Modular ESC Motors Drone (II part)

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***Abstract*—In recent years, the use of drones has increased in a wide range of applications, including delivery, inspection, and mapping. However, the limited flight time of drones and the need for rapid battery replacement or recharging has become a major challenge for their extended use.**

In this paper we present an innovative method for creating a communication link between a flight controller (FC) and an electronic speed controller (ESC) in a drone using ultra-wideband (UWB) technology. Our approach utilizes a UWB module to transmit control signals between the flight controller and the ESCs.

Our idea is to apply a modular approach in which various modules containing the propulsion system can be attached to an arbitrary frame to make it fly. Specifically, in this paper, our goal is to physically make the modules that will make up the drone. For these it was necessary to draw and design the PCB, make the 3D model and print it. In addition, we worked on the previous design, replacing the drone support structure with a transparent body for the drone to better highlight the absence of a wiring harness for connection and further flight testing.
To finish, we have also defined a quick guide on how to assemble the PCB and mount it on the dedicated module.

We believe that our proposed method, utilizing UWB technology, will be a key step forward in the development of efficient and reliable drones that doesn't have any geometric constraint.

I. Introduction

DRONES, also known as unmanned aerial vehicles (UAVs), have become increasingly popular in recent years for a variety of applications. The development of micro-electro-mechanical systems (MEMS), sensors, fabrication, navigation methods, remote control capabilities and power storage systems have enabled to design and manufacture of a wide range of UAVs which can be used in many circumstances and tasks. Therefore, UAVs vary widely in their sizes, configurations, and performances.
Drones are typically controlled by a flight controller, which manages the drone's flight by adjusting the speed of its motors.

The main components of a UAV are:

- UAV Airframe: it refers to the physical structure of the UAV, which provides the framework for attaching various components. It also gives the UAV its shape, size, weight, and aerodynamic properties.
- Flight Controller: it uses sensors such as accelerometers, gyroscopes, magnetometers and GPS to estimate the UAV's attitude and position. It is responsible for controlling the UAV motion and stability by controlling the motors speed.
- Payload: it is any equipment or devices that are carried by the UAV. This can include cameras, external sensors, delivery packages or other specialized equipment depending on the specific application of the UAV.
- Propulsion system: it provides the necessary thrust to enable the UAV to fly and perform its intended functions. It is made up by the Electronic Speed Controllers (ESC), the motors and the propellers. The choice of the propulsion system depends on the desired characteristics and mission of the drone.

As we said, nowadays, drones are used in a variety of applications and this represents a great challenge on designing a drone. In fact when designing a drone we choose its dimension, the number of rotors, the size of the propellers and motors. These drone's specification are selected depending on the constumer's application, considering its flight time, the payload, the maneouvrability and the safety needed. It comes by itself the necessity of a large number of different drones able to perform the specific applications effectively and with an adeguate performance.

In the rapidly evolving field of unmanned aerial vehicles (UAVs), the concept of modular drones presents a significant leap forward, enabling customizability and adaptability for a wide range of applications. This approach allows for the assembly of UAVs tailored to specific tasks, whether it be for agricultural monitoring, search and rescue operations, or advanced content delivery systems. Modular drones offer the advantage of easy upgrades and repairs, reducing downtime and operational costs. Nowadays, when the term 'modular' is approached in the world of UAVs, reference is often made to the case of the Drone Reconfigurable Architecture (DRA), who refers to a system design that enables drones to extend their communication range and capabilities through the use of relay drones. In this architecture, drones act as mobile nodes that can either transmit data directly to a base station or pass it through other drones acting as relays. In our case, however, modularity takes on a different aspect.

The main purpose for this work was to devise and design the PCB for the modules [1], based on the application specific needs. We then focused on creating the 3D model of the various modules and assembling them.

This paper is organised as follows: In section **II**, we present our work, where we show the technology used, the hardware and we outline the research and development process of our solution.
Here we will mainly focus on the definition and presentation of the PCB, both from a theoretical point of view and a quick description of the one designed for our project. In addition, we decided to show our final result of the printed form.
In section **III**, the founding elements of our project are

[1]These modules derive from the previous project, [1], are divided into two types, slave and master, and will be analysed in more detail in the section II-B

analysed, including the development of the new modules and the creation of the PCB. In addition, to complete the work of the previous project, in which we tested and verified the operation of UWB technology for motor control, other flight tests have been performed. The drone used for this test is a closer approximation of the idea we wanted to validate. Also in this setup we realized a drone with a plexiglass frame to highlight the absence of wire communication between the components.

