UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

Master's degree in Applications and Technologies for Unmanned Aircraft Systems

MASTER THESIS

TITLE: **Development of improvements in UAS for difficult access environments**

MASTER DEGREE: **Master's degree in Applications in Technologies for Unmanned Aircraft Systems (Drones)**

AUTHOR: **Sergio Leandro Schnorr Flores**

ACADEMIC ADVISOR: **Luis Gonzaga Alonso Zarate**

DATE: **07/07/2023**

ABSTRACT

The objective of this document is to study and verify the development and improvements in Unmanned Aircraft Systems (UAS) for difficult access environments since this matter is a critical area of research and innovation. As the use of UAS in various applications continues to expand, the need for these systems to operate in challenging environments such as mountainous terrain, dense forests, or urban areas with high-rise structures is increasing.

The main motivation to start developing this project was the challenge exposed in the Xprize Rainforest Competition. The $10M XPRIZE Rainforest is a five-year competition to enhance the understanding of the rainforest ecosystem. I am part of the semifinalist team, **Providence Plus**, a multidisciplinary team composed by scientists from UPC, CSIC, MIT, and TUDelf.

The purpose of this challenge is to obtain the maximum amount of information on biodiversity in the rainforest, using drone technology in this type of environment, with all the difficulties inherent in this environment that must be overcome and that are also the subject of analysis in this work, to propose and compare the different solutions and technologies to achieve the objectives of said challenge. As resources for competing in Xprize Challenge are limited and the final solution shall be scalable, the technologies evaluated must be cost efficient and practical.

The first difficulty in this kind of environments is the signal strength and signal quality, not only for the drone commands but for the video and telemetry data. In this work, different solutions will be compared since analogic to digital technology.

The second difficulty is autonomy, in terms of energetic supply. Taking into account the Rainforest environment and environmental policies, the most suitable technology available is batteries. There are several types of batteries that are suitable for drones, depending on the size, weight, and specifications of the drone. There will be a comparison between the most popular ones. Apart from that, an analysis of different propulsion configurations (ideal motors and propellers) will be carried out in order to achieve an optimal flight time without compromising the structural integrity of the drone.

The third difficulty is reducing noise levels, in order to avoid disturbing the wildlife and with the goal in mind of having the best images possible, a study of different propellers will be carried out.

Finally, durability and weather resistance: Rainforests are characterized by high humidity, heavy rainfall, and extreme heat. Drones used in this environment must be built to withstand these conditions and be weather-resistant. This may involve using materials that can withstand moisture, designing waterproof

housing for sensitive components, and installing heat dissipation systems to prevent overheating.

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$c = speed\ of\ light = [m/s]$

$f = frecuency\ [Hz] = [1/s]$

$T = Period = [s]$

$\lambda = wavelenght\ [m]$

$S = Sensitivity\ [dBm]$

$G = Gain\ [dB]$

$G_{TX} = Gain\ of\ the\ transmitter\ [dB]$

$G_{RX} = Gain\ of\ the\ receiver\ [dB]$

$L_{TX} = Loos\ of\ the\ transmitter\ [dB]$

$L_{RX} = Loos\ of\ the\ receiver\ [dB]$

$P_{RX} = Reciever\ Power\ [dB]$

$L_{pol} = Polarization\ Loss$

$A_{ef} = effective\ aperture\ of\ the\ antenna\ [m^2]$

$P = Power\ [W]$

$V = Voltage\ [V]$

$I = Intensity\ of\ electical\ courrent\ [A]$

$Q = Battery\ capacity\ [mAh]$

$R = Electrical\ Resistance\ [\Omega]$

$d = distance\ [m]$

$m = mass\ [g]$

$E_b = Bettery\ Energy\ [Wh]$

$KV = Motor\ revolitions\ per\ volts\ in\ 1\ minute = [r.p.m \times V]$

$\pi = Númber\ pi = 3.14159\ [Adimensional]$

Glosary of abbreviations.

UAV	*Unmaned Aerial Vehicle*
UAS	*Unmaned Aerial System*
RPAS	*Remotely Piloted Aircraft System*
FAA	*Federal Aviation Administration*
FC	*Fligth Controler*
FPV	*First Person View*
LOS	*Line of Sight*
VLOS	*Visual Line of Sight*
NLOS	*Non-Line of Sight*
BVLOS	*Beyond Visual Line of Sight*
BLOS	*Beyond Line of Sight*
GNSS	*Global Navigation Satellite System*
GPS	*Global Positioning System*
IMU	*Inertial Measurement Unit*
LED	*Light-emitting diode,*
LiPo	*Lithium Polymer*
LiIon	*Lithium-ion*
LHCP	*Left-Handed Circular Polarization*
RHCP	*Right-Handed Circular Polarization*
OSD	*On Screen Display,*
PDB	*Power Distribution Board,*
PCB	*Printed circuit board*
RF	*Radiofrequency*
USB	*Universal Serial Bus, Bus serie universal.*
VTX	*Video transmitter, Transmisor de video*
FC	*Flight Controller*
ESC	*Electronic Speed Controller*

RC	*Radio Controller*
LNA	*Low-Noise Amplifier*
PA	*Power Amplifier*
TBS	*Team Black Sheep*
RSSI	*Received Signal Strenght Indicator*
EIRP	*Equivalent Isotropic Radiated Power*
SNR	*Signal-to-Noise Ratio*
SINR	*Signal to interference and Noise Ratio*
TX	*Transmission*
RX	*Receiver*
nSmP	*Battery configuration (n = number of cells in series; m = number of cells in parallel)*
UPC	*Universidad Politécnica de Cataluña*

1 INTRODUCTION

1.1 Motivation

Drones have become an increasingly important tool in a wide variety of sectors, including agriculture, construction, exploration, transport, topography, surveillance, logistics, entertainment and more.

However, most drones are designed to operate in controlled environments, such as urban areas or farm fields, and have not been adapted to operate in harsh environment. In this work, we will discuss the importance of adapting drones for adverse environments such rainforest, and how it can be achieved.

Tropical rainforests are one of the most important areas on the planet in terms of biodiversity and ecosystems. Various studies have shown that tropical forests play an important role in local, regional and global climate regulation through their influence on the energy, water and carbon cycles. The future of humanity is at stake, the importance to improve nature conservation is one of the most important problems of our time. Therefore, to improve something the first step is to measure it.

The $10 million Rainforest XPRIZE is a global, five-year competition that will accelerate innovation in unmanned and autonomous in situ and remote technologies needed to assess biodiversity. The competition will improve our understanding of the rainforest ecosystem by using rapid data integration to gain new insights that promote the health and conservation of this vital ecosystem.

The rainforest is a very complex and diverse habitat, presenting a wide variety of challenges for drones, including dense vegetation, high humidity, heavy rainfall, natural obstacles, and poor visibility. Therefore, it is necessary to adapt drones so that they can operate in these environments and obtain accurate and detailed information.

This project aims to collaborate with ProvidencePlus team for participating in the Xprize Rainforest competition. In order to win for the competition, the team needs to get as much visual information as possible from the rainforest canopy.

1.2 Objectives

The objective of the project is to present the criteria that allow to choose the best solutions to overcome the challenges posed by the Xprize Rainforest competition. Specifically, the evaluated criteria will be useful for the design of an UAS that assists Providence Plus team with the capture of useful data to allow a taxonomic classification of species under the canopy in the final competition of the Xprize Rainforest.

