



Review

Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential

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ARTICLE INFO

Article history:

Received 25 August 2016

Received in revised form 24 November 2016

Accepted 27 December 2016

Available online 29 December 2016

Keywords:

UAV

3D printing

Rapid prototyping

Additive manufacturing

Smart materials

Structures

Multi-functional

ABSTRACT

Unmanned aerial vehicles (UAV) are gaining popularity due to their application in military, private and public sector, especially being attractive for fields where human operator is not required. Light-weight UAVs are more desirable as they have better performance in terms of shorter take-off range and longer flight endurance. However, light weight structures with complex inner features are hard to fabricate using conventional manufacturing methods. The ability to print complex inner structures directly without the need of a mould gives additive manufacturing (AM) an edge over conventional manufacturing. Recent development in composite and multi-material printing opens up new possibilities of printing lightweight structures and novel platforms like flapping wings with ease. This paper explores the impact of additive manufacturing on aerodynamics, structures and materials used for UAVs. The review will discuss state-of-the-art AM technologies for UAVs through innovations in materials and structures and their advantages and limitations. The role of additive manufacturing to improve the performance of UAVs through smart material actuators and multi-functional structures will also be discussed.

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1. Introduction

Evolution of unmanned aerial vehicles (UAVs) that started during World War II has come a long way for both military and non-military operations. UAVs are finding wide-spread use in fields where employing human operator is either cumbersome and unsafe, or not required altogether. Applications and mission of UAVs now range from agricultural surveillance [1], meteorological data acquisition [2] to disaster monitoring [3], with size varying from that of a small bird to helicopter. Recent trends and reports suggest that the number for UAVs will increase by few thousand for various applications in the near future [4,5], with the final shape and size of the UAV being mission dependent. Table 1 briefly summarizes the classification of UAVs as defined by UVS International [6]. Fixed wing and rotorcraft are the most common types of UAVs available in the market. Fixed wing UAVs have rigid aerodynamically-streamlined wing structure to generate lift as they move. Rotorcraft UAVs, on the other hand, use propellers to generate the lift. This difference allows rotorcraft UAVs to stay stationary and hover at one point, while fixed wing UAVs constantly need to move. Flapping wing UAVs, also called ornithopters, have also

gained popularity among researchers. The design of such UAV takes cue from nature to mimic birds and insects. Flapping wing UAV has several potential benefits over fixed wings devices like better manoeuvring, low speed, vertical take-off and landing [7].

Although a UAV design is specific to its mission profile, one common goal for all is to have high endurance. Higher endurance translates to longer flight time with longer breaks for refuelling or recharging the battery. The basic parameters affecting the endurance of a fuel-powered propeller-driven fixed wing UAV can be calculated using the classical Breguet method as follows:

$$E = K \left(\frac{\eta_p}{BSFC} \right) \left(\frac{C_L^{3/2}}{C_D} \right) \sqrt{\rho} \frac{1}{(w_i/S)^{1/2}} \left[\frac{1}{1 - (w_f/w_i)^{1/2}} - 1 \right] \quad (1)$$

where E is the endurance, K is a constant, η_p is the propeller efficiency, $BSFC$ is the brake specific fuel consumption, C_L is the lift coefficient, C_D is the drag coefficient, ρ is the air density, w_i is the initial weight of aircraft, w_f is the weight of fuel, and S is the wing area.

In order to have longer endurance, one should maximize the aerodynamic parameter $\frac{C_L^{3/2}}{C_D}$, and minimize the structural weight so as to reduce wing loading $\frac{w_i}{S}$ and increase fuel weight fraction $\frac{w_f}{w_i}$. The term $\frac{\eta_p}{BSFC}$ is related to propeller and engine efficiency, and is out of the scope of discussion for this article. Although the

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Table 1
Classification of UAVs as defined by UVS international.

UAV Category	Range [km]	Flight altitude [m]	Endurance [hr]	Max. take-off weight [kg]	Example
Micro	<10	250	1	<5	Wasp III
Mini	<10	150–300	<2	<30	Raven
Medium range	70–200	5000	6–10	1250	Sky spirit
Medium altitude long endurance	>500	14000	24–48	1500	Predator
High altitude long endurance	>2000	20000	24–48	12000	Global hawk

above equation only holds for fuel-powered propeller-driven fixed wing UAV, it gives general idea that having a good aerodynamics and light aircraft structure is of utmost importance for any type of flying vehicle.

Another important aspect in the design phase is the manufacturability of the UAV, which in turn is dependent on the material. Conventional fabrication technologies for UAVs include CNC hot-wire cutting for foam and balsa wood, and manual lay-up for composite. Conventional fabrication technologies are mature as they have been around for long. However, they do suffer from some disadvantages like multi-steps, labour intensive processes [8], high costs for moulds [9] and long processing time [10]. In addition to that, for UAV fabrication, the conventional methods are more process dependent than design oriented and this puts a glass ceiling for building innovative structures. For instance, recent research on topology optimization and cellular structures have resulted in complex lightweight UAV structures that cannot be fabricated using conventional manufacturing techniques [11]. These limitations have coaxed researchers to look for alternate methods.

The motivation of this review paper is to keep research community abreast with latest technological advancements in materials and structures of additively manufactured UAVs. This paper discusses the emergence of AM for UAVs and how they differ from conventional manufacturing methods. Research direction in materials and structure for UAV is discussed in-depth. Particularly, the advantages and potential of AM technologies on the improvement aerodynamics and structural efficiencies of UAVs are emphasized. The paper highlights issues, challenges and future directions for the realization of fully printed lightweight UAV with desired features.

2. Additive manufacturing

Additive manufacturing (AM) refers to a group of fabrication techniques in which parts are fabricated layer by layer directly from CAD file [12–14]. Introduction of AM has not just revolutionised field of UAVs but has impacted the entire manufacturing arena by simplifying the design and easing the fabrication process. AM, more than any other technology, has served as the bridge between digital and physical disruption. The ability to turn digital file into physical objects allows people to design, scan, share, and send digital representations of physical objects. The disruptive technology of AM has changed the way the object is assembled and has simplified designing of complex parts [15]. Fig. 1 shows the differences in design processes between conventional and additive manufacturing methods. The agile nature of AM processes enables rapid production without necessitating major change in manufacturing setup. The economic benefit of the AM processes is manifested especially in the low volume production.

Several additive manufacturing materials for aerospace applications have been researched on like metals [16–18], ceramics [19], thermoplastics and composites [20,21]. UAVs and aerospace components routinely exploit additive techniques like fused deposition modelling (FDM), selective laser sintering (SLS), stereolithography (SLA), selective laser melting (SLM) and electron-beam melting (EBM). To date, FDM, SLA, polyjet and SLS have been used to ei-

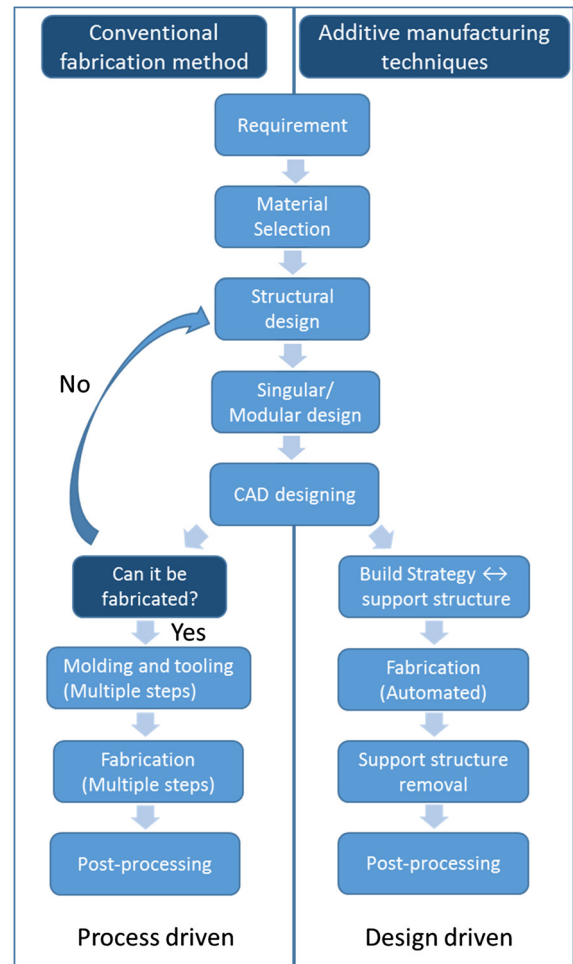


Fig. 1. Flow-chart depicting the differences in the process-flow for conventional and additive manufacturing techniques.

ther fully print the UAV structures or fabricate certain parts of UAV structures. Fig. 2 shows the timeline of the development of additive manufacturing technologies and their applications in UAV. Below we discuss the various AM techniques employed to fabricate UAVs in-depth. The section studies the state-of-the-art, potential, advantages and limitations of the AM methods used for UAVs. A summary of the advantages and disadvantages of different AM techniques for UAV is shown in Table 2.

2.1. Fused deposition modelling (FDM)

In this method, objects are created layer-by-layer by extruding a heated plastic filament through a nozzle. A wide range of thermoplastics can be processed via this method such as polylactic acid (PLA) [37], Nylon [38] and aerospace grade Ultem™ [39]. Fig. 3(a) shows the schematic of fused deposition modelling technique. The exploitation of AM for fabricating flapping wing UAVs can be traced back to 1998 when Michelson et al. used FDM to

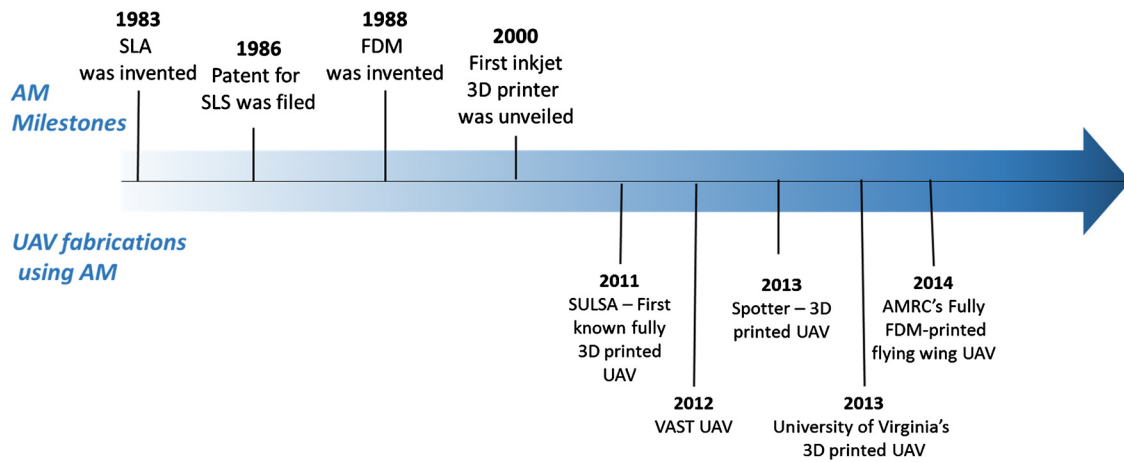


Fig. 2. Timeline representing development of main additive manufacturing processes and AM fabricated UAVs.

