[1; 2], ZHUO WEI WONG[1; 2] and ERDAL KAYACAN[1]

[1]*School of Mechanical and Aerospace Engineering,* [2]*Singapore Center for 3D Printing (SC3DP), Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore*

Email: {yunus002, wong1002}@e.ntu.edu.sg; erdal@ntu.edu.sg

ABSTRACT: Over the past two decades, we have witnessed increased interest in rapidly growing unmanned aerial vehicles technologies triggered by numerous commercial applications. However, production cost is still a challenge due to the complexity of the manufacturing process of unmanned aerial vehicles. Recently, additive manufacturing has been associated with the production of unmanned aerial vehicles due to its ability to produce complex structures with lower cost. In this investigation, the current state of the art of the development of additive manufacturing for unmanned aerial vehicles is reviewed in terms of its lightweight structure, design stages and functional components.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have recently been one of the most attracting applications in aerospace engineering. Especially, with the implementation of UAVs to civilian applications like first-aid (Lennartsson, 2015) or agriculture (Saari et al., 2011), they will continue being a part of our lives in the near future. Accordingly, low-cost production of UAVs will gain more attention. However, conventional UAV production methods, *e.g.* injection molding for plastics and machining, drilling, lathe for metals, result in an excessive use of raw materials with many manufacturing stages. Moreover, applying composite materials to such systems requires intensive labor and long production time whereas their modification is not easy. On the other hand, considering the factors increasing the cost of production, additive manufacturing (AM) looks promising and is about to find its own place in the production of complex but lightweight UAVs with being cheaper and less labor demanding. In addition, its ability of on-demand printing and less number of stages of manufacturing make the production process more efficient, and obviously less time consuming.

The main motivation of this study is to acquire the necessary information on the production of low cost and lightweight UAVs. By investigating the advantages and disadvantages that the AM technology brings along on the design and manufacturing processes, a detailed analysis is carried out from the aeronautical engineering point of view. For this purpose, in Section 2.1, lightweight structures are covered by examining their economic impacts with pointing out the techniques of topology optimization, infill reduction, and bionic studies. In Section 2.2, the factors acting on AM are investigated on numerous wind tunnel testing models whereas their economic superiority over the conventionally manufactured models and their inherent mechanical weaknesses are stressed. Later, the AM of whole UAV bodies is introduced by keeping the interest on the fused deposit modeling (FDM) and selective laser sintering (SL). Last but not least, the promising areas of AM, namely structural electronics and 4D printing, are presented in Section 2.3. Finally, the future perspectives are given with the possible modifications needed for the current AM technology in Section 3.

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2. DEVELOPMENT OF AM FOR UAVS

2.1. The use of AM for lightweight structures

UAVs need to have lightweight structures to improve their efficiency in energy consumption, resulting in a longer flight endurance, and payload capacity. In this subsection, recent applications in topology optimization, bionic studies, and infill modification for achieving a lightweight UAV structure are covered.

2.1.1. Topology optimization

Topology optimization is a mathematical approach to achieve an optimized distribution of material on any structure. An example is in (Walker & Liu, 2015) where the optimization of a wing is obtained by meshing the 3D CAD model and applying the necessary amount of material to the required positions under certain load conditions. Besides, employing a similar approach, an optimized aerospace bracket is designed in (Brackett, Ashcroft, & Hague, 2011) which is given in Fig. 1. This technique allows the wing structure and the bracket to achieve maximum stiffness with a minimum weight. However, there are still limitations in terms of topology optimization algorithms and mesh generation problems of complex 3D CAD models which have to be taken into consideration during the design process. Figure 2 shows such a mesh distortion problem (Tomlin & Meyer, 2011). In accordance with that, topology optimization was only done on simulations in earlier years since traditional manufacturing methods were insufficient for geometrically complex structures. However, by adopting AM in the manufacturing line, lightweight, stiff but intricate structures are achieved whereas the reduction of material usage saves a significant portion of manufacturing cost (Zhu, Zhang, & Xia, 2015).