In section **IV**, some considerations are made about our project, what we have achieved and found during the work. The last section **V**, concludes the paper and presents possible future developments highlighting pros and cons of our implementation.

II. Description of the work for the project

Our project consists on developing a wireless communication between a flight controller of a generic UAV and its propulsion system. The control signals generated by the flight controller are sent to the motors using a unidirectional wireless connection, thus removing the cables constraint. The architecture we propose to realize a modular drone relies on two types of modules, as previously anticipated. The first one is the **master module** which consists of a transmitter module which reads the signals that a FC generates and send the informations via UWB. The second one is the **slave module** which consists of a receiver module, a battery, an ESC and a motor with its propeller. The receiver reads the messages sent by the master and generates the PWM for the ESC.

The flight controller, thanks to the data of various sensors such as accelerometers, gyroscopes, magnetometers, barometers, and GPS performs different actions: stabilization, navigation to a specific location or by following a predetermined flight path through waypoints or navigation by following commands received from the operator via a radio controller. Generally the flight controller uses as control algorithm a PID control which adjusts the motor speeds by sending PWM signals to the ESCs. In our project the signal is not sent directly to the ESCs, instead the information about the duty cycle is collected by the MCU of the transmitter module and then sent via UWB to the receiver modules. The message contains the address of every receiver followed by the duty cycle it has to be reproduced.

A. *Quick theory review from previous work*

Ultra-Wideband (UWB) technology is a wireless communication technology that uses extremely short-duration, low-power radio pulses to transmit data over a wide frequency range. It is characterized by its ability to transmit data at very high speeds over short distances, while consuming minimal power. UWB is used in a variety of applications including high-speed data transfer, indoor positioning, radar imaging, and wireless sensor networks. It is also commonly used in applications that require low power consumption and high levels of security [2] [3].

UWB technology revolutionized wireless communications with unparalleled convenience and mobility in devices for home and office. Ideal for short-range WPANs, UWB is the go-to solution for transmitting high-bandwidth data like video and audio wirelessly across multiple devices.

UWB offers major advantages, including efficient use of existing radio service spectrum without interference. Its large transmission bandwidth offers immunity to interference effects and improved multipath fading robustness, making it reliable and less prone to signal degradation.

Related to our project, we can highlight the pros and cons of this technology:

- Very high data rate, which allows for the transmission of large amounts of data over short distances quickly;
- Low power consumption, which means that it consumes less power than other wireless technologies, making it ideal for battery-powered devices;

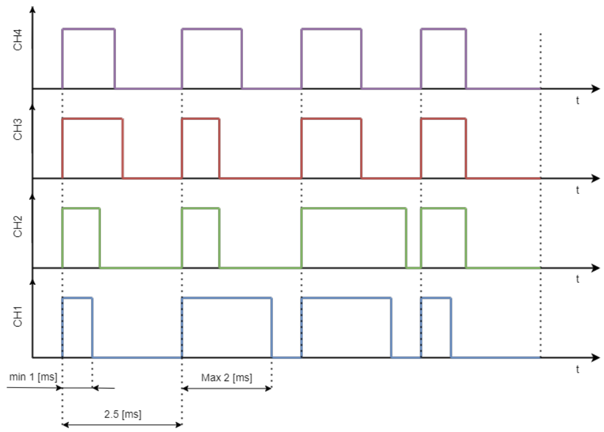

Fig. 1. Quadcopter FC PWMs example

- It can operate using spectrum already occupied by existing radio services without causing interference, which makes it an efficient use of scarce spectrum resources;
- UWB technology can be susceptible to interference from other wireless devices operating in the same frequency range.

B. Modules

The modular drone is composed by an arbitrary number of slave modules and one master module. The master module consists of different components:

- **Flight Controller (PixHawk4)**: It contains all the sensors, including GPS to provide the drone with precise positioning capabilities, and algorithms to stabilize the UAV. It generates the control signals for the motors. It generates one independent PWM signal per channel, so in the case of a quadcopter four PWMs. The PWM signals have a fixed frequency (400 Hz in our case) and they are synchronized so the rising edges of every channel occur at the same time. The falling edges are of course dependent on the duty cycle (DC) of the specific channel. The minimum DC, which correspond to 0 rpm is 40% (i.e. minimum duration of 1 ms) and a maximum of 80% (i.e. minimum duration of 2 ms) which corresponds to full throttle as shown in Fig. 1. The data from the GPS integrates with the flight controller's system to enhance flight stability and navigation accuracy.
- **Radio Receiver**
- **Battery**
- **Power Distribution Board**
- **Transmitter Module (Custom PCB with UWB Module)**: it's wired to the flight controller and it mounts a DWM1001c module. Its purpose is to acquire the PWM signals from the FC and send the duty cycle information to the receiver modules. This component is placed on the PCB designed by us, together with all the other useful components, such as the voltage regulator and the conditioning circuit. For a more detailed description of the board, see section III.

