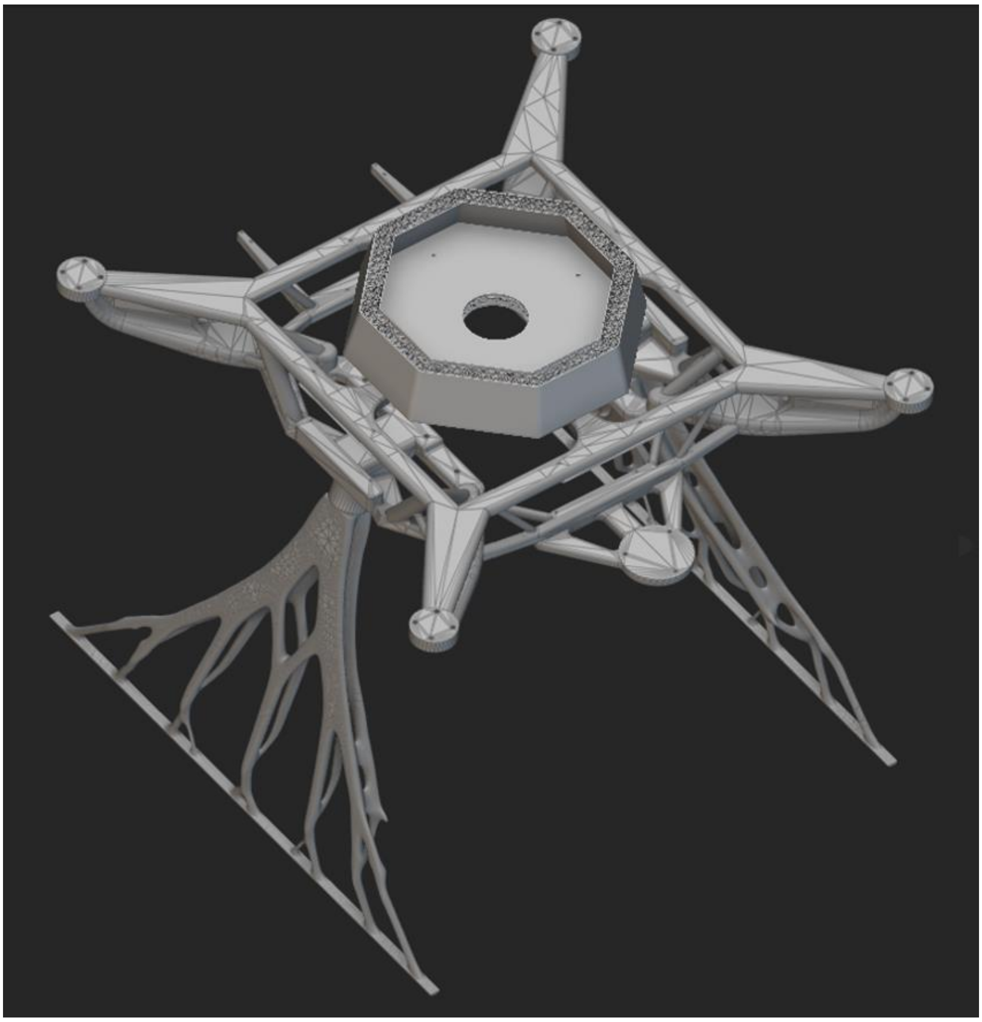
SME Digital Manufacturing Challenge 2024

Structure Design and Optimization of Agriculture Duty Drone based on Additive Manufacturing



University of Waterloo   Mechanical and Mechatronics Engineering

Project team

B.Eng. Xianchen Ouyang
Graduate student
x7ouyang@uwaterloo.ca

B.A.Sc. Lubin Wang
Graduate student
l273wang@uwaterloo.ca

Advisor

Prof. Mihaela Vlase
Professor
mihaela.vlasea@uwaterloo.ca

Contents

1. Executive Summary

In recent years, with the rapid development of remote sensing and control technology, various Unmanned aerial vehicles (UAVs) have been widely used in agricultural scenarios. Large drones can undertake large-scale seed sowing and pesticide spraying in areas where ground equipment and manpower are difficult to operate. The introduction of UAV technology has reduced the work intensity of farmers to a certain extent and improved crop production efficiency. In precision agriculture, UAVs are used to monitor agricultural environments. UAVs can be used to effectively monitor crop growth conditions, diseases and insect pests to ensure crop quality [1], [2]. Therefore, improving the performance of existing agricultural drones will have a positive impact on ensuring agricultural safety.

Designing highly integrated lightweight UAV structures can improve the load ratio or endurance of the drone, which is an important way to optimize the drone system. Due to its unique manufacturing principles, additive manufacturing (AM) makes it possible to manufacture complex lightweight structures. The use of additive manufacturing technologies to manufacture highly integrated lightweight agricultural drones has huge application potential.

This project focused on the structural design of a quadcopter UAV platform for spraying pesticides or for crop monitoring in precision agriculture. The materials and manufacturing processes are determined based on AM principles. Based on functional and performance requirements, the structure of the drone is designed and optimized by topology optimization and lattice optimization. In the end, digital and physical infrastructure and cost analysis are applied to evaluate the final design.