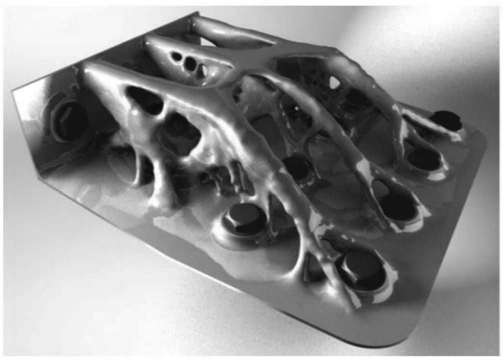

Figure 1. Example topology optimized aerospace bracket for building using a metal AM process (Brackett et al., 2011).

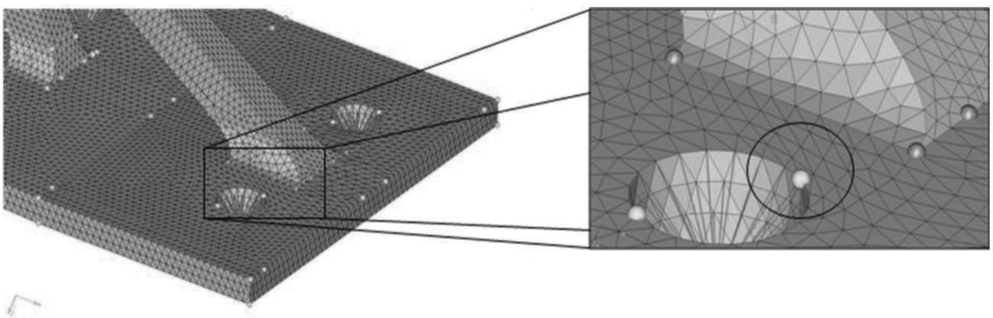

Figure 2. Distorted mesh cells on a hinge design (Tomlin & Meyer, 2011).

2.1.2. Bionic database studies

The main idea of using the bionic database for design is to mimic the nature and thus to produce optimal geometries for a given application. Considering the wing structure of a UAV; the pressure resistance to the aerodynamics forces on the wing will need a cellular structure such as honeycomb for energy absorption. In this case, the initial design is inspired by the nature to reduce the excess material in the design (Emmelmann, Sander, Kranz, & Wycisk, 2011).

To optimize such a cellular structure for a UAV wing, studies are focused on the comparison of their mechanical properties (Moon, Tan, Hwang, & Yoon, 2015). The selection of suitable cellular structure from the bionic database and performing the structural test is the major component of a design process (Xing, Chen, Xing, & Li, 2012). Cellular structures are difficult to manufacture with the conventional manufacturing while AM technology allows the utilization of the bionic database in real life applications (Chu, Graf, & Rosen, 2008). The proper selection of cellular structures will allow UAV wings to have high stiffness with the least amount of material to save the production cost.

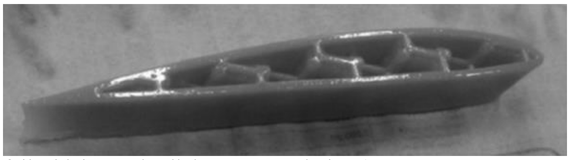

Figure 3. Airfoil with internal cellular structure design (Moon, Tan, Hwang, & Yoon, 2015).

2.1.3. Infill modification approach

This approach makes use of the inbuilt function of a 3D printer or the software by modifying the amount of printing infill for a structure. Experiments are based on the adjustment of the infill density, pattern and orientation to obtain the UAV structures with the required stiffness and least amount of weight (Chris, James, & Jamey, 2016). By infill reduction, material usage is reduced which, in turn, reduces the overall production cost and time. However, the reduction in this approach is generally uniform which results in a decrease in strength all over the structure. Figure 3-4 illustrate this relationship between the infill density and of strength of a given robot part with different printing patterns (Belter & Dollar, 2015).