We implemented the PWM acquisition through Programmable Peripheral Interconnect (PPI). PPI allows to trigger a task in one peripheral as result of an event occuring in another peripheral while excluding the CPU from these operations. The synchronization clock of PPI is 16 MHz. We dedicated one timer for each PWM channel. The interconnections are between an event on each pin connected to the FC and the Capture Compare (CC[0]) register of the associated timer. In this way when a rising or falling edge is detected, the timer counter is automatically and almost immediately saved in the register. In order to retrieve the information we need, which is the duty cycle, we have to distinguish between the time the rising and falling edges occur. To do so when an edge is detected the counter value is saved in the register without the intervention of the CPU, then the CPU enters in an interrupt routine which is designed to distinguish the edge and to save the counter value in memory. The duty cycle of the signals are then computed by the simple relation:

$$\mathrm{DC} = \frac{T_{fall} - T_{rise}}{T} \tag{1}$$

where T_{fall} and T_{rise} are the times at which the falling or rising edge occur and T is the period of the signal which is 2.5 ms in our setting. In order to transfer the PWM informations to the receivers we create a message made up by the adress of every receiver followed by the duty cycle that must be replicated. The message is sent at the end of every input PWM period, which is every 2.5 ms.

The slave modules are the ones that can be added in arbitrary number to the airframe in order to increase the maximum payload or flight distance. They are made up by:

- **Battery**
- **ESC Module**
- **Motor with Propeller**
- **Receiver Module (Custom PCB with UWB Module)**: Also in this case the communication module is the DWM1001c.
- **Clamp System**: which allows the entire module to be attached to the main frame, as can be seen in Fig. 2, 3 and 4.

In the slave module the PWM generated by the FC must be replicated. To do so, the output GPIO of the MCU is connected to its timer which is configured in order to provide a fixed frequency square wave of 400 Hz. The timer gets started when an initialization signal is sent by the transmitter. That event is a sync signal and when it is received every transmitter starts its timer. When a command is sent by the transmitter (i.e. every 2.5 ms), every receiver looks for its address in the message and reads the desired DC. To apply the new DC, the CPU changes the value of the CC[0] register which causes the duty cycle to change. For more information on this section, please refer to the previous report [1].

C. PCB

The main aim for this phase of the project was to design and build the PCB that would serve as the main element for the various modules. A Printed Circuit Board (PCB) is an integral part of modern electronic devices, providing a platform for interconnecting various electronic components.

A PCB consists of several key elements:

- **Substrate**: The base material of the PCB, often made of fiberglass-reinforced epoxy laminate, provides structural support and insulation.
- **Conductive Layers**: Thin layers of copper bonded to the substrate. These layers are etched or printed with specific patterns to create the circuitry.
- **Components**: Electronic components such as resistors, capacitors, integrated circuits (ICs), and connectors are mounted on the PCB and connected via soldered joints to the conductive layers.
- **Traces and Pads**: Conductive pathways (traces) on the PCB connect different components, while pads provide areas for component soldering.
- **Silkscreen**: Information such as text, symbols, and labels are printed onto the PCB's surface, aiding in component placement, polarity, and assembly details.

Fig. 2.

Fig. 3.

III. System Design and Implementation

In this section, therefore, we will describe the heart of our project, describe the new modules and, above all, how the PCB works.

A. *Modules Design*

As a final result, we wanted to try to devise, through 3D modeling, a first idea of modules, especially for the receivers. The latter are fundamental for the realization of the modular drone because, in addition to containing different fundamental elements, they are also used in supporting the main frame, which should be composed of a more or less symmetrical object, as in this case for a cubic box. As you can see from the images above, our idea is to take advantage of the shape and size of the central frame, which can have any shape (for the moment we have focused on something symmetrical), around which several slave modules will be placed.