2. Industry Overview

Multi-rotor UAVs are the mainly used configurations for precision agriculture drones, including quadcopters, hexacopters, and octocopters. The design and construction of these UAVs have their own characteristics, and each has its own strengths in different mission scenarios. Quadcopter UAVs are favored for their unique geometry and good flight stability, the rotors of a quadcopter drone provide four upward lifting forces. Four motors provide the power, with two opposing suspects of the four rotors turning clockwise and the other two rotors turning counterclockwise. The force adjustment of the four rotors allows for maneuvers such as pitch angle and traverse roll [2].

Conventional agriculture quadcopter shares a similar structure with all other quadcopter drones, while having a higher requirement on the loading capability for storage tanks and sprays based on use-case scenario. At the same time, the drone being designed should also keep the power unit - motor, adaptable batteries, flight controller, navigation systems, and monitoring camera devices loaded on its drone body. Under this condition, a conventional solution would need mounting brackets, a large number of screws, nuts, and connectors that may consist of different materials for assembly and installation. These would add unnecessary weight to the drone body that doesn't contribute to its mechanical performance. Conventional manufacturing methods are also limited in terms of design flexibility. In contrast, additive manufacturing offers a high degree of geometric freedom. When considering the demand for adjustment based on mission, traditional manufacturing methods are less adaptable to customization and often require multiple parts to be manufactured separately and then assembled, which can increase the cost and inefficiency. Another problem that exists is assembly of drones requires a lot of time and assembly skills, which hampers their application in many fields. Therefore, there is a need to develop a lightweight quadcopter structure with a minimum number of parts, and enhanced structure to achieve a higher thrust-to-weight ratio by low weight and reliable strength.

In the field of aerospace manufacturing, several AM technologies have been utilized for fabricating UAV structures, including fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), and selective laser melting (SLM) [3]. This process involves utilizing the principle of Design for Additive Manufacturing (DfAM) for the design and manufacturing process of components or whole drone structures. Taking advantage of AM, topology optimization and lattice structures are widely used to improve load ratio and optimize structural dynamic performance [4], [5], [6], [7], [8], [9], [10], [11].

3. Design, Functionality and Durability

3.1 Function and Performance Objectives

The key accessories on drone assembly include batteries, a navigation device, and a PTZ (Pan–tilt–zoom) camera. An electronic device container is installed on the drone body. The weights of these accessories are used for load case analysis. The information and the weights of these key accessories are listed in Table 1.

Table 1. Accessories information and weight table.

Battery	Electronic device container	Navigation device	PTZ camera
654g	500g	34g	300g

For the whole drone assembly, its structure needs to be able to withstand the loads in different moving states (accelerating, steady state, decelerating, turning, etc.) and falling or impacts during landing. The flight conditions of the drone are listed in Table 2.

Table 2. The flight conditions of the drone

Flight condition	Acceleration(X)	Acceleration(Y)	Acceleration(Z)
Climb	0	0	0.5g
Landing	0	0	0
Forward flight	0	gsinα	-gcosα
Back flight	0	-gsinα	-gcosα
Left flight	-gsinα	0	-gcosα
Right flight	gsinα	0	-gcosα

* The value of α can be set in the flight controller, usually 5°-10°.

Based on the flight conditions, the load cases of the drone body during take-off and impact in the landing process are listed in Table 3.

Table 3. The main load/force details on the drone body for optimization criterion.

Take-off status with the acceleration of 0.5g		
Loads/forces	**Magnitude (N)**	**Direction**
Lifting force	165(total)	straight up
Load from batteries	39(total)	straight down
Load from electronic device container	7.5(total)	straight down
Load from PTZ	4.5(total)	straight down
Load from navigation device	1.5(total)	straight down
Falling status with an instantaneous speed of 3m/s		
Loads/forces	**Magnitude (N)**	**Direction**
Impacting force	176 (total)	straight up

*The calculation of impacting force is based on the assumption of a uniform downward speed of 3m/s and a contact time of 0.2s.

Besides the performance requirements for load cases, the objective for the lightweight is a total weight of the drone body less than 17% maximum take-off weight of the entire drone (<1.9kg). At the same time, the center of gravity of the drone body needs to be as close as to the center of the drone. Other requirements include a highly integrated drone body structure with acceptable assembly performance and manufacturability for SLS.

In addition, electronic devices that are sensitive to vibration, including the flight controller, receiver, and sensors need to be prevented from moving and vibration during the operation process, as well as the isolation of impact and vibration. The components used for housing such electronic devices need to be designed with the function of isolation from impact and vibration. Such assemblies must possesses energy absorption and shock-damping characteristics [12].

3.2 Structural Design and Optimization

The overall basic design parameters are determined by function and performance requirements, as well as the principles of UAV structural design. To meet the requirement of 11kg maximum take-off weight, while maintaining enough thrust-to-weight ratio (>1.8), the 5010 brushless DC motors and 17-inch propellers are selected for the design. Considering the installation location of electronic components and the propeller diameter, the wheelbase of the drone is 651mm. To ensure that there is enough space for agricultural equipment to be installed, the overall height of the drone is 441.5mm.

nTop is utilized for the drone body's topology optimization and finite element simulation based on the mechanical properties of PA11-CF for SLS. Using topology with design and manufacturing constraints, the spatial distribution of the material can be obtained and the results of topology optimizations are used as the references for iterative designs in Solidworks 2023. The final design of the drone is based on the geometric features from topology optimizations. The lattice structures for the design are also analyzed and generated in nTop.

Uni-body drone body

To ensure that the UAV design maintains a high level of integration, many structures used to install various equipment are integrated into the integrated fuselage. Due to the large number of equipment installed, several topology optimization processes are applied to obtain a more proper design space for the final topology. The workflow of the topology optimizations for the drone body is shown in Figure 1.