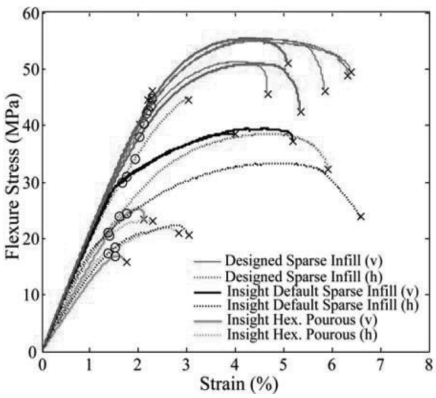

Figure 4. The flexural stress strength of vertically (v) or horizontally (h) printed robot finger (Belter & Dollar, 2015).

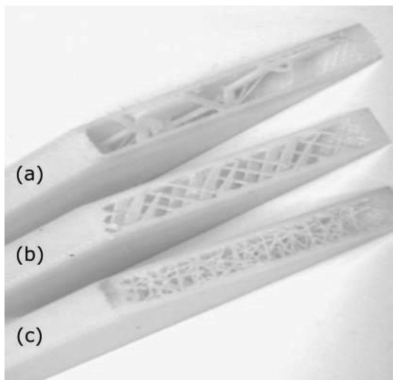

Figure 5. a) Insight hexagonal porous infill, b) Insight default sparse infill, c) Designed sparse infill (Belter & Dollar, 2015)

2.2. Design of wind tunnel models and UAVs for AM

2.2.1. Surface roughness

In literature, several wind tunnel test models produced by AM methods are available. In such tests, the accurate fabrication of the models carries high importance since the results of aerodynamic and structural analyzes are drastically affected by the surface roughness of the models (Springer et al., 1997a). One of the main factors causing distortion on the model surfaces is the contact points of the support material with the main surface. In this context, AM methods, *e.g.* FDM, inherently tend to have higher surface roughness compared to the conventional models. However, this is also dependent on proper orientation of part drawing on software interface and how the printing process is run since the amount of support material and its contact points with the model can be reduced by the appropriate design and model orientation. Consequently, surface quality is a key element determining the aerodynamic reliability of an additively manufactured model.

2.2.2. Effects of build space

It is also worth noting that AM of a UAV is not only affected by the appropriate design methodology but also by the 3D printer itself. As highlighted in (Chuk & Thomson, 1998), the size of the build space of a 3D printer is another major factor determining the shape of the design. At first glance, this may look like a substantial disadvantage of AM since it does not allow the printing of components having a larger volume than the printing room. However, the portability of a product should also be taken into account at the design stage. From this point of view, in (Wang et al., 2015), a good example of how the portable UAV components can be 3D-printed with keeping the structural integrity is given. Although currently available 3D printers do not allow massive components to be printed, part by part production is still possible without losing the complexity which makes the AM quite useful in terms of production, especially for the manufacturing of relatively smaller models without an investment for a huge printer.

2.2.3. Structural stiffness

After the description of the effects of surface roughness and build space, an evaluation of the additively manufactured wind tunnel models by their structural stability and stiffness is needed. Compared to the original metal models, an additively manufactured model should be able to have both the similar mass and stiffness characteristics and distributions while representing the original geometry as indicated in (Zhu et al., 2011). Considering the wind tunnel models given in Table 1, general approaches when producing wind tunnel models are using either -as in the earlier experiments carried out by the scientists from NASA- fused deposit modeling (FDM) and selective laser sintering (SLS) or stereolithography (SL). Other methods are generally not employed primarily due to the surface roughness problems. In (Wang et al., 2015), the SL structure is supported by a metal frame made of 30CrMnSiA whereas a nickel coating is applied onto the surface of the model described in (Zhou, Li, Zhang, & Zeng, 2008). Meanwhile, in (Zhu et al., 2011), the wing is completely supported by a so-called "Aluminum wing-box". Figure 5 includes a special model where the whole aircraft fuselage and wings are produced by AM while the control surfaces of the model are supported by the steel parts enabling it to be applicable to the subsonic wind tunnel tests (Zhu et al., 2014). Among the covered wind tunnel models, the model in (Dang-guo, Yan, Zheng-yu, Chao, & Wei-jun, 2013) is the only one which is fully 3D-printed. Although the models were successfully manufactured, stiffness and thus the deformations under excessive aerodynamic forces are still challenging tasks limiting the printable models. As a result, the majority of the wind tunnel models produced by AM are commonly supported by some other metal components or frames, which increase of the production cost could also be seen in the Table 1.

