Propelling Past Innovation Ceilings by 3D Printing Drones

Whitepaper Overview

Additive manufacturing ("3D printing") is a manufacturing process that has proven to be extremely well-suited to applications that require a combination of high affordability, freedom of design, and fast turnaround. Unmanned aerial vehicles ("UAVs"), colloquially referred to as drones, are a robotic technology that has proven to be extremely well-suited to data collection, transportation of items, and STEAM education, among other emerging applications. 3D printing has proven to be an accessible manufacturing method for UAV users that want to affordably and quickly produce UAV hardware, as 3D printing allows for design innovations that improve UAV performance that are not feasible with conventional fabrication methods, especially in cases involving parts with complex geometries and/or low volume part production. Challenges persist with both the anisotropic properties of 3D printed parts that increase susceptibility to part failure and the regulatory uncertainties surrounding UAV quality control. However, opportunities for growth persist as material science research continues to advance cost-competitive opportunities in the area of 3D printing UAV parts.

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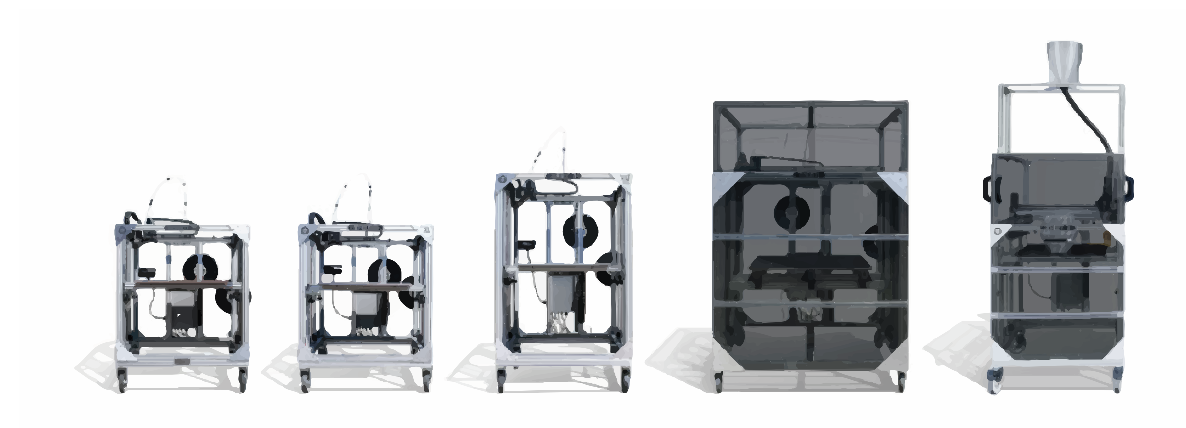

re:3D Inc.® is breaking through the current limitations of 3D printing to unlock new applications and growth markets worldwide. Gigabot, re:3D's flagship technology, enables industrial strength, large format 3D printing at an affordable price point. With build volumes starting at eight cubic feet and a robust construction, Gigabot can print objects up to 30x larger than competing desktop models. re:3D's customer base comprises an esteemed group of specialty manufacturers, engineers, designers, universities, and hobbyists in over 50+ countries around the globe.

Currently, re:3D is scaling manufacturing operations, and exploring alternate materials and feedstocks with global leaders in material and life sciences. We're so excited to see how 3D printing changes the world, and we're enjoying all the adventures along the way.

We want to encourage the spread of 3D printing and support the diverse ideas for 3D printing applications, one Gigabot at a time.

Maheen Khizar, Technology Analyst

August 2019

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What is 3D printing?