In addition, the master module will be placed on the main body, again trying to position it so as to balance all the forces in play. We focused on the conception and design of the slave modules, as they needed a form that could contain all the components and at the same time be able to attach easily and effectively to the main body, like the box in our case. As far as the slave modules are concerned, the dimensions adopted for the CAD are: 100x61.2x61.5 mm (L x W x H). This concerns the size of the box used to contain the battery, ESC module and wiring. The plate underneath, the piece used to support the main hunger from underneath, has the following dimensions: 100x60x10 mm (L x W x H). It is important to point out that the measures taken are based on the electrical and mechanical components used in our specific case. Therefore, a different battery change or a different motor-propeller system requires a different design. The total weight of the module, including the steel bars, is approximately 600 g.

As far as the master module is concerned, a case was not designed to contain all the components as it would have less impact on the final result of the work. In the future, a case could be considered, perhaps based on the design of the one used for the slaves modules, but with a different anchoring method.

We therefore chose to take advantage of a 'clamp' shape, as you can see from the Fig. 3, that would allow us to have a trade-off between simplicity and efficiency. Specifically, we were interested in choosing a design that would allow the modules to be added and removed quickly and easily, but at the same time would fit the object in question in the best possible way and have good resistance during the flight period.

It was decided to place all the weight of the module at the top, i.e. where the motor, battery compartment, PCB and ESC are located.

We also decided to use a honeycomb grill design for the battery compartment, Fig. 4, to avoid excessive overheating. In addition, we opted to place the motors and blades particularly close to the main frame to minimise the bending moment and keep everything as compact as possible.

It follows that the slave module consists of a lower and an upper base, which are held together by two aluminium bars and a threaded rod to provide clamping. By means of a bolt with butterfly nut positioned in the central bar, it is possible to modify the distance between the two bases. It was noted that it might be useful to add non-slip material on the side of the two bases that comes into contact with the main body in order to increase friction and improve the grip during flight.

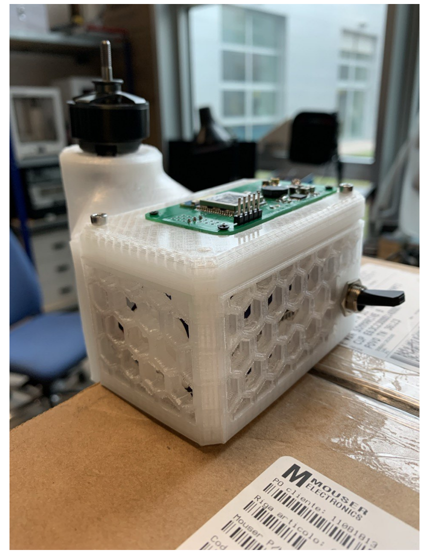

Fig. 4.

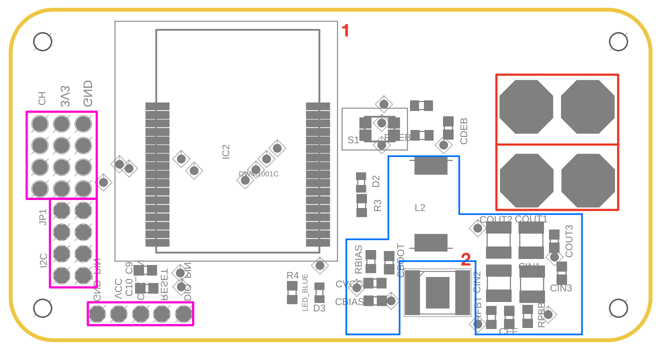

Fig. 5.

B. PCB Design

In this section we will set out the key points for the implementation and proper functioning of the boards.

As seen in the subsection II-B, modules are composed of several components, the main element being the UWB module on the PCB. As the power source for the module is the battery, which has been chosen to be 4s (i.e. 14.8 V) a voltage regulator is needed to drive the 3V3 logic of the IC. In order to operate, the voltage regulator needs a conditioning circuit, which is also used to set the output voltage. We must then provide the power supply to the ESC module and also connect the board to either the ESC logic if the module is a slave one, or to the FC if it is the master.

So, as our main job, we focused on designing the PCB. Based on our needs, the board we designed had to fulfil a few but necessary criteria. Among these was certainly the small size, which was necessary in order to fit into the module and to maintain a low weight. The dimensions are: 75x38.7x1.6 mm (L x W x H). Another fundamental criterion was to be able to insert all the necessary elements, among them we have:

- UWB module (1)
- Voltage converter (2)
- Conditioning circuit
- Connectors (red square): one is for the battery and one is for the ESC
- Pins (pink squares)
- Conditioning circuit (blue group)
- Reset button (S1): required to reset the UWB module

Below you can see the diagram of our board, drawn through the use of Autodesk Fusion 360 software, including all the elements on it and listed above. As said, the main component