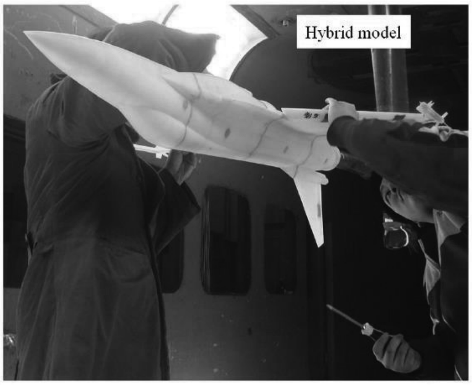

Figure 6. Hybrid model with steel-supported control surfaces (Zhu et al., 2014).

2.2.4. Manufacturing of intricate structures

One of the major advantages of AM over conventional manufacturing methods is manufacturing time efficiency and cost of production, especially when intricate and complex structures are to be formed. Additively manufactured structures with a lot of details, *e.g.* wind tunnel models, are produced in a much simpler manner with less number of stages as shown in Table 1. Therefore, AM requires less intensive workload while eliminating the need for purchasing expensive tools and excessive use of materials (Berman, 2012).

Table 1. Comparison of methods, materials, and cost of wind tunnel models with time consumption

Model	AM Method & Material	Conventional Methods for Support Structure/ Original Production Method	Support Structure Material/ Original Structure Material	Cost of Production		Manufacturing Time	
				AM Method	Support Structure Cost/ Original Model Cost	AM Method	Original Method
(Wang et al., 2015)	SL, Polymer-Resin	Machining and electrode cutting for the frame	30CrMnSiA	$2000	$800, Metal Frame	62 hours	13-15 days, Metal Frame
(Zhu et al., 2011)	SL, Polymer-Resin	Machining for the frame	41Cr	$700	$4000-5000, Metal Frame	35 hours	10-14 days, Metal Frame
(Dang-guo et al., 2013)	SL, Polymer-Resin	lathe, milling, drilling, and line-incising	40Cr Alloy Steel	<$250	>$1200	2 hours	1 month
(Springer & Cooper, 1998)	FDM, ABS	machining	Aluminum	$3100	$15000	2-3 weeks (incl. design process)	3.5 months (incl. design process)

2.2.5. AM of a whole UAV body

Wind tunnel models are good indicators of how useful and promising the AM could be for the aerospace engineering applications. Nevertheless, as the sample models suggest, FDM or SLS technology could not be efficiently applied for the wind tunnel testing methods and SL showed a superior characteristic compared to the other AM methods in terms of the obtainment of stiffer products (Springer, Cooper, Springer, & Cooper, 1997b). However, there is a significant volume of research going on aiming of producing the whole UAV body by using the FDM and SLS methods. A copy of an elliptical wing aircraft, which was previously used during the World War II, is manufactured in one week by SLS at the University of Southampton while keeping the necessary aerodynamic characteristics. The same aircraft took off from a Royal Navy Ship as well, indicating that such low-UAVs would also be applicable to different environments ("Southampton engineers," 2015). Subsequently, the research gained another perspective with the implementation of a newer UAV design to a strategic trade program in Europe (Ferraro et al., 2014). In addition to the advances of SLS in Southampton, two designs of the University of Virginia, one conventional fixed wing model, and one flying wing aircraft, both of which are produced by FDM are successfully completed (Chris et al., 2016). Besides the universities, there are also several 3D-printing companies involved in the development of the AM for UAVs. The intention is to implement the available techniques in the market to the UAV concept. Thus, for instance, the Stratasys Company, which is also the manufacturer of the first jet powered additively manufactured UAV with the Aurora Flight Sciences, cooperated with the Georgia Institute of Technology, Purdue University, and Brigham-Young University to create a UAV with the largest wing span so far. Their design also completed the flight tests successfully (Chris et al., 2016). Figures 6-7 highlight some of these successful aircraft designs. To sum up, the ongoing research and studies show that the FDM and SLS techniques which had been found inefficient for the manufacturing of the wind tunnel models can now be applied to the real-time applications of UAVs with ease and for much lower cost and labor.