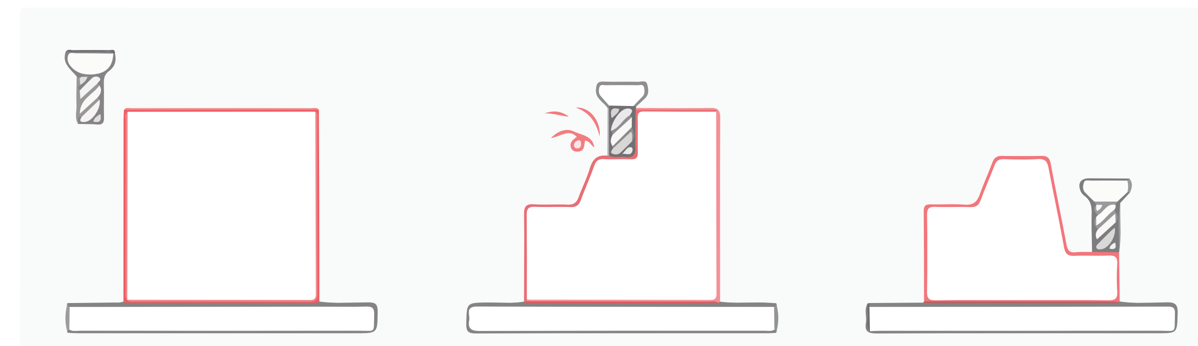
The International Organization of Standardization reviews and publishes standardized 3D printing terminology. The most recent publication was released in 2015, titled ISO/ASTM 52900, which will soon be replaced by a publication due for release in 2020 [1]. The ISO/ASTM 52900 standard was published in 2015 and is the most recent reviewed publication of 3D printing terminology. There are seven classifications of 3D printing technology.

1. Material Extrusion (FDM): Material is selectively dispensed through a nozzle or orifice
2. Vat Polymerization (SLA & DLP): Liquid photopolymer in a vat is selectively cured by UV light
3. Powder Bed Fusion (SLS, DMLS & SLM): A high-energy source selectively fuses powder particles
4. Material Jetting (MJ, Polyjet): Droplets of material are selectively deposited and cured
5. Binder Jetting (BJ): Liquid bonding agent selectively binds regions of a powder bed
6. Direct Energy Deposition (LENS, LBMD): A high-energy source fuses material as it is deposited
7. Sheet Lamination (LOM, UAM): Sheets of material are bonded and formed layer-by-layer

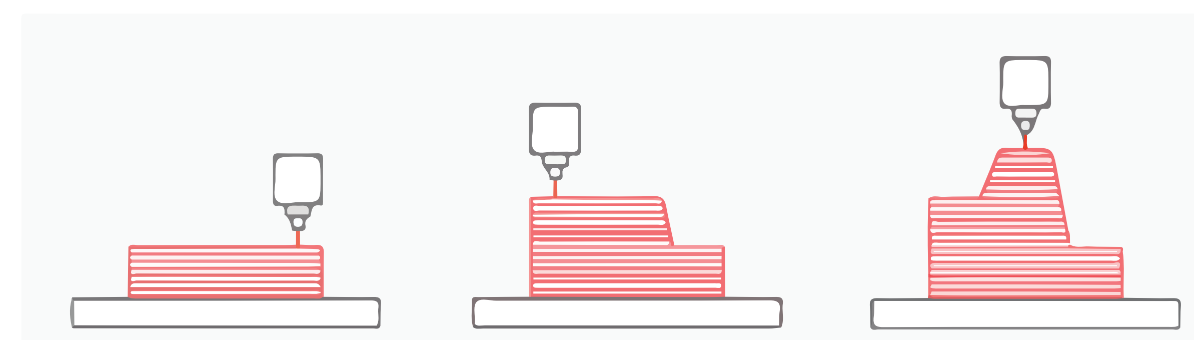
Source: 3D Hubs [2]

3D printing is an additive manufacturing method that offers more freedom of design and faster design cycles compared to traditional subtractive manufacturing methods. 3D printing is typically most cost-competitive for users operating under one or more of the following constraints - low volume production, production of complex geometries, and rapid design cycles. [3]

Subtractive manufacturing



Additive manufacturing



Source: 3D Hubs [2]

Terminology

What are drones?

Drones are a colloquial term for unmanned aerial vehicles (UAVs). UAVs are “sustained in flight by aerodynamic lift and guided without an onboard crew...may be expendable or recoverable and can fly autonomously or semi-autonomously” [5].