The topology optimization constraints for the uni-body drone body include a planar symmetry constraint for the whole structure, a mass fraction of less than 30% and displacement constraints for different geometry structures. To ensure the stability of flight motion, the displacements of four arms are restricted to less than 2mm. For the area installing the navigation device, the displacement constraint is set to be less than 0.1mm to minimize the impact of vibration on positioning. For the remaining structures of device installation, the displacement should be restricted to 0.5mm.

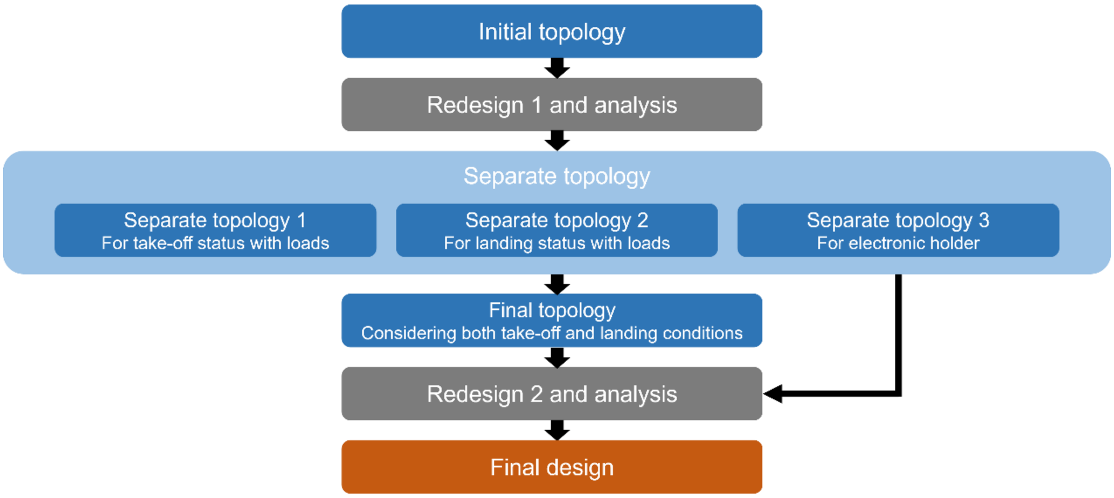


Figure 1. The topology optimization and validation iterations to determine the final design domain.

The design domain for final topology optimization contains all the key geometries for the function and performance requirements, which are shown in Figure 2. These geometric features are preserved in the topology optimization. The optimization result is illustrated in Figure 2.

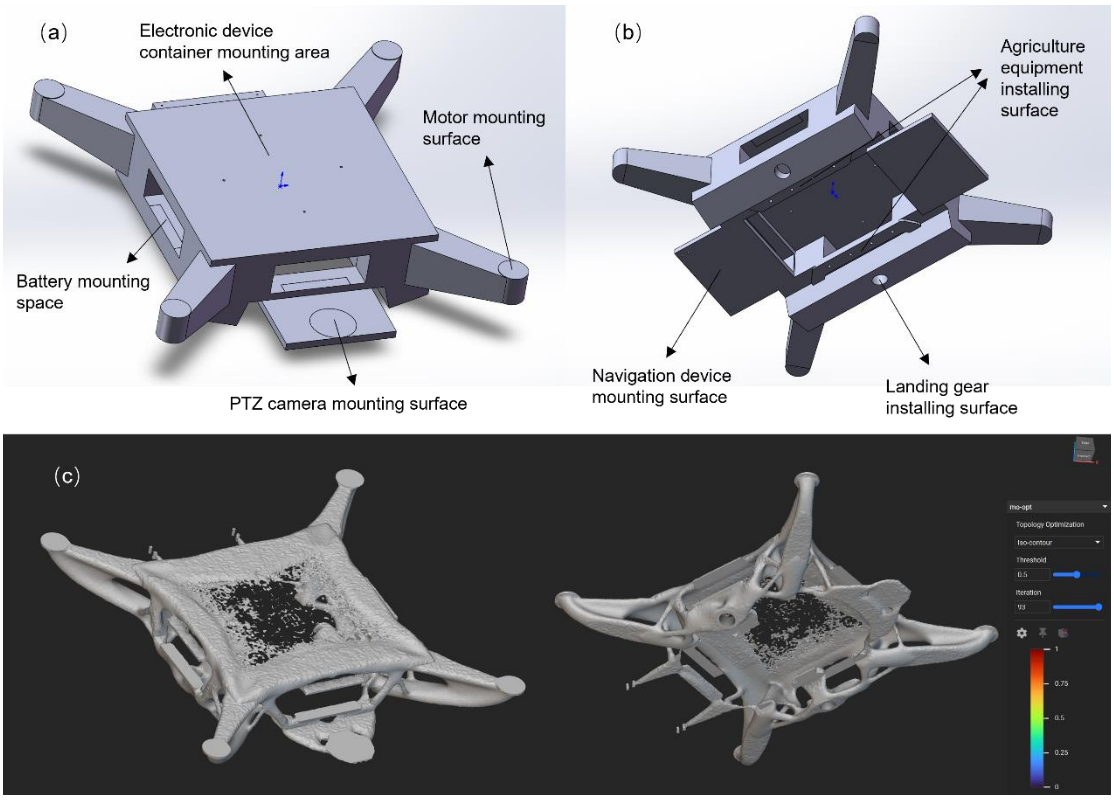


Figure 2. (a) and (b) The locations of necessary geometric features for assembling. (c)The result of the final topology optimization.

