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Overview of Hydrogen Hybrid Unmanned Aerial Vehicle technology, FDM manufacturing and comparative case study of FDM and injection molding manufacturing cost.

by

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Overview of Hydrogen Hybrid UAV technology, FDM manufacturing and comparative case study of FDM and injection molding manufacturing cost.

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Abstract

This thesis consists of two main topics. The first part is about the composition and function of a hydrogen hybrid drone, examining many aspects of its qualities and lifecycle. The second part revolves around working principals of Fused Deposition Modeling manufacturing examining its various applications and the most commonly used materials.

In the beginning chapter, there is a short description of the history and evolution of UAVs, the concept of hybridization and the basic difference in terms of components and function compared to a non-hybrid system. Then a performance and capability comparison between hybrid systems and solely battery powered ones takes place. Afterwards the sustainability of hybrids as far as fuel, manufacturing and lifecycles are examined. In the end of the first segment the various applications of the hybrid drones are described along the benefits they bring to the applied fields.

Following the first part, there is a description of the hybrid drone designed by the University of Thessaly, as part of a research program, with the use of FDM manufacturing in its fabrication. Then the following chapter explains additive manufacturing and deepens into the FDM manufacturing method and examining the adoption in the modern industry. Following, there is some information about the properties and applications of the most common simple and composite materials used in this method.

In the final chapter a case study takes place, in which the cost of injection molding is compared to the cost of FDM for the manufacturing of a plastic component.

Επισκόπηση της τεχνολογίας των υβριδικών μη επανδρωμένων αεροχημάτων υδρογόνου, της μεθόδου κατασκευής FDM και συγκριτική μελέτη κόστους παραγωγής με τις μεθόδους FDM και Injection Molding.

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Περίληψη

Η παρούσα διατριβή αποτελείται από δύο βασικά θέματα. Το πρώτο μέρος, αφορά τη σύνθεση και τη λειτουργία ενός υβριδικού drone υδρογόνου, εξετάζοντας πολλές πτυχές των ιδιοτήτων και του κύκλου ζωής του. Το δεύτερο μέρος, αναφέρεται στις αρχές λειτουργείας της διεργασίας FDM, εξετάζοντας τις διάφορες εφαρμογές της και τα πιο κοινά υλικά που χρησιμοποιούνται σε αυτή.

Στο πρώτο κεφάλαιο, γίνεται μια σύντομη περιγραφή της ιστορίας και της εξέλιξης των UAV, της έννοιας του υβριδισμού και των βασικών διάφορων ως προς τα εξαρτήματα και τη λειτουργία των υβριδικών και των μη υβριδικών συστημάτων. Στη συνέχεια, γίνεται μια σύγκριση της απόδοσης και των δυνατοτήτων μεταξύ των υβριδικών συστημάτων και των συστημάτων που είναι εφοδιασμένα αποκλειστικά με μπαταρίες. Στη συνέχεια, εξετάζεται η βιωσιμότητα και το περιβαλλοντικό αποτύπωμα των υβριδικών συστημάτων υδρογόνου όσον αφορά τα καύσιμα, την κατασκευή και τον κύκλο ζωής τους. Στο τέλος του πρώτου τμήματος, περιγράφονται οι διάφορες εφαρμογές των υβριδικών μη επανδρωμένων αεροχήματων μαζί με τα οφέλη που προσφέρουν στο κάθε τομέα που χρησιμοποιούνται.

Μετά το πρώτο μέρος, ακολουθεί η περιγραφή του υβριδικού drone που σχεδιάστηκε στο πανεπιστήμιο Θεσσαλίας, στα πλαίσια ενός ερευνητικού προγράμματος, οπού έγινε η χρήση της μεθόδου FDM για την κατασκευή του. Στη συνέχεια, το επόμενο κεφάλαιο εξηγεί την έννοια της προσθετικής κατασκευής, εμβαθύνει στη μέθοδο κατασκευής FDM και εξετάζει την χρήση της στη σύγχρονη βιομηχανία. Ακολουθούν ορισμένες πληροφορίες σχετικά με τις ιδιότητες και τις εφαρμογές των πιο κοινών απλών και σύνθετων υλικών που χρησιμοποιούνται σε αυτή τη μέθοδο.

Συνοψίζοντας, υπάρχει η μελέτη μιας περίπτωσης στην οποία εξετάζετε το κόστος της μεθόδου injection molding σε σύγκριση με την μέθοδο FDM για την παραγωγή ενός πλαστικού εξαρτήματος.

Contents

List of Figures

List of Tables

1) Fuel cell and battery hybrid drones.

1.1) An introduction to the hybrid UAVs concept

The idea of an unmanned aerial vehicle (UAV) has been around for over a century now, with the first experiments taking place during World War 1, in the form of small radio-controlled planes for target shooting powered by small Internal Combustion Engine (ICE). Later they took the form of bigger planes and missiles for military use in the 1940s and 1950s and they remained this way for many decades (1). As time went on and advancements took place UAVs evolved in the many forms and uses that are currently available. The past 30 years fueled by the advancements in semiconductors and battery technologies, and the changes in the needs and culture of the synchronous society have made drones more mainstream and accessible. This rise in commercial and recreational use increased the demand for drones smaller in size, cheaper, more accessible and simpler to use. Drones found many uses in the hands of professionals in sectors like goods delivery, first response, surveillance, inspection, agriculture, videography and many others. The ICE power plant, though, wasn't suitable for the smaller lighter drones due to the relatively high weight to power ratio of low power engines, so the ICE power plant gave its position to the combination of batteries and electric motors. Most commonly used combination is the Lithium Polymer and the Brushless DC motors. Recently the needs of the commercial market for longer flight times and environmental sustainability sparked experimentation with hybrid propulsion systems **(Figure 1)**. The concept although existing already in other industries like the automotive, the locomotive and the marine, is far from simple to implement and many things needed to be reworked in order for the hybrid powertrain to fit the application and improve on the performance. For most UAVs for commercial use,

Figure 1:Hydrogen hybrid UAVs
Source: https://hydrogentoday.info/en/hydrogen-powered-drone/

hydrogen has been proven to be the most effective fuel, advantages of which will be presented in a later chapter. Although hybrid systems seem like the way to go, adaptation has been very slow due to the general low adaptation of Hydrogen as fuel and energy storage and the lack of support infrastructure. Also, the legislation causes difficulties since public concern for privacy and safety makes the laws strict or unclear and can vary from one country to another. Currently, the state of Hybrid powered UAVs (Hydrogen, Fuel shell and battery combination) is:

- Many researches are currently taking place in the field trying to find the best design for each application and the most efficient type of energy management system.
- Some universities have ongoing projects aimed at designing and building such drones and their support infrastructure.
- Limited number of companies already have drones or complete packages (Drones, Ground refueling stations, either mobile or stationary Controllers and different accessories for the drones to match the different uses). (2)

As times goes on more and more research, innovation and investments take place, hydrogen will become more accessible, and its popularity is expected to grow and so will do the Hybrids powered by it. Also, as drone operators increase, and the fields of use expand, the legislation will become more uniform and friendly toward UAVs across the different countries. Drone market is predicted to double by 2030 with an increase in all the end consumer markets (commercial, recreational and military)(3). All these are an indication that hybrid drones will soon be widely adopted and popularized, especially in the commercial sector. In this paper the research is limited to the adaptation of the hybrid design and its effects on the 3 sectors with the biggest financial and humanitarian impact, the last mile delivery, the first response, security and surveillance and the agricultural one.

1.2) Multirotor UAV physical Components

Hybrid drones are similar to the typical battery powered ones with some design changes in order to accommodate the extra components required. Typically, a conventional multicopper drone is made from a frame that houses the battery, receiver, speed controller for the motors and dc/dc converters. On the frame there are arms attached that extend outwards and at the end of them the motors with the rotors are mounted. On most occasions, there is an even number of rotors, with an equal number spinning in opposite directions in order to counteract the rotating inertia and stabilize the drone, rare are the occasions of usage of odd number of rotors that are sized accordingly in order to counteract the inertia. Other components are also attached like legs to land on, protective covers for the electronics and the rotor blades. The extras a hybrid system has are the fuel cell, the hydrogen tank, a battery appropriate for hybrid combination, DC/DC converters and the power management system (PMS) (4).

1.2.1) Fuel Cell

The Fuel cells **(Figure 2)** are categorized according to the chemicals they use as electrolytes, catalysts, and the fuels they can run on. The most common ones used in the industry are the polymer electrolyte membrane fuel cell (PEMFC) also known as proton exchange membrane fuel cells, solid oxide fuel cell (SOFC), and direct methanol fuel cell (DMFC), consuming hydrogen, hydrocarbons and methanol respectively. The PEMFC are the ones used in the case of hydrogen hybrid multirotor levitating drones. They are characterized by their relatively high efficiency compared to other cells, high system and stack specific power, convenient operating temperature and easy start up. PRMFCs have the ability to start up at low ambient temperatures, as low as -20°C, and to operate consistently and efficiently at an internal cell temperature of 60-120°C, which means less heat up and time to reach peak efficiency, at 100°C there is also a benefit that the water byproduct is being turned into steam making its exhaust easier. These relatively low temperatures make active cooling of the fuel cell necessary, especially when we want peak efficiency in a wide range of ambient temperatures, adding to the overall footprint of the system. SOFSs can run on Hydrogen as well and although they cost less to produce and have a bit grater lifespan, their slightly lower efficiency and relatively higher weight make

Figure 2: Intelligent Energy PEM Fuel Cell for UAV usage
Source:https://www.unmannedsystemstechnology.com/feature/pem-fuel-cells-in-unmanned-systems-qa-with-intelligent-energy/

them a poor choice for multirotor drones and sensible only in fixed wings flying UAVs or in hybrid configuration with turbines. PEMFCs weight advantage comes from the simple design with a dead-end anode, since it has no return or vent, and an open cathode so the produced water can escape. Water exhaust is very important in FCs in general as if it will not get removed properly it can flood the membranes and hurt its efficiency and performance. (5), (6), (7), (8), (9)

1.2.2) Hydrogen storage tank

Hydrogen when being in standard temperature and pressure has a density of just 0.089kg/m^3 so to be a viable option for energy storage means that it has to be way denser and especially for UAV that space is limited, and Energy density is more important than anything else. There are three main types used for hydrogen storage:

1. Compressed hydrogen gas: This is the most common type of storage with hydrogen gas compressed to pressures between 35 to 70MPa and can achieve density between 23.3 to 42kg/m^3. It is the most common method that allows fast refueling while keeping things simple. High pressures although mean relatively heavier fuel tanks and higher safety risks. Against all the drawbacks this has grown to be the dominant method in the UAV industry.

2. Liquified hydrogen: At −252.87°C and 1bar hydrogen liquefies and its density reaches 71kg/m3. In this form the energy density is vastly improved, and it is safer for storage. Storage tanks are lighter but require insulation in order to maintain the low temperatures and safe function. The liquification prosses is more energy demanding since cooling is required and handling hydrogen in that form needs more attention making that process more suitable for big scale applications.