“Conventional fabrication technologies for UAVs include CNC hot-wire cutting for foam and balsa wood, and manual lay-up for composite...[which] suffer from disadvantages like multi-steps, labour intensive processes, high costs for molds, and long processing time...and puts a glass ceiling on building innovative [UAV] structures” [6]. 3D printing allows users to surpass this UAV innovation ceiling. Even when traditional manufacturing methods are an option, 3D printing acts as an accelerator for innovation by offering rapid design cycles at low cost. FDM, SLA, SLS, and Polyjet have been documented as 3D printing technologies used for fabricating UAVs with topologies and cellular structures that improve UAV performance beyond what is possible with conventional fabrication technologies [6].

According to the Boston Consulting Group, UAVs “in Europe and the US will comprise more than 1 million units and generate $50 billion per year in product and service revenues” [7]. As UAVs take off in a myriad of industry applications, fabrication of UAVs will increase, offering an opportunity for additive manufacturing to contribute its unique value-add for users operating under one or more of the following constraints - low volume production, production of complex geometries, and rapid design cycles.

re:3D User Experiences with 3D Printing UAVs

Steve Brandt, U.S. Air Force Academy
Propelling STEAM Education Forward by 3D Printing Prototypes

3D printing offers high design flexibility, rapid design cycles, and comparatively low fabrication cost for low-volume production. These characteristics make 3D printing well-suited to educators aiming to produce tangible teaching tools and improve students' technical experience with computer aided design (CAD) methods. For aerospace educators, 3D printing offers an unprecedented method for feasibly fabricating UAV prototypes for testing and analysis. For Steve Brandt, the decision to use a re:3D Gigabot was largely guided by a vision to improve UAV prototyping at the U.S. Air Force Academy, home to one of the most well equipped aeronautics labs in the United States.

The Gigabot's intersectional occupation of large print volume and affordability allows Brandt to print large, functional UAV prototypes from complex designs that are difficult to fabricate with traditional subtractive manufacturing techniques.

> "A 3D printed part can meet all of those contours [of the UAV design] and have the strength...we need to fly. There's a significant amount of savings in simply reprinting [a UAV] instead of re-machining it."

Brandt's savings have been generated by a reliance on 3D printing over time-intensive traditional fabrication methods. Within the spectrum of 3D printing technologies, Brandt's reliance on FDM has incurred additional savings, as the method allows for the use of comparatively more affordable materials. As the primary function for Brandt is to move through rapid UAV design cycles, minimal functionality is maximally efficient to learn what is necessary to reach a final prototype.

> "[Our students] have unique ideas and all want to try something. [3D printing] allows us as educators to let the students see if they can succeed or learn from failure, which is just a great way to teach. [The students] close the learning loop when they realize they can design, build, and fly something that they didn't really have the skills to do nine months prior."

For educators around the world, 3D printing can offer a method for allowing students to interact with tangible, real-world connections to abstract concepts introduced in the classroom. This bifurcated approach to learning can reinforce applications of the concept, and build confidence in a student's ability to problem-solve across iterations of their own design. This value can be accessed by other STEAM educators aiming to bring visions full-circle in their own classrooms.

[quotes edited for clarity]

re:3D User Experiences with 3D Printing UAVs

Eugen Toma, Pegasus Aerospace
Printing Carbon Fibre UAV's with a re:3D Gigabot

3D printing offers unparalleled flexibility for small-scale UAV manufacturers. Pegasus Aerospace, one of the earliest re:3D Gigabot users, has been using 3D printing to design, test, and deliver bespoke UAVs for a variety of client applications. Whereas STEAM educators garner value in utilizing 3D printing to produce minimally viable proofs of concept, Pegasus Aerospace's use of 3D printing to produce high-fidelity UAVs demonstrates the full spectrum of value added to the UAV fabrication process.

