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3 NOMENCLATURE

RMS	Rapid Manufacturing System
FDM	Fused Deposition Modeling
LOHAN	Low Orbit Helium Assisted Navigator
SULSA	Southampton University Laser Sintered Aircraft
GPS	Global Position System
VAST	Variable Airspeed Telescoping
MIT	Massachusetts Institute of Technology

4 INTRODUCTION

The state of the art is the result of bibliographic referencing of 3D printed parts for UAV applications. This result is the enumeration, description and conclusions of the interesting references used in this study.

This document includes footnote links, which mainly consist in videos of the manufacturing processes and personal opinions of RMS skilled engineers and designers. The conclusions of the state-of-the-art have been extremely useful for the aim of this study, since the knowledge of existing 3D printed UAV features has been used as a starting point of the project.

5 EXISTING 3D PRINTED UAV

The references have been selected by aerospace application. The information have been purged to remove unreal properties, counterfeiting and advertising.

State-of-the-art researching has been done on 3D printing forums, Universities websites and technology news. Since references has been worldwide located, this study has contacted the authors of the references by e-mail to contrast the information. According to this, the referenced features of this models have not been checked in situ.

5.1 VULTURE 2

Vulture 2 is the Low Orbit Helium Assisted Navigator (LOHAN) turned to 3D printing (1). This rocket have been composed by a rocket motor and an autopilot system. It will be released into the edge Earth's atmosphere carried up with a Helium weather balloon and its Global Position System (GPS) will guide it to a desired landing site.

The rocket has been designed by postgraduate students from the University of Southampton with the supervision of Professor Jim Scanlan. The prototype has been realized using crafted Southampton University Laser Sintered Aircraft (SULSA) as the basis and UK 3D Printing service firm 3T RPD¹ collaborates in the process of printing the plane. The SULSA team has used plastic Additive Manufacturing (AM) and nylon Selective Laser Sintering services of 3T for the rocket manufacture. The four parts of the plane simply clipped together to form an UAV with a 1.2m wingspan.

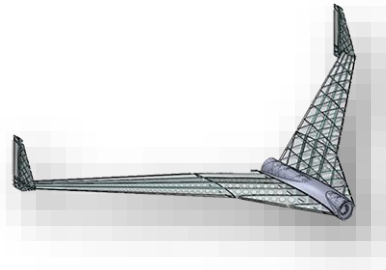


Figure 1 VULTURE 2 render (1)

CAD design drawings created by SULSA (see Figure 1), were sent to 3T's team of CAD Engineers who incorporated the snap fittings required to hold the 4 nylon parts together to form the overall aircraft. They also designed mountings and channels to hold the 10 internal components, enabling the motor, battery, avionics and controls to be clipped into place inside the main fuselage, and two servos, one in each wing.

VULTURE 2 concept is interesting for this study because all of these features were incorporated into the aircraft's design and the ability of plastic AM to create hinge features and clips meant that they were built as integral parts to the main components, thereby increasing their functionality and reducing the need for additional parts to be fitted post-build. No screws or other mechanical fasteners were used in the design at all.

¹ 3T RPD Ltd is an Additive Manufacturing UK Company. See: <http://www.3trpd.co.uk/>

5.2 SULSA

Led by Andy Keane and Jim Scanlan of the University of Southampton, SULSA team manufactured the first 100% 3D printed UAV in 2011. It was a 1.2 m wingspan model.

Wing were a RMS powerful demonstration. The Super marine Spitfire, see Figure 2, was among the most maneuverable fighter aircraft of the Second World War because its wings were of an ultra-low-drag elliptical design. But it was a nightmare to produce, requiring complex machinery and production expertise. SULSA demonstrated that with 3D printing they could go back to pure forms and explore the mathematics of airflow without being forced to put in straight lines to keep costs down.