3. Chemical hydrogen generation: Hydrogen is produced on demand from hydrogen carrying substances and solutions with chemical reactions such as hydrolysis, alcoholysis, or thermolysis most times in combination with a catalyst. These hydrogen carriers are stable in ambient conditions and demand small amounts of energy and time to release the contained hydrogen, which can be as high as 19.6%wt. The most common carriers used are: Sodium Borohydride ($NaBH_4+H_2O \rightarrow 4H_2+NaBO_2$), Ammonia Borane

($NH_3+BH_3 \rightarrow NH_2BH_2+H_2$) and, Liquid Hydrocarbons ($CH_2O_2 \rightarrow H_2+CO_2$). This method is not suitable for multirotor UAVs as it adds to the complexity weight and creates the need to manage the other reaction product. It is tested for use in fixed wings UAVs. (10)

As mentioned above, the dominant hydrogen handling method for UAVs is compression and storage in tanks **(Figure 3)**. These tanks are quite a challenge to build since they have to possess many properties in order to achieve the required performance. To begin with, these tanks have to be the lightest possible in order to maintain good energy density for the hybrid power system. Then, they must be very safe, with the European Union issuing the Transportable Pressure Equipment Directive 2010/35/EU (TPED) mandating a safety factor of 2.25 for pressure loading before bursting, 11,250 refill cycles, 20-minute resistance to standard bonfires, penetration resistance enough to withstand a 7.62mm bullet impact and all these for a 15-year lifespan. Tanks are built with 5 methods, depending on the pressure they are meant to hold up and the environment they have to operate in: 1) Fully metallic vessels. Usually built from Titanium or Aluminum alloys and meant for pressures of up to 20MPa. 2) Metallic vessel with a circumferential composite layer at the cylindrical part of the vessel. Usually built with carbon fiber and resin composite and are good for pressures from 25 to 30MPa. 3)Fully metallic construction with metallic liner. Liner's purpose is mostly to prevent leaks. Used for 30 to 70MPa tanks. 4)Fully composite construction with polymer liner for up to 70MPa. 5)Fully composite construction without liner for uses that can surpass 70MPa. The most dominant methods, for the UAV market, are the 3rd and 4th since they have the lowest weight to mass storage capacity while being very safe and durable. (11), (12), (13)

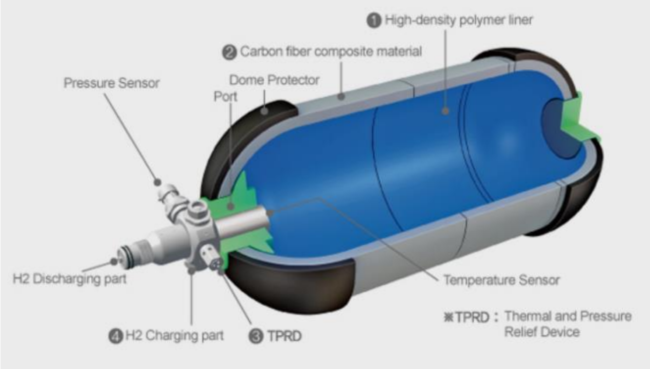

Figure 3: Hydrogen storage tank
Source:https://sustainableskies.org/hydrogen-powered-drone-makes-ocean-flight/en storage tank

1.2.3) Battery

Fuel Cells are very good at providing constant power and can do it efficiently for a specific range of power outputs. A multirotor UAV on the other hand can produce spikes and dips in the power demand, depending on gaining or losing altitude, which means that a fuel cell (FC) as a unique power source is a strategy that won't be able to outperform in efficiency and endurance the conventional battery and ICE powered drones. The solution lies in the addition of a battery or a supercapacitor, hence the hybrid term is used, that can provide power when the system demands more power than the provided by the FC and can store excess for later use. Due to the high number of charge/discharges cycles a hybrid system goes through batteries selected must have a big lifespan and depending on the UAVs power requirements an adequate discharge rate capability. Typically, the batteries used based on popularity are Lithium Polymer (Li-Po), Lithium Ion (Li-on) and Nikel Melat Hybrid (Ni-MH). As mentioned earlier supercapacitors are an option as well. They can achieve higher power, better lifespan, and durability (in overcharging and spikes) while having a wider range of operating temperatures, but all these come at the cost of lower power density and lower capacity (milliamperes/hours). Notable is also the benefit of smoothing out any voltage fluctuations on the electrical system, offering more stability, better dynamic response and less strain for the electronics. Supercapacitor usage is a field being studied and experimented with, that shows good results for use in a hybrid system alone or in addition to a battery (14).

1.2.4) DC/DC converters

DC/DC converters, despite being a simple component, play an important role. Their work is to ensure that the voltage that goes to the motors, the avionics and the fuel cell (FC) control modules, which are all very fragile to power fluctuations, is smooth and steady. There are two topologies of DC/DC converters, the isolated and the non-isolated ones. The first ones are used in low and medium power applications and are able to achieve high voltage ratios and galvanic isolation, while the other type is simpler, smaller but only capable of low voltage ratios. DC/DC converters are always used for connecting the FC to the UAV's DC bus, since its voltage output can vary a lot depending on the load. Bidirectional converters, controlled by the Energy

Management System (EMS), are used for the battery, as it must be able to both take power and charge. (15) (16) (4) (10)

1.3) Energy Management Strategy (EMS)

Hybrid propulsion systems purpose is to combine the power sources, as many as there might be, in a way that that the advantage of each source is shown but their limitations are being overshadowed and covered by the other ones. In order for these advantages to show there has to be an intelligent way of controlling the energy drawn from each source in an optimized way so to use the least amount of fuel and thus maximize flight time. This role is fulfilled by the Energy Management Strategy (EMS). In the literature, we stumble across two strategy types: passive and active.

1.3.1) Passive EMS

The passive EMS is the topology that the power sources are connected directly to the systems DC link and the power provided to the propulsion mechanisms is mandated purely by their characteristics. This EMS type requires neither additional converters nor controllers, which means it makes the whole construction relatively simpler, cheaper, lighter and reduces the power losses. The lack of the abovementioned components, of course, reduces the power efficiency of the circuit and allows for voltage fluctuations on the DC link, thereby shortening the lifetime of the components, especially the fuel cells (FCs), which is an expensive component, and the avionics board, which is quite critical and if a fault occurs mid-flight it will be fatal for a UAV. Also, in order to achieve a reliable DC bus, sharing energy sources must be meticulously sized. Passive EMS is popular in small UAVs.

1.3.2) Active EMS

An Active EMS is a topology that the power sources are connected to the DC link via converters and switches, and are operated by a computer, usually called Energy Management Computer (EMC). Sensors, placed on the UAV, track live data, and take measurements, such as speed, altitude, hydrogen consumption, battery status, voltage outputs, load on motors, and more others depending on the design, physiology and purpose of the UAV. The collected data are sent to the EMU, which is programed to read the data and take actinons so to achieve the most efficient, by many aspects, flight. Many strategies are used for programing the EMC, with each one having a different approach to flight optimization and resource usage. Mainly there are three types of approaches in these strategies: rule-based (RB), intelligent-based (IB), optimization-based (OB), and frequency separation based (FSB).

1.3.2.1) Rule-based EMS

Rule-based EMS is a control based on predetermined thresholds and maps. The EMC, essentially, is constantly comparing the data that receives from the sensors with fixed values and acts with predetermined moves to bring the values received closer to the fixed once, that are supposed to be the optimal for each occasion. The rule-based control framework is driven by Proportional-Integral (PI) controllers and as a method requires little computational power, meaning small footprint and power draw. The drawback of this method is that it is based on values from results of tests from past conditions and flights, which little times will be identical to the actual working conditions, meaning that the full potential is not unlocked. Also, it depends strongly on the designer’s knowledge which might be limited, and the accuracy of the tests that determine the fixed values that all have some margin of error. In addition, the fixed nature of the value and the map means that there is no possibility of using Artificial Intelligence to make the UAV improve and adjust itself to the various uses and conditions it will be subjected to. Its simplicity and ease of application though, make it easy to apply RB control easily and reliably to any UAV, making this quite a popular control method.

1.3.2.2) Intelligent-based EMS

Intelligent-based control methods, in general, are based on developing an automatic control algorithm that mimics human decision-making behavior. Fuzzy Logic (FL) is the major intelligent-based EMS, used in hybrids, and in hybrid UAVs consequently, and is constructed using membership functions and IF-THEN rules. It has a fast response while being able to tolerate perturbations and that it handles nonlinear membership functions with ease. The major difference of FL to RB control methods if that in FL rules are more like probabilities than rules that make the EMS prioritize energy sources and choose strategies depending on the occasion instead of standard maps and fixed values that lead to just trying to make sensor readings ideal no matter the occasion. This difference makes the Fl system, and intelligent-based systems in general, more energy efficient and better for the component health and longevity since they manage them more gentle and more efficient. Similarly to RB, the FL method is a very good on-line controller with low computational demand, but also, dependent on the experience of the designer. Another popular intelligent-based control method is the Neural Network (NN) that has a similar form to the beforementioned. This method implements nonlinear mapping with the use of mathematical proof. It incorporates capabilities like self-learning, high speed retrieval and associative memory. Although the NN methods seem superior and offer more efficiency it can suffer from what designers call paralysis, which is a result of the objective function's complexity and results in algorithm failure. To avoid that the algorithm has to be "trained" before use, thus resulting in more storage and computational power demand on beard the UAVs computer, resulting to higher cost and higher EMC power draw.

1.3.2.3) Optimization-based EMS

Optimization-based strategies start by setting up a cost function and constraints around it, then depending on the type it is being handled accordingly. There are two types of controlling methods, the non-causal and casual. Non-casual controlling methods are, typically, based on three algorithms Dynamic Programing (DP), Linear Programing (LP), and Pontryagin's Minimum Principle (PMP). These algorithms are part of the optimal control theory and are applied only offline due to their big computational load. The two most common Casual Control method algorithms are Model Predictive Control (MPC) and Equivalent Consumption Minimization Strategy (ECMS), with MPC being able for online, real-time applications and ECMS for both online and offline. From all the above mentioned the most widely used methods are the DP, the ECMS and the MCP.

1. Dynamic Programing (DP), in general, I very popular optimization algorithm and is considered to be ideal for energy management in hybrid propulsion systems (HPS). The core function of DP is to take a complicated prosses and break it down to many corelated simple processes. The optimum solution occurs from minimizing a not desirable outcome, accounting for current and upcoming cost of control choices. This prosses is very good for given operating conditions and requires a database to be set up with statistics and historical

data. This results in accuracy but at the cost of high computational burden, rendering this method good for off-line use and for evaluating other methods.

2. Equivalent Consumption Minimization Strategy (ECMS), as energy control algorithm works without restrictions and targets on achieving the minimum energy consumption for every moment. In order to account for the different energy sources power consumption is converted to hydrogen consumption for charging the battery and hydrogen equivalent stored in the battery. To keep the State of Charge (SOC) of the battery inside a safe and reasonable range a variable is added to the control function, called penalty factor.