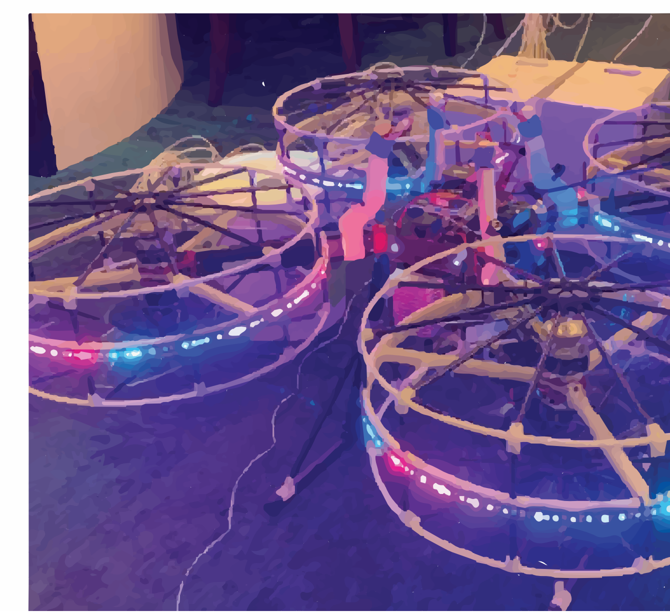
For Eugen Toma, Chief Technology Officer of Pegasus Aerospace, the decision to utilize a re:3D Gigabot made it affordable to utilize the kind of large print volume suited to printing UAV parts. Toma prints with Carbon Fiber PLA and Carbon Fiber Nylon, both carbon fiber reinforced polymers (CFRP), to fabricate high-fidelity UAV parts.

> "We print all our [UAV] components with 50-100 micron resolution, and when using CFRP, the components turn out very nice, without any striations or much post-processing work. We designed and built a heating box to attach to the side of the Gigabot to pre-warm the [CFRP] and reduce the frequency of filament breakage. We have found the CFRP to be extremely abrasive, so the nozzles have to either be replaced frequently or upgraded to hardened nozzles."

Toma also manually lays up UAV parts, including the fuselage, wings and control surfaces, with carbon fiber to further improve strength, UV resilience, and waterproof parts. This process offers an example for a more cost-efficient method to improve the strength-to-weight of UAVs while CFRP 3D printing technology continues to mature and decrease in cost.

Toma's current practices have allowed for high-fidelity, affordable, small-batch fabrication of UAV parts. One of Toma's next innovation challenges is to continue to increase print volume to fabricate molds for UAV parts. The current activities of Pegasus Aerospace offer insight into what UAV fabrication may look like in the future - a series of innovation ceilings propelled through iterative innovations.



Source: Pegasus Aerospace

Intersectional Synergy between 3D Printing and UAVs

There is no authoritative guide on which UAV parts can be 3D printed. However, there are an array of published examples of printed UAV parts that can be viewed holistically to attain an understanding of what is currently possible.

Case Study
The First Documented Fully 3D Printed UAV, SULSA

The first documentation of a fully 3D printed UAV is the Southampton University Laser Sintered Aircraft (SULSA). SULSA was designed under the constraints of a £5000 budget, 1.5 meter wingspan, and ultra-low drag. 3D printing allowed the designers to "go back to pure forms and explore the mathematics of airflow without being forced to put in straight lines to keep costs down." [8] This resulted in the ability to integrate WWII-era aviation designs that were "notoriously difficult to fabricate using conventional fabrication techniques", including low-drag elliptical wings taken from the Spitfire design and a geodesic internal design from the Vickers Wellington bomber [9].

SULSA has "a one-week assembly time, weight of 3 kg (6.6 lb), a 2-meter (6.6-foot) wingspan, a top speed of almost 100 mph (161 km/h)", and was deployed by the British Royal Navy in 2016 for test flights in Antarctica [10].

SULSA offers an example of 3D printing allowing for low-cost development and deployment of innovative UAV designs. For defense aerospace users, 3D printing offers a unique value proposition for producing UAVs on-site, reducing shipping costs, and producing UAVs for tasks that require a small series of one-way flights, reducing the per-unit cost sunk in fabrication.

Source: 3DPrint.com [11]

Intersectional Synergy between 3D Printing and UAVs

Currently Common UAV Prints
Frames and Mounts

There are some UAV parts that are well-documented on 3D printing forums and online UAV communities as being well-suited to 3D printing on limited budgets. Commonly printed parts include frames to encase sub-components and mounts to attach accessories. 3D printing these parts can provide accessibility to modularity that improves performance and broadens function, like printing mounts to support data transmission and printing frames with complex geometries to improve strength-to-weight optimization. Frames and mounts are non-electric UAV components, making them well within the domain of current 3D printing technologies. Frames and mounts can be fabricated from thermplastics, and the print itself can be machined and treated to better suit the unique UAV use case.