The optimized result is redesigned in Solidworks. The structure is modified in a more simplified geometry which contains features suitable for SLS printing. The redesigned structure is validated in nTop and Solidworks. The optimized drone body weighs 1.58 kg, which meets the lightweight objective (<1.9kg). The center of mass of the drone body is close to the geometry center, which is suitable for maintaining a proper flight status. Figure 3 presents the stress analysis in the take-off status and falling status. The maximum stress of 10MPa in two statuses is below 23MPa (maximum allowable stress with a factor of safety 2).

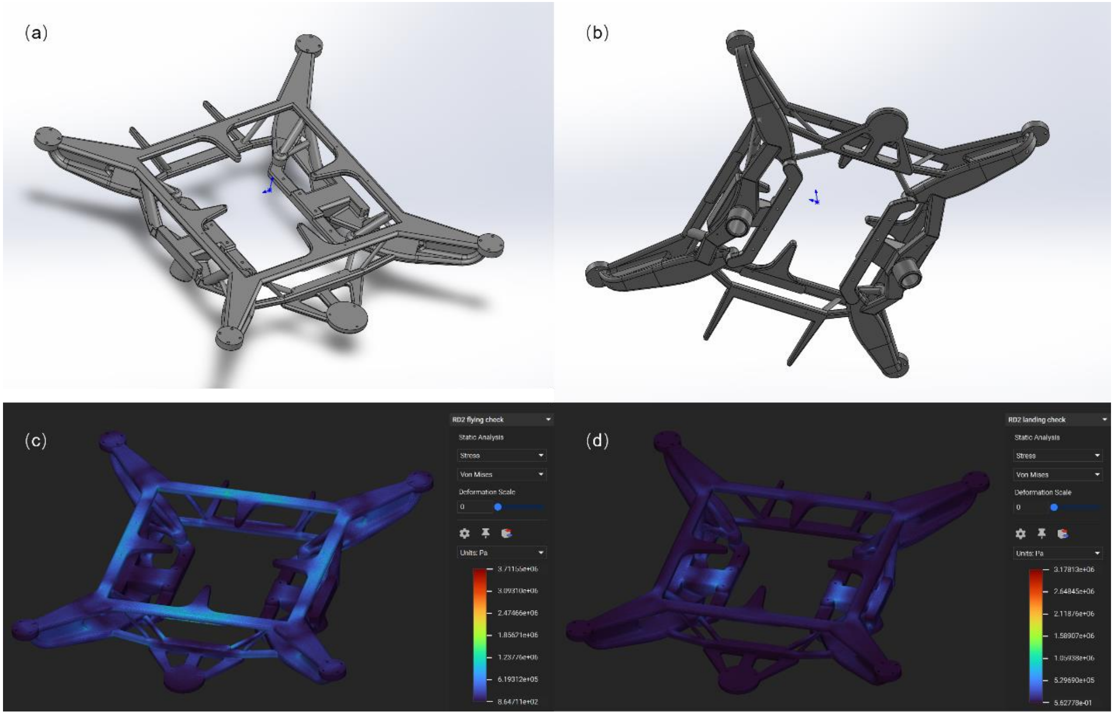


Figure 3. (a) and (b) The redesign of the uni-body drone body. (c) The finite element simulation result of take-off status. (d) The finite element simulation result of falling status.

Landing gear

The design of the landing gears is based on topology optimization result in falling status. The total impacting force on the landing gears is approximately 176N with a straight-up direction. The initial design domain, the impact force direction and the optimized result are presented in Figure 4. An outside face of a cylindrical shape is preserved as a passive region for mating with the drone body.

As presented in Figure 5 (a) and (b), the optimized landing gear is shelled and latticed based on stress distribution to achieve lighter and more manufacturable structures. The shell thickness is ramped from 1.5 mm to 5 mm for the least stressed area and most stressed areas. Gyroid lattice structures with varying thickness fill the space between the walls following the stress map. As presented in Figure 5 (c), in falling status, the maximum stress is about 11.2MPa, which is below 23MPa (maximum allowable stress with a factor of safety 2). After applying lattice structures, the weight of one landing gear is reduced from 258g to 203g.

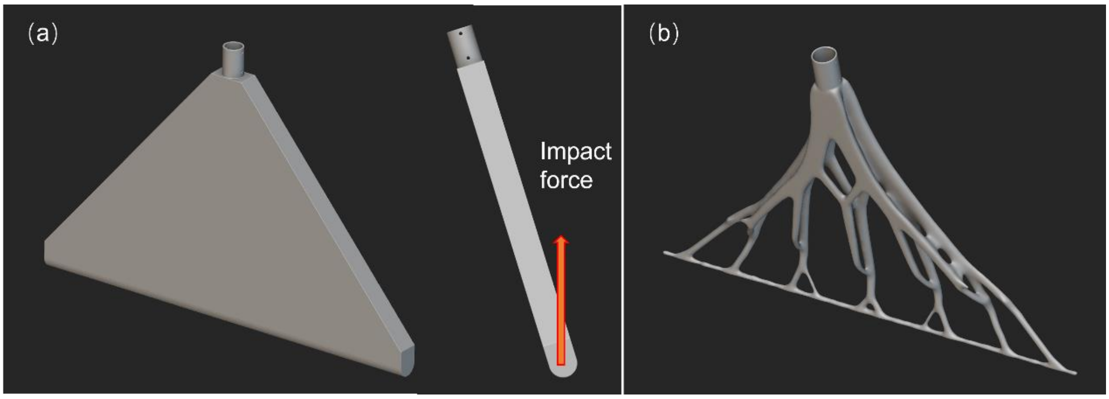


Figure 4. (a) The initial design domain for topology optimization and the direction of impact force on one landing gear. (b) The topology optimization result based on the abovementioned constraints.