Table 2

Advantages and disadvantages of different AM techniques employed to fabricate UAV.

Types of AM techniques	Advantages	Disadvantages	Name of UAVs/ printed parts	Ref.
FDM	- High strength material such as Ultem is available - ABS plastic has higher survival rate compared to balsa during impacts	- Obvious stair stepping effect in z-direction - Poor surface finish compared to polyjet and SLA	Fully printed UAV structure AMRC UAV VAST UAV Entomopter frame, gear, tail	[22] [23] [24] [25] [26]
Polyjet	- Ability to create functionally graded parts with multi-material printing - Ability to print fine features - Good surface finish - Insignificant stair stepping effect	- Slow recovery rate from high loading condition - Strength of AM material is still inferior to that of the biological bone	Lattice structure wing strut Bat-like ornithopter Replica of insect wing	[27,28] [29] [30]
SLA	- Ability to print fine feature size - Good surface finish - Insignificant stair stepping effect	- Degradation of photosensitive materials leading to poor performance under load. - Low tensile strength of material	Entomopter Stingray UAV Flap Wind tunnel UAV model	[25] [31] [32] [33]
SLS	- Ability to print parts with good mechanical strength - Large build area - Relatively low cost	Rough surface finish	SULSA UAV Scaled-down UAV model for wind tunnel test Spotter UAV	[34] [35] [36]

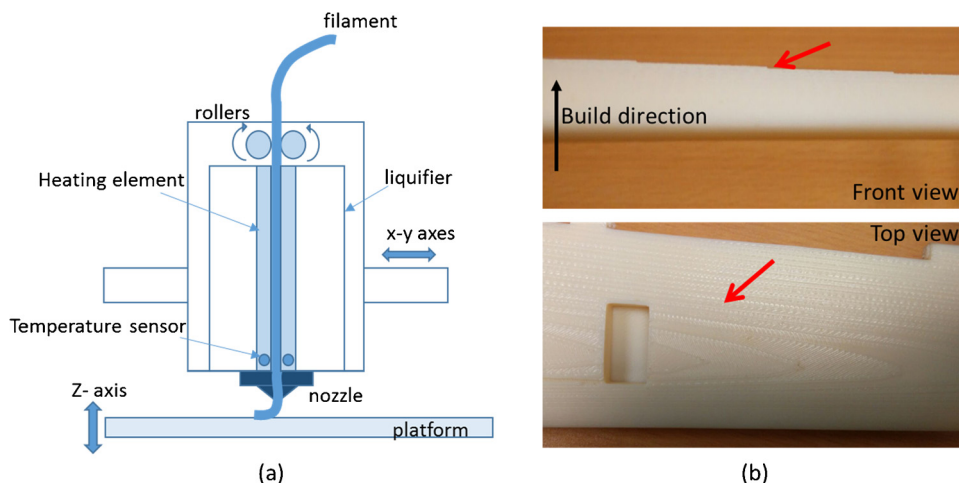
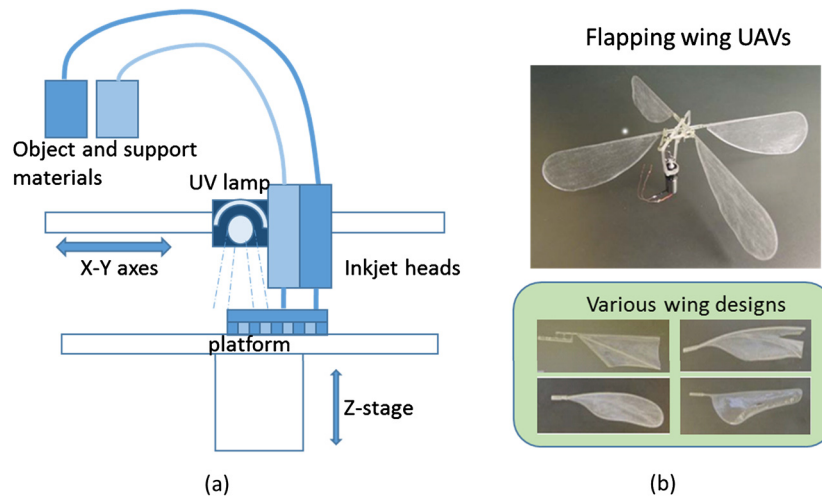


Fig. 3. (a) Schematic of fused deposition molding (FDM) process and (b) stair stepping effect observed on the wing structure when fabricated using FDM technique.

Table 3

Summary of properties of different materials processed through additive manufacturing techniques.

Material	Techniques	Density (g/cm ³)	Tensile strength (MPa)	Young modulus (MPa)	Fatigue threshold (MPa)	Specific tensile strength	Ref.
ABS	FDM	1.07	10–20	1400–2000	9–14	10–20	[40–43]
Nylon	SLS	1.01	44–45	1600–1700	18	44–45	[44–48]
Ultem	FDM	1.27	45–60	1500–1800	N.A.	37–47	[39]
PPSF	FDM	1.29	70	2340	N.A.	54.26	[49]
Verowhite	Polyjet	1.17	23–35	1200–1800	N.A.	19–30	[50]
ABS-like	SLA	1.19	28–34	2534–2740	N.A.	23–29	[51]
ABS	Injection molding	1.0063	34–41	2500–2700	N.A.	34–41	[52,53]
Balsa wood		0.27	64	10400	N.A.	236	[54]

**Fig. 4.** (a) Schematic of Polyjet additive manufacturing technique and (b) different flapping wing designs fabricated using Polyjet for UAV application [30].

build strong and intricate wing rib structure of entomopter [25]. Tiny features such as the hollow micro passages were incorporated into the wing structures to allow venting of gas for directional control. Easter et al. explored acrylonitrile-butadiene-styrene (ABS) material for printing wing structure using FDM printer [22]. Their group showed that parts could be redesigned and reprinted quickly several times without the need of mold, thus reducing the overall time and cost. They did a comparative analysis between ABS and UltemTM, stating that although UltemTM has better mechanical properties (Table 3), the ability of ABS to print complex inner features outweighed them. This was due to the lack of dissolvable support materials available for UltemTM, thus restricting the design flexibility. The work also concluded that ABS plastic has higher survival rate compared to balsa during impacts. These scientific conclusions were used to design and build a blended-wing-body UAV. A blended-wing-body UAV, commonly known as the flying wing, fabricated by the University of Sheffield Advanced Manufacturing Research Centre (AMRC) also used FDM method to save cost and processing steps [23]. Zhang et al. attempted to print frame, tail, and gears for flapping wing UAV using Acrylonitrile Butadiene Styrene copolymers (ABS) material [26]. However, they found out that using ABS alone was not sufficient to provide the required strength, and they eventually reinforced the parts with carbon fibre rods and polyester films for better strength. Revisiting the designs through elimination of support structures further helps to save time and material. Researchers from Massachusetts Institute of Technology (MIT) eliminated the need of support structure for wings [24] by placing the structure at an angle of 45°. This simple modification eliminates post-processing complexities and reduces the overall weight of the structure as internal support structures can be avoided.

It can be observed that FDM is extensively used to fabricate critical structures of UAVs due to its ability to print high strength materials. However, due to the limitation of the build size of FDM, the structures were mostly printed in modular parts and later connected using carbon rod to enhance the stiffness. Bigger build platform in the future would benefit the fabrication of one-piece wing structures to preserve the structural integrity and to allow the realization of the full-scale topology. Another limitation of FDM is the stair-stepping effect observed in the z-direction (Fig. 3(b)), which roughens the contour of the final structure. Hence, care should be taken when deciding the printing direction of the wing structure to have a good surface finish on the wing.

2.2. PolyjetTM

PolyJetTM 3D Printing operates much like inkjet printing, but as opposed to jetting drops of ink onto paper, PolyJetTM jets out layers of curable photo-sensitive resin onto the building platform [12]. Fig. 4(a) shows the schematic of PolyJetTM Technique. This technique uses soluble resin for the support structures, making it easier to be removed later either by hands or by soaking in bath. Post-processing is not needed for the printed parts meaning that parts are ready directly after printing. One advantage of PolyJetTM is the ability to mix and print different materials into a single model giving users the flexibility to achieve more optimal designs. The work by Moon et al. was motivated by the need to develop agile, fuel efficient and flexible UAV design, fully capable of operating in variable environment. Using AM technology the group could incorporate various lattice structures, such as 3D Kagome, 3D pyramidal and hexagonal diamond into the wing truss to achieve light weight UAV [27]. They used polypropylene-like photopolymer to construct the lattice structures. Their work demonstrates

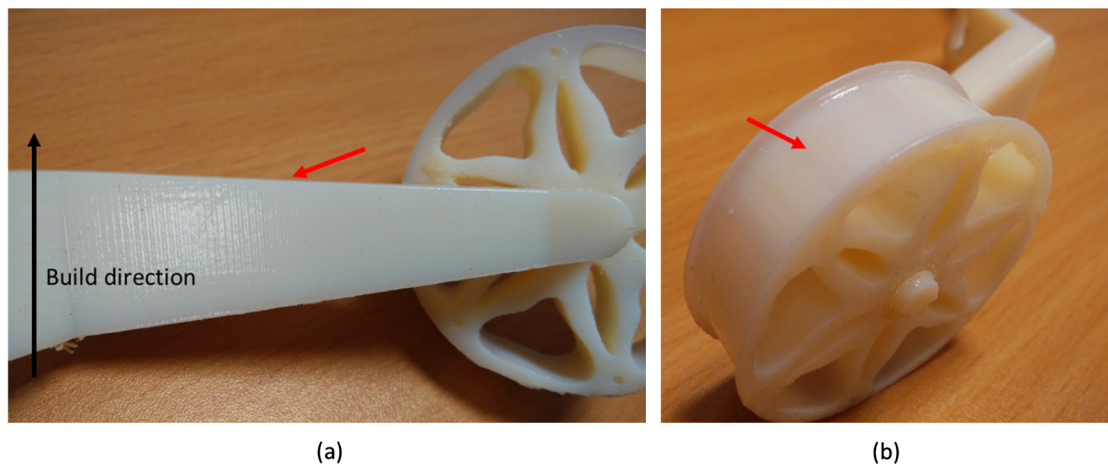


Fig. 5. (a) Image depicting the smooth surface finish of a Polyjet printed part with no stair stepping effect and (b) smooth surface finish can be obtained around the circumference of the wheel.