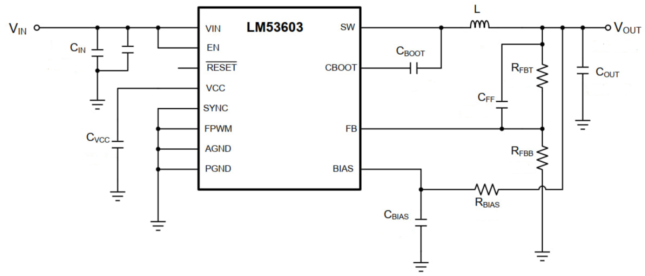

Fig. 6.

on our board is the UWB module, so the rest has been planned for the purpose of its operation. First you will need to set the input and output voltage levels of the regulator according to your needs. So a further choice we had to make was to choose a voltage regulator suitable for our purpose.

We decided to use a switching and not a linear regulator because it is more efficient, and we do not have strict constraints on the precision of the power supply. Moreover, since we are dealing with a voltage drop of more than 10 V and a maximum current of 3 A, the usage of a linear regulator would have been more complicated from a dissipation point of view. Linear and switching regulators are distinguished by their operational methods, with linear regulators using resistance variation to manage output voltage, leading to higher heat dissipation. This makes them less efficient, especially in applications with a significant voltage drop. Consequently, they tend to be bulkier due to the need for components that can handle the heat. In contrast, switching regulators employ a fast-switching mechanism that offers greater efficiency by minimizing heat production, allowing for a more compact and lightweight design. This efficiency makes switching regulators ideal for energy-sensitive applications, where maximizing battery life or reducing energy consumption is crucial.

Specifically, the regulator chosen by us (LM53603) has a circuit in which it is possible to set the desired output voltage, in our case an output voltage of 3.3 V was required, with an input voltage of 14.8 V provided by the battery. In addition, the maximum current that can be delivered by the regulator is 3 A which guarantees enough power to the UWB module.

The output voltage of the regulator can be tuned following Equation (2), by choosing proper resistor on the feedback loop. Namely R_{FBB} and R_{FBT}. Usually R_{FBT} is limited to a maximum value of 100 $k\Omega$. In addition, a feed-forward capacitor C_{FF} may be required to optimize the transient response.

$$R_{FBB} = R_{FBT}\left[\frac{1V}{V_{out} - 1V}\right] \tag{2}$$

In order to connect the board to the FC the twelve pins highlighted in pink on the upper left of Fig. 5 must be used. Each row represents a channel, which is then connected to a specific GPIO of the MCU (SPIS_MISO, SPIS_MOSI, GPIO_8, GPIO_15). In order to use the board as a slave module, only channel0 must be used.

We also decided to provide access to other GPIOs and to the I2C bus for possible expansion and for debugging purposes.

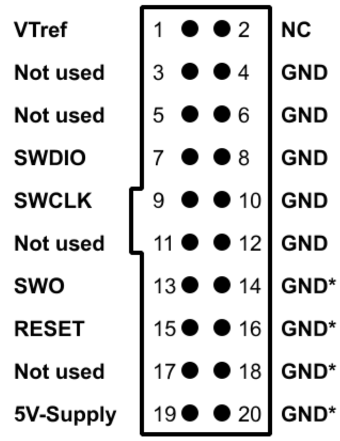

Fig. 7.

Finally, five lanes are dedicated to the programmer and they can be accessed by the (CLK, DIO, RESET, VCC, GND) pins. Depending on the type of module we would like to obtain, a slight modification will be necessary with regard to soldering the pins on the board. There are a just two differences between the two boards. The first one is that the master has female connectors on all channels to be connected to the FC, while the slave only has a male on CH0. The second is the code that they have to run. This topic will be further explained in subsection III-C.

At the ends of the PCB we find the connectors for connecting the battery, which will power both the circuit on the board and the ESC module. In addition, we added a switch between the battery and the regulator input, as you can see in the Fig. 4. This makes it possible to safely disconnect the power supply in case of problems.

C. Using the boards

In order to use the PCBs the proper firmware must be loaded. To do so we use a J-Link programmer. It is a debug probe for programming and debugging embedded systems via JTAG or SWD interfaces, widely supported across various CPU cores and development environments. In our case, we opted for the SWD version, Serial Wire Debug, which is a 2-pin interface (SWDIO/SWCLK). In the Fig. 7 the pinput diagram of the interface. In case you want to modify the firmware on the board you need to connect the J-Link debugger pins VTref, SWDIO, SWCLK, RESET, GND to the programming pins on the PCB. Note that you need to connect VTref to the VCC pin, and before loading the code you need to power up the board, so the debugger can check the power supply.