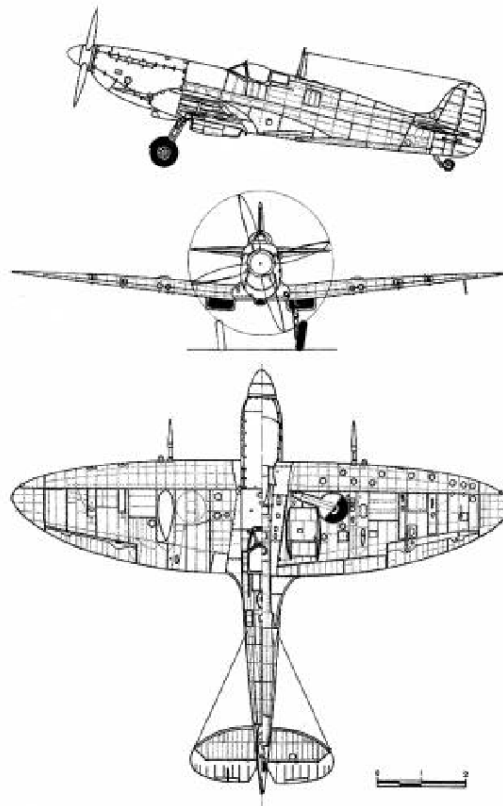


Figure 2: Super Marine Spitfire (2)

SULSA manufacturing process: the 3D printer first slices up an object's computerized design into hundreds of easily printable layers. Each layer is then "printed" by training a laser beam on a bed of polyamide plastic, stainless steel or titanium powder –

depending on the object being created – tracing out the entire 2D shape required for that layer. The laser's heat fuses the particles together at their boundaries. Once each layer is complete, more powder is scattered over it and the process repeated until a complete UAV is produced. What the printer spits out is a powdery "cake" from which the desired object can be retrieved simply by pulling it out.

A UK-based 3D-printing firm, 3T RPD of Greenham Common, Berkshire, joined the venture, agreeing to print the UAV out of hard nylon.

The budget for the Southampton University Laser Sintered Aircraft (SULSA) was 6.000,00 €, which imposed a number of design constraints. The aircraft would have no undercarriage to keep complexity and weight down, necessitating the use of a launch catapult – and a belly landing. It would be electric-motor-powered to eliminate the need for starting equipment and heavy fuel. And it would have a V-shaped tail rather than the usual upside-down-T, so that only two parts had to be printed instead of three.



Figure 3: SULSA 100% 3D printed UAV (2)

SULSA, see Figure 3, is an interesting reference for this study because this model is focused on demonstrates 3D printing aeronautical applications. This model wingspan and length are similar dimensions and proportions to CATUAV models.

5.3 2SEAS

The latest European iteration of the EU-commissioned 3D printed UAV is called 2SEAS (see Figure 4), which will eventually patrol the English Channel and the North Sea, it will be assisting the coast guard, police and other authorities in the UK, Netherlands, Belgium and France in illegal fishing, drug-boats and monitoring general risks to shipping.



Figure 4 2SEAS flight operation (2)

2SEAS, like previous reference SULSA, has been created by University of Southampton aeronautical engineers Jim Scanlan and Andy Keane. It has a large 4 meter wingspan and is capable of flying as long as 5 hours at 100km/h. The wings and the tail are made out of carbon fiber, but the central wing box, fuel tank and engine mounting are all manufactured using 3D printing tech.

This reference is interesting for the study because uses a hybrid technology between composites and 3D Printing. It shows that RMS will not be able to improve all parts and the optimum system could include composite standardized element.

5.4 PTERA

SOLID CONCEPT² has printed the smallest jumbo jet, Boeing 737, in collaboration with Area-I³. During the week of July 16-19th, 2012, Area-I carried out the initial evaluation flights of its Prototype Technology Evaluation Research Aircraft (PTERA) under NASA contract. All flights were performed with Middle Georgia College at the Heart of Georgia Regional Airport in Eastman, GA under FAA Certificate of Authorization 2012-ESA-38.

PTERA (see Figure 5) uses a variety of 3D printed parts for its control surfaces as well as unique ducting in the circulation control variant airframe. The RMS used in this model is the Selective Laser Sintering (SLS).



Figure 5 PTERA take-off operation (3)

This reference is interesting for this study because it shows how 3D printers have changed the aeronautical industry, since any University, Engineering Office or Manufacturing Company can transport ideas to the real world. The rapid, easy and low cost manufacturing technology is able to allow a UAV Market explosion since there are many undiscovered ways in which additive manufacturing can help in manufacturing aircraft parts.

² SOLID CONCEPT is a Rapid Prototyping Company. See: <http://www.solidconcepts.com/>

³ AREA-I is an aeronautical UAV designer Company. See: <http://areai.aero/>

5.5 MAAX

The MAAX (see Figure 6) is a two-stroke powered UAV with 10 hours endurance and 9 Kg payload capabilities. Designed for being used by state/federal agencies, military, and universities needing a platform for ISR missions and experimental payloads. The modular nose payload section can house Electro Optical/Infrared (EO/IR) payloads. This device has been manufactured by UAV SOLUTIONS⁴ using Stratasys 3D Printers.