3. Model Predictive Control (MPC) is a popular method among the process control industry due to its robust algorithm. It is constructed using equations of state, by contrast to the other methods that are based on accurate or complex models and, by consequence, transfer functions, thus resulting in lower computational burden. Its major benefit compared to other control methods lies in the finite horizon it has, which allows for a flexible swap between the effort of calculating online to solve a minimum principal and the offline effort to generate the penalty surface function. This makes this method very well-suited for nonlinear or dynamically uncertain systems and there, also, exists the ability of tuning the horizon length depending on the control strategy used, the computational effort available, model accuracy, disturbances, and external conditions. This tuning ability is very important since restricting disturbances protects the EMS, increasing its lifespan, but on the other hand the model is susceptible to uncertainties which means that the designers have to access and choose a trade of. MCP is designed to predict the SOC and the mechanical power the system will draw, and it does that with the same accuracy as the ACMS but at lower computation time. This method although its advantages and its tunability, is yet to be used to FC powered UAVs as the incorporation of the adaptiveness is a demanding task, but the popularization of hybrid UAVs will eventually require the adoption of MCP.

1.3.2.4) Frequency Separation based EMS

Frequency separation based (FSB) or frequency decupling based is an important EMS method that utilizes techniques like low-pass filters, wavelet transform and rapid Fourier transforms resulting in a separation of power demand to individual, easier to handle, frequencies. It is well known, although, that the higher the number of transients, the higher the mechanical and chemical stress is applied on the FC and the Battery, resulting in reduced lifespan. To combat this problem this method is preferred to be used in combination with other methods. Most commonly is used in conjunction with rule-based EMS (FS-RB EMS). In this orientation the system divides the power drawn from the sources by filtering the decomposed frequencies and referring to the fuel cell only the low ones to avoid big fluctuations and thus enhancing its lifetime. However, his method doesn’t account for the SOC and the current used for charging and discharging the battery, resulting in excess stress and thus performance degradation. Important here is to set limits in order to keep a minimum SOC on the battery, in case of emergency (e.g., fuel cell failure, DC/DC convertor failure) and to be within the well operating limits provided by the manufacturers of the FC and the battery. FS-RB overall is a medium computational load method that with a good set up beforehand can be very efficient.

(17) (18) (19)

2) Performance and capabilities comparison of hybrids to conventional drones.

As mentioned earlier, the concept of hybridization is to combine two power systems to harvest the benefits of both and foreshadow each one's weaknesses. The hydrogen FC and battery combo for powering UAVs, in the beginning came as a suggestion for solving the range issue of the commercial battery powered UAVs and secondly as a relatively environmentally friendly, reliable, and able to scale in size for the various payloads and purposes. In the following paragraphs overall performance and capabilities, and environmental impact will be compared.

2.1) Benefits

The biggest improvement Hydrogen has is the very big energy density it can achieve when compressed or even liquified **(Figure 4)**. By nature, it has a very low density of only 0.08988 g/L so to be a viable option as energy storage, when space is limited, so it has to be compressed to pressures that can reach up to 70MPa (1000 psi) or superchilled and liquified (20) (13). To caption the difference in space the compression prosses makes the example of the Toyota Mirai is examined (21). Hydrogen is stored at 70 MPa, a very efficient pressure for storage on vehicles, where the density is roughly reaching 38 kg/m^3. Across the vehicle's two tanks 5 kg of hydrogen are stored, taking up 0,1224 m^3 while the same amount of hydrogen at STP conditions would take up approximately 55.500 m^3. Hydrogens energy density of roughly 131 MJ/kg (results as the average of 120 MJ/kg LHV and 142 MJ/kg HHV), unfortunately the tanks weight 87kg by themselves thus bringing the total energy density to just 6.8 MJ/kg. Although there is a big decrease, it is still very high compared to the density of typical Li-ion batteries used in road vehicles today, ranging from 0.7 MJ/Kg to 1.1 MJ/Kg (14). In the case of hybrid UAVs, the majority of the commercially available

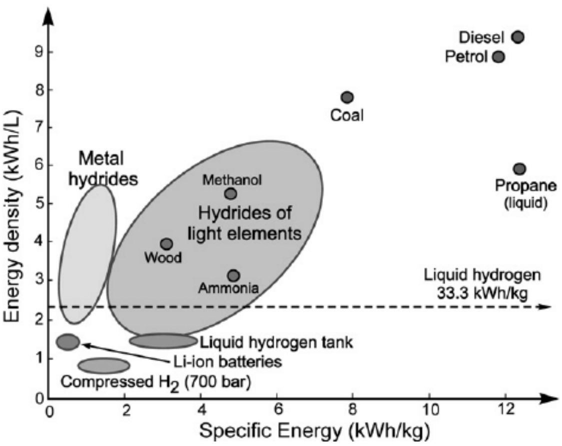

Figure 4: Energy density and specific energy of various storage methods.
Source: https://www.researchgate.net/figure/Energy-densities-of-various-energy-storage-materials-and-technologies-illustrating-the_fig3_238394762

tanks store hydrogen at 35MPa making for a density of 23 kg/m^3, by taking the example of the Q042H35 tank made by Luxfer Gas Cylinders that is able to store 1 kg of hydrogen and weights 25 kg (22). This makes for 26 kg of total weight, roughly 131 MJ of total energy stored and 5,03 MJ/kg of energy density which is still quite higher than the 0.9 MJ/kg to 1,5 MJ/kg of the typical Li-Po batteries used in most UAVs (14) (23). This calculation, though, accounts neither for the rest of the components like the FC, the hydrogen flow regulator, the EMC nor for the weight savings of the smaller battery used by the hybrid system. But even with all these added components the final energy density is still higher than the one of a purely battery dependent system (24). This increase means more energy can be stored and longer flights can be accomplished, with many drones found in the literature to be able to fly on average roughly four times longer than the battery only counterparts (as in carrying capacity). Longer flight times mean less down time, thus more utilization of vehicles and equipment, and better investment return. Also, more time flying enables users to reach further and do things that they couldn't do before with a conventional UAV because they were out of reach, or they needed more time to complete and even sometimes replace other aerial vehicles like planes and helicopters. Additionally, regarding refueling, the inferior range allows for bigger distances between refueling, resulting in fewer refueling stations. Due to hydrogen being easier to carry around and load into the UAVs it enables the use of mobile ground control and refueling station **(Figure 5)** even more efficiently than a mobile battery swapping station. Finaly the hybrid systems, although they seem to be more unreliable due to the complexity and the higher number of parts and systems on board, they are actually more reliable and robust due to the power sources that when both work they function complementary to each other but is case of failure of the one the other can take on the task of completing the mission or at least bringing the UAV to a safe landing (12) (25).

Figure 5: Hylium Industries Ground control and refueling mobile station
Source: https://hylium-industries.com/hx

2.2) Drawbacks

Hydrogen hybrids, however, have some disadvantages as they are more complex and expensive to build, expensive to operate and are overall heavier and bulkier than their conventional counterparts. Part of these drawbacks is due to the fact that hydrogen fuel, as of today, is more expensive than electricity. For example, 1kg of hydrogen stores on average 36.35kWh of energy (141.9 MJ (HHV) = 39.4 kWh, 120.1 MJ (LHV) = 33.3 kWh) , meaning power coming from hydrogen and a typical PEMFC with 60% efficiency (Price per Kg of H2/(energy content per kg of H2 * FC efficiency)) would cost: in Greece 0.339 €/kWh (7.34 €/kg after a 5.18 € subsidy), in Germany 0.577 €/kWh (11,83 €/kg, which is close to the European average) (26) and in the US 0.74 $/kWh or 0.68 €/kWh (16$/kg or 14.75 €/kg). On the other hand the electricity prices after subducting the 20% loss from charging a battery (assuming an average, due to the variations on charger kilowattage and battery technology) (23) results in: 0.287 €/kWh in Greece (kWh price for end household consumer after tax 0.23 €/kWh), 0.5 €/kWh in Germany (0.4 €/kWh) (27) and 0.207 $/kWh or 0.187 V/kWh in US (0.166 $/kWh) (28). (prices are for early July 2024). A very notable difference, depending on the state of the economy, the hydrogen mix (how it is produced and taxed based on carbon footprint) and the supply network hydrogen can fetch multiple times the electricity cost making it unsuitable for powering things. The big upfront cost of the Hydrogen tank and FC also require a substantially bigger investment. Also, hybrid systems due to their higher weight and mass fall behind in terms of agility and maneuverability and speed which can be an issue when flying in rough weather or trying to respond fast (6) (29).

3) Hybrid system lifecycle environmental impact review and comparison

For the greatest part of modern human history humans have been trying to make their footprint on the environment as small as possible in order to preserve the natural environment and ensure that the climate and conditions will be optimal for life and the spices conservation. Hybridization is one of the greatest ways of using energy and materials more efficiently thus making a great impact in this effort. Unmanned Vehicles in general is one of the fields the concept is being experimented with and applied to in the past couple of decades and thus its environmental impact has still margin for improvement. In the following paragraphs the various ways a UAV, with a hybrid propulsion system, affects the industries that apply to and the suggested ways to improve that will be examined.

3.1) Environmental impact of manufacturing.

The implementation of the hybrid system in the UAV industry didn't come only as a way to get more flight time and capabilities but as a way to decrease the environmental impact of their construction and use. Although the goal of reducing their footprint is, currently, far from being achieved, the latest advances in technology and the environmental targets set by many countries around the world make it seem achievable. UAVs, like all other vehicles, have two things that have to be looked at when their eco consciousness is being studied, the impact of their production and the impact of their use during their lifecycle, including refueling and maintenance. The first major resource intense part that has a notable impact is the Fuel Cell. PEMFC is the most common FC type used in hybrid UAVs, and it is made from polymers, catalysts, metal or plastic housing and graphite, from which the three first can be recycled very efficiently (30). The catalyst, most often Platinum (Pt), alloyed sometimes with Ruthenium (Ru) to resist CO poisoning, has the biggest footprint since it is one of the rarer elements found in earth's crust and most times is found alloyed with other metals making it even harder to extract. Its refinement is extremely energy intensive since it has very low concentration and has to be melted to 1500^{o}C in order to meet and separate the alloys. Its recycling is taking place in two ways, either by oxidizing its carbon substrate with an acid, or by burning it away and melting the Pt

(31) (23). Both are very harmful methods, one by creating the problem of disposing of the acid and the sulfur oxide released and the other by being very energy demanding, fortunately these methods have a high recovery rate of over 95%. The rest of the FC components are simple and excluding the graphene are recycled like other conventional metals and polymers. Next in the line is the fuel tank that is usually constructed from carbon fiber reinforced polymer (CFRP) combined with a metal or polymer liner. Its construction is very energy demanding, with lots of power required for the production of fibers and for baking the final product in big temperatures for curing the resin polymer. Usually, CFRPs at the end of their lifecycle are either used in furnaces as fuel for cement or power production, either they are recycled by shredding the parts down to small pieces and adding them to new parts with usually inferior properties, like nonstructural and cosmetic parts. Lately another method has emerged, by the National Composites Centre of the UK in partnership with Lancashire-based B&M Longworth Ltd, called DEECOM® process that uses superheated steam to remove the polymer and leave behind the fibers without damaging them so they can be directly reused **(Figure 6)** (32). All the abovementioned have a massive carbon footprint with 1 ton of carbon fibers being responsible for roughly 20 to 25 tons of CO2 emissions (33). Batteries are the other very environmentally encumbering part since mining for the minerals they contain not only has a big carbon footprint but are processes that release many harmful gases and contaminate the water with hazardous chemicals. Recycling these batteries can be done in two ways, either by using a smelting process (pyrometallurgy) or with a liquid based chemical leaching process (hydrometallurgy), that can achieve recovery rates of up to 95% (34). Unfortunately, in order to not release harmful chemicals and be kept as ecofriendly as possible their cost ends up quite high, most times higher than mining new material, and thus, as of today, only around 5% of the Li-based batteries are recycled in the EU and US. Other parts like the circuitry, converters, motors, frame parts and rotor blades are common parts used in many other machines that exist long