In case you want to load the master firmware: open the ”transmitter” project, that you can find in the repo of this project and hit ”run”. This will load the firmware on the MCU and that’s it.

Slave modules need a bit more of care. As each slave module must replicate the PWM signal of a specific FC channel, you must tell the module which channel it has to replicate.

To do so you have to change the ”RECEIVER_ADDR” macro in the receiver_mockup project, which again, you can find on the repo. The map of FC channels to ”RECEIVER_ADDR” is the following:

- CH1 : 0xC5
- CH2 : 0xC6
- CH3 : 0xC7
- CH4 : 0xC8

So for the slave module which will be placed on the frame as motor one, you must choose 0XC5 as address.

IV. Experimental results

The following section sets out the experimental results obtained during the work performed. These include technical data concerning the PCB and modules, observations on what was obtained and any suggestions for future improvement of the work performed.

A. PCB and Modules

The printed modules seem to meet the requirements for this project. We noted that by adding non-slip material on the contact surfaces of both bases the clamp is much more stable as the grip increases.

We assembled five PCBs: one for the master and four slaves. We also assembled the four slaves module and the master one. Unforunately we were not able to run real flight tests, as one of the PCB was not properly working, as the output voltage from the regulator was about 4 voltage and burnt the UWB module. As there were not enough components to assemble another board we couldn’t carry out further analysis. Beside that we encountered many troubles in assembling the board with this last design that we would like to highlight for future improvements.

First of all the slaves tolerances were too tight for an easy placement of all the components, so more care will be needed in future version to address this issue. Another important note regards the PCB battery and ESC connectors. We thought that having two XT60 connectors pointing straight to the inside of the module would have been beneficial for an easy install of all the components. That turned out to not be true, as they are very bulky and we had to solder the battery cables directly on the PCB as no space was left after placing all the components. Perhaps it could have been better to use 90 Degrees connectors that would allow a better cables management. Another improvement would be to use a BMS on each module, so that it is possible to always leave the battery inside the module and charge it from an external port without the need to remove the battery every time charging is required. Additional safety measures could be included as the use of a fuse to preserve the battery in case of short circuits, and in any case, to prevent that too much current flows to the ESC, thus burning it. Another possible improvement could be the realization of a PCB for the switch. Actually cables have been directly soldered to the switch pins, but that operation requires a lot of care in the way cables are soldered, especially to avoid 90 Degrees bending, but the main problem remains the time needed to complete the assembly. A breakout board for the switch would allow a much easier management of the cables.

Overall we encountered many problems in the cable management, which were difficult to be understood and addressed in the design phase. We thus believe that further version of the module will result in a smarter and cleaner setup, especially regarding the first assembly and maintenance of the modules.

From a mechanical viewpoint it could be exploited the possibility of separating the battery from the electronics, perhaps by placing the battery on the lowest part of the clamp, thus lowering the center of mass which is supposed to increase

Fig. 8.

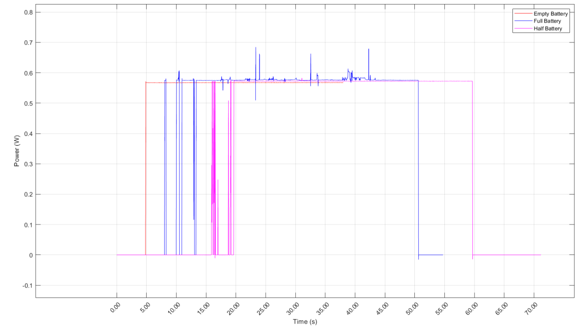

Fig. 9.

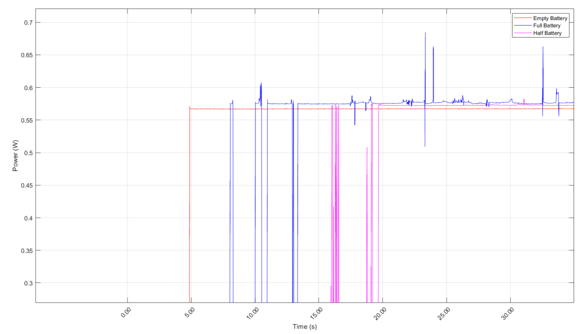

Fig. 10. Detail of the complete plot to better highlight the difference between the three powers.

the stability. This possibility is however as the moment hard to discuss at both of the designs should be ready to flight in order to truly understand the differences. Lastly it might be useful to modify the fastening mechanism by removing the wing nut and inserting an insert for the use of a drill, in order to speed up and make the grip on the main body more effective.