Figure 6 MAAX evaluation flight (4)

MAAX product reference is interesting for this study due to the dimensions and the supported payload. With 2,13m length and 4,88m wingspan and 9Kg of maximum payload weight, it clearly demonstrates the existence of large UAV models manufactured by RMS.

⁴ UAV SOLUTIONS is a rapid manufacturing and design of unmanned systems Company. See: <http://uav-solutions.com/>

5.6 3D Printed hover Ornithopter

This project currently focuses on developing a flapping-wing hovering insect using 3D printed wings and mechanical parts. An ornithopter with a mass of 3.89 g has been constructed using the 3D printing technique and has demonstrated an 85-second passively stable untethered hovering flight. See Figure 7.



Figure 7 Ornithopter (5)

Hovering insect flight exhibits the functional utility of printed materials for flapping wing experimentation and ornithopter construction and for understanding the mechanical principles underlying insect flight and control. Several previous results from this reference include evolved flapping patterns for a hovering ornithopter and a record-setting flight of the first passively stable untethered hovering ornithopter.

The point of this reference is to show that the use of 3D printing technology has greatly expanded the possibilities for wing design, allowing wing shapes to replicate those of real insects or virtually any other shape. It has also reduced the time of a wing design cycle to a matter of minutes.

5.7 TORNADO fighter jet 3D printed metal part

BAE Systems⁵ engineers have created and flown a 3D printed metal part, camera bracket, for the first time on-board a Tornado fighter jet, paving the way for using 3D printed parts in other military kit. See Figure 8.



Figure 8 TORNADO fighter jet (6)

This UK Company also have engineers designing and producing 3D printed functional components at RAF Marham to support the aircraft when it is being maintained on the ground. The parts are made of a plastic material and include protective covers for Tornado cockpit radios, support struts on the air intake door and protective guards for Power Take-off shafts. BAE Systems estimates that the use of these parts will cut the cost of repairs, maintenance and service to the Royal Air Force since some of the parts costs less than 121.33 € for piece to manufacture.

⁵ BAE Systems is a worldwide UK global defence, aerospace, naval and security company. See: http://www.baesystems.com/home?_afrLoop=631862490323000

5.8 AMRC & BOEING

University of Sheffield's Advanced Manufacturing Research Centre (AMRC) engineers have developed an unmanned aerial vehicle using rapid prototyping technology, with the support of Boeing's Design & Prototyping Group. See Figure 9.

RMS used have been the fused deposition modelling (FDM) technology. Material and 3D printer used have been ABS plastic on a Stratasys Fortus 900mc. ARMC model consists of only 9 parts: 2 wings, 2 elevons, 2 spars, 2 wing end fences and a central spine.



Figure 9: AMRC UAV model (7)

This is an interesting reference for this study since this UAV has similar features to CATUAV models. The 1.5 m wingspan UAV weighs near 2Kg and has been printed in less than 24 hours without any material support.

5.9 NASA Mars Rover

The Rover is integral to NASA's mission to extend human reach farther into space. Even though it is not a UAV, it also has some features pretty interesting for this study. Its cabin can accommodate two astronauts for days as they study extraterrestrial surfaces. Its twelve rugged wheels on six axles grapple over irregular, unsure terrain. And its forward-jutting cockpit can tilt down to place its observation bubble low to the ground. See Figure 10.



Figure 10: NASA Mars Rover (8)

NASA engineers have printed about 70 Rover parts directly from computer designs, in the heated chamber of a production-grade Stratasys⁶ 3D Printer. RMS used have been a Fused Deposition Modeling (FDM) and ABS material.

The interest of this reference is not the Mars Rover but the Stratasys Patents. A Stratasys 3D printing Patent Search⁷ have found 433 related results. It means that this study will must be sensible to 3D Printer systems Patents, intellectual properties and author rights.

⁶ STRATASYS is a USA 3D printers Company. See: <http://www.stratasys.com>

⁷ Espacenet is a Web site for Patents Search. See: <http://worldwide.espacenet.com>

5.10 RDASS 4

Designed by Leptron⁸, RDASS 4 (See Figure 11) is a UAV that weighs only 2.27 Kg. Its four battery-powered electric motors enable it to hover at 30.5 m altitude with a 800 m line of sight. The device carries a wide range of cameras and other electronic equipment.