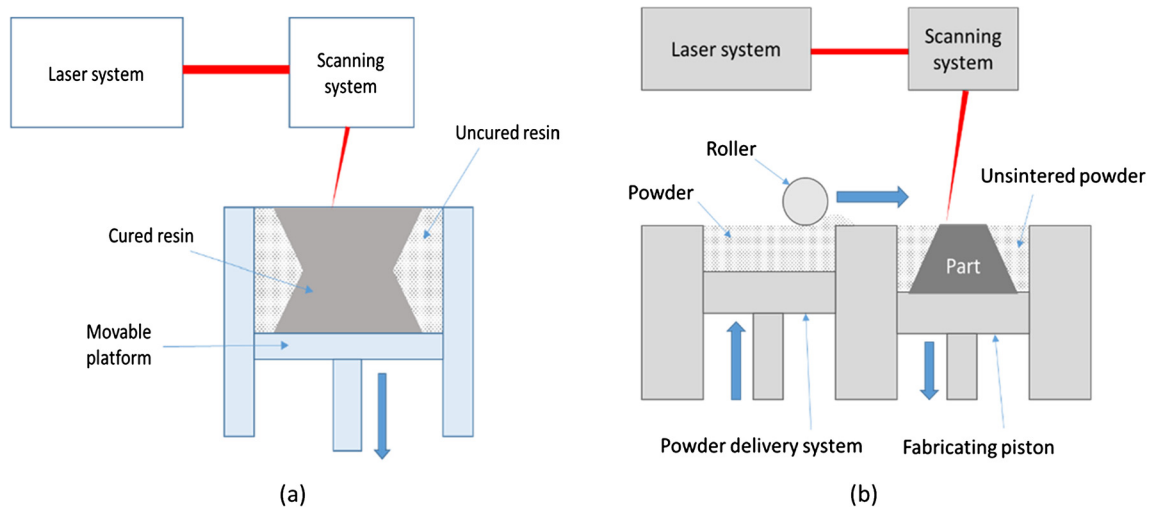


Fig. 6. Schematic diagrams illustrating the working mechanism of (a) stereolithography (SLA) and (b) selective laser sintering (SLS).

AM's flexibility in creating negative mould with intricate inner features, a feat difficult to achieve using conventional methods [28]. Functional parts have also been fabricated via Polyjet™ using UV curable acrylic plastic material such as skeletal structure of a bat-like Ornithopter [29]. Through the use of CAD and AM techniques, the biomimetic skeleton structure with good joint flexibility was achievable. The skeleton was fabricated using an Objet Connex 500 (Objet, Ltd, Rehovot, Israel), which has an improved resolution of 0.002 mm. This enables small features to be placed throughout the structure. However, they noted that the strength of AM material was inferior to that of the biological bone. Richter et al. also additively manufactured different wing designs using Polyjet™ technology. The designs were replica of real insect wings (Fig. 4(b)) [30] and do not need moulds and tooling, thus shortening the design process and lowering the prototyping cost.

In general Polyjet™ provides a better surface finish and structural accuracy compared to FDM making it ideal to fabricate functional parts [55]. Fig. 5 shows a landing gear for UAV printed in one-build using Polyjet™ technique. It can be seen that the stair-stepping effect on the gradient contour of the wheel is barely noticeable resulting in smooth surface. Although this technique is capable of fabricating parts with material properties similar to those of ABS thermoplastics (Table 2), one disadvantage is the slow recovery rate from high loading condition. Experiment on evaluating the recovery rate of the Polyjet™ printed honeycomb structures by

Yap et al. showed that only 80% of the shape was recovered after one hour of unloading [56]. This makes it less ideal for fabrication critical UAV structures.

2.3. Stereolithography (SLA)

Stereolithography is the first commercially available additive manufacturing process developed by 3D Systems in 1986 [57]. This technique uses ultraviolet (UV) light to polymerize photosensitive liquid resin in a layer-by-layer manner. There are two types of stereolithography setups, namely the micro-stereolithography and the digital light projection (DLP) [58]. In the microstereolithography, the direction of the laser beam is controlled by the computer and the laser will scan through the resin bit by bit, resulting in higher resolution (Fig. 6(a)). In DLP system, a digital mirror device (DMD) consisting of an array of mirrors, that can be rotated independently, is used. By controlling the mirrors, the pattern on each layer can be illuminated to completely polymerize the layer at one go. However, unlike Ployjet post-processing is needed in SLA to fully cure the printed parts. Michelson et al. used SLA to build intricate wing rib structure of entomopter [25]. SLA enabled easy fabrication of intricate wing structure designs consisting of hollow micro-passage and mechanical parts such as 4-bar linkage [59], servo holder [60] and camera gimbal [61]. Farnsworth et al. also explored SLA to manufacture a 14% scale model of a stingray UAV [31]. Williamson et al. used SLA to manufacture flap

and its supporting components in one piece eliminating the need for assembly and glue joint [32].

The use of SLA in the fabrication of critical structural components of UAV is very limited due to the stability of the SLA material. Artzi et al. noted that SLA printed UAV models kept at room temperature sagged considerably under their own weight after a few months [33]. Kim et al. estimated that the strength decreased by 25% at 30 °C, and by 50% at 40 °C [62].

2.4. Selective laser sintering (SLS)

Selective laser sintering process employs selective melting and solidifying of each successive powder layers to build complex 3D parts made of thermoplastics, metal or ceramics [63]. The working principle of SLS is depicted in Fig. 6(b). Continuous wave carbon-dioxide (CO₂) laser, with average power of several 100 W to kW, is guided by the Galvano mirrors and selectively scans the layer of powder according to the CAD file. The unsintered powder acts as support for the successive layers and overhanging portion of the printed parts [64]. The use of SLS on fixed wing type UAV was first demonstrated by researchers from Southampton University in 2011 [34]. They printed both fuselage and wing out of nylon material [34]. Stiff, lightweight and complex geodesic structures were used in this UAV design. In addition to that, the main wing was designed elliptical to demonstrate the ability to fabricate conventionally-hard-to-fabricate wing design. Parts were finally put together using a “snap fit” technique requiring no fasteners. Researchers from University of New South Wales used Carbonmide to manufacture UAV model via SLS for wind tunnel test [35]. The scaled down model of the UAV can be printed with ease by resizing the CAD model, thus demonstrating the ability of AM to fabricate object of different sizes without the need for new tooling. Carbonmide exhibited good flexural strength (75 MPa) and flexural modulus (2.8 GPa) at density of 1.158 g/cm³ (30% carbon fibre content), which make it ideal for parts that require high strength [65]. Ferraro et al. attempted using SLS system to manufacture a twin-fuselage UAV, Spotter, with Nylon material [36]. This work explores the potential of AM in designing a complex main fuel tank for the Spotter UAV. Converting the complex design with intricate inner features into physical form would not have been possible by conventional manufacturing. The design was essential to add multi-functionality to the structure by contributing to lift, wing support and sine-wave baffle, which prevents the fuel from sloshing from side to side.

One disadvantage of SLS printed part is the rough surface finish of printed parts. It has been shown by Sachdeva et al. that the surface roughness (Ra) of SLS as-printed part is about 6.9 micron [66], which is about 5 times higher than SLA [67]. Radeztsky et al. has shown that micro-meter surface roughness has a strong influence on crossflow-dominated transition, which is critical to swept wing [68]. Hence, post-process surface treatment such as polishing and buffering is usually needed after printing.

3. Roles of AM in improving the structural and aerodynamics efficiencies of UAV

This section discusses the role played by AM in improving the structural and aerodynamic efficiencies for the UAV.

3.1. Improving structural efficiency

Structural efficiency of an UAV can be improved via two methods, i.e. the use of lightweight structures and the use of high-strength-to-weight materials.

3.1.1. The use of lightweight, lattice & topology optimized structures

Taking cue from the nature, honeycomb structures have been widely used in the form of sandwich panels by aircraft designers to reduce the weight. To date, different types of cellular structures have been tested. It is known that the strut size and the pattern of the cell affects the stiffness of the resulting mesoscopic structure [69,70]. Varying the size and type of cellular structure in different parts gives the designers more flexibility to create functionally graded objects, which would eventually result in a more optimized assembly. It was observed that the performance of a conformal truss with variable strut sizes and orientation is superior to a uniform truss [71–73]. However, unlike uniform cellular honeycomb structures, functionally graded structures with varying sizes and orientation are hard to manufacture via conventional method. AM, on the other hand, can successfully fabricate functionally graded structures with ease [74]. Topology optimization is the process of determining the optimal shape and distribution of materials in the design domain while preserving the structural requirements [75] and is fast gaining interest of researchers. Several topology optimization software such as Optistruct, Tosca, and Genesis, are now available to help enhance design performance [76]. This approach has been applied to optimize aircraft structures such as fuselage [77], wing box ribs [78] and nacelle hinge brackets [79]. Manufacturing limitations such as sizing constraints, casting directions, symmetry and repeated patterns are taken into consideration while performing topology optimization [80]. Additive manufacturing having the ability to fabricate complex part from the digital file complements the topology optimization techniques. For instance, in a feasibility study of applying topology optimization on wing structure, Walker et al. printed the optimized wing structure using photopolymer plastic and aluminium via Polyjet™ and selective laser sintering respectively [11]. In their study, they found out that the thin features should be thickened to avoid structural failure. They also noticed the inability of SLS to create overhang features. Deaton et al. noted that there is a need to study the additional considerations that are essential to efficiently convert topology optimized designs to additive manufactured parts [75]. These comprised of enhanced modelling for residual stresses, interface conditions and manufacturing constraints such as overhang angle and minimum deposition tolerances. In short, AM techniques enable the creation of the functionally-graded structures, conformal mesoscopic cellular structures, and complex topology optimization with ease. All these features are direct consequence of layer-by-layer nature of the AM techniques.