1) PCB Power Consumption: An important aspect, when designing a UAV and choosing the onboard battery, is the power consumption since it affects the flight time. The main factors to deal with are: the payload, the components that need to be supplied and the propulsion system. Considering these factors we can decide the battery capacity needed to be used. By choosing the modular drone design, the consideration to be done regarding the power consumption may seems to change. This because not only we need more components that need to be supplied, such as the trasmitter and the receivers, but also we need to consider the different ways the PWM signals can be sent to the ESCs. However those changes can be considered negligible as the power consumed by the electronic components of the drone are on the order of a few watts, meanwhile the power needed for the propulsion system to make the drone fly are in the hundreds of watts. So regarding the power consumption our solution practically consume the same amount as the other drones. The only consideration to make is that the modular drone is composed of an arbitrary number of separate modules, so each of them need its own battery. We therefore wanted to analyse our PCB using a multimeter, in order to be able to analyse the energy usage required by the board.

We chose to repeat the test three times, battery full, empty and at half charge. We therefore decided to measure the power consumed by the board in 3 different situations, Fig. IV-A1 and IV-A1, obtaining very similar graphs.

The tests are carried out for a few seconds at three different voltages, 16.8, 16 and 14.8 V, to simulate the state of charge of the individual battery. From the plots obtained, it is possible to estimate the power output of the board, which is around 0.55 W. For a study under operation of the module, it would be necessary to power the entire system, including the ESC module and electric motor. The results obtained, however, would be highly specific to our case, as this would depend on various factors such as the type of propeller, the type of motor, or the load derived from the main frame.

2) Theoretical load calculation: A further study we carried out, on a theoretical level, was to estimate the maximum load a single slave module could lift. For this calculation, a single slave module was taken into account, while on a mathematical level we employed the following formula to first calculate the thrust (T), [4] [5]:

$$T = A \cdot \text{RPM} \cdot \frac{d^{3.5}}{\sqrt{\text{pitch}}} \cdot (B \cdot \text{RPM} \cdot \text{pitch} - V_0) \qquad (3)$$

where A $= 4.392399 \times 10^{-8}$ and B $= 4.233333 \times 10^{-4}$ are two constants, RPM is the propeller rotations/min, pitch is related to the propeller (in.), d is the propeller diameter (in.), V_0 is the propeller forward airspeed (m/s) that for our case is equal to zero because we are in the hovering case.

In our case we have a 10x4.5” propeller and a motor generating a Kv, that represents the number of revolutions as a function of supply volts, is equal to 750 rpm/V, so $RPM = 750\text{x}14.8 = 11,100\ rpm$. Hence, what we obtain is a value of $T = 39.03\ N$, which corresponds to a theoretical

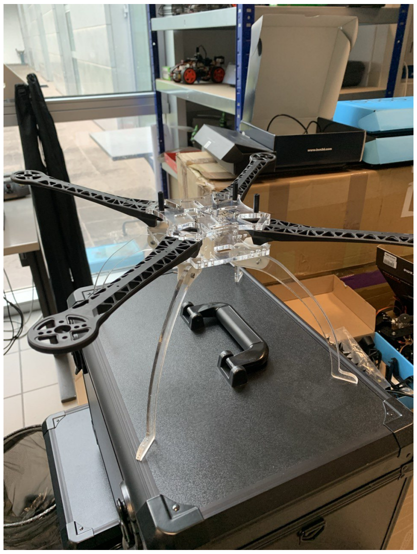

Fig. 11.

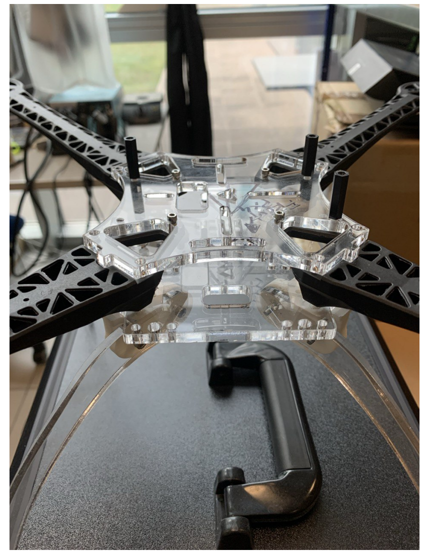

Fig. 12.

load of 3.98 kg. This result also includes the weight of the single module, about 600 g as mentioned above.