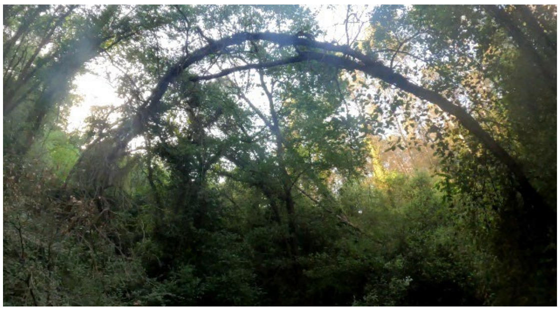


Figure 1. Rainforest

Drones used in this environment must be built to withstand **hostile conditions; such as signal potential loss, battery life, humidity and unpredictable obstacles**.

So, each specific objective will find the most optimal solution for each challenge.

There are various types of signals involved in a UAS, mainly **control link**, **video transmission link and telemetry link.** Each of them has its sensitive and limitations.

1. The video transmission link: comparison between different existent technologies (analog and digital video) and alternative solutions to ensure video signal over the canopy.

2. Control link: testing and comparison between various control protocols including TBS Crossfire and Express LRS.

3. Effectively use of telemetry information in order to evaluate the communication status of the different link systems of the UAS.

4. Find the most suitable configuration of batteries in order to increase the flight time enough to accomplish the mission required.

5. Humidity environment will involve designing waterproof housing for sensitive components or taking other measures to isolate these sensitive components.

6. Take into account that the design of the drone is maneuverable enough so that an experienced pilot can avoid obstacles through a first-person vision system.

1.3 Scope and Limitations.

Based on the objectives described above, the project contemplates some very delimited restrictions in which, throughout the development of the project, they have remained within the margins described below.

- Low cost. This objective is essential to achieve. Although there are drones that are capable of performing the proposed task, their price is usually very high, therefore it is proposed to provide an economical and effective solution.
- Easy assembly. Faced with possible accidents or collisions of the drone when it is being used, it is essential that the user be able to repair it by disassembling and reassembling the drone in a simple way.
- Robustness. The drone has to be durable over time, despite the fact that it has plastic parts, the joints of the parts must be robust enough to withstand the stresses generated in the operation.
- Lightness. The weight of the drone is a fundamental point, it will influence its maneuverability and flight autonomy. In addition, the limitations of the electronic components used must also be taken into account in order to have a sufficient margin to allow safe operation.
- Autonomy. This point is directly related to the previous one, sufficient autonomy must be achieved to be able to complete the task without worrying about losing the drone.
- Protection against water. Because the drone will be designed to operate in a rainforest environment, it must have some type of protection against water. Although the drone will not be designed to be completely submerged, the electronic components must have some protection from possible splashes of water.
- Modular. Despite the fact that this project intends to carry a payload of specific dimensions, the drone must be versatile enough to be able to carry loads of similar weight and of different geometries.
- Basic mechanical components. The necessary components of the drone fuselage for its assembly must be easily acquired by the user in order to be able to replace any part that requires it easily and economically
- Basic and affordable electronic components. In the same way as in the previous point, electronic components can be easily purchased.
- Use of Open-Source Software. In order to guarantee the versatility of the final product, the software used has to be free, thus allowing it to be used at no additional cost.

1.4 Justification description

Technical Challenges and Restrictions to overcome:

Teams will have **24 hours** to explore **100 hectares** of tropical rainforest and produce: (1) a biodiversity assessment; and additionally in the Finals, (2) Insights from data analyses that communicate the value of the standing forest.

Teams will deploy their solutions from a Base Station located outside of the Competition Area. During testing, **solutions may operate within the forest and up to the maximum altitude at which unmanned aerial vehicles are allowed to operate** (under regulations locally coordinated by XPRIZE for the purposes of Testing in the Competition Areas).

During each round of testing, teams may deploy multiple systems, vehicles, and other technologies. **Teams may not have any humans within the designated Competition Area**. However, teams may employ humans outside the Competition Area and at the Base Station for:

- Assembly and maintenance of Solution in preparation for testing;
- Technology deployment and recovery;
- Remote-controlled operations and/or supervision of completely autonomous operations;
- Recharging, swapping, or refilling power sources;
- Receiving data transmissions and/or downloading data;
- Data analysis, including Species identification and
- Other necessary activities as approved by XPRIZE.

Once the Time Limit clock starts, it will not be stopped if the Solution leaves the Competition Area for any reason, including returning to the Base Station to refill, exchange, or recharge a power source.

Teams may not leave vehicles or other equipment in the Competition Area without prior written approval from XPRIZE and the Judging Panel. The competition intends to incentivize unmanned and autonomous technologies that will return to Base Camp without direct human assistance. In the event of an accidental loss of a Solution in the Competition Area requiring human-assisted recovery, or inability to recover the Solution within a reasonable timeframe, a team's **overall score will be penalized at the Judging Panel's discretion**. Unless otherwise stated, teams will be responsible for recovery of any Solution lost in the Competition Area.

There will be **no physical connection between humans in the Base Station and the Competition Area.** While the Solutions must function without a physical link to operators, untethered "connectivity" between the Base Station and the systems is welcome.

Transportation of the solution system must be possible to the remote testing location once in the country (such as with a **single pickup truck**).

Safety is a top priority for this competition and to minimize the impact of the competition on the rainforest environment, Solutions must minimize environmental harm and ensure safety of participants and surrounding communities. All teams must comply with the following requirements:

- Teams will comply with all existing environmental, health, and safety regulations in the entire Competition Area including base camp and transit region.
- Site specific regulations will be shared after the announcement of Testing Locations.
- Any emission of acoustic, electro-magnetic, laser, optical or other energy must be compliant with any existing regulations and best practices for the Competition Area.
- Teams may not use nuclear reactor power sources or in any way allow emission of harmful chemical or biological pollutants.
- Teams may not employ any form of life in their approaches to the challenge.

- Teams must minimize harm to any form of life in their approaches to the challenge. If a team's Solution might impact life, this must be declared and accepted by the Judges in the team's Qualifying and Semifinal technical submissions as well as prior to deployment in the Competition Area.
- Document their approach to health, safety and environmental compliance
- Teams must recover equipment that is deployed within the Competition Area. Any disposable portions of the system must be declared and accepted by Judges as causing no harm prior to deployment in the Competition Area.

Solution:

One solution to the previously mentioned technical challenges is the study of this project; this project will focus on comparative analysis of technologies and will showcase the criteria needed to develop an unmanned aerial system for capturing images with a flight platform with a camera capable of flying both above and below the canopy in the middle of a rainforest.

Automatic identification of flora and fauna species from the images taken by the UAS can be achieved using computer vision and machine learning techniques, this latest point will be carried out by another member of our team.

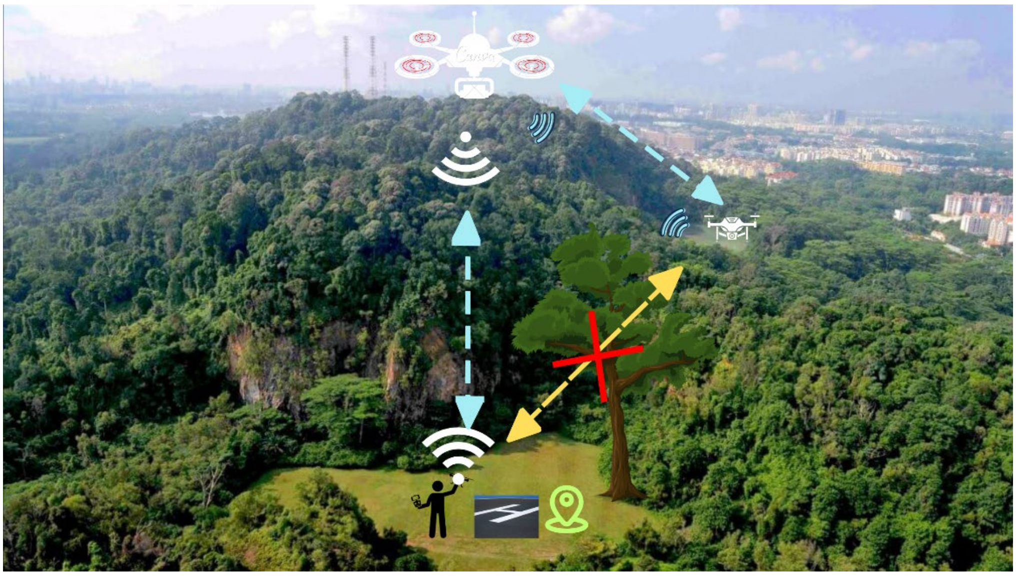


Figure 2. Overcoming the challenge for the possible communication loos.