3.1.2. The use of high-strength-to-weight materials

Last decade has seen paradigm shift in terms of material usage. Both aviation and UAV industries are now moving towards composite materials, which combine numerous advantages like high strength, low weight, high corrosion, fatigue resistance and easy processing [81]. Composites are materials consisting of two or more materials, which together produce beneficial properties that cannot be attained with any one constituent alone. The processing of composites using conventional fabrication techniques is often tedious and additive manufacturing has demonstrated replacing labour intensive steps with simpler ones. UAVs such as the Dark Star, Pioneer, Searcher, Eagle Eye and Phoenix have been fabricated using composite materials [82]. Composites can also be tuned to provide ‘stealth’ capabilities and low thermal expansion [81], making them attractive for defence and high altitude applications. One example of UAV incorporated with stealth technology is the Boeing’s X-45B [81]. Recent trends have also seen rise in use of graphite, Kevlar and glass fibre based composites for UAV applications [83,84]. However, carbon-fibre reinforced plastics (CFRP) stand out for the niche application of UAV [85–87]. The CFRP material is known for high specific strength-to-weight ratio ow-

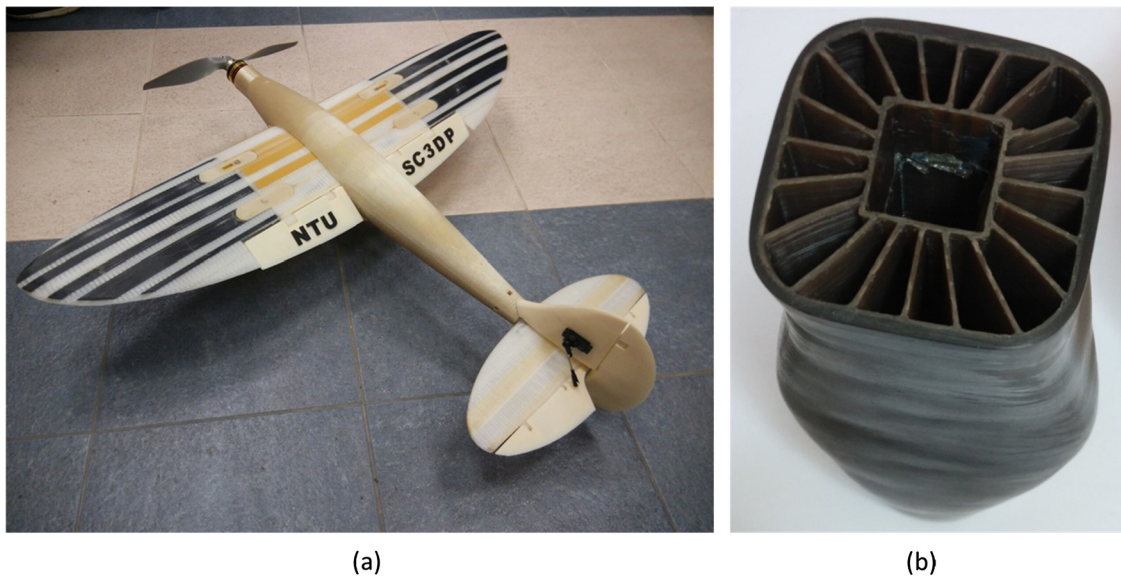


Fig. 7. (a) Additively manufactured UAV employing fibre composite material for wing structures. Continuous Filament Fabrication (CFF™) was employed to print the parts. Picture courtesy, Singapore centre for 3D printing, Nanyang Technological University, Singapore. And (b) fused deposition molding (FDM) printed structure with intricate core design and woven fibres encapsulating the core.

ing to its unique structure, consisting of load bearing fibre and load transmitting resin material. Conventional technologies take a complex route and require a mold for printing CRFP materials. Fibre and resin have to be laid out manually in alternate fashion and cured under high pressure to achieve desired strength [88]. CFRP can be easily additively manufactured using stereolithography and fused deposition modelling [89–96]. FDM remains the popular choice as it allows the flexibility of printing through simple modification in printer head or nozzle. Ning et al. used short carbon fibre and achieved a tensile strength of 40 MPa [90]. Currently, the tensile strength of additively manufactured CFRP is about 100 MPa [92]. The authors have also attempted fabrication of UAV wing using fibre (carbon, glass and Kevlar) and Nylon to create high strength-to-weight structure through additive manufacturing (Fig. 7(a)). Ueda et al., however argued that AM printed CFRP has low tensile strength and attributed it to the low printing resolution of the FDM printer. Hence, the performance of CFRP is limited by the printer capability instead of the material. Like CFRP, microscale-fibre reinforcement (MCF) also suffers from drawbacks like poor out-of-plane performance and presence of gaps between fibres, thus resulting in cracks. Research community is now turning towards nanoscale materials like carbon nanotubes (CNT) to replace microscale fibres for selective reinforcement of matrix-rich regions. Bekyarova et al. carried out a work on development of advanced structural composites based on engineered multiscale CNT-carbon fibre reinforcement [97]. They infiltrated CNT-coated carbon fabric panels with epoxy resin to enhance inter-laminar shear strength and out-of-plane performance.

3.2. Improving aerodynamic efficiency

It has known that at high lift coefficients, the induced drag can account for as much as 50% of the total drag [98]. Hence, it is desirable to reduce the induced drag. From aerodynamic theory, elliptical wing offers the lowest induced drag providing an elliptical span-wise lift distribution. This shape, however, is hard to manufacture using conventional techniques but can be achieved using AM techniques. For aerospace applications, it is always desirable to that have multi-purpose aircrafts that can perform various missions and fly in different flight conditions. Major improvement can be obtained by changing or morphing the shape of the wings

to maximize its performance in different flight environments [99]. Morphing wings require actuators to reconfigure their air foil profile and adapt to changing flight environments. Thus, alterations in the geometry of the wing might be used to control flight, suppress flutter, reduce buffeting effects, and maximize fuel economy.

A detailed review on morphing wing of aircrafts by Soffa et al. concluded that for low-speed-small UAVs, smart materials should be used for actuation [100]. Also, it is necessary to have integrated and distributed smart materials actuators to support aerodynamic loads and avoid transmission loss. Although the printing of smart materials for shape changing structures is still new, it has got a lot of potential in realizing the integrated and distributed actuators, in which materials can be selectively deposited and orientation to produce a functional object.

4. Potential of additive manufacturing for UAVs

4.1. Multi-material printing

Aspiration to have a smart system with various functionalities on one platform has surged the need to look for multifunctional materials, where different parts will be fabricated using combination of materials. Multi-material systems offer several advantages for UAV application like high strength, high resistance to corrosion, low weight and low density. It is envisioned that multi-materials with higher mechanical strength can replace the existing single material components and thus reduce the wear and tear [101]. It is also possible to further reduce the overall weight of the UAV by designing a single platform system using multi-materials. Although multi-materials add extra flexibility and uniqueness to the final structure, their processing increases complexity. Additive manufacturing helps to assimilate materials that can be melted, e.g. metals, ceramic and composites. So far AM techniques have been exploited to fabricate single-material parts only. Research to use AM for multi-material fabrication has gained momentum recently, and particularly limited to FDM, laser sintering and stereolithography. There are few approaches can be employed to produce multi-material components viz. discrete, layered and graded. Discrete formation allows materials to have different and distinct material boundaries; layered technique positions different materials layer by layer; and for functionally graded material the com-

position is varied over distance. FDM presents itself as a viable candidate for multi-material fabrication as it has separate nozzles for build and support materials. Espalin and coworkers [102,103] modified the existing FDM system by incorporating a sliding platform to transport components in-between two FDM machines to demonstrate variable layer thickness material fabrication. Lappo et al. conducted advanced research in selective laser sintering (SLS) to process multi-materials [104]. SLS can process any material that can be obtained in powder form and can be fused by heat, thus opening the door to experiment with wide material combinations. In another research carried out by Ott et al. recoating mechanism was used, which included appertaining process model to enable precise control of multi-material structures [105]. Stereolithography is especially attractive for multi-material processing as it offers high quality surface finish and dimensional accuracy [106–108] and a simple modification of commercial machine can enable it to work with combination of materials. However, multi-material printing technology is still in its infancy, and there is a lot of room for improvement. Investigations are necessary to study separation and compatibility of various materials, obstruction due to previous layers and order of the process flow.

4.2. Smart materials for morphing

Morphing UAV has the advantage of changing the shape to adapt to different flying conditions, making sure that the UAV's aerodynamics performance is optimum for all flight conditions. Smart materials have been extensively explored by researchers as actuators for wing morphing, thus permitting the replacement of conventional servo, pneumatic, hydraulic, or motor-like actuation devices [109]. There are three basic requirements for the smart material actuators for wing morphing, namely to be flexible enough to have large shape change; to be able to withstand aerodynamic loads, and to have fast response time [110]. A comprehensive review by Barbarino et al. details the use of smart materials for wing morphing through conventional methods [109]. However, there has been still no report on additively manufactured smart material actuators to date in author's knowledge. Additively manufactured smart materials such as piezoelectric (PZT) materials and shape memory polymers (SMPs) have received vast attention recently. An additively manufactured prototype of smart and soft composite, capable of achieving tip deflection of 57 mm, was fabricated by Ahn et al. using multi-nozzle FDM through extrusion of ABS filament and deposition of SMA wires [111]. Raasch et al. observed that annealing of the materials enhances the shape recovery process. However, the speed of recovery (about 15 min) was still found to be too low for any real application [112]. Piezoelectric composites have also been studied for morphing UAV applications. Piezoelectric composites can be processed using FDM via two methods, i.e. through direct fused deposition of ceramics (FDC), where PZT powder is mixed with the base material to create the filament [113] and through an indirect method, AM mould is first created and PZT slurry is filled in the void. In the work by Safari, they showed that the maximum tip deflection can be controlled and changed between 20–76 mm by varying the ratio of PZT to electrostrictive of the monolithic monomorph bending actuators from 1:3 to 3:1 [114]. In another work, Turcu et al. showed that orientation angle of the raster had an effect on the piezoelectric voltage coefficient, thus highlighting the capability of AM to modify the piezoelectric effect of the printed part [115]. In another work Zarek et al. explored a shape memory polymer (SMP) called polycaprolactone (PCL) to print complex structures using SLA technique [116].