B. Transparent frame

In parallel to this project, we spent part of our time modifying the drone used for the previous project. The main aim was to redesign the uav's supporting structure using a transparent material, plexiglas in our case. In this way, it is possible to emphasise the absence of wiring between the flight controller and the motors, which therefore exploit the UWB technology previously implemented.
As can be seen from the Fig. 11 and 12, the pieces were drawn by cad to form an s500-type frame, after which they were laser-cut from 5mm plexiglass.

Further modifications concern the use of more batteries, in our case 5, i.e. 1 for the master module and 1 for each slave module used. We decided to apply 4 because ideally this number of modules will be used for a classic setup. Furthermore, as can be seen from the Figures 13 and 14, each battery, esc module and regulator are arranged on each arm in order to facilitate wiring and to come as close as possible to the final concept.
Also notice from these latest pictures the choice of creating a real module as far as the master is concerned, again for the purposes of the final concept. Flight tests showed an improvement in the stability of the drone. This could be due to the fact that, compared to the previous time, the mass of the drone is greater due to the presence of four batteries instead of just one on the main frame. Therefore, with the same force exerted by the motors, which have not been changed, and using the same code, the moment of inertia will be greater and therefore the vibrations reduced.

These improvements can be clearly seen in the flight test video, which is compared with that of the previous design [1].

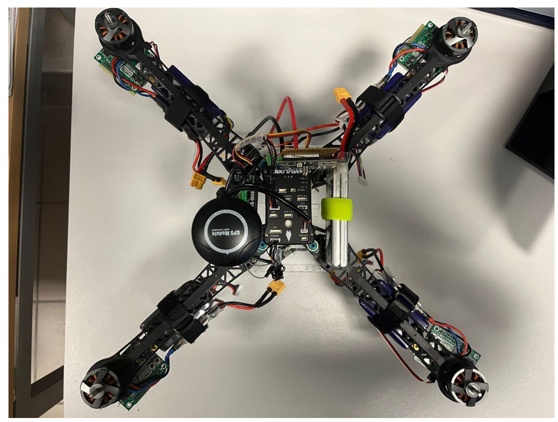

Fig. 13.

V. Conclusion

After designing and testing a modular drone prototype, we have demonstrated that it is feasible to create a UAV with interchangeable modules that can be quickly and easily replaced. Our design offers a flexible and customizable solution that allows users to easily adapt it to different applications and environments.

We believe that even though we were not able to run real tests on the new modules, the behaviour will be similar to the one obtained with the plexiglass drone, as the communication link is exactly the same and the position of masses around the frame is similar.The testing of the drone showed that it can perform well in different configurations, both with the traditional and wireless connected ESCs setup, [1], While the vibrations in the latter could have been introduced by the delays and asynchronization in communication.

Overall, we believe our design provides a promising solution for a more efficient and adaptable drone. Future work would involve fixing up the broken board in order to be able to test the modules on a real flight. It might be also advisable to revise the communication scheme and the PWM reading to

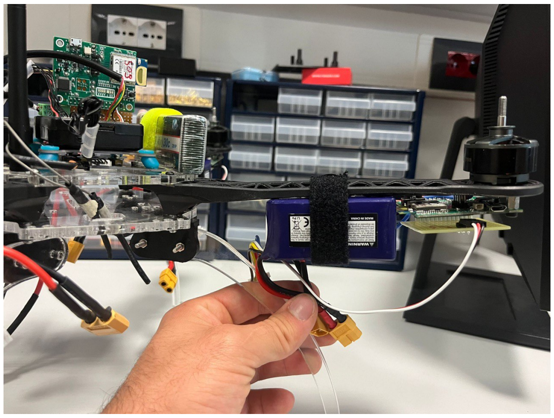

Fig. 14.

improve the stability of the drone. Other improvements on the slave modules has been discussed in Section IV-A.

While in the previous work we modified an existing UAV to validate our idea, in this one we worked on the design and creation of the wireless modules. The next step would be the introduction of algorithms to estimate the relative position of the modules. That would be the next step towards the possibility of creating a plug and play system in which, once the modules are attached to the body, they reconstruct the shape of the drone (i.e. where the motors are). Provided that a flight controller is able to handle a non standard frame, those modules could be placed in an arbitrary shape.

Lastly, it could be interesting to optimize the modules exploiting lighter materials, other anchoring methods or other module shapes.

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