As it is shown on the Figure 2 the pilot is pretending to control a drone in a remote location in the middle of a rainforest. One of the main challenges in this scenario is the communication loss, therefore an assistant drone is required to repeat the signal over the obstacles of the dense vegetation.

There are other difficulties mentioned in the objectives of this project in this environment, such as the battery life, humidity and physical obstacles.

1.5 Project Plan and Schedule.

After waiting for the ProvidencePlus team (with whom I was collaborating through a student scholarship from IRI) to qualify for the semifinals, I started setting up the objectives for this project

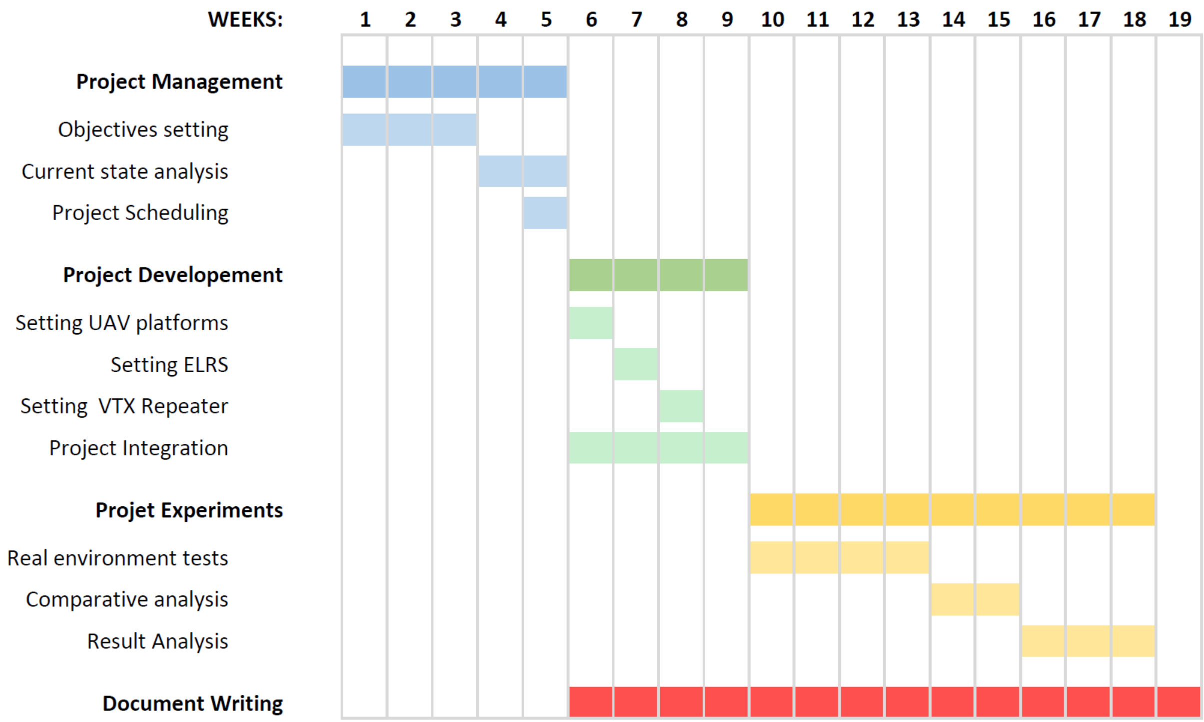


Figure 3. Gantt Chart

The whole project was divided into four sections. The first three weeks were dedicated to understanding the challenges of similar environments in the Xprize Rainforest competition. Once identified, the next two weeks were devoted to researching different commercial and non-commercial solutions from various companies and developers for dealing with difficult environments related to drone technologies. Therefore, over the next four weeks, different hardware was integrated to set up several UAV platforms for testing different solutions. In the following four weeks, testing at the flight field was carried out. To carry out the integration of the entire project, the next five weeks were dedicated solely to investigating and advancing the planned objectives.

In the next two weeks a comparative analysis from the different tested technologies was carried out. In the three following weeks, the results of the previous analysis were developed.

Finally, during the last week and in parallel with other tasks, the written project was done as well.

2 DRONE TECHNOLOGICAL STATE OF THE ART.

This section will study the state of the art focused on drone technology for obtaining information from the environment in different use cases.

As the study of biodiversity is not of common interest to all developers of drone technology, drones will be mentioned in more uses that require equivalent technology to achieve similar objectives.

- ✓ **Drone-assisted collection of environmental DNA from tree branches for biodiversity monitoring.** This drone combines a force-sensing cage with a haptic-based control strategy to establish and maintain contact with the upper surface of the branches with the objective of collecting surface eDNA using an adhesive surface integrated in the cage of the drone.

Figure 4. Drone-assisted collection of environmental DNA
https://www.science.org/doi/10.1126/scirobotics.add5762

- ✓ **DJI Matrice 350RTK.** This drone is the latest launch in DJI Enterprise commercial sector. With clear advantages from its predecessor, Matrice350 RTK has higher protection against the environment (IP55) and better signal power, up to 20 km and 2,7 max payload capacities, it means that it has different options for using multiple payloads. The main use cases for this aircraft are: surveillance, public security, inspections, cartography, topography and more.

Figure 5. DJI Matrice 350RTK
https://enterprise.dji.com/es/matrice-350-rtk

- ✓ **DJI Matrice30.** It is a smaller version of the Matrice350 RTK, the main difference apart from the size is that the payload on this aircraft is fixed. Two versions of this aircraft are available, DJI Matrice30 and DJI Matrice30T, the only difference between them is the thermal sensor implemented on the payload. One ventage from this drone over the Matrice300/350, is that it is compatible with the DJI Dock. The DJI dock is a portable fast charging station that can be deployed in remote locations, it has IP 55 protection and the drone can operate up to 7 km away from it.

Figure 6. DJI Matrice30

https://enterprise.dji.com/es/matrice-30?site=enterprise&from=nav

- ✓ **DarwinFPV Hulk Waterproof FPV Drone.** This is a hobbyist FPV waterproof drone mainly used for cinematic flights. It has an IP67 rating and armor for individual parts of the drone's electronics. This aircraft is ideal for flying in harsh environments. There are two main options for video transmission: analog and digital with the DJI O3 Air Unit. One of the main disadvantages is its flight time, which is around a maximum of 5 minutes (without payload) and it´s recommended payload is up to 240 grams.

Figure 7. DarwinFPV Hulk Waterproof FPV Drone

https://darwinfpv.com/products/darwinfpv-hulk-waterproof-cinematic-fpv-drone

The following UAV platforms are developed by Garuda Robotics, the drone company responsible for the testing days at the XPRIZE Rainforest Semifinals in Singapore. Their 'Cerana Series' is an unrivaled class of all-round multicopters designed for autonomous operations in complex urban environments.

Designed for both aerial image capture as well as parcel deliveries, the Cerana Series can be customized for multiple purposes. From EO/IR cameras, LiDAR, clamps designed to drop eCommerce packages, to winched delivery while hovering.