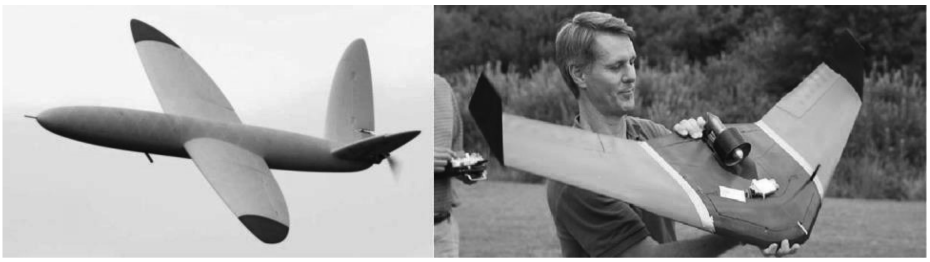

Figure 7. First additively manufactured aircraft and the vehicle from University of Virginia (Chris et al., 2016).

Figure 8. SEAS20 (Ferraro et al., 2014) and the fixed-wing UAV from University of Virginia (Easter, Turman, Sheffler, Balazs, & Rotner, 2013).

2.3. AM of UAV functional components

2.3.1. AM of structural electronics

Recent research has also been focusing on AM of structural electronics. This process involves the printing of the thermoplastic substrate, embedding the electronic components; followed by deposition of conductive ink to complete the structural electronics. By this manner, a fully functional additively manufactured circuit board is produced (Lopes, MacDonald, & Wicker, 2012) (Aguilera et al., 2013) (Hoerber et al., 2014) (Shemelya et al., 2015). One of the problems confronted during AM of the printable conductive ink is the low performance of the ink on the polymer base (Aguilera et al., 2013). In (Ahmadloo & Mousavi, 2013), a new ink formula is developed for an antenna so that the conductivity could be ensured. Besides, another method of AM, aerosol jet technique, is applied to the electronics printing technology which is capable of printing both conductive and semi-conductive materials (Hoerber et al., 2014). The print head of an aerosol jet printer is able to translate itself with respect to the substrate to print a conformal antenna on cylindrical structures as can be seen in Fig. 8 (Paulsen, Renn, Christenson, & Plourde, 2012). This allows higher design freedom as designers no longer need to restrict themselves to the space of the printed circuit board while eliminating the weight of the conventional printed circuit board. All in all, the incorporation of aerosol jet technique with existing AM technology is in progress towards the goal of a single build sequence to reduce the cost of inventory in manufacturing.

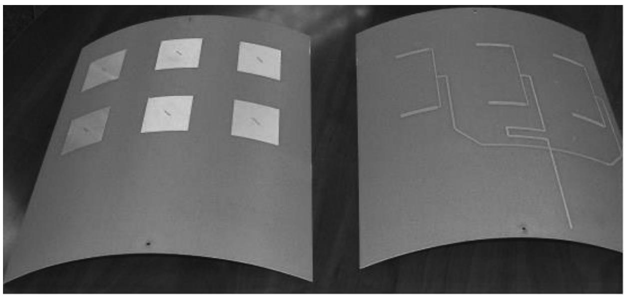

Figure 9. Phased array antenna printed on a rigid, cylindrical surface (Paulsen et al., 2012).