4.3. Multifunctional structures

A multifunctional structure by definition performs multiple functions on a single platform. [117]. In the traditional structural design approach, the load-bearing and non-loadbearing functions are considered separately, which normally leads to a sub-optimal part with penalty of unnecessary weight [117]. With the advent of AM techniques, multifunctional structures can be printed via the use of hybrid manufacturing technologies, where layering process is combined with subtractive process [118–123] or two AM processes can be integrated [124]. Fig. 7(b) shows FDM printed intricate core structure with woven fibres encapsulating the core, a possibility of hybrid manufacturing to create lightweight and high strength parts. Multifunctional structures are being explored for UAV, where energy harvesting and storage devices are fabricated on load-bearing parts. These devices will allow optimum weight and space when manufactured additively. Solar cells for UAV has been attempted using direct write technologies like inkjet printing, where AM techniques fabricate grid lines [125–127] and active layer [128,129] on the UAV body. Ho et al. [130] and Goh et al. [131] have also demonstrated zinc-manganese dioxide micro-battery for energy storage and patch antennas respectively using additive manufacturing. Printing electronic components directly on to the UAV will help further reduce the total weight of the structure.

4.4. Printing on-site on-demand

It is a normal practice to have excess of spare parts of UAV and aircrafts stored away in for maintenance and emergency. However, cost of holding the parts in the inventory can be high [132]. Furthermore, there is a risk in piling up spare parts as that might render then obsolete and unusable after certain time. Additive manufacturing could potentially simplify this supply chain problem by printing on-demand and on-site [15]. According to a study, printing on-site and on-demand reduces lead time, inventory storage and transportation cost [133]. US Navy saw the potential of this approach and envisioned a 30% cost reduction and yield increase in parts on-demand [134,135].

4.5. New UAV concepts

There are some applications where UAV may not be recovered after completing its mission, either due to shortage of power supply or destruction. [136]. Hence, it is desirable to build low-cost UAVs for such applications [137]. Conventional manufacturing techniques such as injection moulding require substantial processing and expensive tooling. Additive manufacturing provide an alternative and easy way to fabricate inexpensive and disposable UAVs. The cost cutting comes from the AM's ability to reduce manufacturing steps and fabricate parts without the need for expensive tooling.

5. Challenges of AM

UAVs are now being employed for diverse applications and have to function in multiple environments. Changes are sought in their physical form, altitude, weight, strength and durability to meet the ever growing functionalities. The motivation of using AM is to derive a solution that can meet the end user requirements. However, the field of AM is in its infancy and there are road-blocks to be crossed to adopt it as a commercial solution. Some of the limitations encountered are discussed below.

5.1. Limited choice of high performance materials

Materials play an important role in determining the final weight and performance of the UAV. The material innovation in carbon-fibre reinforced polymer (CFRP) through additive manufacturing concentrates more on short-fibres [90,138,139], which generally have poor mechanical properties compared when compared to those fabricated using conventional methods. Poor mechanical strength is also exhibited by additively manufactured continuous-fibre reinforced composites [140]. The mechanical strength can be improved by enhancing the adhesion between carbon-fibre and matrix polymer. Moreover, CFRP can only be printed in straight and horizontal directions and it is difficult to manipulate the fibre orientation freely, thus limiting the applications of CFRP on curved structures. Research can be directed to explore more ways to freely lay the fibres for better mechanical properties.

5.2. Anisotropic material properties

Another disadvantage of the additive manufacturing is the inherent anisotropic property of the printed parts. AM techniques uses layer-by-layer approach to fabricate a part by melting a filament, curing the photo resin and melting the powder bed, thus introducing a thermal gradient. As a result, the microstructure of the materials would tend to grow in certain direction causing different mechanical property along the layer (x - and y -directions) and across the layers (z -direction) [42,141]. A typical example of such anisotropy is brittle nature of FDM-produced part, which has good strength only in x - and y -direction [22,142]. Whiskers of carbon fibres can be introduced in the z -direction to enhance the mechanical strength.

5.3. Manufacturing-induced porosity

Layer-by-layer manufacturing approach can lead to induced porosity in the designed part due to incomplete densification [143]. The formation of voids due to improper deposition of material or sub-optimal processing parameters will eventually cause the additively manufactured parts to have higher porosities than the design values [22]. This is undesirable as the strength of the printed part might be inferior to the predicted value. Improvement in densification is required to alleviate the discrepancy between the design and printed parameters.

5.4. Characterization of AM materials

Sufficient and reliable data on the mechanical properties of the AM materials are needed for good finite element analysis. Insufficient knowledge on AM material properties may lead to inaccurate prediction of strength and material usage, just as what Easter et al. encountered [22]. Hence, characterization of AM materials is an important step before embarking on printing. Mechanical properties of materials are normally characterized at the coupon level, where coupons are oriented in the x -, y -, and z -directions to capture the anisotropic mechanical properties of the additively manufactured parts [42]. Mechanical properties of the AM parts will vary in printing directions, raster orientation and raster style. Hence, a detailed characterization of the printed material properties in different orientations will help account for some limitations.

5.5. Small build volume

Small build platform poses assembly and flexibility issues, where UAVs must be broken down into smaller sections. Assembly of smaller parts not only introduces complexity but also increases the overall weight as additional fasteners are required [22]. In

Table 4

Cost comparison of different manufacturing processes employing various materials.

Processes	Materials	Costs (\$/lb)	Ref.
FDM	ABS	7–115	[147]
	Polycarbonate	113	
	Poly(lactic acid)	7–25	
	Stratasys ultem	220	
SLS	Nylon	40	[146]
Injection molding	ABS	1.29	
	Nylon 66	1.81	

addition to that, redesigning the structure into smaller modular parts would also lower the structural integrity. UAV manufacturing would definitely benefit from larger build platforms in AM machines.

5.6. Certification and quality assurance

Certification and quality assurance is an important step before the additively manufactured UAVs can be commercialized. AS/EN9100 is one of earliest standard that is used worldwide in aerospace industry [144]. Various standards on small UAV systems have been developed by the American Society for Testing and Materials (ASTM) committee together with the Federal Aviation Administration (FAA). For instance, ASTM F3003 ascertains the quality assurance requirements for the design, manufacture and production of a small unmanned aircraft system (sUAS) [145]. There is need to have quality assurance and control of materials used in AM methods. As of now, there is only one certified aerospace grade thermoplastic material UltemTM available. In addition, ASTM F3003 requires the process to be carried out in controlled conditions. If such standards are to be followed for AM systems then new means need to be devised to develop in-situ monitoring and feedback mechanisms.

5.7. Material and manufacturing costs

As discussed extensively in earlier sections, AM techniques eliminate the need for tooling. With cost for tooling out of equation, the manufacturing cost per unit for AM UAVs becomes relatively constant as shown in Fig. 8. For instance, a 2 m UAV (with structural weight of 3.92 kg) printed by Easter et al. costed about \$5700 [36]. On adding the tooling cost, a rough estimate of total UAV price comes close to \$740,000 if injection molding was to be used to manufacture the UAV and it would have required to produce 130 units to break even [146]. This means that additive manufacturing is more economical when total build volume is lesser than 130 units, beyond which injection molding should be used instead. Material costs of AM materials are, however, higher than that of the conventional techniques. This is because additional processes are needed to make the material into the forms that are suitable for AM processes. For example, materials are made into filament in the case of FDM whereas for SLS process, materials are pulverized. The costs of the AM materials are shown in Table 4. This makes AM a less viable and economical solution for higher build volumes. In nutshell, there seems to be a threshold production volume below which employing AM technique is cheaper. However, above the threshold build volume the conventional manufacturing methods are more cost effective. It is predicted that the cost of material and equipment will continue to drop as AM becomes more common [147], thus lowering the cost of additively manufactured UAV.

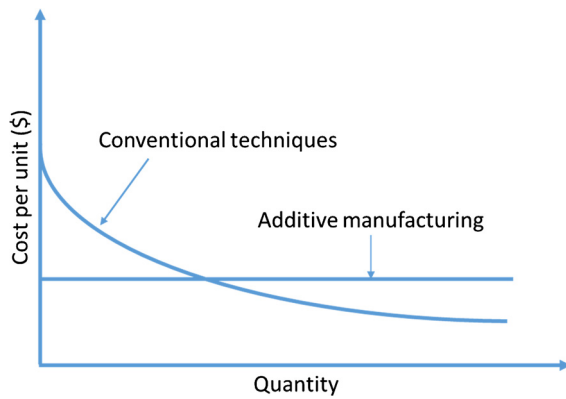


Fig. 8. A graph depicting the cost per unit vs quantity for conventional and additive manufacturing techniques.

6. Conclusion

Additive manufacturing techniques have garnered much interest for fabrication of UAVs. AM gives flexibility to designers to fabricate complex structures, which are hard to fabricate using conventional methods. AM techniques do not require moulding and tooling, thus saving time, cost and effort. The paper discusses in-depth how AM methods can improve structural and aerodynamic efficiency of UAV. It is also envisioned that AM can provide viable solutions for supply chain issues and reduce the operating costs by providing on-site and on-demand printing capability. Despite all the advantages of AM, it still suffers from limitations that need to be addressed. Lack of high strength-to-weight materials, dearth of characterization methods, anisotropic properties and small build volumes mar the scope of AM to become a viable commercial solution. Recent surveys have suggested that the fabrication of small-volume manufacturing of UAVs will increase tremendously by 2025 [148]. With focused effort in development of materials, design, structure and printer technology, AM will find increasing application in the production of UAV components. Hence, there is no doubt that AM has indeed carved its niche in UAV application area and will only continue to grow in future.