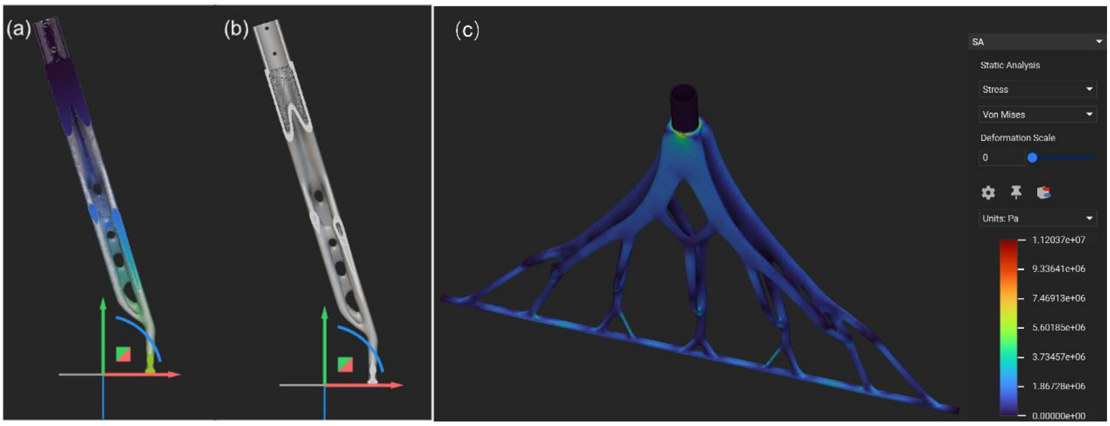


Figure 5. (a) The stress distribution map inside the landing gear. (b) The ramped shell and lattices in the landing gear. (c) The finite element simulation result of optimized landing gear in falling status.

Electronic device container

Lattice structures demonstrate a greater ability to damp vibrations than solid, bulk specimens. This enhanced damping capacity is attributed to amplitude-related internal friction phenomena, primarily occurring at the beam joints and longitudinal beams in the lattice structure [13]. Strut-based lattices are more flexible and have lower Young's modules, which indicate that they will be effective in absorbing low energy of vibration. Considering the purpose of vibrational damping, strut-based lattice could be preferred [14]. The ability of lattices to dampen mechanical vibrations increases with a decrease in volume fraction and an increase in unit cell size, inertial mass, and excitation frequency. This increased vibration damping is linked to higher dissipation of mechanical energy into heat and a shift of the first resonance frequency peak towards lower excitation frequencies [15].

From all strut-based lattice structures available in ntop, Body centered cubic (BCC) lattice is chosen as the damping material. The design for the electronic device container is illustrated in Figure 6. The BCC lattices are generated between the Internal and external layers of the electronic device container with a thickness of 1m and a unit cell size of 7mm.

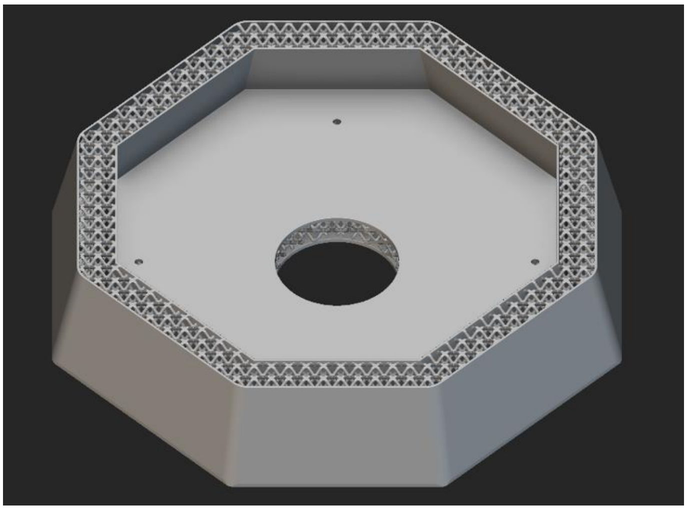


Figure 6. The design of the electronic device container with BCC lattices inside.