2.3.2. 4D printing

4D printing is a manufacturing process that allows a multi-material model to transform its shape over time. For this purpose, different materials are strategically placed in a 3D geometry and a stimulant is applied for a shape transformation to take place (Pei, 2014). In that sense, with 4D printing, smart materials such as shape memory polymers (SMP) would be applicable to the field of aerospace engineering (Yang, Chen, Wei, & Li, 2015). The application of 4D printing has a high potential for producing functional components such as soft actuators in order to eliminate the usage of servo motors for control surfaces in UAVs (Shintake, Rosset, Schubert, Floreano, & Shea, 2015). Active surfaces of a UAV would also be driven by employing these polymers in a similar sense with the dielectric elastomers where the mechanical movement is controlled by voltage. For instance, the research in (Rossiter, Walters, & Stoimenov, 2009) is able to demonstrate the fabrication of a dielectric elastomer actuator using a poly-jet 3D printer. However, due to the need of elastomer pre-straining, which is impossible with current AM systems, the performance of the actuator is currently not at the level of conventional ones. In short, 4D printing is a new and promising research area with many alternative solutions. The development or modification of current AM systems is needed to overcome the given issues and to make use of the 4D printing idea.

3. CHALLENGES AND FUTURE PERSPECTIVES

For the completion of AM of a whole UAV, there are still many challenges ahead. The production of lightweight structures with AM techniques such as FDM require the reinforcement of support materials in the printed structure. Besides, existing printing techniques do not allow the production of an enclosed structure as it will result in the support material to be trapped within. Therefore, topology-optimized or cellular structures need to be manufactured in separate parts. Development in the technique of support material removal can improve the practicality in the production of such structures. In addition, due to the complexity of internal structure, removal of support material becomes time-consuming and impractical. Development of AM without a need for any support material would encourage the use of geometrically complex structures.

Wind tunnel models produced so far by AM are generally resin models of SL which are reinforced with metal frames internally to provide the optimal performance in terms of weight, structural stiffness, and aerodynamics. The tendency to use SL for wind tunnels does not seem to change in the near future. However, printing UAV models designed for subsonic flights, where the surface quality may not be that crucial as it is for the transonic or supersonic wind tunnel models, are still possible by using SLS or FDM. Future development in multi-material printing, as well as thermoplastics, would improve the build quality of the wind tunnel models and create opportunities for unconventional UAV designs. Lastly, build space in the existing 3D printers is another limitation of the AM. Thus, single-step production of a UAV larger than the build space is not possible. Studies on the effects of separate parts production for topology optimized or cellular structures can be initiated to potentially remove the design constraints in terms of the build space.

Printing of structural electronics has a huge potential, but the current conductive ink used on AM systems has low conductivity restricting the development of this technology. Therefore, studies are generally carried out to improve the performance of conductive inks. In the near future, an increase in the numbers of the sensors, circuitries, and antennas produced by AM are expected by the authors of this study since the research on conductive materials have already offered some new solutions. Moreover, automation of the embedment of electronic components is also expected to be the next step of current manual embedment processes. In addition, 4D printing may also be considered as a brand-new promising and exciting field of research. Although the current applications of dielectric elastomers and SMPs are at an early stage of development, further improvement on 4D Printing technology, design methods, and material will allow the implementation of printed dielectric elastomer for aerospace application.

4. CONCLUSION

With the increase in the demand of UAVs, production cost of UAVs needs to be reduced. Lightweight but complex UAVs designed with the help of topology optimization or cellular structures by AM can be produced while cutting down the material and labor cost. Besides, for the production of wind tunnel models, which is an outstanding application area of AM in the aerospace engineering field, hybrid methods demonstrated the most practical approach for good surface quality, higher stiffness, and low-cost production. Lastly, the current development in AM of functional components for UAVs is still in its initial phase but there are already circuitry, sensor and antenna applications of structural electronics.

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