Conflict of interest statement

None declared.

Acknowledgements

This work was supported under the grant by National Research Foundation (NRF).

References

- [1] C. Zhang, J.M. Kovacs, The application of small unmanned aerial systems for precision agriculture: a review, *Precis. Agric.* 13 (2012) 693–712.
- [2] T. Spiess, J. Bange, M. Buschmann, P. Vörsmann, First application of the meteorological Mini-UAV/M2AV, *Meteorol. Z.* 16 (2007) 159–169.
- [3] S.M. Adams, C.J. Friedland, A survey of unmanned aerial vehicle (UAV) usage for imagery collection in disaster research and management, in: 9th International Workshop on Remote Sensing for Disaster Response, 2011.
- [4] U.M. Research, U.S. Military Unmanned Aerial Vehicles (UAV) Market Forecast 2010–2015, Available at UAV Market Research: <http://www.uavmarketresearch.com/> 2011.
- [5] J.T.K. Ping, A.E. Ling, T.J. Quan, C.Y. Dat, Generic unmanned aerial vehicle (UAV) for civilian application – a feasibility assessment and market survey on civilian application for aerial imaging, in: IEEE Conference on Sustainable Utilization and Development in Engineering and Technology, STUDENT 2012, 2012, pp. 289–294.
- [6] T. Turgut, Manufacturing and Structural Analysis of a Lightweight Sandwich Composite UAV Wing, Thesis of MS, Middle East Technical University, 2007.
- [7] J.W. Gerdes, S.K. Gupta, S.A. Wilkerson, A review of bird-inspired flapping wing miniature air vehicle designs, *J. Mech. Robot.* 4 (2012) 021003.
- [8] D.S. Cairns, J.D. Skramstad, J.F. Mandell, Evaluation of hand lay-up and resin transfer molding in composite wind turbine blade structures, in: International SAMPE Symposium and Exhibition, 2000, pp. 967–980.
- [9] E. Atzeni, L. Iuliano, P. Minetola, A. Salmi, Redesign and cost estimation of rapid manufactured plastic parts, *Rapid Prototyping J.* 16 (2010) 308–317.
- [10] J.-P. Kruth, M.-C. Leu, T. Nakagawa, Progress in additive manufacturing and rapid prototyping, *CIRP Ann. Manuf. Technol.* 47 (1998) 525–540.
- [11] D. Walker, D. Liu, A. Jennings, Wing design utilizing topology optimization and additive manufacturing, in: 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum (AIAA 2016-1246), 2016.
- [12] Z. Sun, X. Tan, S.B. Tor, W.Y. Yeong, Selective laser melting of stainless steel 316L with low porosity and high build rates, *Materials & Design* 104 (2016) 197–204.
- [13] S.L. Sing, J. An, W.Y. Yeong, F.E. Wiria, Laser and electron-beam powder-bed additive manufacturing of metallic implants: a review on processes, materials and designs, *J. Orthop. Res.* 34 (2016) 369–385.
- [14] J.M. Lee, W.Y. Yeong, Design and printing strategies in 3D bioprinting of cell-hydrogels: a review, *Adv. Healthcare Mater.* 5 (2016) 2856–2865, <http://dx.doi.org/10.1002/adhm.201600435>.
- [15] T. Campbell, C. Williams, O. Ivanova, B. Garrett, Could 3D Printing Change the World, in: Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC, 2011.
- [16] D. Clark, M. Bache, M. Whittaker, Shaped metal deposition of a nickel alloy for aero engine applications, *J. Mater. Process. Technol.* 203 (2008) 439–448.
- [17] E. Brandl, B. Baufeld, C. Leyens, R. Gault, Additive manufactured Ti-6Al-4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications, *Phys. Proc.* 5 (2010) 595–606.
- [18] P. Kobryn, N. Ontko, L. Perkins, J. Tiley, Additive Manufacturing of Aerospace Alloys for Aircraft Structures, DTIC Document, 2006.
- [19] N. Travitzky, A. Bonet, B. Dermeik, T. Fey, I. Filbert-Demut, L. Schlier, et al., Additive manufacturing of ceramic-based materials, *Adv. Eng. Mater.* 16 (2014) 729–754.
- [20] S. Kumar, J.-P. Kruth, Composites by rapid prototyping technology, *Mater. Des.* 31 (2010) 850–856.
- [21] B.G. Compton, J.A. Lewis, 3D-printing of lightweight cellular composites, *Adv. Mater.* 26 (2014) 5930–5935.
- [22] S. Easter, J. Turman, D. Sheffler, M. Balazs, J. Rotner, Using advanced manufacturing to produce unmanned aerial vehicles: a feasibility study, in: SPIE Defense, Security, and Sensing, 2013, 874204.
- [23] Tim, FDM-printed fixed wing UAV (17 July 2014). Available <http://www.amrc.co.uk/featuredstudy/printed-uav/>.
- [24] M. Stern, E. Cohen, VAST AUAV (Variable AirSpeed Telescoping Additive Unmanned Air Vehicle), Society of Manufacturing Engineers, Dearborn, Mich, 2013.
- [25] R.C. Michelson, S. Reece, Update on flapping wing micro air vehicle research-ongoing work to develop a flapping wing, crawling entomopter, in: 13th Bristol International RPV/UAV Systems Conference Proceedings, Bristol, England, 1998, pp. 30–31.
- [26] T. Zhang, C. Zhou, S. Su, Design and development of bio-inspired flapping wing aerial vehicles, in: International Conference on Advanced Robotics and Intelligent Systems, ARIS 2015, 2015, pp. 1–6.
- [27] S.K. Moon, Y.E. Tan, J. Hwang, Y.-J. Yoon, Application of 3D printing technology for designing light-weight unmanned aerial vehicle wing structures, *Int. J. Precis. Eng. Manuf. Green Technol.* 1 (2014) 223–228.
- [28] Y.E. Tan, S.K. Moon, Inflatable wing design for micro UAVs using indirect 3D printing, in: 11th International Conference on Ubiquitous Robots and Ambient Intelligence, URAI 2014, 2014, pp. 545–546.
- [29] S.J. Furst, G. Bunget, S. Seelecke, Design and fabrication of a bat-inspired flapping-flight platform using shape memory alloy muscles and joints, *Smart Mater. Struct.* 22 (2013) 014011.
- [30] C. Richter, H. Lipson, Untethered hovering flapping flight of a 3D-printed mechanical insect, *Artif. Life* 17 (2011) 73–86.
- [31] J. Farnsworth, J.C. Vaccaro, M. Amitay, Aerodynamic performance modification of the stingray UAV at low angles of attack, *AIAA J.* 46 (2008) 2530–2544.
- [32] G. Williamson, Experimental Wind Tunnel Study of Airfoils with Large Flap Deflections at Low Reynolds Numbers, 2012.
- [33] D. Artzi, E. Kroll, Lessons from wind tunnel models made by rapid prototyping, in: Proc 50th Israel Annual Conference on Aerospace Sciences, 2010.
- [34] A.K. Jim Scanlan, SULSA – Southampton University Laser, Sintered Aircraft (16 July 2011). Available http://www.southampton.ac.uk/~decode/index_files/Page804.htm.
- [35] N.A. Ahmed, J. Page, Manufacture of an unmanned aerial vehicle (UAV) for advanced project design using 3D printing technology, *Appl. Mech. Mater.* (2013) 970–980.
- [36] M. Ferraro, A. Lock, J.P. Scanlan, A.J. Keane, Design and Flight Test of a Civil Unmanned Aerial Vehicle for Maritime Patrol: The Use of 3D-Printed Structural Components, 2014.