- ✓ **Cerana X8-28.** Cerana X8 combines significant lifting capacity and weather resistance to provide a rugged, reliable multirotor aircraft ready for missions ranging from lightweight parcel delivery to asset inspections utilising specialised sensors. In its folded transport configuration, Cerana X8-28 is the most compact UAV in its class, enabling new possibilities for front-line operations. Its bullet point is its payload capacity up to 8 kilograms.

Figure 8. Cerana X8-28
https://garuda.io/cerana-x8/

3 TECHNOLOGY COMPARISONS.

In this section different technologies of components for drones will be compared in order to set the bases to establish the criteria to build an unmanned aircraft system adapted for operating in an environment such a rainforest.

3.1 Drone link systems.

As a starting point the drone link depends on two set of equipment. On one hand, radio controller and receiver equipment that allows having telemetry data and controlling the aircraft. On the other hand, the video transmission signal that allows the pilot to see what the drone is seeing in real time.

3.1.1 Video Link System

Video link system refers to the technology and infrastructure used to establish a communication link between the UAS and a ground station, enabling the transmission of live video feed from the drone to the operator or observer on the ground.

The video link system typically consists of the following components:

Camera: The drone is equipped with a camera or a payload that captures video footage. The camera can vary in terms of quality, resolution, and capabilities, depending on the specific purpose and requirements of the UAS mission.

Transmitter: The drone is equipped with a video transmitter that converts the video signal from the camera into a format suitable for transmission. The transmitter is responsible for encoding and modulating the video signal onto a radio frequency (RF) carrier wave for wireless transmission.

Antennas: The drone's video transmitter is connected to an antenna or multiple antennas, which broadcasts the encoded video signal wirelessly. The antennas play a crucial role in transmitting the signal efficiently and ensuring a reliable link between the drone and the ground station.

Ground Station Receiver: On the ground, a receiver antenna is connected to a ground station. The receiver captures the video signal transmitted by the drone's antenna and converts it back into a usable format for display and further processing.

Ground Control Station (GCS): The GCS is a command-and-control center where the UAS operator or pilot monitors and controls the flight of the drone. It typically consists of a computer, display screens, and control interfaces. The video link is established between the GCS and the ground station receiver, enabling the operator to view the live video feed.

Display and Data Processing: The video feed received at the ground station is displayed on the screens of the GCS, allowing the operator to monitor the drone's surroundings in real-time. The video may also be processed and enhanced using specialized software to improve clarity, stabilize the footage, or overlay additional information.

The video link system in a UAS enables the operator to have situational awareness, monitor the drone's flight path, navigate obstacles, conduct inspections, perform surveillance, and make informed decisions based on the live video feed. It is a vital component for many applications of UAS, including aerial photography, videography, search and rescue operations, infrastructure inspections, agriculture monitoring, and more.

Drone video transmission is directly related to the acronym "FPV"

FPV, which stands for First Person View, refers to a perspective commonly utilized in remote-controlled vehicles, including drones and racing cars. It involves the real-time transmission of a live video feed captured by a camera mounted on the vehicle to a display device, such as goggles or a monitor, worn or held by the operator. This enables the operator to perceive the vehicle's movement and surroundings from a first-person perspective, simulating the experience of being onboard the vehicle. FPV technology enhances precision and immersion for operators, facilitating navigation through obstacles, high-speed racing, and various professional applications such as aerial photography, cinematography, search and rescue operations, and inspections of challenging or inaccessible areas.

In the case of FPV drones, a small camera is mounted on the drone, capturing the live video feed of the drone's surroundings. This video feed is then transmitted wirelessly to a display device, such as goggles or a monitor, worn or held by the pilot. The pilot can see exactly what the drone's camera sees, as if they were onboard the drone, hence the term "First Person View."

There are two systems used for transmitting video for FPV: analog and digital.

3.1.1.1 Analog Video System

Since its inception, analog video transmission systems have been at the forefront of the FPV world.

Analog video transmission in FPV has its roots in the television and video signal transmission industry. As FPV drones gained popularity, enthusiasts and pilots sought a way to transmit real-time video from the drone's perspective. This led to the adaptation of existing analog transmission technologies to meet the needs of FPV.

Some of the advantages of the analog video systems are:

- ✓ Analog video transmission offers **Low Latency,** allowing pilots to receive near real-time video footage. This low latency is crucial for precise maneuvering and obstacle avoidance during FPV flight.
- ✓ In situations where other pilots are also using video systems, the analog system has proven to be **More Resistant to Interference**. This is partly due to the simple and robust nature of analog transmission.

- ✓ As it is a system that has been on the market for a longer time, there is **a greater offer** from different manufacturers, which forces them to compete using better features and reducing the cost.
- ✓ The analog FPV system **is compatible** with a **wide range of equipment** and accessories available on the market. Additionally, it is a **more cost-effective** option compared to advanced digital video solutions.
- ✓ Due to its simplicity, analog video does not have any encryption, so it is **easier to broadcast the signal** to many viewers at the same time with **the same quality and fluidity as the main pilot.**
- ✓ Again, thanks to its simplicity, it is **more feasible to manufacture signal boosters** or **signal repeaters** for analog video.
- ✓ The development of analog video transmitter technology does not take into account possible power level limitations. Therefore, some transmitters can be found that work with **power levels much higher** than the digital system.

Some of the downsides of the analog video are:

- Analog transmission has **limited video quality** compared to digital systems. The resolution and sharpness are lower, which can make it challenging to identify fine details and textures during flight.
- Analog video requires a higher bandwidth than digital video, therefore, in the same frequency range, there will be **fewer usable analog signal channels**.
- Overall, the analog FPV system has a more **limited range** under the same power input conditions, compared to digital solutions. This is due to the analog nature of the signal, which is more susceptible to degradation and interference as the transmission distance increases.

As the first example of Analogic Video transmission, its worth mentioning one of the best receiver modules on the marked available today, the Rapid-fire Module.

RapidFire specifications:

- Sensitivity: -96 dBm
- Power: 5V @ ~ 350mA
- Diversity Antenna Input

Figure 9. RapidFire 5.8 GHz Goggle Module.

https://www.immersionrc.com/fpv-products/rapidfire/

The RapidFire FPV Analog Module is a video receiver module widely utilized in FPV systems that employ analog video transmission. Manufactured by ImmersionRC, a prominent company in the FPV industry, this module is designed to enhance the reception and processing of analog video signals. It incorporates ImmersionRC's proprietary RapidFire technology, which employs advanced algorithms and processing techniques to improve video quality and reduce signal interference. The module features two independent receiver modules that work in parallel, enabling simultaneous reception from two antennas and enhancing signal strength and diversity reception. With support for various antenna types and a user-friendly interface for setup and configuration, the RapidFire FPV Analog Module is compatible with a wide range of FPV goggles and screens that accept analog video input. It is highly regarded for its ability to optimize video reception, offering improved performance and a more enjoyable FPV experience.

The Rapidfire Module previously mentioned requires a pair of antennas to be able to work properly, then its worth mentioning next the most versatile and highest performing antenna line for FPV. The Lumenier Double AXII 2 is one of a kind that combines two antenna elements into a single high gain omnidirectional antenna network.

Lumenier AXII 2 specifications:

- Gain: 4.7dBiC
- Axial ratio: 1.0 (near perfect)
- Bandwidth: 5.3GHz-6.2GH
- Radiation Efficiency: 98
- SWR: <=1.5:
- Weight: 17
- Size: 190mm x 17.5mm
- Cable: Semi-rigid RG402
- Connector: Right-Angle SMA

Figure 10. Lumenier AXII 2 Omnidirectional Antenna

https://www.lumenier.com/products/antennas

The Lumenier Double AXII 2 antenna is capable of both receiving and transmitting signals, although its radiation pattern makes it more suitable as a receiving antenna in most scenarios. With its higher gain and "doughnut" style radiation pattern, it offers extended range. However, it does have nulls (areas of weak signal) directly above and below the antenna, as well as smaller nulls around the 50-degree areas. When used as a receiving antenna in a vertical orientation, the Double AXII 2 provides excellent signal coverage within a 32-degree field of view. It can also be used as a transmitting antenna on the aircraft's transmitter, but it's worth noting that tilting or banking during flight may result in signal loss within the antenna's null areas. Consequently, it is generally recommended for receiving purposes.