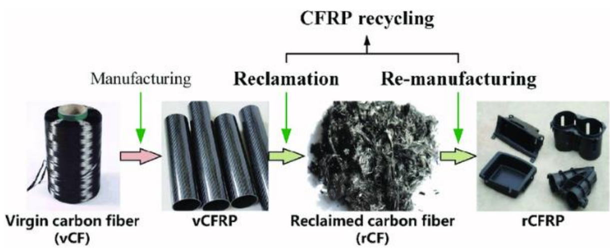

Figure 6: CFRP reclamation

Source:https://www.researchgate.net/figure/Recycling-Process-from-Virgin-Carbon-Fiber-to-CFRP_fig1_360967537 enough to have already been optimized to a decent degree as far as their environmental impact goes. Currently by comparison to the conventional drones the impact is roughly at the same level (35). Finaly, with advancements in recycling technics, new battery types based on materials that exist in abundance like graphene, sodium, iron zinc and sulfur and that can also last more charge/discharge cycles, and FCs that use such materials as well and have longer lifespan can substantially improve sustainability.

3.2) Hydrogen production environmental impact

Hydrogen was observed for the first time in 1520 by Paracelsus after being generated by metal dissolution in sulfuric acid. In 1788 it officially got its name by the French chemist Antoine Lavoisier and shortly after in 1789 it got produced by electrolysis for the first time by Adriaan Paets van Troostwijk and Jan Rudolph Deiman. (36) From then it has come a long way and has found many uses mostly in the chemical, pharmaceutical, oil refining, fertilizer and metallurgical industry having ended up being a necessity to most of them. Due to its relatively high cost of production, it has limited implementation outside the above-mentioned sectors and has not met widespread use as energy storage and providence for home use and for transportation yet (37). These sectors are very critical to push away from fossil fuels since, according to the EPA (U.S. Environmental Protection Agency), the transportation alone accounts for 14% of global C02 emissions while energy and heat production for houses and small business account for another 25% (38). So, the main goal for the researchers and the industry is to drive down the prices of production, storage and transportation. Their second one is to lower the cost of production from renewable sources until it becomes lower than the one of non-renewables. Hydrogen is categorized by the production method as **(Figure 7)** (29) :

- Blue for hydrogen that has been made from natural gas reforming and coal or biomass gasification, all in combination with carbon capture and storage (CCS).
- Turquoise from natural gas pyrolysis with CCS.
- Grey as all the previous, but without the implementation of CCS.
- Black from bituminous quality coal gasification.
- Brown for lignite type coal gasification.

- Green from electrolysis with the use of wind and geothermal energy.
- Yellow from electrolysis with solar power.
- Pink from electrolysis with nuclear power.

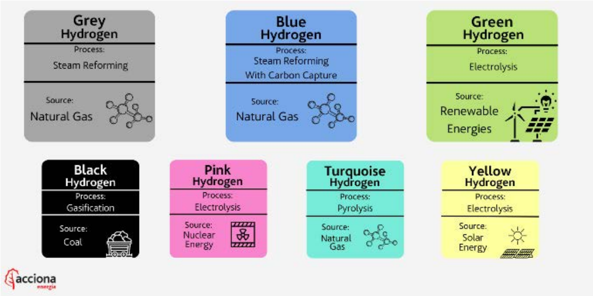

Figure 7: Hydrogen production categorization

Source:https://www.acciona.com.au/updates/stories/what-are-the-colours-of-hydrogen-and-what-do-they-mean/

From these categories carbon natural and renewable are only the Green and Yellow and by many the Biomass gasification method is considered to be one such method as well. This is based on the fact that biomass is created by absorbing carbon, most commonly via photosynthesis, from the environment and then the carbon is being released back during gas production and consumption. Biomass is also using byproducts of another processes, like olive oil and livestock production, sewage or garbage disposal, and utilizing them. These byproducts would be otherwise left to naturally decompose releasing ammonia, methane, carbon oxides and many other pollutants to the environment, that by gasification, and especially if combined with CCS methods, can all be collected and turned into either nonpolluting subsenses or stored safely. So, by using biomass not only non-renewable resources are being saved and waste is also being reused, helping, that way, other sectors reduce their final environmental footprint as well (39). In the market today close to 95% of hydrogen is derived from natural gas, oil reforming and coal gasification with about 80% of it without any CCS method implemented. Almost 5% comes from electrolysis with most as a byproduct of sodium hypochlorite production, and a small percentage being eventually from electrolysis with renewable sourced power (40). After taking into consideration that after reforming the hydrogen has 75% of the energy the consumed natural gas contained, it is pretty obvious that in the transportation sector especially, after the losses that occur during storage transportation and conversion back to electricity, where necessary, is probably not even an improvement over using straight up fossil fuels at this time (41). This huge partition of grey hydrogen is due to the low cost and simplicity of naturel gas reforming and the relatively big cost of carbon capture technologies. Currently it is estimated that the cost increase for implementing CCS ranges from 44% to 60% (42). All these are projected to change with organizations like the IEA (International Energy Agency) estimating a rise in demand for hydrogen of 50% from 2022 to 2030 accompanied by a plethora of new production facilities being planned or built, all of which are meant to be for green or blue hydrogen, meaning that they are all expected to be renewable powered, or have some form of CCS implemented (43). European union is has created a framework in order to support the transition to hydrogen and push it to become green by designing big infrastructure projects and subsidizing the build of storage and production facilities , especially near already existing or planed green energy production facilities, in order to promote hydrogen as a storage of green energy, increase its flow in the European industry and lower its price (44). Many countries around the world are also promoting hydrogen and ammonia, which is also made from hydrogen with the addition of nitrogen, as the best fuel for the green transition. The way this is done is by subsiding with many infrastructure projects such as pipelines and refueling station constructions as well as investing in many companies that have shown promising research results or innovative ideas. Technologies are also improving rapidly with many advances in electrolyzer technologies and transportation methods and equipment that help eliminate the losses (45). A great example of all these is Hysata, which is an Australian electrolyzer manufacturer, whose innovative product features a capillary feed electrolyzer **(Figure 8)** and delivers up to 95% efficiency, a big improvement over the 75% efficiency offered by the available options on the market today, and is reported to have received 20.9 million AUD in subsidies to boost its manufacturing and eventually scale their production (46). Additionally new production methods are being put into trial or are being tested to determine if they can go to scale like biohydrogen production. Biohydrogen is a product of microorganisms like algae and bacteria which by changing

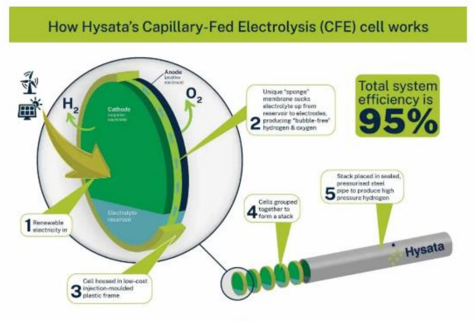

Figure 8: Hysata's capillary fed electrolyzer.
Source:https://reneweconomy.com.au/breakthrough-bluescope-vestas-back-42-5m-raising-for-australian-hydrogen-start-up/

environment conditions (Ph, humidity, temperature, sulfur content etc.) or by giving them specific feed can shift from what they naturally produce to making H2 (47) (48). As of today, using hydrogen as fuel doesn't make things much more environmentally friendly. Nevertheless, hydrogen is considered and expected by many to play an important role in the energy sector in the near future and with that many investments and projects on the horizon it seems quite likely to actually be.

4) Hybridization benefits in popular sectors

The commercialization of UAVs has uncovered so many applications and uses for them, especially in the hands of professionals for various jobs and work fields. Hybridization has come to improve even more on the capabilities and extend the use in even more fields. The most benefited fields of use are: first response, security and surveillance, agriculture, dusting and flora development monitoring, and finally parcel and equipment transportation.

4.1) Security and Surveillance, Inspection and First Response.

Safety, in general, is the field that will always be in the prosses of further improvement. Drones have been revolutionizing many procedures in this field with the most notable usage examples being first response, in the form of providing first aid, defibrillator and establishing network connection in remote areas for emergency communication, surveillance and data collection for police, military and finally helping technicians do inspections in hard-to-reach installations. Hybrid drones could make an impact in all these sectors, since the longer flight times unlock huge potential and many new uses. Police in the U.S. in the past decade has been successfully adopting conventional drones for responding to emergency calls for non-life-threatening emergency calls, like a burglary with no hostages, or to obtain vision and assess a situation or a suspect that could potentially put an officer in danger (49)(50). This use despite making a big impact, helping on saving the lives of crime victims, putting officers out of danger and ensuring that crime suspects are getting in custody faster has more potential yet to uncover. As mentioned in past paragraphs, typical battery powered multicopter drones can fly for roughly 20 to 30 minutes while their hybrid counterparts can go for up to 90 minutes and a winged for up to 8 hours (51), this huge increase in flying time means they can be used for highway patrolling in almost every part of interstates and country roads. They can also be used for patrol since operating them might not be cheap overall but, depending on the cost of operating a patrol vehicle, it can potentially be more efficient to use drones equipped with cameras operated by humans or even equipped with some form of AI to recognize movement and objects and assess the danger before sending the proper response (52). Currently drones used for construction and installations inspection are limited by the distance they can fly before needing to recharge thus limiting the area that can be covered in one go and the distance of the lunching site to the inspection area. The extended range of Hybrid systems can substantially increase the efficiency the inspection takes place in many usage cases like onshore and offshore wind turbines, solar panel fields, power cables and pylons, factory bridges, tall chimneys and flare towers, even when they are actively working (53). Drones have also been utilized in healthcare and emergency response by delivering AEDs and first aid kits, samples of biological material to take faster results, blood packages and for carrying antennas in order to create a network for ground search and rescue units or for remote vehicle and machinery operation (54). The longer endurance and higher payload will benefit all the prementioned activities by carrying out more first aid equipment further, supporting more remote areas while retaining the transportation and logistics cost relatively low.