- [37] D. Drummer, S. Cifuentes-Cuellar, D. Rietzel, Suitability of PLA/TCP for fused deposition modeling, *Rapid Prototyping J.* 18 (2012) 500–507.
- [38] J. Griffey, Types of plastics, *Libr. Technol. Rep.* 50 (2014) 13–15.
- [39] A. Bagsik, V. Schoeppner, E. Klemp, FDM part quality manufactured with Ultem® 9085, in: 14th International Scientific Conference on Polymeric Materials, September 2010.
- [40] J. Lee, A. Huang, Fatigue analysis of FDM materials, *Rapid Prototyping J.* 19 (2013) 291–299.
- [41] J.F. Rodriguez, J.P. Thomas, J.E. Renaud, Mechanical behavior of acrylonitrile butadiene styrene (ABS) fused deposition materials. Experimental investigation, *Rapid Prototyping J.* 7 (2001) 148–158.
- [42] S.-H. Ahn, M. Montero, D. Odell, S. Roundy, P.K. Wright, Anisotropic material properties of fused deposition modeling ABS, *Rapid Prototyping J.* 8 (2002) 248–257.
- [43] A.K. Sood, R. Ohdar, S. Mahapatra, Parametric appraisal of mechanical property of fused deposition modelling processed parts, *Mater. Des.* 31 (2010) 287–295.
- [44] H. Zarringhalam, N. Hopkinson, N. Kamperman, J. De Vlieger, Effects of processing on microstructure and properties of SLS Nylon 12, *Mater. Sci. Eng. A* 435 (2006) 172–180.
- [45] I. Gibson, D. Shi, Material properties and fabrication parameters in selective laser sintering process, *Rapid Prototyping J.* 3 (1997) 129–136.
- [46] S.R. Athreya, K. Kalaitzidou, S. Das, Mechanical and microstructural properties of Nylon-12/carbon black composites: selective laser sintering versus melt compounding and injection molding, *Compos. Sci. Technol.* 71 (2011) 506–510.
- [47] B. Van Hooreweder, F. De Coninck, D. Moens, R. Boonen, P. Sas, Microstructural characterization of SLS-PA12 specimens under dynamic tension/compression excitation, *Polym. Test.* 29 (2010) 319–326.
- [48] B. Van Hooreweder, D. Moens, R. Boonen, J.-P. Kruth, P. Sas, On the difference in material structure and fatigue properties of nylon specimens produced by injection molding and selective laser sintering, *Polym. Test.* 32 (2013) 972–981.
- [49] S.S. Crump, Direct rapid manufacturing with real production plastics using Fused Deposition Modeling (FDM), in: Euro-uRapid Conference, Stratasys, Frankfurt, 2002.
- [50] M.W. Barclift, C.B. Williams, Examining variability in the mechanical properties of parts manufactured via polyjet direct 3d printing, in: International Solid Freeform Fabrication Symposium, August, 2012, pp. 6–8.
- [51] J. Dulieu-Barton, M. Fulton, Mechanical properties of a typical stereolithography resin, *Strain* 36 (2000) 81–87.
- [52] H. Oktem, T. Erzurumlu, I. Uzman, Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part, *Mater. Des.* 28 (2007) 1271–1278.
- [53] B. Ozcelik, A. Ozbay, E. Demirbas, Influence of injection parameters and mold materials on mechanical properties of ABS in plastic injection molding, *Int. Commun. Heat Mass Transf.* 37 (2010) 1359–1365.
- [54] P. Soden, R. McLeish, Variables affecting the strength of balsa wood, *J. Strain Anal. Eng. Des.* 11 (1976) 225–234.
- [55] C. Reinders, Reducing production costs of E-mobility components by using polyjet 3D printing, Presented at the 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Kissimmee, Florida, 2015.
- [56] Y.L. Yap, W.Y. Yeong, Shape recovery effect of 3D printed polymeric honeycomb, *Virtual Phys. Prototyping* 10 (2015) 91–99.
- [57] F.P. Melchels, J. Feijen, D.W. Grijpma, A review on stereolithography and its applications in biomedical engineering, *Biomaterials* 31 (2010) 6121–6130.
- [58] R. Liska, M. Schuster, R. Inführ, C. Turecek, C. Fritscher, B. Seidl, et al., Photopolymers for rapid prototyping, *J. Coat. Technol. Res.* 4 (2007) 505–510.
- [59] J. Bartelds, Design and Control of a Modular End-Effector for UAVs in Interaction with a Remote Environment, 2012.
- [60] E. Kaufman, K. Caldwell, D. Lee, T. Lee, Design and development of a free-floating hexrotor UAV for 6-DOF maneuvers, in: Aerospace Conference, IEEE, 2014, pp. 1–10.
- [61] C. Torno, C. Hintz, L.R.G. Carrillo, Design and development of a semi-autonomous fixed-wing aircraft with real-time video feed, in: International Conference on Unmanned Aircraft Systems, ICUAS 2014, 2014, pp. 1021–1028.
- [62] G. Kim, Y. Oh, A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost, *Proc. Inst. Mech. Eng., B J. Eng. Manuf.* 222 (2008) 201–215.
- [63] S. Kumar, Selective laser sintering: a qualitative and objective approach, *JOM* 55 (2003) 43–47.
- [64] E.C. Santos, M. Shiomi, K. Osakada, T. Laoui, Rapid manufacturing of metal components by laser forming, *Int. J. Mach. Tools Manuf.* 46 (2006) 1459–1468.
- [65] C. Yan, L. Hao, L. Xu, Y. Shi, Preparation, characterisation and processing of carbon fibre/polyamide-12 composites for selective laser sintering, *Compos. Sci. Technol.* 71 (2011) 1834–1841.
- [66] A. Sachdeva, S. Singh, V.S. Sharma, Investigating surface roughness of parts produced by SLS process, *Int. J. Adv. Manuf. Technol.* 64 (2013) 1505–1516.
- [67] R. Udriou, L. Mihail, Experimental determination of surface roughness of parts obtained by rapid prototyping, in: 8th WSEAS International Conference on Circuits, Systems, Electronics, Control and Signal Processing, Puerto De La Cruz, Tenerife, Canary Islands, Spain, 2009, pp. 283–286.
- [68] R.H. Radetzky, M.S. Reibert, W.S. Saric, Effect of isolated micron-sized roughness on transition in swept-wing flows, *AIAA J.* 37 (1999) 1370–1377.
- [69] C.C. Foo, G.B. Chai, L.K. Seah, Mechanical properties of Nomex material and Nomex honeycomb structure, *Compos. Struct.* 80 (2007) 588–594.
- [70] H. Wang, Y. Chen, D.W. Rosen, A hybrid geometric modeling method for large scale conformal cellular structures, in: ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2005, pp. 421–427.
- [71] H.V. Wang, D. Rosen, Computer-Aided Design Methods for the Additive Fabrication of Truss Structure, School of Mechanical Engineering, Georgia Institute of Technology Atlanta, 2001.
- [72] A.-J. Wang, D. McDowell, Optimization of a metal honeycomb sandwich beam-bar subjected to torsion and bending, *Int. J. Solids Struct.* 40 (2003) 2085–2099.
- [73] S.A. Burns, Recent Advances in Optimal Structural Design, ASCE Publications, 2002.
- [74] L. Murr, S. Gaytan, F. Medina, H. Lopez, E. Martinez, B. Machado, et al., Next-generation biomedical implants using additive manufacturing of complex, cellular and functional mesh arrays, *Philos. Trans. R. Soc. Lond. A, Math. Phys. Eng. Sci.* 368 (2010) 1999–2032.
- [75] J.D. Deaton, R.V. Grandhi, A survey of structural and multidisciplinary continuum topology optimization: post 2000, *Struct. Multidiscip. Optim.* 49 (2014) 1–38.
- [76] X. Guo, G.-D. Cheng, Recent development in structural design and optimization, *Acta Mech. Sin.* 26 (2010) 807–823.
- [77] J.-H. Zhu, Y. Li, W.-H. Zhang, Topology optimization with shape preserving design, in: Proceedings of 5th International Conference on Computational Methods, Cambridge, UK, 2014.
- [78] L. Krog, A. Tucker, M. Kemp, R. Boyd, Topology optimization of aircraft wing box ribs, in: 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 2004, pp. 1–11.
- [79] M. Tomlin, J. Meyer, Topology optimization of an additive layer manufactured (ALM) aerospace part, in: Proceeding of the 7th Altair CAE Technology Conference, 2011, pp. 1–9.
- [80] J.-H. Zhu, W.-H. Zhang, L. Xia, Topology optimization in aircraft and aerospace structures design, *Arch. Comput. Methods Eng.* (2015) 1–28.
- [81] J.K. Borchardt, Unmanned aerial vehicles spur composites use, *Reinf. Plast.* 48 (2004) 28–31.
- [82] C. Shaojie, Application and research of composite for UAV, *Aircr. Des.* 3 (2003) 005.
- [83] C. Soutis, Fibre reinforced composites in aircraft construction, *Prog. Aerosp. Sci.* 41 (2005) 143–151.
- [84] Y.-M. Zhang, P.-F. Zhao, Y. He, J.-L. Zhao, Composite for Structure of UAV, 2005.
- [85] J. Simsiriwong, R.W. Sullivan, Experimental vibration analysis of a composite UAV wing, *Mech. Adv. Mat. Struct.* 19 (2012) 196–206.
- [86] R. Sullivan, M. Rais-Rohani, T. Lacy, N. Alday, Structural testing of an ultralight UAV composite wing, in: Proceedings of the 47th AIAA/ASME/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Newport, RI, 2006.
- [87] W. Frohs, H. Jaeger, Carbon fiber & composite material, 炭素 2011 (2011) 174–178.
- [88] Y. Miyano, M. Kanemitsu, T. Kunio, H.A. Kuhn, Role of matrix resin on fracture strengths of unidirectional CFRP, *J. Compos. Mater.* 20 (1986) 520–538.
- [89] K.-I. Mori, T. Maeno, Y. Nakagawa, Dieless forming of carbon fibre reinforced plastic parts using 3D printer, *Proc. Eng.* 81 (2014) 1595–1600.
- [90] F. Ning, W. Cong, J. Qiu, J. Wei, S. Wang, Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling, *Composites, Part B, Eng.* 80 (2015) 369–378.
- [91] K. Pandey, Natural Fibre Composites for 3D Printing, 2015.
- [92] M. Ueda, M. Namiki, A. Todoroki, Y. Hirano, R. Matsuzaki, 3D printing of continuous fiber reinforced plastic, in: Proceedings of SAMPE Seattle, 2014.
- [93] G. Zak, A. Chan, C. Park, B. Benhabib, Viscosity analysis of photopolymer and glass-fibre composites for rapid layered manufacturing, *Rapid Prototyping J.* 2 (1996) 16–23.
- [94] G. Zak, M. Haberer, C. Park, B. Benhabib, Mechanical properties of short-fibre layered composites: prediction and experiment, *Rapid Prototyping J.* 6 (2000) 107–118.
- [95] C. Cheah, J. Fuh, A. Nee, L. Lu, Mechanical characteristics of fiber-filled photopolymer used in stereolithography, *Rapid Prototyping J.* 5 (1999) 112–119.
- [96] D. Karalekas, Study of the mechanical properties of nonwoven fibre mat reinforced photopolymers used in rapid prototyping, *Mater. Des.* 24 (2003) 665–670.
- [97] E. Bekyarova, E. Thostenson, A. Yu, H. Kim, J. Gao, J. Tang, et al., Multiscale carbon nanotube-carbon fiber reinforcement for advanced epoxy composites, *Langmuir* 23 (2007) 3970–3974.
- [98] N. Baullinger, V. Page, High Altitude Long Endurance (HALE) RPV, AIAA paper, 1989.