Figure 11: RDASS 4 (Leptron Web site)

Leptron uses an FDM 3D Printer system to build end use parts for the RDASS 4. The core components take 48 hours to print while smaller components average six hours. The printed parts are suitable for form and fit evaluation, functional testing and end use parts.

RDASS 4 has been an interesting reference for this study because it shows the importance of the print speed in the manufacturing technology. Therefore, the duration time of printing phase shall be taken into account when assessing the viability and feasibility of CATUAV RMS.

⁸ Leptron is a leader in remotely piloted helicopters focusing on law enforcement, military and civilian uses. See: <https://www.leptron.com/corporate/products/rdass4/specs.php>

5.11 *Select Tech Geospatial*

SelectTech Geospatial⁹ has proved that an innovative company could make a UAS (See Figure 12) quickly and with limited resources. This side project succeeded without funding or the expertise of aeronautical engineers. Executive Director Frank Beafore relied on a trial-and-error approach, learning from each iteration. The Used Manufacturing process has been FDM 3D printing, to avoid tooling.



Figure 12: Select Tech Geospatial UAS flight test. (9)

SelectTech have used a trial-and-error approaching method, since they were not skilled designers in the aeronautic field. They started designing a 1.21m wingspan wing by printing an airfoil shape with the thinnest skin possible. Next step was an evaluation test that showed buckling issues. Therefore they had to introduce tubular spars as reinforcements, see Figure 13, and continue the process until the UAS flew.

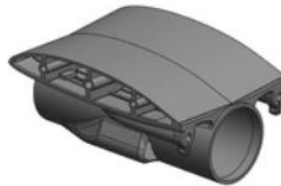


Figure 13: Select Tech UAS wing to fuselage part design. (8)

The interest of this reference are the new opportunities offered by RMS. SelectTech have used the commercial side of RMS, since it is clear that a new UAS was secondary to demonstrating what is possible with 3D printing: to show its clients that a complex product could be made, tested and manufactured without the overhead of computer simulation and wind-tunnel testing.

⁹ SelectTech Geospatial is home to the Dayton Regions' Advanced Manufacturing Facility, located at the Springfield Beckley Municipal/Air National Guard airport in Springfield, OH. See: <http://www.sgamf.com/>

5.12 VAST AUAV

Variable Airspeed Telescoping (VAST) Additive UAV is a prototype designed and RMS manufactured in Massachusetts Institute of Technology (MIT) Lincoln Laboratory. This project has been sponsored by the U.S. Air Force under contract and in collaboration with 3D IMAGING.

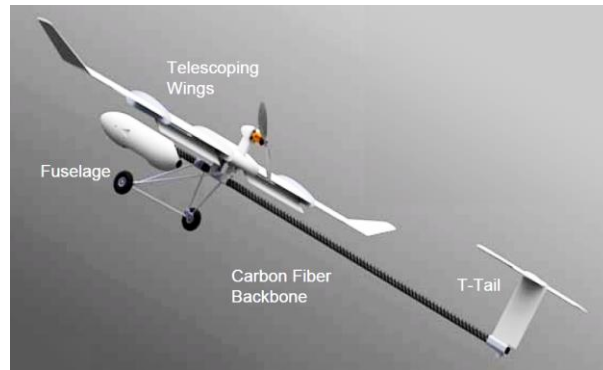


Figure 14: VAST AUAV Described parts view (10)

VAST AUAV was made by RMS, FDM on a Stratasys Fortus 400mc. Structure was primarily FDM except for a carbon fiber backbone that all the parts (see Figure 14) were attached to. Designed to be highly modular, the aircraft was essentially 3 reconfigurable pieces: the fuselage pod on the front with the avionics and batteries, the wings (see Figure 15), and the empennage. To adjust the CG for different payloads you could move all the parts around until you balanced and had the stability margin you needed.

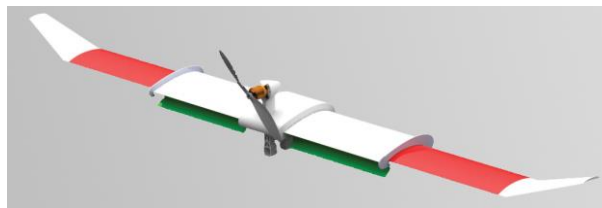


Figure 15: Telescoping Wing design (10)

Wings were printed without support material and with an internal structure designed to support required load. Incorporated carbon fiber spars which doubled the strength to weight ratio.