4.2) Agriculture

Pesticide application has been in practice from ancient civilization with Sumerians using sulfur and Persians, later, using Pyrethrum for removing unwanted insects for the gardens. The last two centuries the advancements in chemical industry and the continuously growing demand for food has made spraying pesticides and fertilizers a necessary part of the agriculture industry (55). Drones developed and started being used in this industry in the mid to late 90s, with the pioneer being Yamaha with the RMax **(Figure 9)**, a single rotor ICE powered drone, which was originally used for spraying rice fields in rural Japan helping farmers to overcome the difficulty they had from carrying equipment in the fields due to the elevation the mountainsides caused (56). The remarkable developments of the past decades in UAV technologies have extended the uses in the precision agriculture segment, such as crop and monitoring, yield prediction, crop and plant classification, weed detection, early detection and prevention of diseases while offering high efficiency, cost-

Figure 9: Yamaha RMax
Source:https://www.researchgate.net/figure/Yamaha-RMAX-permission-obtained-6_fig1_348685843

effective process monitoring and increased profitability. Currently all these are served by either small battery powered drones or by big drones with ICEs of small, fixed wing planes, with no hydrogen hybrids mentioned to have implemented yet. Although the little implementation there are models available on the market, like the H2D55 from HEAVEN DRONES **(Figure 10)**, and there is prediction that show a massive rise in the use of drones in the sector (57). Their main benefits are that they are versatile as far as exchanging payload for flight time can make them a good option for dual purpose drones. They could be either equipped with a high-resolution camera and advanced operating systems for monitoring and recognizing plants, growth rate and abnormalities or be equipped with a tank, pump and spray nozzle to be used as a duster that if configured right could be refilled with hydrogen and pesticide/fertilizer at the same time fast and efficient on the field (58). Also it is much greener and safer option than the ICE powered drones and small planes that consume gasoline diesel or low lead aviation fuel since all these usually contain additives to help combustion and have quite low environmental standards , substantially lower than the ones applied in the road going vehicles, producing that way more particles and volatile hydrocarbons that end up in the exhaust gasses and eventually on the crops that are destined for consumption and can end affecting the end consumers health (59).

Figure 10: HEAVEN DRONES H2D55
Source:https://agtecher.com/el/%CF%80%CF%81%CE%BF%CF%8A%CF%8C%CE%BD/h2d55-hevendrones

4.3) Last mile delivery

The rise in e-commerce of the last two decades spiked the demand for transport and delivery services thus reshaping the logistic sector in general. To handle the workload and be able to deliver parcels in competitive times and cost, innovations took place like automatic shorting systems like warehouse item picking and transporting robots. A use was also found for drones, which have proven very effective when it comes to doing a single delivery like food or parcel fast delivery services. (60) Drones also enabled the expansion of delivery services to more remote areas while having a relatively low environmental impact since operating drones have proven less impactful than their truck equivalent (61) (62). Hydrogen hybrid drones offer extended range and better load capacity, thus enabling the delivery companies to extend the fast delivery option for heavier orders, more remote places or to deliver multiple parcels at once (63). Hydrogen refueling stations for such drones, also, take up less space than their battery charging station thus making them more space efficient for installing them on existing courier centers or for equipping delivery trucks, which can also be hydrogen hybrids, with mobile refueling stations and applying a hybrid drone and truck delivery model, in which the truck is used as a small mobile hub and drones make the final deliveries (64).

5) Drone built by the Mechanical Engineering Department of the University of Thessaly

The past couple of years a small group of undergraduate and postgraduate students under the supervision on Dr Bouzakis Emmanouil have studied and designed a hybrid UAV **(Figure 11).** The project started as proof of concept and as an interesting and innovative technological field for students to work on, learn about and do their thesis on. The drone was modeled with the purpose of last mile delivery, a very hot topic of use examined and tested by many companies globally. The initial target set was a vertical takeoff UAV that would be relatively cheap to manufacture, utilized as many off the self and easily accessible components, capable of flying for at least two hours, reach speeds of up to 30 km/h and carry a maximum payload of two kilograms.

Figure 11: Hybrid UAV by Uth
Source: Karagiannis Christos

5.1) The design of the drone.

After research and simulations, the design the team came up with was a frame that consisted of two Carbon Fiber Reinforced Polymer (CFRP) plates (EasyComposites 250x470x1mm) held together by metal studs with plastic parts in between to create space and to connect the frame with the four arms ,that consist of Carbon Fiber Square Box Section (EasyComposites 20-17), extending out in order for the four electric motors (T-Motor U8 II KV150) to attach on and to create space for the four propellers (T-Motor G28*9.2 CF) to clear the frame. The size of the basic frame was modeled around the size of the hydrogen storage tank which was chosen to be a 3L tank (H3DYNAMICS F3 (3L)) capable of holding 63 g of hydrogen at a pressure of300 bars. For the powerplant an 800W fuel cell (H3Dynamics Aerostack A-800) was chosen, which is a 45-cell PEM with operating temperature ranging between 0°C to 40°C. Other components used are the speed controllers (T-Motor Alpha 60A 12s), the battery (8s - 29.6v - 5000mAh – 65C), a hydrogen pressure regulator (H3DYNAMICS), carbon fiber tubes (EasyComposites 8-7) used for landing legs and many 3D printed parts used as bases, brackets and mounting points necessary for the assembly. After calculating the mass of the parts, it added up to 7.33 Kilograms and after adding the 2Kg payload it reaches 9.33Kg which after accounting for the 62gams of hydrogen that can be supplied from the tank, it makes up to 130 minutes of flight time.

A secondary concept that was also examined for later development was the ability to extend the operation of the drone to environments with temperatures above 45°C, which is over the maximum operating temperature of the FC. To accomplish this the idea of using aluminum as the central piece of the main frame and heatpipes to transfer heat from the FC to the foam to be dissipated to the environment, was examined and simulated. Aluminum foam is an advanced material that combines high strength to weight ratio, high surface area per unit volume and its rough and porous surface improves drastically the thermal performance compared to plane aluminum sheet (65). Design has shown promising results and is definitely a field that could be further research.

5.2) The use of FDM manufacturing in the project.

As mentioned before, one of the key goals of the project was for the drone to be easy and cheap to build. For that reason, the Fused Deposition Modeling (FDM) method, commonly known as 3D printing (3DP), was used to create some additional custom parts needed. The material of choice is PA6-CF12, a polyamide reinforced with carbon fibers. The parts are proposed to be treated afterwards by annealing them in salt powder, which essentially is remelting the polymer to unify the material and remove the effect of layer adhesion, thus eliminating anisotropy in the tensile strength (66). This material was the preferred one due to its stiffness, high strength-to-weight ratio and relatively high temperature resistance and its availability.
(67)

6) Fused Deposition Modeling

6.1) An introduction to Fused Deposition Modeling.

Additive Manufacturing (AD) technologies are an advanced type of processes used to create parts and objects by fusing or depositing the necessary material together. ISO/ASTM 52900-15 is dividing AD into seven distinct process categories (68):

1. Binder jetting: A Bonding Liquid is selectively injected into powdered material forming that way a part that is considered a form of composite material.
2. Direct energy deposition: Thermal energy (e.g. laser, plasma arc, or electron beam) is used to momentarily liquify and fuse material as it is being deposited.
3. Material extrusion: Material is extruded and selectively deposited through a nozzle.
4. Material jetting: Droplets of material are deposited and then solidify.
5. Powder bed fusion: Thermal energy is used to fuse specific regions of a layer of powder together and with the solidified part of layer directly under.
6. Sheet lamination: Sheets of predetermined shape and material are bonded together, forming a solid object.
7. Vat photopolymerization: Liquid polymer inside a Vat is selectively cured by light activated polymerization thus solidifying to uniform piece.

From these methods the four most used are: [1] Stereolithography (SLA) which is a form of Vat photopolymerization developed in the early 80s, [2] Selective Laser Sintering (SLS), a form of powder bed fusion, developed in the mid-1980s, [3] Fused Deposition Modeling (FDM), A type of material extrusion, developed in the late 1980s, and [4] Polyjet modeling (PJM) ,which is a form of material jetting developed in the early 2000s (69). FDM was specifically patented and trademarked in 1989 by Scott Crump, who later founded STRATASYS and in cooperation with IBM Watson brought in 1996 the first 3D printer in the market. The fact that the name is trademarked is the main reason the prosses is most often referred to as 3D printing or Fused Filament Fabrication (FFF) (70). Since then, hardware and software have come a long way and 3D printers have gone from being expensive machines used only by companies and labs for Rapid Prototyping and for small baches of parts, to being obtainable for relatively cheap and operatable by anyone with basic knowledge and instructions, thus having become the most used type of all the AM process (71). All in all, the FDM manufacturing process is nothing complicated but in order to be created other advancements had to take place before in semiconductor and hardware technology and in computer and material sciences.

6.2) How FDM works

The way FDM works **(Figure 12)** is that an extruder heats thermoplastic and then forces it through a small hole on the tip of the extruder's nozzle. The material as it comes out of the hole is deposited on a usually heated platform and as the extruder moves it creates a 2-dimensional shape forming a layer. When the layer is completed either the extruder moves up or the building platform goes down enough so the next layer will be extruded on top of the already existing one. Repeating this prosses multiple times will eventually build up a 3-dimensional object and as the thermoplastic slowly cools down it gains back its original material properties having now being reformed to the desired shape. The guidance the machine follows in order to perform the right moves to form the object correctly is provided by the user in the form of instructions written in some programming language, usually G-Code, which is the most widespread Computer Numerical Control (CNC) programming language used for computer aided manufacturing (72). These instruction sets are created by programs called slicing programs or slicers and are and take into account all the necessary steps and parameters needed to create the part, such as layer height, nozzle speed, diameter and temperature, material type and the object stereolithography file (.stl), which is created by a computer aided design (CAD) program and depicts the exact size and form of the desired object (73) (74). The most common form the material is being fed in is in the shape of a filament, thus the prosses is also referred to as fused filament fabrication (FFF) (75). Some extruders are designed to be fed with material in the form of granules (sometimes referred to as pellets), the form that polymers are produced in the first place and is referred to as Fused Granule Extrusion (FGE) **(Figure 13)**. What sets the two methods apart is that pellets are cheaper than filament, since they

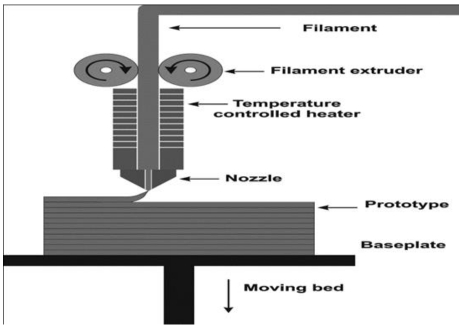

Figure 12: FDM operation schematic
Source:https://www.researchgate.net/figure/Schematic-of-an-FDM-3D-printer-Reproduced-with-permission-from-12_fig1_292985550

require no extra process to be produced, allowing for lower production costs. Additionally, the granule feed mechanism is larger than the filament one, taking up more space and is unable to adjust material feed rate momentarily thus making the 3d printer suitable for larger, lower resolution objects that require no supports and don't have big overhangs. All these attributes make FGE a very well-suited method for near-net shape printing (76). The way this method of manufacturing functions is taking advantage of the plastic properties materials exhibit when heated above a specific temperature, thus the compatible materials are thermoplastics and composites with thermoplastic matrix. Most commonly used materials are: (77)

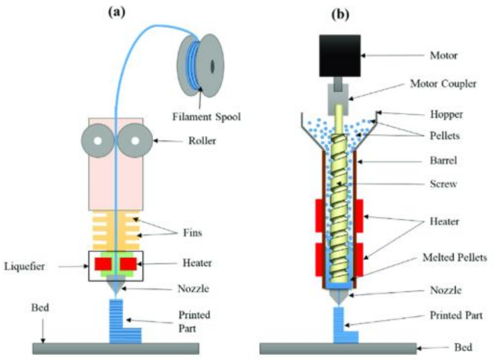

Figure 13: FFF to FGE comparison
Source:https://www.researchgate.net/figure/Schematic-of-a-FFF-process-and-b-pellets-extrusion-process_fig1_351945696

1. Polylactic Acid (PLA)
2. Acrylonitrile butadiene styrene (ABS)
3. Polycarbonate (PA)
4. Polyethylene terephthalate glycol (PETG)
5. Nylon
6. Thermoplastic polyurethane (TPU)
7. Acrylonitrile Styrene Acrylate (ASA)
8. Polyetheretherketone polymer (PEEK)
9. Thermoplastic elastomer (TPE)
10. Polyethylene terephthalate (PET)
11. Polyetherimide (PEI) (marketed as ULTEM® resin
12. Polyvinyl alcohol (PVA)
13. High impact polystyrene (HIPS)
14. Carbon fiber composites usually with Nylon, PLA or PETG matrix
15. Kevlar composites
16. Fiberglass composites
17. Metal powder incorporated filaments

6.3) The impact on various industries.