- [99] O. Bilgen, K. Kochersberger, E.C. Diggs, A.J. Kurdila, D.J. Inman, Morphing wing micro-air-vehicles via macro-fiber-composite actuators, in: *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, HI, April, 2007, pp. 23–26.
- [100] A. Sofla, S. Meguid, K. Tan, W. Yeo, Shape morphing of aircraft wing: status and challenges, *Mater. Des.* 31 (2010) 1284–1292.
- [101] L.L. Howell, A. Midha, T. Norton, Evaluation of equivalent spring stiffness for use in a pseudo-rigid-body model of large-deflection compliant mechanisms, *J. Mech. Des.* 118 (1996) 126–131.
- [102] D. Espalin, D.W. Muse, E. MacDonald, R.B. Wicker, 3D Printing multifunctionality: structures with electronics, *Int. J. Adv. Manuf. Technol.* 72 (2014) 963–978.
- [103] D. Espalin, J. Alberto Ramirez, F. Medina, R. Wicker, Multi-material, multi-technology FDM: exploring build process variations, *Rapid Prototyping J.* 20 (2014) 236–244.
- [104] K. Lappo, B. Jackson, K. Wood, D. Bourell, J. Beaman, Discrete multiple material selective laser sintering (M2SLS): experimental study of part processing, in: *Solid Freeform Fabrication Symposium*, The University of Texas, Austin, Texas, 2003, pp. 109–119.
- [105] M. Ott, M. Zaeh, Multi-material processing in additive manufacturing, in: *Proceedings of the Solid Freeform Fabrication Symposium*, 2010, pp. 195–203.
- [106] J.-W. Choi, H.-C. Kim, R. Wicker, Multi-material stereolithography, *J. Mater. Process. Technol.* 211 (2011) 318–328.
- [107] R.B. Wicker, F. Medina, C. Elkins, Multiple material micro-fabrication: extending stereolithography to tissue engineering and other novel applications, in: *Proceedings of 15th Annual Solid Freeform Fabrication Symposium*, Austin, TX, 2004, pp. 754–764.
- [108] J. Corney, R.B. Wicker, A.V. Ranade, F. Medina, J.A. Palmer, Embedded micro-channel fabrication using line-scan stereolithography, *Assem. Autom.* 25 (2005) 316–329.
- [109] S. Barbarino, O. Bilgen, R.M. Ajaj, M.I. Friswell, D.J. Inman, A review of morphing aircraft, *J. Intell. Mater. Syst. Struct.* 22 (2011) 823–877.
- [110] T.A. Weisshaar, Morphing aircraft systems: historical perspectives and future challenges, *J. Aircr.* 50 (2013) 337–353.
- [111] S.-H. Ahn, K.-T. Lee, H.-J. Kim, R. Wu, J.-S. Kim, S.-H. Song, Smart soft composite: an integrated 3D soft morphing structure using bend-twist coupling of anisotropic materials, *Int. J. Precis. Eng. Manuf.* 13 (2012) 631–634.
- [112] J. Raasch, M. Ivey, D. Aldrich, D.S. Nobes, C. Ayranci, Characterization of polyurethane shape memory polymer processed by material extrusion additive manufacturing, *Addit. Manuf.* 8 (2015) 132–141.
- [113] M. Allahverdi, S. Danforth, M. Jafari, A. Safari, Processing of advanced electroceramic components by fused deposition technique, *J. Eur. Ceram. Soc.* 21 (2001) 1485–1490.
- [114] A. Safari, M. Allahverdi, E. Akdogan, Solid freeform fabrication of piezoelectric sensors and actuators, *J. Mater. Sci.* 41 (2006) 177–198.
- [115] S. Turcu, B. Jadician, S. Danforth, A. Safari, Piezoelectric properties of novel oriented ceramic-polymer composites with 2–2 and 3–3 connectivity, *J. Electroceram.* 9 (2002) 165–171.
- [116] M. Zarek, M. Layani, I. Cooperstein, E. Sachyani, D. Cohn, S. Magdassi, 3D printing of shape memory polymers for flexible electronic devices, *Adv. Mater.* (2015).
- [117] R.F. Gibson, A review of recent research on mechanics of multifunctional composite materials and structures, *Compos. Struct.* 92 (2010) 2793–2810.
- [118] S. Akula, K. Karunakaran, Hybrid adaptive layer manufacturing: an intelligent art of direct metal rapid tooling process, *Robot. Comput.-Integr. Manuf.* 22 (2006) 113–123.
- [119] O. Kerbrat, P. Mognol, J.-Y. Hascoët, A new DFM approach to combine machining and additive manufacturing, *Comput. Ind.* 62 (2011) 684–692.
- [120] K. Karunakaran, S. Suryakumar, V. Pushpa, S. Akula, Low cost integration of additive and subtractive processes for hybrid layered manufacturing, *Robot. Comput.-Integr. Manuf.* 26 (2010) 490–499.
- [121] X. Xiong, H. Zhang, G. Wang, Metal direct prototyping by using hybrid plasma deposition and milling, *J. Mater. Process. Technol.* 209 (2009) 124–130.
- [122] Y.-A. Song, S. Park, Experimental investigations into rapid prototyping of composites by novel hybrid deposition process, *J. Mater. Process. Technol.* 171 (2006) 35–40.
- [123] F. Liou, K. Slattery, M. Kinsella, J. Newkirk, H.-N. Chou, R. Landers, Applications of a hybrid manufacturing process for fabrication of metallic structures, *Rapid Prototyping J.* 13 (2007) 236–244.
- [124] A. Joe Lopes, E. MacDonald, R.B. Wicker, Integrating stereolithography and direct print technologies for 3D structural electronics fabrication, *Rapid Prototyping J.* 18 (2012) 129–143.
- [125] P. Kopola, B. Zimmermann, A. Filipovic, H.-F. Schleiermacher, J. Greulich, S. Rousu, et al., Aerosol jet printed grid for ITO-free inverted organic solar cells, *Sol. Energy Mater. Sol. Cells* 107 (2012) 252–258.
- [126] Y. Jang, I.H. Tambunan, H. Tak, V.D. Nguyen, T. Kang, D. Byun, Non-contact printing of high aspect ratio Ag electrodes for polycrystalline silicon solar cell with electrohydrodynamic jet printing, *Appl. Phys. Lett.* 102 (2013) 123901.
- [127] A. Mette, P. Richter, M. Hörteis, S. Glunz, Metal aerosol jet printing for solar cell metallization, *Prog. Photovolt., Res. Appl.* 15 (2007) 621–627.
- [128] C.N. Hoth, P. Schilinsky, S.A. Choulis, C.J. Brabec, Printing highly efficient organic solar cells, *Nano Lett.* 8 (2008) 2806–2813.
- [129] C. Yang, E. Zhou, S. Miyashishi, K. Hashimoto, K. Tajima, Preparation of active layers in polymer solar cells by aerosol jet printing, *ACS Appl. Mater. Interfaces* 3 (2011) 4053–4058.
- [130] C.C. Ho, J.W. Evans, P.K. Wright, Direct-write dispenser-printed energy storage devices, in: *SPIE Defense, Security, and Sensing*, 2010, 76792A.
- [131] G.L. Goh, J. Ma, K.L.F. Chua, A. Shweta, W.Y. Yeong, Y.P. Zhang, Inkjet-printed patch antenna emitter for wireless communication application, *Virtual Phys. Prototyping* 11 (2016) 289–294.
- [132] G. Janssen, I. Blankers, E. Moolenburgh, A. Posthumus, TNO: The Impact of 3-D Printing on Supply Chain Management, 2014.
- [133] S.H. Khajavi, J. Partanen, J. Holmström, Additive manufacturing in the spare parts supply chain, *Comput. Ind.* 65 (2014) 50–63.
- [134] W.E. Frazier, Navy workshop aims to cut costs, *Adv. Mater. Process.* 41 (2008) 43–46.
- [135] W.E. Frazier, Direct digital manufacturing of metallic components: vision and roadmap, in: *21st Annual International Solid Freeform Fabrication Symposium*, 2010, pp. 717–732.
- [136] P.E. Pounds, Paper plane: towards disposable low-cost folded cellulose-substrate UAVs, in: *2012 Australasian Conf. on Robotics and Automation*, 2012.
- [137] P.E. Pounds, S.P. Singh, Integrated electro-aeromechanical structures for low-cost, self-deploying environment sensors and disposable UAVs, in: *IEEE International Conference on Robotics and Automation, ICRA 2013*, 2013, pp. 4459–4466.
- [138] H.L. Tekinalp, V. Kunc, G.M. Velez-Garcia, C.E. Duty, L.J. Love, A.K. Naskar, et al., Highly oriented carbon fiber-polymer composites via additive manufacturing, *Compos. Sci. Technol.* 105 (2014) 144–150.
- [139] S. Christ, M. Schnabel, E. Vorndran, J. Groll, U. Gbureck, Fiber reinforcement during 3D printing, *Mater. Lett.* 139 (2015) 165–168.
- [140] L.J. Love, V. Kunc, O. Rios, C.E. Duty, A.M. Elliott, B.K. Post, et al., The importance of carbon fiber to polymer additive manufacturing, *J. Mater. Res.* 29 (2014) 1893–1898.
- [141] B. Vrancken, L. Thijs, J.-P. Kruth, J. Van Humbeeck, Heat treatment of Ti6Al4V produced by selective laser melting: microstructure and mechanical properties, *J. Alloys Compd.* 541 (2012) 177–185.
- [142] D. Lundström, K. Amadori, P. Krus, Automation of design and prototyping of micro aerial vehicle, in: *47th AIAA Aerospace Sciences Meeting and Exhibit*, Orlando, FL, USA, 2009.
- [143] S. Eshraghi, S. Das, Mechanical and microstructural properties of polycaprolactone scaffolds with one-dimensional, two-dimensional, and three-dimensional orthogonally oriented porous architectures produced by selective laser sintering, *Acta Biomater.* 6 (2010) 2467–2476.
- [144] AS 9100 – Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations, SAE International, 2016, p. 54.
- [145] ASTM Standard F3003-14, Standard Specification for Quality Assurance of a Small Unmanned Aircraft System, sUAS, ASTM International, West Conshohocken, PA, 2014, www.astm.org.
- [146] Custompart.net. (22 November). Available <http://www.custompartnet.com/>.
- [147] Wohlers Associates Inc., Wohlers Report 2012, Wohlers Associates, Inc., Fort Collins, Colorado 80525, USA, 2012.
- [148] Teal Group Predicts Worldwide Civil UAS Production Will Total \$65 Billion in Its 2016 UAS Market Profile and Forecast (2016). Available <http://tealgroup.com/index.php/about-teal-group-corporation/press-releases/129-teal-group-predicts-worldwide-civil-uas-production-will-total-65-billion-in-its-2016-uas-market-profile-and-forecast>.