Parameter	Configuration	Value	Units
Wing Span	Extended	2,03	m
	Retracted	1,42	m
Wing Area	Extended	0,3245	m ²
	Retracted	0,2361	m ²
Stall speed		3,13	m/s
Maximum speed		26,8	m/s
Weight		3,175	Kg
Battery		2x5400	mA/h
		11,1	V
Motor	(Brushless)	300	W
Endurance	(best cruise)	1	Hour

Table 1: VAST AUAV Parameters (10)

This reference is interesting because it shows that major institutions like MIT have private and government support to develop new manufacturing systems like VAST AUAVs designed in June 11, 2013, a year ago. Thereby, this study has been focused on a topic of the current worldwide research.

5.13 WENDY

Wendy is a 3D printed UAV designed and manufactured by Steve Eastern and Jonathan Turman, University of Virginia engineering students. The MITRE Corporation, a McLean-based federally funded research and development center, sent them a job announcement: to build over the summer an unmanned aerial vehicle, using 3-D printing technology. In other words, a plastic plane, to be designed, fabricated, built and test-flown between May and August. A real-world engineering challenge, and part of a Department of the Army project to study the feasibility of using such planes.

Wendy is a standard aircraft configuration with FDM structure made of ABS material. It is made of assembled parts "printed" to achieve a 2m wingspan model. In its test flight reached a cruising speed of 72.4 km / h. See Figure 16.

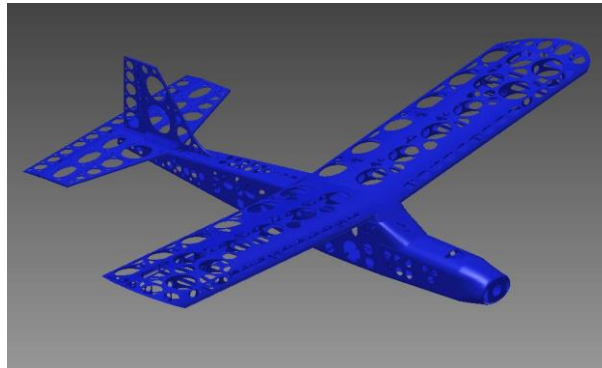


Figure 16: Wendy 3D printed UAV (11)

The main point of this reference is the feasibility of 3D printing technology in the real world of engineering. Wendy was a successful path between University and industry due to the knowledge of a new technology Manufacture with real interest.

6 CONCLUSIONS

The stat-of-the-art shows the feasibility of the RMS for UAV applications. There is a wide range of UAV models manufactured with this technology, but only four flight-tested. The main conclusions have been the followings:

- 3D printing is a present-day starting technology.
- The result does not depend directly on the economic investment.
- Designer knowledge and configurable 3D printer are key factors.
- Parts joining and assembly is required for UAV application.
- Recyclable material is a good selection; biodegradable and excellent one.
- 3D printing technology is specializing in specific applications.

Table 2 shows the references that have been designed, 3D printed and flight-tested. The selected references have been developed by recognized Universities with a private and/or governmental support. The manufacturing system has been the fused deposition method and the weight range between 2kg and 4kg. Therefore this technology shows a poor lightweight performance compared with standard UAV technologies.

UAV	University	Sponsor	Year	Manufacturing System	Weight	Wingspan
					[g]	[mm]
SULSA	Southampton	3T RPD LTD	2011	FDM	3000	1200
WENDY	Virginia	MITRE	2012	FDM	-	1981
VAST AUAV	MIT	USA AIR FORCE	2013	FDM	3175	2032
ARMC	Sheffield	BOEING	2014	FDM	2000	1500

Table 2: Flight tested 3D printed UAV references

During the researching process, new attractive ways for using RMS have been found. This study has taken into account these extra applications in order to increase the feasibility of the UAV day-to-day requirements.

The future plans, according to the references, of the 3D printing designers and engineers will be:

- Include UAV control by surface morphing technology.
- Eliminate the use of support material in parts printing.
- Oversize the available printing volume of joining methods.
- Improve printing speed.
- Add new materials.
- Improve accuracy.

This references and conclusions will be taken into account for next stages.

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Santpedor
June 2th, 2014

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