The FDM process has many advantages and thus it has managed to revolutionize many industries and bring improvements to various sectors. A major improvement happened to the product design process as it offers fast, cheap and simplified Rapid Prototyping, allowing for many tries and versions of parts and products before finalizing the design without requiring molds or timely handcrafting.

All these lead to saving manufacturers time and money and offering to end consumers better and more refined products. Material technology and the capabilities of the machinery have advanced a lot since FDM was first patented, offering a wider selection of materials for various uses, improved properties and advanced extrusion techniques that can extrude more complex shapes, are faster and require lower maintenance. This technology is used for many purposes in the automotive and aerospace industry, in textile manufacturing, in the ballistics sector, in pharmaceutical and medical industries, in electronics, robotics, construction, culinary arts. (78)

6.3.1) Automotive and aerospace industry.

The capabilities and latest developments of FDM manufacturing have caused the aerospace and automotive industries to adopt this method and use it in various applications. Extrusion machines (3D printers) can create relatively fast, cheap and with great accuracy molds, usually short lifespan ones, that are a great fit for making prototypes, experimental models and for small baches of parts. The ability to extrude composite materials with continuous fibers makes possible the creation of lightweight parts with competitive, relatively to other methods, strength to weight ratio. Adjusting the infill of parts built with FDM either by just changing the infill ration or by changing the shape/pattern of the infill is another advantage that allows for convenient control of the strength to weight ratio of parts and the impact behavior, both of which are very important aspects when designing parts that need to crumble to absorb impact or to fail in specific ways to protect a vehicle’s passengers or other more important components (79).

6.3.2) Textile and fabric industry

3D printers have the capability to create complex designs with great precision. This makes them a more suitable option, than traditional methods, for creating prototypes or even end products in some cases. For textiles there is a huge selection of natural fibers available with various properties, depending on origin, with one common characteristic, their relatively high roughness that makes it easy to adhere thus making them a great material for 3D printing (80). These fibers in order to adhere to cellulosic fabrics are combined with pastes, which are cellulose acetate or other biomaterials (81). Knitting fabrics is something that with the current materials is not a better option than the traditional methods, although there are some designs with limited implementation that have been used. Most notable is NASA's "Space Fabric" **(Figure 14)** that is based on a chainmail design and was created originally with the purpose of use in deployable devices that should be able to fold and if proven successful even for capturing thing, protecting astronauts and equipment and for creating a footing that won't melt on ice or sink in sand surfaces (82).

Figure 14: NASA's Space Fabric
Source:https://www.core77.com/posts/65465/NASAs-3D-Printed-Metallic-Fabric

6.3.3) Ballistics industry

Evolution of weaponry brought also evolution in armor against them, with the lates development being the MAS (Multilayer Armor System), which is built using multiple layers of usually synthetic materials including Kevlar and aluminum. NFRPCs (Natural Fiber Reinforced Polymer Composites) are a new type of material that has proven that if used at a fiber volume fraction of at least 30% it has great and structural integrity that can replace Kevlar layers in MAS armors (83). Nanocomposites are materials that are currently examined and are showing promising results. Specifically, the addition of Nano-clay or graphene in glass epoxy composites improved fiber-matrix adhesion and fiber-matrix interface bonding resulting in better energy absorption, especially in high velocity impacts (84). Using FDM to create armor with such composites can minimize material waste, require fewer active labor and makes equipment fitment personalization easier, with the best example of this use being the production of

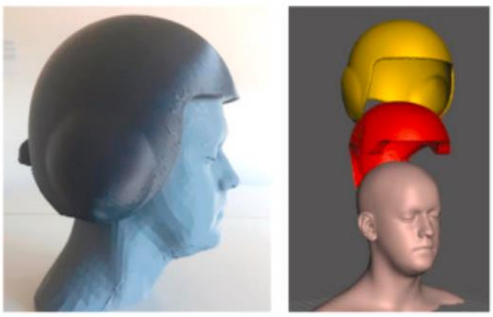

Figure 15: ballistic helmet personalized liner
Source:https://www.sciencedirect.com/science/article/pii/S2405844024033590

ballistic helmets that are labor intensive have multiple layers and are hard to be a perfect match on the user's head **(Figure 15)** (85).

6.3.4) Pharmaceutical and medical industry

FDM is a method that has deeply penetrated the pharmaceutical and medical industry with many active uses already and many more being subjected to trials and experiments. 3D printing offers a flexible, adaptable and on demand solution for a wide range of requirements, including personal protective gear, medical equipment, and even temporary isolation facilities. This technology's versatility makes it an ideal tool for mitigating the consequences of socio-economic shifts and supply chain disruptions, allowing for rapid production of critical items as needed. During the COVID-19 pandemic its impact was substantial, especially in the first months when the demand for medical equipment spiked, and the supply plummeted due to quarantines. (86) Biomaterial use is a great fit in the medical sector as organic materials are better for use on and in humans and are more acceptable by public, with a great example being the addition of natural fibers to common polymers creating stronger, lighter materials and which depending on the fiber type can exabit antimicrobial properties, breathability and texture improvements. (87) FDM manufacturing is a good match in the field of biomedical structures and prototypes, which includes a broad spectrum of uses, from surgical procedures and orthotics to implants, as well as educational tools in anthropology and medical training. One of the notable benefits it has is its ability to create complex composite structures with locally controlled properties, achieved by adjusting deposition density and strategy. This enables the creation of distinct regions within a part, mimicking the characteristics of natural bone, and accurately modeling the non-uniform variations in material density and distribution within a region (88). Nanotechnology enables the creation of materials that can mimic the intricate properties of biological tissues, including electrical conductivity, chemical activity, and responsiveness to stimulations, thereby bridging the gap between synthetic and living systems. Biopolymers can be utilized for synthesizing nanocomposite materials suitable for three-dimensional scaffolds **(Figure 16)** for targeted drug delivery systems, tissue engineering, wound dressings, and antimicrobial films (78).

Figure 16: Biopolymer scaffold
Source:https://www.aniwaa.com/buyers-guide/3d-printers/3d-bioprinting-3d-bioprinters/

6.3.5) Electronics

Mixing conductive materials in polymers creates composites that can, depending on the filler content, achieve high electrical conductivity. Fillers used are typically carbon-based materials like graphene and the final composites formed are corrosion resistant, light and easy to shape offering an easy way of creating simple circuits and a good substitute for other metals in applications like sensors, coatings, batteries, electrodes and magnetic field insulators (78). Conductive composites can also be integrated (Figure 17) into designs and given the higher elasticity of the polymer matrix, compared to copper, alumina and carbon traces, more flexible and durable circuits can be created with a single manufacturing method (89).

Figure 17:Integrated circuitry

Source:https://www.researchgate.net/publication/261718977_3D_Printing_for_the_Rapid_Prototyping_of_Structural_Electronics

6.3.6) Robotics

Most research taking place on FDM with composite thermoplastics is limited to materials with reinforcement of short fiber additives that can be premixed, made into a spool of filament and then use it directly in the extruder of conventional 3D printers. The use of robotic arms and 5-axis machines, that can extrude in every direction they can reach, has enabled the experimentation with long continuous fibers that can be inserted into the stream of flowing thermoplastic. Optimizing the direction the fibers are placed can take full advantage of the fibers strength resulting in very strong parts. This way of forming fiber reinforced parts is advantageous compared to the conventional methods since it doesn’t require a mold to be made for every different design, the part’s geometry is not limited to a design that can fit in a mold and it can create single piece hollow parts leaving little waste material in the end (90).

6.3.7) Construction industry

The construction industry is a sector that takes time to change and adopt new technologies. While the rest of the industries have moved to the digital era and have adopted modern manufacturing techniques and digital technologies, house and infrastructure building is done the traditional way with limited improvements, mostly in materials and energy efficiency. Experimentation and limited use for projects orientated to proof of concept have been done with large extrusion machines. These machines are either designed like a scaled-up 3D Printer **(Figure 18)** or, most commonly, designed like a large robotic arm, they are utilizing big feed mechanisms and large nozzles and use as a building material fast setting cementitious materials with various additives called “modifiers” to enhance their properties and setting time (91). Building is done the same way as with small scale objects with limitations to overhangs and vertical slope since the pastes used take significantly more time than common thermoplastics to harden. Additional mortar needs to harden fast enough to support the weight of the subsequent layers, but not so fast that it prevents adequate bonding between the layers (92). Often reinforcements are added manually and strategically by inserting steel rods between the layers or by piercing the layers of the construction before the material hardens. When designs call for windows and doors the machines are paused and the frames are added in place, ensuring good fitment and seal as the material is still relatively soft, and then the extrusion is resumed. Experiments have been carried out by prepositioning in the building site the plumbing as well, saving with this technique time and cost. Time saved is so significant that this method has been proposed as a solution for creating shelter in natural disaster occasions. The construction industry is accountable for roughly 37% of the total greenhouse gases emitted globally, which

Figure 18: Large cement paste extrusion machine
Source:https://www.3dnatives.com/en/3d-printing-construction-240120184/

can be significantly improved by the utilization of new techniques and materials (93). FDM in combination with low-carbon materials like clay-rich soil, sand and straw mixtures or other materials as a bio- stabilizer, are tested as a way to reduce carbon footprint of small residence and construction. (94)

6.3.8) Culinary arts

3D printing has extended its application in the food sector and has opened new abilities, techniques and designs for food production. Taking advantage of the latest developments that allow for precision, variation in texture and shape, and in combinations with edible ingredients can achieve consumer acceptance and sensory perception of foods. The variety of edible materials available is wide, including chocolates, fruit and vegetable purees, doughs, and protein blends and is constantly expanding. Food 3D printing enables nutrient and portion control while minimizing food waste making it a useful tool for space exploration and remote places, like Antarctica research centers (95).