Pictured above: A rendering of a PLA UAV frame printed using SLS
Source: Sculpteo [12]

Pictured above: A 3D printed UAV camera mount
Source: All3DP [13]

Intersectional Synergy between 3D Printing and UAVs

Published Opinion
The Singapore Centre for 3D Printing

The Singapore Centre for 3D Printing recently published an article detailing a summary of the advantages and disadvantages of [3D printing] methods used for UAVs [6]. The article analyzes four 3D printing methods, FDM, Polyjet, SLA, and SLS, used to print UAVs. The findings are as follows.

Method	Advantages	Disadvantages
FDM	• High strength material such as Ultem is available • ABS plastic has higher survival rate compared to balsa [wood] during impacts	• Obvious stair-stepping effect in z-direction • Poor surface finish compared to polyjet and SLA
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 3D printed material is still inferior to that of the biological bone
SLA	• Ability to print fine feature size • Good surface finish • Insignificant stairstepping effect	• Degradation of photosentitive materials leading to poor performance under load • Low tensile strength of material
SLS	• Ability to print parts with good mechanical strength • Large build area • Relatively low cost	• Rough surface finish

Source: Singapore Centre for 3D Printing [6]

While this published opinion offers one set of views on the advantages and disadvantages of FDM, Polyjet, SLA, and SLS, there are several additional comments worth making. UAV fabricators' ideal material for printing would have high strength, low cost, low degradation, and low drag. 3D printing that results in rough surface finish and stair stepping typically results in increased drag, which is an undesirable inefficiency for UAV flights. However, there is documentation of processing to improve surface finish and reduce stair stepping, "by starting with a 3D print and [finishing] on a mill...to leverage the speed and design flexibility of 3D printing with the high accuracy of CNC milling" [14]. This dual-fabrication solution to improving UAV performance requires access to both types of machinery, which may be more costly for users. However, it is a strong counter-example to a published opinion on the advantages and disadvantages of 3D printing. Put another way, there is a large degree of flexibility and possibility offered by the emerging intersection of 3D printing and UAVS.

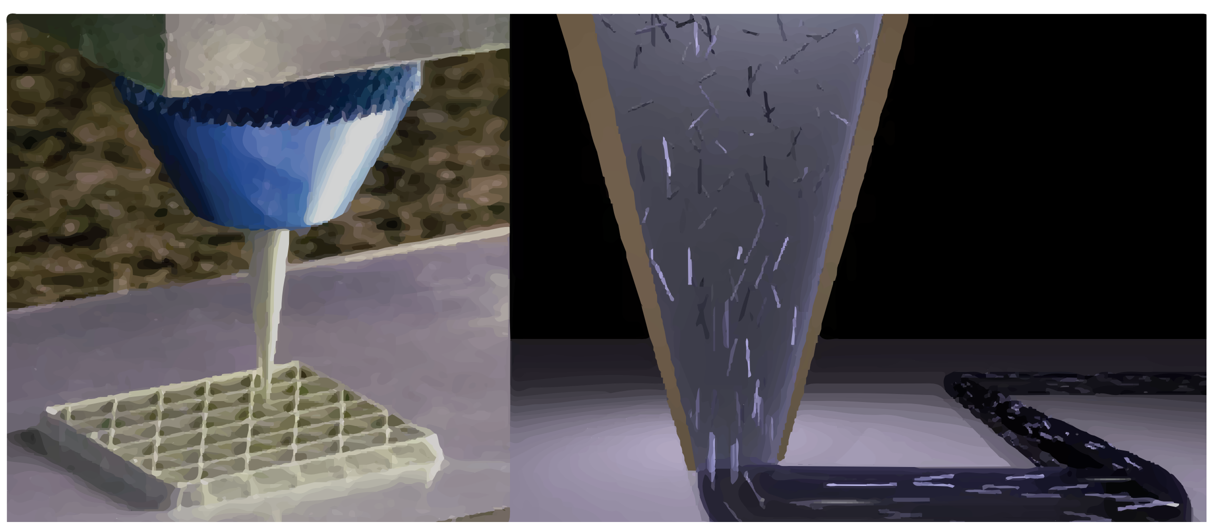
Source: Computer Aided Technology [12]