Final design assembly

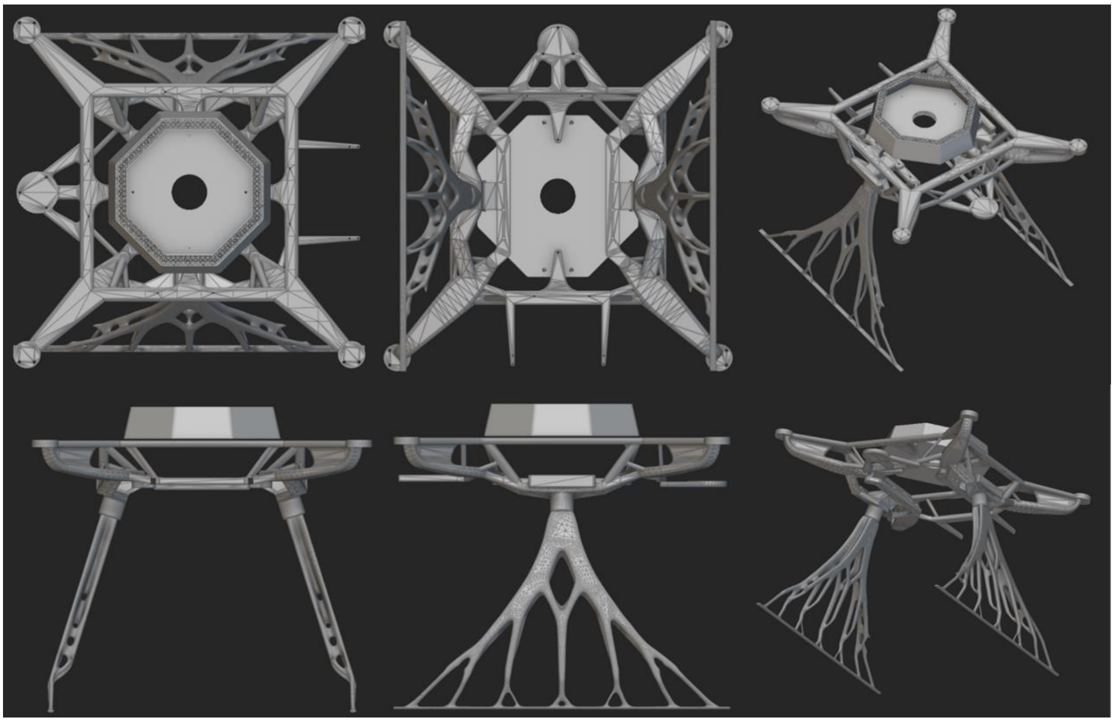


Figure 7. The final assembly of the whole drone.

4. Design Integration and Utilization of DDM Materials and Processes

In this project, Selective Laser Sintering (SLS) is selected for fabricating the UAV components. SLS does not require support structures and this advantage allows for printing intricate designs in one piece. Additionally, SLS is known for its strong interlayer adhesion, imparting near-isotropic mechanical properties to the printed parts, resulting in durable and functional components. The process is also precise and consistent, and the excess powder that isn't sintered can be easily removed and recycled using methods like spraying or sieving, helping to minimize waste and enhance material efficiency [16], [17], [18]. The processes follow the Selective Laser Sintering category according to ISO/ASTM 52900.

The chamber envelope is an important factor to be considered for this drone. The TPM3D S600DL is specifically designed for large printing objects. It features a substantial build area of 590×590×790 and is equipped with a pair of 140-watt lasers [19]. The printer allows the integrated drone body to be printed as a whole body. To achieve higher printing efficiency, the pair of landing gears would still be separated to diminish the height of the object, as well as prevent too much-unused volume. Therefore, the connection between the drone body, and the landing gears is designed to be kept.

Engineering polymers are the most common material in Selective Laser Sintering (SLS) due to their suitable properties for a wide range of applications [20]. Fiber-reinforced composites (FRC) are a type of composite materials that use fiber materials as the reinforcing phase and polymer as the matrix. Due to the characteristics of a high strength-weight ratio, high corrosion resistance, and low density, FRC is often used to replace traditional metal materials in the fields of aerospace manufacturing [21]. Due to the manufacturing principles and characteristics, discontinuous FRCs have been widely used in SLS. The components manufactured by discontinuous FRCs with SLS demonstrate high performance and huge application potential. By comparing different FRC materials, PA11 CF is selected for the design due to the consideration of mechanical properties and prices. More detailed mechanical properties of PA11 CF are listed in Table 4 [22].

Table 4. Mechanical properties of PA11 CF.

Tensile modulus E_{11}=E_{22} (XY)	**Tensile modulus E_{33} (Z)**	**Shear modulus G_{12}**	**Shear modulus G_{13}=G_{23}**	**Poisson's ratio v_{12}**	**Poisson's ratio v_{13}=v_{23}**
2950MPa	1490MPa	1093MPa	532MPa	0.35	0.4

*Due to the layer-by-layer forming characteristics of SLS, PA11 CF exhibits weaker mechanical properties in the forming direction and is isotropic in the forming direction perpendicular to the forming direction.

*Due to limited information, the shear modulus of PA11 CF refers to similar PA materials.

Due to the manufacturing characteristics of additive manufacturing technology, the design of AM products is closely integrated with the selected manufacturing technology itself, compared to traditional manufacturing technology. Thanks to mature digital design and manufacturing software such as nTop, the preliminary design flow and verification simulation of this project can be completed in a computer environment, which greatly reduces the cost of design and verification. At the same time, based on digital design, the model can be designed and optimized more conveniently based on the selected AM technology while taking into account manufacturing constraints, such as the design of lattice structures and topology optimization based on numerical calculations.

5. Digital and Physical Infrastructure: Systems Integration, Utilization, Value Chain Leverage, Agility, Lean and Continuous Improvement

Nowadays, additive manufacturing technology has great potential in mass manufacturing products. Large manufacturing corporations can use additive manufacturing technology to produce high-quality products. The use of SLS technology to manufacture highly integrated and lightweight drone components greatly reduces the components required for a single drone, thereby simplifying the manufacturing process. Fewer component types mean a simpler production line layout. Simplified production processes can reduce companies' costs in the manufacturing stage to a certain extent.