Together with an omnidirectional antenna, it may be useful to apply another directional antenna or “patch antenna” to perform better long-range penetration when pointing directly to the aircraft. To match this purpose, there are many high directional antennas on the marked available, but since Lumenier is a reliable brand, its worth mentioning next the Lumenier AXII DUO Patch Antenna 5.8 GHz. It offers the highest performance from a high gain mini patch antenna designed for FPV. The Lumenier AXII DUO Patch features a best in class 95% efficiency, most mini patch antennas are typically below 75%.

Lumenier AXII DUO Patch Antenna specifications:

- Frequency: 5.8GHz
- Bandwidth: 280 Mhz
- Gain: 12.2 dBi
- Beam Width: 80° H. 40° V
- Right Hand Circularly Polarized
- SMA Connector (Fits Fat shark Goggles and others using SMA)
- Dimensions: 73mm x 35mm x 9mm (21mm with SMA)
- Weight: 18grams

Figure 11. Lumenier AXII DUO Patch Antenna

https://www.lumenier.com/products/antennas

The previous mentioned components are part of the ground station receiver. Next, there will be introduced the equipment for the aircraft. The first equipment to talk about is the VTX (Video Transmitter). The VTX is a device to transmit analog or digital video signals from a drone or other remoted-controlled vehicle to a receiver on the ground. It is a crucial component in FPV systems as it enables the real-time transmission of video footage from the airborne vehicle to the pilot or observer.

The VTX converts the video signal captured by the camera on the vehicle into a format suitable for transmission over radio frequencies. It then broadcasts the video signal wirelessly to a compatible receiver, typically located on a ground station or FPV goggles worn by the pilot. This allows the pilot to see a live video feed from the vehicle's perspective, providing an immersive and real-time flying experience.

As mentioned before, one of the big advantages of Analog Video transmission for FPV was that since this technology is more mature, more developers are manufacturing high power VTXs with switchable output power levels.

Taking as an example, the new Foxeer 5.8G Reaper Infinity 5W 40CH VTX has an incredible max output power of 5000mW.

Reaper infinity VTX Specifications:

- Input Voltage: 9 – 36 V.
- Output Voltage: 5V.
- Channels: 40.
- Power: 25mW / 500mW / 1500mW / 3000mW / 5000mW.
- Weight: 58 g.
- Mounting Hole: 20x20 mm M2.
- Size: 41x20x17 mm.
- Connector: SMA.
- Consumption: 9V/3A ; 36V/0,8A.

Figure 12. Foxeer 5.8G Reaper Infinity 5W 40CH VTX.

https://www.foxeer.com/foxeer-5-8g-reaper-infinity-5w-40ch-vtx-g-531

The Reaper Infinity needs an antenna to transmit the video, so having in mind that Lumenier antennas were considered for the ground station receiver, it will be considered the Lumenier AXII 2 Long Range 5.8GHz Antenna for the VTX.

Lumenier AXII 2 Long Range Features:

- Significantly Improved Range with a Higher Gain (2.2dBic Gain)
- Wider Bandwidth (5.3-6.2GHz)
- Cleaner Signal and Better Rejection to Interference
- More Durable - Improved Injection Molded Housing
- Virtually Perfect Axial Ratio

Figure 13. Lumenier AXII 2 Long Range Antenna

https://www.getfpv.com/lumenier-axii-long-range-5-8ghz-antenna-rhcp-2.html

3.1.1.2 Digital Video System

With technological advancements, digital video solutions have emerged for FPV. These offer various improvements compared to the analog system, such as higher resolution, superior video quality, and advanced transmission capabilities.

Some advantages of the Digital Video Systems are:

- ✓ Video Quality: Digital systems can provide higher resolutions, sharper images, and more accurate colors compared to the analog system. This allows pilots to see details more clearly and have a more immersive visual experience
- ✓ Range and Interference Resistance: Digital systems provide better experience when flying through obstacles since they have better resistance to interference, as digital transmission can correct errors and adapt to changing environmental conditions by changing from one scale of frequencies to another dynamically.
- ✓ Advanced Features: Digital systems can offer additional features, such as the ability to record high-definition videos, better penetration when flying through certain obstacles and better resistance to multipath interferences specially in a metallic environment where the analog video starts to fail.

Some of the disadvantages of the Digital Video Systems are:

- Increased latency since it is transmitting a lot more information due to the high-quality image.
- Freezing imaging when loosing connection, that can be worst when it gets to a breakpoint where pilot can only see a black screen.
- Technical difficulties for adapting or creating signal booster devices or signal repeater devices to improve the range and penetration.

The first company to launch the digital video transmission was DJI, with a quadcopter called DJI FPV back in march 2nd, 2021.

Figure 14. DJI FPV.

https://store.dji.com/es/product/dji-fpv?site=brandsite&from=insite_search&vid=101601

From that point DJI designed an AIR unit that the users could assembly to their custom aircrafts to have the digital video transmission in new drone builds. The main problem with the first air unit manufactured by DJI was its weight and size, apart that its range and video quality still had some issues to be solved.

Then some companies that came from the analog world associated with DJI to develop alternatives to the first Air Unit, such as Caddx and Runcam, both developed digital VTX´s for the DJI environment.

Next innovation for DJI in this field was the develop of a new drone with a completely new Digital system called O3, the DJI Avata.

Figure 15. DJI AVATA.

https://www.dji.com/es/avata?site=brandsite&from=insite_search

Most recently, DJI started manufacturing their last digital video transmitter. O3 has clear ventages out of their first digital air unit improving video quality but adding some more latency (more than 30ms) to the video transmission.

Figure 16. O3 Air Unit.

https://www.dji.com/es/o3-air-unit?site=brandsite&from=insite_search

DJI Googles2 Specifications.

RCDS18

DJI Goglees 2 Features:

Weight: 290 g.

Resolution: 1920 x 1080 px

Refresh Rate: 100 Hz.

Frequency: 2,4 GHz or 5,8 GHz

2,4 GHz: <20 dBm (FCC/CE/SRRC/MIC/KC)

5,1 GHz: <20 dBm (FCC/CE/MIC/KC)

5,8 GHz: <20 dBm (FCC/SRRC/KC), <14 dBm (CE)

Figure 17. DJI Goggles 2

https://www.dji.com/es/goggles-2?site=brandsite&from=landing_page

In parallel other companies have developed their own digital transmission systems, like Caddx that associated with Fatshak to develop the Avatar Walksnail Digital System.

The Avatar Walksnail Digital System have some advantages over the DJI environment, but it also has some downsides.

Communication Frequency: 5,725 – 5,850 GHz.

Power input: 7-21 V (2S-5S)

Transmission Power: Up to 1200 mW.

CADDX Avatar Walksnail Digital System.

Polarization: LHCP.

Bandwidth: 5.6 GHz – 6 GHz.

Average Gain: 1,9 dBi

Radiation frequency: ≥97%

Figure 18. CADDX Avatar Walksnail Digital System

https://caddxfpv.com/collections/walksnail-avatar-system/products/walksnail-avatar-hd-fpv-system-with-pro-camera?variant=44928160465198

On one hand it is more versatile, it counts with a larger variety of video transmission systems with less size and weight and they provide less latency (around 22ms). On the other hand, the video quality is not as good as the DJI O3.