Emerging Research Areas

3D Printing Composite Materials

One goal for UAV designers is to maximize a UAV's specific strength ("strength-to-weight ratio"). To increase strength, one could simply increase material reinforcement. However, this increase in material weight places an increased load on the battery supply, decreasing flight time. Holding battery density constant, increasing a UAV strength-to-weight ratio entails turning to novel materials.

Composite materials are "made of a matrix and binder, constituents with different physical or chemical properties...when these materials are combined, the new material has different characteristics from the individual components" [15]. 3D printing materials like ABS, PC, PLA, and PA can be reinforced with matrices of carbon fibre, carbon nanotube, and graphene to improve 3D printed UAV part strength-to-weight ratios.

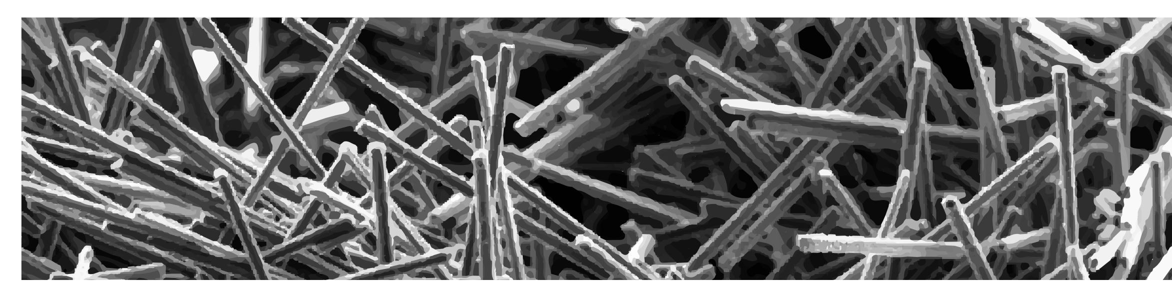


Pictured above: A rendering of composite material printing
Source: New Atlas [14]

Carbon Fiber Reinforced Polymers

"Carbon fiber is made up of aligned strands of carbon atoms that exhibit extremely high strength in tension...when grouped and adhered together using a bonding agent, the fibers distribute load smoothly and form an incredibly strong, light composite material" [16]. A rule of thumb is that "a carbon fiber structure of equal strength to a steel structure will weigh one-fifth the amount of the steel structure" [17]. Carbon fiber reinforced polymers (CFRP) differ from traditional thermoplastics in that they are a combination of thermoplastics and carbon fiber strands, resulting in comparatively higher tensile strengths. The carbon fiber strands can either be chopped into short segments or embedded as continuous strands, with the latter offering more strength and reliability [18].

The use of CFRP can increase strength-to-weight ratios in 3D printed UAV parts, allowing for increased performance and capabilities. Currently, the easiest way to 3D print CFRP is FDM [19]. CFRP filament is abrasive and prone to clogging, which can be managed with hardened steel or ruby nozzles, higher printing temperatures, and slower printing speeds [19]. CFRP is electrically conductive, which can result in part degradation over time if exposed to electrical currents. This degradation can be monitored through electrical impedance topography, allowing for users to remain aware of any part failures [20].



Pictured above: A rendered close-up of carbon fiber chopped into short strands
Source: Markforged [16]

Emerging Research Areas

Batteries and Electrical Components

Other UAV parts may become more easily printable as research on 3D printing materials and techniques matures. Areas of interest include 3D printing as a fabrication technique for batteries and electrical components used to operate the UAV. Several research groups have published articles on advances in 3D printing batteries and electrical components that can stand as pilot examples for UAV components that may be more easily printable in the future.