7) Comon types of materials for FDM

As mentioned above FDM manufacturing is taking advantage of the change in phase and plastic properties materials exhibit when heated to a specific temperature. To understand material behavior, it is important to note that the two key temperatures are the glass transition temperature (Tg), where the material transitions from a solid to a fluid state, and the melting temperature (Tm) at which the material turns form solid or rubbery to a liquidus state. The temperature that is important for this process is Tm, as the material is liquid and exhibits no elastic properties thus retaining no stress when extruded out of the nozzle and having no risk of deformation from residual stresses (96). Additives are usually mixed into the polymers in order to enhance various properties like Young's modulus, friction coefficient and humidity absorption. This temperature is not standard, and it varies depending on the type of material and the additives it contains. This is important since two filaments or granules of seemingly the same material that are produced from different manufacturers might have different additives that either as a side effect or on purpose can change the Tm (73). The plethora of materials and modifications to their consistency is huge and in the next paragraphs the properties and uses of the most common of them will be quoted

7.1) Simple materials

Thermoplastics are a big category of materials which is well established in the industry and in most people's everyday life. FDM manufacturing is taking advantage of the thermoplastic's properties and with its capabilities attend their use to new fields or improve on the existing ones.

7.1.1) Polylactic acid (PLA)

Polylactic acid is a lightweight, eco-friendly polymer that can biodegrade within the body and is also compostable. It is a semi-crystalline bio-based material that is derived by fermenting corn starch, sugarcane, or cassava roots and offers a promising alternative to traditional plastics. (97) PLA print temperature range of 160 to 230 degrees Celsius, which is in the lower side of the spectrum, and doesn't need a heated bed to avoid deformation, making it a convenient choice. Notably, PLA is non-toxic, cost-effective, and exhibits impressive physical properties, including hardness and strength, although being susceptible to brittleness (98). Its biodegradability, the ability to host other materials acting as matrix in composites, combined with its excellent physical and biological properties, makes it an ideal material for a wide range of applications, from tissue engineering to biosensors (99).

7.1.2) Acrylonitrile butadiene styrene (ABS)

Acrylonitrile butadiene styrene is among the first materials developed for FDM and it is derived from petroleum. It requires temperatures between 215°C and 250 °C to print and due to the high heat, it has a tendency to warp during cooling, thus requiring a bead heated between 90°C to 120°C to print right. ABS is cheap to manufacture, resistant to wear and impact, and can withstand higher temperatures as its Tg is 105°C, but its high temperature requirement and bad UV resistance make it a choice for specific only applications (100). Despite these limitations, ABS has found numerous applications, such as the creation of microdevices and microfluidics (73).

7.1.3) Acrylonitrile styrene acrylate (ASA)

Acrylonitrile styrene acrylate has a structure similar to ABS with similar material properties, print settings and abilities. It was developed as a weather resistant alternative since its noticeable difference to ABS is the significantly improved UV resistance (101).

7.1.4) Polyvinyl alcohol (PVA)

Polyvinyl alcohol is a water-soluble synthetic polymer. It is printed using the same settings as PLA and is mainly used as support material, as it is easy to remove by soaking the object in water (100). It also has other more advanced applications like dental models and for the creation of a biomaterial in which it is combined with cells for regenerative medicine (102).

7.1.5) Thermoplastic elastomer (TPE)

Thermoplastic Elastomers is a flexible material that can absorb and distribute loads through deformation. Printed at temperatures between 180°C and 230°C, TPE does not require a heated bed, allowing for a simpler printing process. Due to its flexibility, TPE filaments have to be fed directly into the extruder, without having to go through a Bowden tube first, to ensure smooth and consistent printing (103). Its properties have made a significant impact in the textile industry, enabling the creation of printed clothing that is comfortable and durable. Additionally, TPE is also used in the production of personalized orthotic insoles, which provide optimal support and comfort for individuals with foot-related issues (104).

7.1.6) Polycarbonate (PC)

Polycarbonate is a transparent material that can withstand high temperatures, has some flexibility and is very impact resistant. The high temperature resistance, though, translates to high print temperatures of 200°C –280°C and bed temperatures of between 80°C and 100°C (105). Regardless of these disadvantages PC's exceptional biomedical properties have made it a popular choice for a wide range of applications, including orthopedic and dental uses, as well as tissue engineering (106)

7.1.7) Polyethylene terephthalate (PET)

Polyethylene terephthalate is a petroleum-based thermoplastic, printed at temperatures between 210°C and 230°C and has similar properties to ABS being strong flexible, cheap and biodegradable with the disadvantage that it absorbs moisture. Its biocompatibility though makes it a great option for biomedical scaffolds to support tissue growth (107).

7.1.8) Polyethylene terephthalate glycol (PETG)

Polyethylene terephthalate glycol is a modified version of polyethylene terephthalate (PET), where glycol has been incorporated to enhance its properties. Ideal extrusion temperatures are in the range of 220°C –250°C and a bead heated to 60°C is also required (108). It offers superior tensile strength, flexibility and chemical resistance, with the only drawbacks being the high porosity which can be actually desirable in some applications like bone models and orthopedics (109).

7.1.9) Polyetheretherketone polymer (PEEK)

Polyetheretherketone polymer is a polymer of organic origin that exhibits great mechanical properties, chemical resistance, biocompatibility and lubricity. It is significantly more elastic than PLA and ABS, yet it requires very high extrusion temperatures of 330°C to 440°C, which by many 3D Printers are not achievable (110). PEEK has a wide range of applications from aircraft parts, racing cars, drones up to joint replacements, spinal implants, joint replacement, prosthetic devises and dental devices (111).

7.1.10) Polyamide (PA)

Polyamide or Nylon, as most people know it, is a petroleum derived polymer. It is known for its impact resistance, tensile strength, low friction coefficient and for its low creep potential that allows it to operate at temperatures of up 120°C for prolonged periods of time. Nylon in order to print needs temperatures between 220°C to 250°C and bead temperature is recommended to be 95°C (112). It has many applications in the automotive industry for friction and deformation resistant parts and molds. Nylon is also biocompatible, making it a viable option for prosthetics (111).

7.1.11) High impact polystyrene (HIPS)

High impact polystyrene is a polymer capable of withstanding high impacts and is mainly used for prototyping. To print properly it needs 210°C to 240°C and a hot bed between 80°C to115°C (113). Due to its comparable printing conditions to ABS and its solubility in limonene, it is used as support material for ABS structures in biomedical applications, enabling the creation of complex geometries and internal structures that can be easily dissolved away (114).

7.1.12) Cellulose materials

The increasing demand for sustainable and eco-friendly materials has sparked high interest in cellulose-based materials as they are accessible, flexible, low cost, and biodegradable. As a result, cellulose materials are being explored for a diverse range of applications, including decorative elements, medical devices, electronic components, and innovative textile products (115).

7.2) Composite materials

The different combinations of thermoplastic materials with other reinforcement or properties enhancing materials are endless, making composites a huge category of materials and depending on the matrix and the additive they can display all sorts of properties. Their uses and applications are plentiful, and it is no surprise that they are also used extensively in FDM manufacturing.

7.2.1) Polylactic acid with graphene

Graphene is a revolutionary material with many applications, one of which is mixed in small ratios to PLA in order to give to the material exceptional biological and physical properties like enhance mechanical resistance and substantially increase thermal and electrical conductivity. To print such composites temperatures between 210°C and 230°C are required and due to the thermal conductivity of graphene the bed must be heated too (116). This composite has mostly biomedical uses as it can be used to improve cell proliferation with electrical stimulation, for tissue engineering, to make surgical tools and for electromagnetic shielding (117).

7.2.2) Polyamide with carbon fibers

Carbon fibers are one of the most well-known additives used in composites. When added to polyamide it forms a material with great strength to weight ratio, the ability to rupture progressively when overstressed, great shock absorption, heat resistance and low moisture absorption. The addition of the fibers helps to prevent warping during printing thus making it relatively easy material to work with. This composite though, when untreated, is anisotropic and especially when printing with one single continuous fiber **(Figure 19)** that is inserted in the polymer flow stream (118). This can be used as an advantage when a part requires more strength in a certain direction. Carbon Fibers reinforced Polyamide is a very popular material among engineers and hobbyists used in many industries, from automotive to aerospace, and being capable and trusted for creating structural parts.

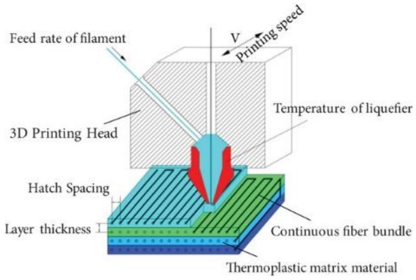

Figure 19:Continius fiber embedding
Source:https://onlinelibrary.wiley.com/doi/10.1155/2022/5424839

Similar to Carbon fiber, other types of ceramic fibers can be used such as Kevlar, Glass and natural fibers like wood, that are more economical, but don't offer that high tensile strength. Other polymers can be used as matrix materials as well offering the correlated changes in properties.

7.2.3) Steel infused polymers

Steel infused polymers are created from the addition of steel powder, most commonly 316L **(Figure20)**, to various polymers and their final properties can change depending on the metal particle content. When the polymer is the dominant material, the results are materials that have the looks of metal but the benefits of a polymer. Although being more brittle they are relatively easy to print, cheap, have improved thermal conductivity, can conduct electricity, can be sanded to near mirror finish and feel like metal to the touch. They are used mostly for cosmetic purposes and for special applications like creating embedded circuitry into parts. When the metal is dominant the composites need more additives to bind than just the polymer but possess great mechanical properties and can be used for tooling, prototypes and small production baches (119).

Figure 20: BASF Ultrafuse 316L filament
Source:https://www.matterhackers.com/store/c/basf-3d-printing-filament-and-materials/basf-ultrafuse-316l-metal-3d-printing-filament

Similar to steel, other metals like copper or silver can be used to give the composite the corresponding properties like being a great electricity conductor or being antibacterial.

8) Case study: Comparing fabrication cost of FDM and Injection molding.

In the past 2 chapters the characteristics of FDM manufacturing were examined and despite seeming very promising, at this moment the most commonly used method of thermoplastics manufacturing is injection molding. To compare the two methods the example of manufacturing the motor mounts **(Figure 21)** of the drone described in chapter 5 will be used.