Finally, another company called HDZero created their own digital system different from the others, principally because it offers less latency than any digital system available today

HDZero represents an unmatched digital wireless video transceiver technology that has been developed and is entirely owned by Divimath Inc. The HDZero transmitter sends out video streams in an uncompressed format, and nearby HDZero receivers are capable of receiving the video with a fixed latency of under 1ms. Leveraging its innovative de-Noise techniques (patent pending), HDZero achieves an extended range per milliwatt. Furthermore, HDZero seamlessly integrates with existing analog video transmitters and is fully compatible with current race timing systems. With support for MSP canvas mode and the SmartAudio protocol, HDZero seamlessly interfaces with various flight controllers and radio controllers.

HDZero provides a robust video link even with lower SNR and in some cases with full capabilities can be even 5 ms faster than analog video system.

HD Zero Features:

Frequency: 5,8 Ghz

Bandwidth: 5,725 – 5,850 GHz

RF Sensitivity: -105 dBm

Super fixed low latency:

- First pixel latency: 3ms vs analog 2ms
- Frame latency: 14.1ms (3+1000/90) for Nano 90 Camera
- Frame latency: 19.7ms (3+1000/60) for other HDZero 60 fps Camera
- Analog Frame latency: 18.7ms (2+1000/60 for NTSC)
- 4.6ms less latency than analog if Nano90 + HDZero Goggle

Figure 19. HD Zero Digital System

https://www.hd-zero.com/technology

3.1.2 Radio Link system

Radio link systems serve as the primary means of communication between a UAV and its operator. They facilitate the transmission of critical data and commands in real-time, ensuring seamless control and operation of the drone.

When selecting or designing a radio link system for UAVs, several factors should be taken into account:

a) **Range and Signal Strength:** The range of the radio link system determines the maximum distance at which reliable communication can be maintained. Factors such as frequency band, power output, and antenna design influence the signal strength and range capabilities of the system.

b) **Frequency Band:** The choice of frequency band depends on the specific requirements of the application and the regulations set by the governing authorities. Common frequency bands for UAV radio links include 2.4 GHz, 5.8 GHz, and licensed bands such as 900 MHz or 868 MHz.

c) **Signal Interference and Reliability:** Radio link systems should be designed to mitigate signal interference from other devices operating in the same frequency band. Reliability is crucial to ensure uninterrupted communication and avoid signal dropouts or packet loss during critical operations specially when flying the drone beyond visual line of sight and having obstacles in between the drone and the pilot.

d) **Data Bandwidth:** The required data bandwidth depends on the type of information being transmitted, such as telemetry data or high-definition video feeds. Higher bandwidth may be necessary for applications that demand real-time video streaming or complex sensor data transmission.

e) **Security:** As UAVs become more integrated into critical infrastructure and public safety operations, ensuring the security of radio link systems is essential. Encryption and authentication mechanisms should be implemented to prevent unauthorized access and protect data integrity.

There are several radio link systems, nevertheless, two of the most reliable ones will be considered to be compared in this paper: ExpressELRS and TBS Crossfire.

3.1.2.1ExpressELRS control link.

Related to radio link systems, the fist technology to talk about is ExpressELRS, it is a high performance, low latency, long range control link. This technology is developed by an open-source team where any developer or user can contribute for making this system better and better as there are many manufacturers today making hardware compatible with ExpressELRS.

ExpressELRS is designed for long-range and reliable control of drones. It stands for "Express Long Range System" and has gained significant attention and adoption within the FPV community.

Some of the ventages of this control link system are:

- ✓ Long Range Capability: ExpressELRS is specifically designed to provide extended control range for drones, allowing pilots to fly their drones over much greater distances compared to traditional systems. It utilizes lower frequencies and different modulation techniques to achieve longer range performance
- ✓ Open-Source Project: ExpressELRS is an open-source project, meaning that its hardware and software designs are freely available to the public. This allows users to customize and modify the system according to their specific needs, contributing to the community-driven development and innovation.
- ✓ Cross-Platform Compatibility: ExpressELRS is compatible with a wide range of popular radio transmitter systems, including FrSky, Jumper, and TBS Tango. This enables users to leverage their existing radio equipment by simply replacing the internal module or using a compatible external module.
- ✓ Multiple Frequency Bands: ExpressELRS supports various frequency bands, including 2.4 GHz, 868 MHz, and 915 MHz, depending on the region and regulations. The lower frequency bands (868 MHz and 915 MHz) are often preferred for long-

range applications due to their better signal penetration and resistance to interference.

- ✓ Enhanced Security: ExpressELRS employs advanced security features to protect the communication between the radio transmitter and the receiver. It utilizes encryption algorithms to prevent unauthorized access and ensure secure data transmission.
- ✓ Configurable Parameters: ExpressELRS offers extensive configurability options, allowing users to optimize the system according to their specific requirements. Users can adjust parameters such as output power, RF frequency, packet rate, and telemetry settings to achieve the desired performance and balance between range and latency.
- ✓ Telemetry Support: ExpressELRS provides support for bidirectional telemetry, allowing real-time data exchange between the drone and the radio transmitter. This enables pilots to receive crucial information such as battery voltage, GPS coordinates, RSSI (Received Signal Strength Indicator), and other customizable telemetry data on their transmitter's screen.
- ✓ Community and Development: ExpressELRS has a vibrant and active community of users and developers who contribute to its continuous improvement. The community provides valuable support, documentation, and firmware updates to enhance the functionality and compatibility of the system

  It's important to note that technology evolves rapidly, so it's always recommended to consult the official ExpressELRS documentation, community forums, and websites for the latest information, updates, and guidelines related to ExpressELRS radio systems.

Some of the downsides of ExpressELRS are:

- Learning Curve: Setting up and configuring ExpressELRS may require a certain level of technical knowledge and familiarity with radio systems. Compared to off-the-shelf commercial solutions, it may take more time and effort to understand and optimize the system to suit specific needs.
- Limited Commercial Support: As an open-source project, ExpressELRS may have limited commercial support compared to mainstream radio systems. While the community provides assistance and resources, it may be challenging to find dedicated customer support or readily available solutions for troubleshooting.
- Potential Regulatory Concerns: The use of specific frequency bands (e.g., 868 MHz and 915 MHz) for long-range control may require compliance with local regulations. Depending on your region, you may need to obtain appropriate licenses or permissions to operate within those frequencies legally.
- Firmware Development and Stability: As an open-source project, the firmware development for ExpressELRS is ongoing and may still be in active development. While this allows for continuous improvement and innovation, it also means that the firmware may not be as stable or bug-free compared to mature commercial radio systems. Users may occasionally encounter compatibility issues or need to update firmware regularly.

- Upkeep and Maintenance: Like any electronic system, the ExpressELRS requires regular upkeep and maintenance. Firmware updates, receiver checks, and antenna inspections are necessary to ensure optimal performance and reliability.
- Hardware Availability: ExpressELRS being an open-source project, the availability of compatible hardware may vary. It's important to ensure that the specific hardware components (e.g., receiver modules, transmitters, antennas) required for ExpressELRS are readily available or compatible with your existing equipment.

It's worth mentioning that these downsides should be considered alongside the advantages of ExpressELRS. Ultimately, the suitability of ExpressELRS will depend on the individual's needs, technical proficiency, and willingness to invest time in learning and troubleshooting the system.