At the same time, the digital-based design process helps manufacturing corporations realize the scheduling and allocation of resources in multiple regions. Manufacturing corporations can centralize production lines for mass production according to actual needs, or distribute production lines in different regions to meet product maintenance and upgrades. Digital design makes design and manufacturing no longer bound in space. UAV manufacturing companies can set up production lines in different regions and establish production lines with regional characteristics. Thanks to the advantages of AM technology itself, UAV companies can provide more personalized services and optimization based on the production line, and there is no need to replace production equipment or significantly adjust the production line like traditional manufacturing technology.

6. Cost Benefit/Value Analysis

Manufacturing costs arise from many factors in the manufacturing process. Material cost, printer cost and part manufacturing time are some of the most direct factors affecting the overall cost of the product. In addition, many other factors affect the cost of the product at the same time, such as the costs incurred from the production infrastructure, labor costs in the production process, and costs generated from non-raw material resources and electricity [23], [24], [25]. However, these additional costs, which are difficult to evaluate directly, are combined into an overall overhead of 30%.

The cost of a single drone will be assessed primarily based on material costs and equipment costs. Table 5 presents the material cost of each drone assembly.

Table 5. Estimation of material costs per drone assembly.

Material costs of PA11-CF ($/kg)			219
Part	**Quantity**	**Mass (kg)**	**Cost ($)**
Uni-body drone body	1	1.58	345.0
Landing gear	2	0.20	87.6
Electronic device container	1	0.28	61.3
Total material costs ($)			495.0

The estimation of machine costs per part is based on the equation mentioned below

$$Cost_{machine} = \frac{P_{machine} * T_{build}}{\alpha * T_{life}}$$

The machine costs of each component and the overall costs per drone are listed in Table 6.

Table 6. Estimation of machine costs per drone assembly

Machine purchase costs ($P_{machine}$)	444,000 $	
Build time per part (T_{build})	Uni-body drone body	12h
	Landing gear	4.5h
	Electronic device container	3.7h
Machine utilization (α)	95%	
Machine lifetime (T_{life})	10 years	
Total machine costs per drone assembly ($)	108	

Based on the calculation of Table 5 and Table 6, the overall cost per drone assembly is 603$.

7. Conclusions

In this project, a UAV used in agriculture is designed. The project aims to design integrated and lightweight UAV components to improve the payload ratio of the UAV. Using topology optimization, components that meet integration and lightweight requirements are designed and optimized. At the same time, lattice structures are also designed on components to reduce weight and reduce the impact of weak motion on the control system. Due to the unique molding principle of additive manufacturing technology, optimized components and lattices with complex structures that are difficult to fabricate by traditional manufacturing methods can be manufactured.

To develop a structured optimization process for the quadcopter, the project began with defining the functional and performance requirements, based on a reference configuration which included detailed loading conditions, power unit specifications, and expected performance outcomes. The SLS technology and PA11-CF are selected due to the consideration of functional and performance requirements and price-performance balance. The optimization process is iterative, starting with the segregation of major components that require independent printing. This decision is primarily driven by considerations of manufacturing feasibility and economic viability. The design process is completed with results validation in three optimized works: a unibody drone body, a set of landing gear, and an electronic device container. The results analysis confirmed that all three parts met the initial requirements and constraints.

Due to the growing demand for UAVs in precision agriculture, highly integrated lightweight drones manufactured using AM will have huge application prospects and markets.

Reference

[1] D. Murugan, A. Garg, and D. Singh, “Development of an Adaptive Approach for Precision Agriculture Monitoring with Drone and Satellite Data,” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 10, no. 12, pp. 5322–5328, Dec. 2017, doi: 10.1109/JSTARS.2017.2746185.

[2] U. R. Mogili and B. B. V. L. Deepak, “Review on Application of Drone Systems in Precision Agriculture,” *Procedia Computer Science*, vol. 133, pp. 502–509, Jan. 2018, doi: 10.1016/j.procs.2018.07.063.

[3] G. D. Goh, S. Agarwala, G. L. Goh, V. Dikshit, S. L. Sing, and W. Y. Yeong, “Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential,” *Aerospace Science and Technology*, vol. 63, pp. 140–151, Apr. 2017, doi: 10.1016/j.ast.2016.12.019.

[4] R. Xiao *et al.*, “3D printing of dual phase-strengthened microlattices for lightweight micro aerial vehicles,” *Materials & Design*, vol. 206, p. 109767, Aug. 2021, doi: 10.1016/j.matdes.2021.109767.

[5] S. Nvss, B. Esakki, L.-J. Yang, C. Udayagiri, and K. S. Vepa, “Design and Development of Unibody Quadcopter Structure Using Optimization and Additive Manufacturing Techniques,” *Designs*, vol. 6, no. 1, Art. no. 1, Feb. 2022, doi: 10.3390/designs6010008.

[6] S. Patel, A. Bhoi, V. Maurya, A. Wankhede, and R. Bakshi, “DESIGN AND TEST 3D PRINTED LATTICE STRUCTURE FOR UAV,” vol. 07, no. 05, 2020.

[7] T. Laporte, “Design, simulation and optimisation of lattice structures for remote control aeroplane,” *Journal of Intelligent Manufacturing and Special Equipment*, vol. 3, no. 1, pp. 106–114, Jan. 2021, doi: 10.1108/JIMSE-12-2020-0028.