Carnegie Mellon University
3D Printing Microlattice Battery Structures

Researchers at Carnegie Mellon University have found that 3D printing can be used to microlattice electrode architectures that create efficient porous electrodes for lithium-ion batteries. Currently, printed batteries provide orders of magnitude less energy density than traditional batteries [21]. One method for reducing the gap between printed and traditional batteries is through 3D microlattice structures with a hierarchical porosity. The hierarchical porosity prevents electrical disconnections from occurring by providing for effective mechanical stress relief during charge/discharge cycles. Put simply, microlattice structures could theoretically allow for ultra-dense batteries, and by optimizing the distribution of stress through 3D printing, the technology is one step closer to improving ultra-dense battery viability.

This area of research is not yet mature enough for commercial distribution, as “a scalable and repeatable manufacturing process that can control porosity for a wide range of battery materials remains a significant challenge” [21]. However, this research offers insight into what the future of UAV fabrication might look like. Improvements in energy storage and battery density dovetail UAV innovation, as both can contribute to improved strength-to-weight ratios and performance.

Harvard University
3D Printing Embedded Electronics

Voxel8, a Boston startup founded in 2014 out of the Lewis Research Lab at Harvard University, initially found their market fit by producing a 3D printer capable of printing functional circuits to embed electronic components into parts. The team found the design freedom offered by 3D printing to be constrained by the need to design around existing off-the-shelf electronic components. Eliminating this design constraint would allow for users to have unconstrained design flexibility, but would require a cost-competitive solution. Voxel8 leveraged more than 10 years of materials science research produced out of the Lewis Research Lab to commercialize a 3D printer capable of switching between printing circuits with a pneumatic ink dispenser and printing thermoplastic filament.

Voxel8’s founders kit includes a UAV design with 3D printed “exterior body, internal wiring, and embedded components” [24]. This evidences a potential future development in 3D printing UAVs. 3D printing electronic components embedded in UAVs yields an increase in design flexibility, which can in turn allow for increasingly novel aerodynamic designs.

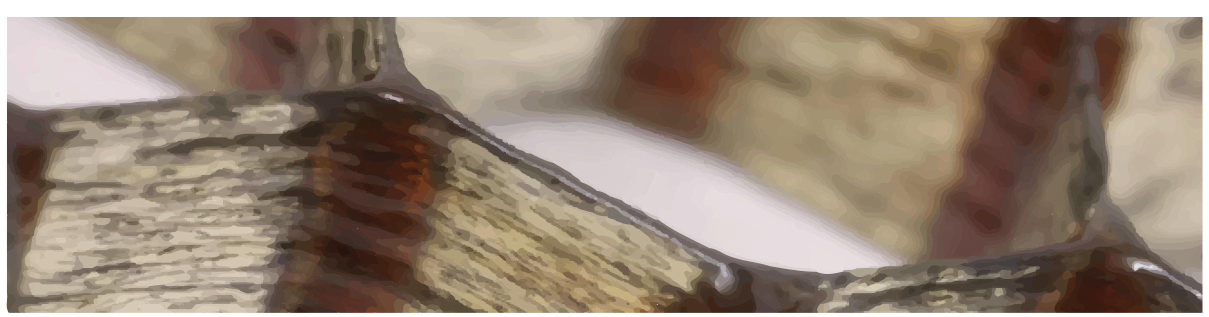
Source: Voxel8 [22]

Conclusion

Looking to the horizon, the UAV innovation ceiling continues to rise as research on UAV materiality and fabrication matures for a spectrum of user groups to benefit from in their own practices. Research on 3D printing as a fabrication process for UAV parts continues to develop, bringing particular value to user groups printing parts with complex geometries, in low-volume batches, and/or with rapid design cycles. These technical advances offer opportunity for further intersectional applications between 3D printing and UAVs.

Systemic influences will also play a significant role in which intersectional applications will mature. In particular, regulatory structures surrounding UAVs are still taking shape and are important to monitor. Once established, these international standards may play an important role in determining which fabrication methods can be used to meet UAV quality control standards.

Incentives to develop efficient fabrication methods and high performance materials for UAVs will help drive the technology forward, and 3D printing offers cost-accessible rapid design cycles of efficient geometries that will help propel UAVs past innovation ceilings.



Pictured above: A new 3D-printed composite material developed at Harvard University that surpasses the lightness and stiffness of balsa wood

Source: New Atlas [14]

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