Considering the most powerful ELRS module by Radiomaster, called “RANGER”, it can be visualized the specifications above:

Specification

- Item: Ranger 2.4GHz ELRS Module
- Regulatory Domain: ISM2400
- MCU: ESP32(main), ESP8285(aux, as ESP backpack)
- RF chip: SX1281IMLTRT
- Frequency Range: 2400 MHz - 2480 MHz
- Maximum packet rate: 500Hz/F-1000Hz (F-1000Hz mode requires EgdeTX 2.7.1 or later)
- Minimum receiver refresh rate: 25Hz
- RF Output Power: 30dBm for FCC, 20dBm for CE (Adjustable by LUA)
- Module bay adapters: JR standard 5pin socket & Nano standard 8pin socket
- Futaba CRSF socket cable: Included
- OLED screen: 64x128px
- Wifi Support: Yes
- Bluetooth support: Yes
- 3-Axis Accelerometer: Yes (STK8BA58 MEMS Accelerometer)
- Built-in RGB light strip
- XT30 Power supply voltage: DC 6V - 16.8V
- Weight: 138g (with Moxon antenna) / 135g (with T antenna) / 126g (without antenna)
- Dimension: 95*51*25mm (without antenna)

Figure 20. Radiomaster Ranger Module

From: https://www.radiomasterrc.com/collections/ranger

For long range operations it is recommended to use the long-range antenna (“Moxon antenna”) that is compatible with the previous “Ranger” module:

Figure 21. Radiomaster Moxon Antenna

From: https://www.radiomasterrc.com/collections/ranger/products/2-4ghz-moxon-directional-antenna

A good receiver for this setup could be the RP3 ExpressLRS 2.4ghz Nano Receiver. It is designed to provide reliable and low-latency communication between a transmitter (such as a radio controller) and a receiver. ExpressLRS aims to offer improved range and performance compared to traditional radio control systems.

In general, a nano receiver, refers to a compact-sized receiver module that is typically used in small-scale RC (radio control) models. These receivers are designed to be lightweight and compact, making them suitable for use in micro and mini-sized drones or other small RC vehicles.

The RP3 ExpressLRS 2.4ghz Nano Receiver has an optimized printed circuit board for better heat dissipation. It counts with Low-Noise Amplifier (LNA) for better receiver range and Power Amplifier (PA) for better telemetry range. Apart from that, it has diversity antenna for improved signal stability and range.

Figure 22. Radiomaster RP3 Diversity Receiver

From: https://www.radiomasterrc.com/collections/receivers/products/rp3-expresslrs-2-4ghz-nano-receiver

The RP3 ExpressLRS 2.4ghz Nano Receiver includes the SX1280 transceiver which provides ultra-long-range communication in the 2.4 GHz band with the linearity to withstand heavy interference. This makes it the ideal solution for robust and reliable wireless solutions.

Figure 23. RP3 ExpressLRS 2.4HGz Nano Receiver

From: *LoRa Connect RF Transceiver, SX1280, 2.4GHz With Ranging | Semtech*

3.1.2.2 TBS Crossfire Control Link.

The TBS (Team Black Sheep) Crossfire is a long-range radio control system specifically designed for drone applications. It is widely regarded as one of the most reliable and advanced radio link systems available for drone pilots.

Here are some key features and information about the TBS Crossfire:

- ✓ Long-Range Capability: The TBS Crossfire system is known for its exceptional long-range capabilities, allowing pilots to fly their drones at extended distances without signal loss or interference. It offers a reliable control link, even in challenging environments.
- ✓ Two-Way Communication: Unlike traditional radio systems, the TBS Crossfire provides two-way communication between the transmitter and the receiver. This bidirectional communication enables features like telemetry data feedback, remote receiver updates, and firmware updates.
- ✓ Frequency Hopping Spread Spectrum (FHSS): The TBS Crossfire system utilizes FHSS technology, which constantly changes the operating frequency in a predefined pattern. This helps to minimize interference from other sources and ensures a stable and reliable connection.
- ✓ Crossfire Transmitter Modules: The TBS Crossfire system consists of two main components: the transmitter module and the receiver. The transmitter module is compatible with popular radio controllers such as FrSky, Futaba, and Taranis. It plugs into the back of the radio controller and provides the long-range capabilities.
- ✓ Crossfire Receiver: The Crossfire receiver is installed on the drone and is responsible for receiving the signals from the transmitter module. It connects to the flight controller and allows for control over the drone's movements. The receiver also provides telemetry data, such as battery voltage, RSSI (Received Signal Strength Indicator), and more.
- ✓ Telemetry Data: The TBS Crossfire system supports telemetry, which means it can transmit real-time data from the drone back to the transmitter. This information can include battery voltage, GPS coordinates, flight mode, and other customizable parameters. Pilots can monitor this data on their radio controller's screen or through additional telemetry modules.
- ✓ Immune to 2.4GHz Interference: The TBS Crossfire system operates on different frequencies than the commonly used 2.4GHz band. This separation helps to minimize interference from other devices, such as Wi-Fi routers, Bluetooth devices, and other drones using traditional radio systems.
- ✓ Frequency Bands: The TBS Crossfire system offers different frequency options to comply with regional regulations. These frequency bands include 868MHz (EU), 915MHz (USA), and 2.4GHz (worldwide). Users should ensure they select the appropriate frequency band for their country or region.

- ✓ Firmware Updates: The TBS team regularly releases firmware updates for the Crossfire system, adding new features, improving performance, and addressing any potential issues. These updates can be applied to both the transmitter module and the receiver, ensuring the system stays up to date with the latest advancements.
- ✓ Crossfire Integration: Many popular FPV flight controllers and drones have native support for the TBS Crossfire system. This integration simplifies the installation process and allows for seamless compatibility between the radio system and the drone's control system.

While the TBS Crossfire radio system offers many advantages and it's known for its long-range capabilities, there are a few potential downsides to consider

- Cost: The TBS Crossfire system tends to be more expensive compared to traditional radio control systems. The transmitter module, receiver, and additional accessories can add up to a significant investment. This cost may be a deterrent for some users, especially those on a tight budget
- Legal Considerations: The TBS Crossfire system operates on frequencies that may require specific licenses or permissions in certain countries or regions. It's essential to understand and comply with local regulations regarding the use of the frequencies utilized by the system. Failure to comply with these regulations can result in legal consequences.
- Limited Range without Antenna Diversity: While the TBS Crossfire system offers excellent long-range capabilities, it may experience reduced range in certain situations, especially without antenna diversity. Antenna orientation and positioning can affect signal strength and performance. Users may need to invest in additional equipment, such as antenna trackers or diversity modules, to optimize signal reception.
- Upkeep and Maintenance: Like any electronic system, the TBS Crossfire requires regular upkeep and maintenance. Firmware updates, receiver checks, and antenna inspections are necessary to ensure optimal performance and reliability. Users must stay up to date with firmware releases and perform routine maintenance tasks to prevent potential issues.
- Limited Availability: Depending on your location, you may find that the TBS Crossfire system is not readily available in local hobby shops. This can make it more difficult to access the system quickly or seek immediate support in case of issues. Online purchasing and shipping may be the primary options, which can involve additional time and costs.

Considering one of the most popular Crossfire modules by TBS, its specifications can be seen above:

Features:

- Frequency Bands: 868MHz (EU, Russia) / 915MHz (USA, Asia, Australia)
- Input Voltage: 3.5 – 13V
- Power consumption: 1.1W (@10mW) – 3.2W (@2000mW)
- Dimensions: 55 x 89 x 15 mm
- Weight: 76g
- Maximum operating range: 30 miles.