[8] J. Qu, Y. Dong, X. Gu, and S. He, “Integrated Frame Topology Optimization Design of Small Quadrotor UAV,” *J. Phys.: Conf. Ser.*, vol. 2292, no. 1, p. 012016, Jun. 2022, doi: 10.1088/1742-6596/2292/1/012016.

[9] H. Guo, M. Li, P. Sun, C. Zhao, W. Zuo, and X. Li, “Lightweight and maintainable rotary-wing UAV frame from configurable design to detailed design,” *Advances in Mechanical Engineering*, vol. 13, no. 7, p. 16878140211034999, Jul. 2021, doi: 10.1177/16878140211034999.

[10] Y. L. Yap *et al.*, “Topology optimization and 3D printing of micro-drone: Numerical design with experimental testing,” *International Journal of Mechanical Sciences*, vol. 237, p. 107771, Jan. 2023, doi: 10.1016/j.ijmecsci.2022.107771.

[11] F. Mesarosch, T. Schlotthauer, M. Springmann, J. Schneider, and P. Middendorf, “Topology Optimization and Production of a UAV Engine Mount Using Various Additive Manufacturing Processes,” in *Proceedings of the Munich Symposium on*

Lightweight Design 2021, J. Rieser, F. Endress, A. Horoschenkoff, P. Höfer, T. Dickhut, and M. Zimmermann, Eds., Berlin, Heidelberg: Springer, 2023, pp. 124–135. doi: 10.1007/978-3-662-65216-9_12.

[12] W. P. Syam, W. Jianwei, B. Zhao, I. Maskery, W. Elmadih, and R. Leach, “Design and analysis of strut-based lattice structures for vibration isolation,” *Precision Engineering*, vol. 52, pp. 494–506, Apr. 2018, doi: 10.1016/j.precisioneng.2017.09.010.

[13] F. Rosa, S. Manzoni, and R. Casati, “Damping behavior of 316L lattice structures produced by Selective Laser Melting,” *Materials & Design*, vol. 160, pp. 1010–1018, Dec. 2018, doi: 10.1016/j.matdes.2018.10.035.

[14] C. Pan, Y. Han, and J. Lu, “Design and Optimization of Lattice Structures: A Review,” *Applied Sciences*, vol. 10, no. 18, Art. no. 18, Jan. 2020, doi: 10.3390/app10186374.

[15] K. Monkova, M. Vasina, M. Zaludek, P. P. Monka, and J. Tkac, “Mechanical Vibration Damping and Compression Properties of a Lattice Structure,” *Materials*, vol. 14, no. 6, Art. no. 6, Jan. 2021, doi: 10.3390/ma14061502.

[16] C. R. M. Brambilla, O. L. Okafor-Muo, H. Hassanin, and A. ElShaer, “3DP Printing of Oral Solid Formulations: A Systematic Review,” *Pharmaceutics*, vol. 13, no. 3, p. 358, Mar. 2021, doi: 10.3390/pharmaceutics13030358.

[17] N. Maqsood and M. Rimasauskas, “A Review on Development and Manufacturing of Polymer Matrix Composites Using 3D Printing Technologies,” Oct. 2020.

[18] V. Tagliaferri, F. Trovalusci, S. Guarino, and S. Venettacci, “Environmental and Economic Analysis of FDM, SLS and MJF Additive Manufacturing Technologies,” *Materials*, vol. 12, no. 24, Art. no. 24, Jan. 2019, doi: 10.3390/ma12244161.

[19] “TPM3D S600DL SLS Printer - Superior SLS 3D printer_TPM3D - TPM3D.” Accessed: Dec. 18, 2023. [Online]. Available: https://english.tpm3d.com/sls-products/sls-3d-printer-s-series/S600DL.html

[20] I. S. Kinstlinger *et al.*, “Open-Source Selective Laser Sintering (OpenSLS) of Nylon and Biocompatible Polycaprolactone,” *PLOS ONE*, vol. 11, no. 2, p. e0147399, Feb. 2016, doi: 10.1371/journal.pone.0147399.

[21] J. Li, Y. Durandet, X. Huang, G. Sun, and D. Ruan, “Additively manufactured fiber-reinforced composites: A review of mechanical behavior and opportunities,” *Journal of Materials Science & Technology*, vol. 119, pp. 219–244, Aug. 2022, doi: 10.1016/j.jmst.2021.11.063.

[22] “Materials,” Sinterit – Manufacturer of compact and industrial SLS 3D printers. Accessed: Dec. 17, 2023. [Online]. Available: https://sinterit.com

[23] M. Ruffo, C. Tuck, and R. Hague, “Cost estimation for rapid manufacturing - laser sintering production for low to medium volumes,” *Proceedings of the Institution of*

Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 220, no. 9, pp. 1417–1427, Sep. 2006, doi: 10.1243/09544054JEM517.

[24] G. Costabile, M. Fera, F. Fruggiero, A. Lambiase, and D. Pham, “Cost models of additive manufacturing: A literature review,” *International Journal of Industrial Engineering Computations*, vol. 8, no. 2, pp. 263–283, 2017.

[25] B. Westerweel, R. J. I. Basten, and G.-J. van Houtum, “Traditional or Additive Manufacturing? Assessing Component Design Options through Lifecycle Cost Analysis,” *European Journal of Operational Research*, vol. 270, no. 2, pp. 570–585, Oct. 2018, doi: 10.1016/j.ejor.2018.04.015.