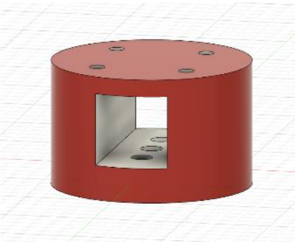

Figure 21: Motor mount. *Source: Hybrid Drone Design (67)*

8.1) Fabrication with FDM

The motor mount is a relatively simple design that shouldn't pose an issue for the majority of commercially available 3D Printers. Currently the fabrication on a Bambu Lab P1S will be examined. The P1S has a building area of 256 x 256 x 256 mm, meaning that 16 parts can be printed at the same time. After considering the recommended settings for Polymaker PolyMide PA6-CF (120) and the structural requirements of the part (100% infill) the time needed for a batch of 16 parts is 1day 16hrs and 26min (40.433 hours) **(Figure 22)**. According to Bambu Lab this 3D Printer is calculated to consume 140w/hr (121), resulting in 5.66 kWh in total for the batch. With an average price of 0.2173€/kWh for 2024 the energy cost is 1.23€ (5.66kWh*0.2173€/kWh=1.2299€). The batch consumes 1020.45grams of material which at the time of calculating is valued at 100€/kg, resulting in 102.04€ per run. For each batch the manual labor of removing the finished parts and preparing the machine for the next is estimated to be roughly 30 minutes, which is valued at 2.9€ (968€/month*(6/25)/8=5.8€/hr for a minimum wage worker). In terms of cost these all add up to: 1.23+102.04€+2.9€=106.16€ per batch or 6.63€ or 6.91$ (USD) per part. During these calculations the cost of the equipment and its maintenance is not taken

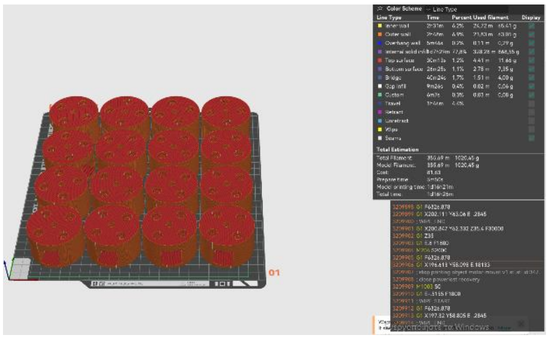

Figure 22: Bach of mounts estimation. Source: Orca slicer

into consideration, as they are too complex and very often come to the personal preferences of the operator for choices like the type of printer and nozzle. This cost per part is steady and can't change no matter the amount of parts produced in total.

8.2) Fabrication with injection molding

Parts created with injection molding have some limitations as far as geometry goes. They must not have thick walls, as it can lead to shrinkage and deformation during cooldown and should be able to come out of the mold easily **(Figure 23).** For this case study we assume that the only change in design will be splitting the part to two separate parts in order for them to be able to come out of the mold with ease, ignoring that some areas might be relatively thick and not ideal for this manufacturing process. For the cost estimation the parts quotation request was sent to 3ERP (122) asking for an estimation of the production costs, considering some different production volumes. The project manager after receiving the design files and the material choice mentioned that all

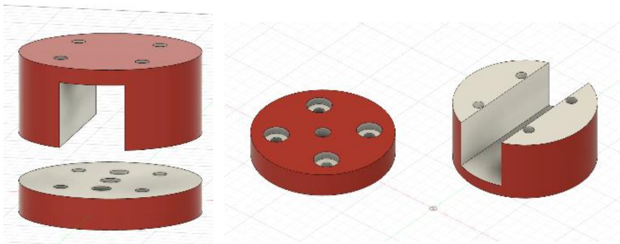

Figure 23: Split motor mount. Source: Motor mount in Fusion360

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No. 25E83031
Date: 28 January 2025
Validity: 30 Days

ITEM	PART NAME	ARTICLE DESCRIPTION	UNIT PRICE	QUANTITY	AMOUNT	LEAD TIME
001	motor_mount_v3.1	Injection Mold Material: S136 Cavity: 1*2 Life: 100000	USD 3,637.00	1	USD 3,637.00	22 days
		Injection Molding Part Material: PA6 CF12 Finish: Smooth Color: Black	USD 3.08	100	USD 308.00	6 days
			USD 1.05	500	USD 525.00	7 days
			USD 0.68	1000	USD 680.00	8 days
			USD 0.51	10000	USD 5,100.00	12 days
			USD 0.40	100000	USD 40,000.00	45 days
001	motor_mount_v3.2	Injection Mold Material: S136 Cavity: 1*2 Life: 100000	USD 3,904.00	1	USD 3,904.00	
		Injection Molding Part Material: PA6 CF12 Finish: Smooth Color: Black	USD 3.38	100	USD 338.00	
			USD 1.23	500	USD 615.00	
			USD 0.83	1000	USD 830.00	
			USD 0.65	10000	USD 6,500.00	
			USD 0.52	100000	USD 52,000.00	
	Shipment Cost	Ship Via: UPS Door to door Delivery time 3-4 days			TBD	

Table 1: 3ERP estimate. Source: Eko Lam,3ERP project manager. (122)

their molding products conform with ISO 2768 mK standard for tolerances and then created an estimate for the project. 3ERP's proposal is the following: **(Table 1)**

Calculating for the final price per part the price of the mold has to be taken into consideration, which results in **(Table 2,3,4)**:

Motor mount bottom	Price per part	Mold cost 3637$	Total cost per part
100	3.08$	3637/100=36.37$	39.45$
500	1.05$	7.27	8.32$
1000	0.68$	3.63	4.31$
10000	0.51$	0.36	0.87$
100000	0.40$	0.036	0.436$

Table 2: Motor mount bottom pricing

Motor mount top	Price per part	Mold cost: 3904	Total cost per part
100	3.38	39.04	42.42$
500	1.23	7.808	9.038$
1000	0.83	3.9	4.73$
10000	0.65	0.39	1.04$
100000	0.52	0.039	0.559$

Table 3: Motor mount top pricing

	100	500	1000	10000	100000
Assembly's total cost	81.87$	17.7$	9.04$	1.91$	0.995$

Table 4: Assembly's total cost

As seen in the proposition, the molds are planned to be made of S136 stainless steel, a type that is referred to as tooling steel and is almost exclusively used for creating molds. The molds are estimated to last for 100000 cycles before risking tolerance incompliance with the abovementioned ISO standard. The molds and their material are at the lower end of the spectrum, as they are of simple design, small size and relatively low production volume. Other types of materials and more complex mold types can be used that yield better lifespan and bigger cost savings at high production volumes.

8.3) Price comparison and recommendations

Production costs of both methods have been inserted in the following graph in order to make comparison easier and help estimate the volume for which injection molding is more cost effective, which seems to be between 2000 and 3000 parts. The massive price differences in very low and very high production volumes are due to the cost of the mold. Something that this comparison hasn't taken into account is the fact that in the case of FDM raw cost is calculated, but in the case of injection molding 3ERP is including some margin of profit and a margin for the cost of the machinery and its maintenance **(Figure 24)**.

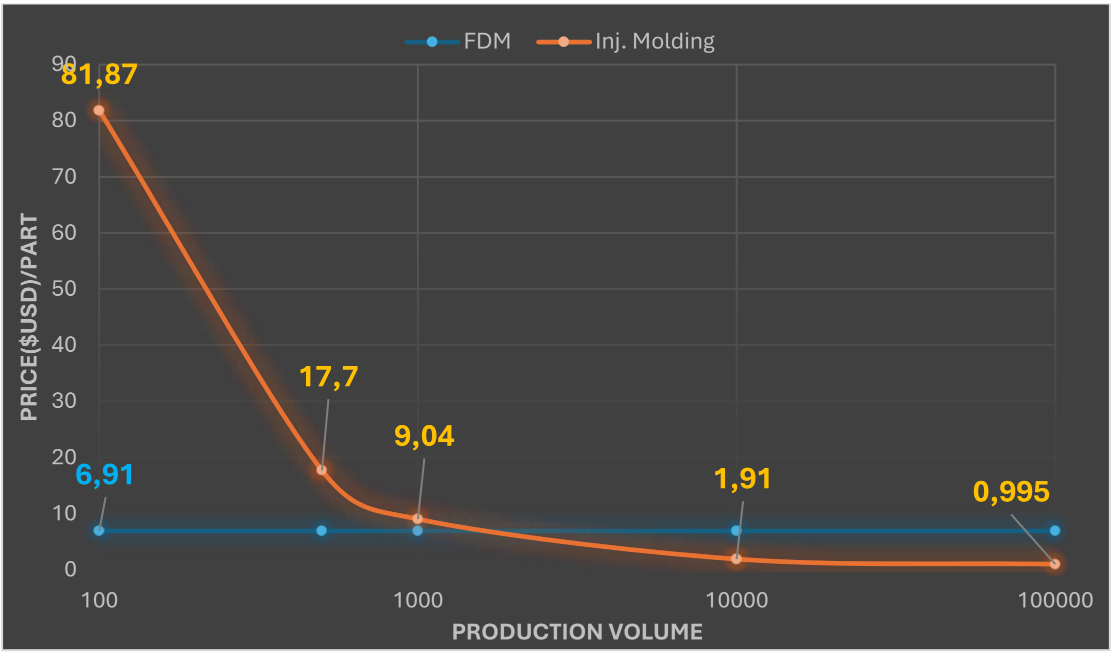

***Figure 24**: Cost comparison for manufacturing a thermoplastic component either by FDM or by injection molding.*

A suggestion for minimizing the cost would be to optimize the part design and make it so the injection mold version would consist of two similar halves, so only one mold would be necessary. This way 8 similar parts would be used, two in each one of the four corners of the quadcopter making it also very efficient for small numbers of manufacturing. For example, 500 drones require 4000 pieces of the same part, thus, being more economical than requiring 2000 top mounts and another 2000 bottom mounts or requiring 4000 pieces of 3d printed mounts in a volume that FDM in proven not effective.

9) Summary

During this two-part diploma thesis, various fields were studied. Firstly, that of the hydrogen hybrid drone and then on the causation of the drone designed by the University of Thessaly team, the method of FDM manufacturing. Finally, a case study was carried out in which the cost of manufacturing a plastic part of the drone that was to be manufactured in-house was compared with the injection molding method. The study and overview of the hybrid UAVs bibliographic sources were used, along with studies done by research organizations and universities. Also, EU and US regulation standards and statistics by trusted organizations were taken into consideration. For the description of the drone designed by the University of Thessaly. Christos Karagiannis was the main contributor, by explaining the design prosses and goals of the project, in addition to sharing the research he had previously done for the competition of his own thesis. Next up, for the FDM manufacturing method bibliographic sources were used along with information found on various manufacturers and companies that are active in related fields. Finaly, for the case study, data were gathered from 3D Printer and filament manufacturers, as well as 3E Rapid Prototyping (3ERP) manufacturing company.

9.1) Conclusion on Hydrogen Hybrid Unmanned Aerial Vehicles

Hybridization is a technology that has already revolutionized many fields and has led to great efficiency and environmental footprint improvements. Its combination with hydrogen, which is considered by many the fuel of a sustainable future, is the best possible combination since it outperforms others in efficiency. The integration of such technology in the UAV industry, while this industry is on the rise, has great potential for wide adoption. The projection to increase the amount of hydrogen produced by renewable energy sources will help to make this technology sustainable and thus relative for many years to come.

9.2) Conclusion on the FDM manufacturing method.

This manufacturing method has benefited the industry and has helped many small creators, hobbyists and students unleash their creativity, experiment and innovate. It has great potential overall, but especially in fields like the medical and the construction there are many innovations yet to be made. The great material selection and the even greater combination of materials for making composites is ,also, showing that the method can have more applications than the ones currently available.

9.3) Case study conclusion

The case study was an investigation, bucked by real numbers and estimates, that showed how the cost per part is changing dynamically depending on the production method and the volume of production, and emphasized the importance of optimizing a design for the chosen manufacturing method. All these highlight the necessity of right research on the needs of a project and attentive planning of every step in order to make the most value for money choices and secure better profit margins and product quality.

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