Figure 24. TBS Crossfire TX – Long Range R/C Transmitter

From: https://www.team-blacksheep.com/products/prod:crossfire_tx

SPECS OF TBS CROSSFIRE TX – LONG RANGE R/C TRANSMITTER:

- Long range, adaptive and robust remote-control system for your aircraft.
- Immune to on-board noise.
- Two-way communication link with real-time link vitals and telemetry.
- Self-healing & frequency hopping (DSSS, FHSS).
- Adaptive bandwidth control and range optimization.
- Serial Modem capable of transmitting MAVLink or other serial protocols (up & downlink).
- RX beacon mode to recover your downed aircraft.
- Super easy binding and configuration via built-in display.
- Low latency, 150Hz update rate (3x faster than typical RC links) control for perfect immersive feeling.
- Two receiver models: 8ch Diversity Rx, 4ch PPM/SBUS Mini-receiver (4g weight!) 8 or 12ch output via PPM/SBUS/CRSF on both receivers.
- Ability to fly with multiple friends at the same time (10 or more).
- Selectable RF power from 10mW to 2W (local restrictions apply).
- Dedicated head-tracking input option for full FPV immersion.
- Transmitter LED shows link health, OLED display for built in configuration.
- Short-Range mobile connectivity telemetry output for smartphone apps.
- Fully configurable by OpenTX and TBS TANGO remote using CRSF protocol.
- CRSF protocol interface to Betaflight, Kiss and Raceflight FCs (lower latency, higher update rate, telemetry support).
- Expansion port for future feature support
- Micro-receiver for smaller drones.
- Software updates via RF Link

One of the most reliable antennas for the TBS module is the TBS Diamond Antenna:

Features:

- Connector: SMA Male
- Weight: 20.6g
- Size: 135 x 120 mm
- Gain: 2.88dB
- Frequency: 850 – 950MHz
- Suggested for: TBS Crossfire TX or TBS Crossfire Micro TX

Figure 25. TBS Diamond Antenna

From: https://www.team-blacksheep.com/products/prod:diamond_antenna

The most popular receiver used in the experiment is the Nano RX (SE) TBS long range receiver.

Features:

- Weight: 0.5g (receiver only)
- Size: 11mm x 18mm
- Requires: Firmware V2.25
- RF Output power (EIRP) = 15,9 dBm
- Power: 1 W
- Sensitivity: -130dBm

Figure 26. TBS Crossfire Nano RX

From: https://www.team-blacksheep.com/products/prod:crossfire_nano_se

The most suitable antenna for its range and durability is the TBS Immortal T V2 Antenna:

Specifications:

Weight: 3.4g
Width: 15cm
Cable length: 80mm
Connector: u. FL / IPX
Maximum gain: 2 dBi

Figure 27. TBS Crossfire Immortal T V2 Antenna

From: https://www.team-blacksheep.com/products/prod:xf_immortal_t_v2_s

3.2 Power Supply

In any radio-controlled or autonomous device, a power source is required, in the case of unmanned aircraft, a typical one are batteries. There are several types of batteries designed for drones. However, the most common are Lithium-ion (Li-ion) and Lithium Polymer (Li-Po) batteries.

On one hand, Li-Ion batteries have become the standard choice for many portable electronic devices due to their reliable performance, moderate energy density, and improved safety features. These batteries use a liquid electrolyte and have a more rigid structure compared to Li-Po batteries. On the other hand, Lithium polymer batteries, often known as Li-Po batteries, are becoming more popular because of how light and slender they are. Li-Po batteries have a higher energy density and less self-discharge because they employ a solid or gel-like polymer electrolyte rather than a liquid one.

The next table contents the advantages and disadvantages of these two kinds of batteries:

	LiPo	Li-Ion
Discharge capacity	High	Low
Lifespan	Regular	Good
Useful life	Low	High
Power density	Worst	Moderate
Safety	Safer	Not so safe
Passive Discharge Rate	Slow discharge	Higher consumption when its not being used
Versatility	Different shapes & sizes	Fixed shape
Maintenance	Needs to be at 30% before storing.	No needed
Pricing	Difficult manufacture	Lower price per cell

Table 1. LiPo Li-Ion batteries, advantages and disadvantages.

Latest studies in solid-state lithium batteries suggest that many disadvantages presented in LiPo and Li-Ion batteries can be overwhelmed. Solid-state batteries have the following potential advantages:

- ✓ No problems relating to vaporization of liquid electrolytes and absence of phase transitions at low temperatures improving low-temperature performance and making them safer to use.

- ✓ More energy density and ease of miniaturization, making them even more efficient.
- ✓ Highly reliable; showing excellent storage stability, no memory effect and very long cycle life making them more eco-friendly.

Unfortunately, as they are still in the development phase, their commercial use in unmanned aircraft is not possible at this time.

3.2.1 Li-Ion Batteries.

As electrical and electronic systems become smaller and more efficient, batteries provide the key to portability, nowadays depending on the purpose, can be special configurations of Li-Ion Batteries thanks to their superior power density compared to LiPo Batteries. However, as listed before, since it has lower discharge capacity the maneuverability of the drone can be affected as the drone is not that responsive.

When the batteries are connected in serial configuration, the voltage is being increased but the capacity remains the same. Whereas in paralel configuration the voltage remains the same but the capacity is increased.

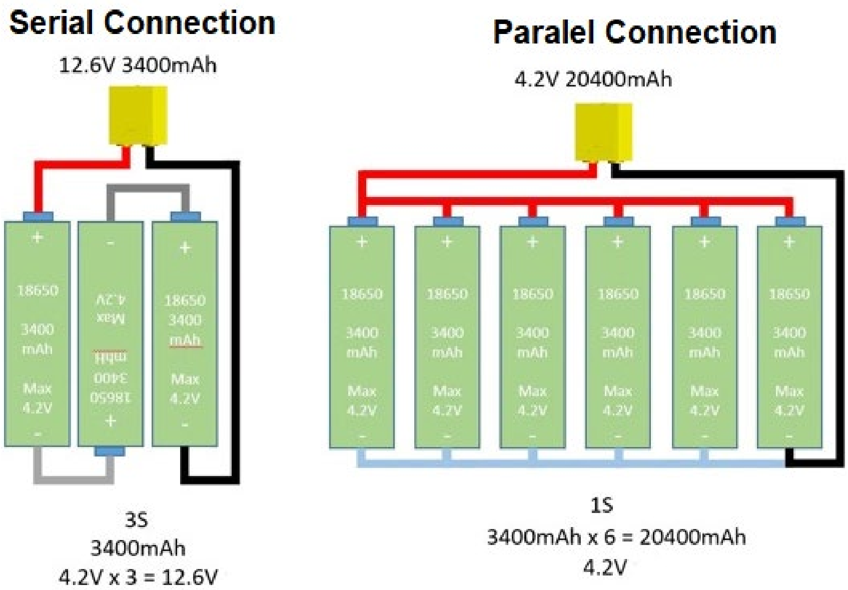


Figure 28. Different configurations for Li-Ion batteries.

Therefore, to create a 4s battery for example, it would require to connect 4 Li-Ion batteries in serial. Additional to that, if it would be needed to increase that 4s battery`s capacity, it would be required to connect it in parallel with another 4s battery previously joined.

The key point of Li-ion batteries is that they can be easily modified to build a bigger battery in capacity terms or a battery with extra cells.

There are different Li-Ion batteries from different companies, but the most recommended for drones are the high-quality ones, an example can be the Sony Konion US 18650VTC6.

Features:

- Capacity: 3120 mAh
- Nominal Voltage: 3.6V
- Capacity: 3000 mAh
- Discharge rate: 30 A continuous
- Dimensions: 18,20mmx67mm
- Weight: 46,6 g
- Max amps: 6.0 A
- Internal Resistance:
- Max. Charge: 4,25 V
- Shut down: 3,0 V

Figure 29. Sony konion US 18650VTC6

https://rc-innovations.es/shop/sony-konion-us18650vtc6-3120mah-3-6v-30a-pin-superior#attr=2008,612

Another valid option for Li-Ion batteries for setting a bigger battery for drones is the Panasonic NCR18650B.

Features:

- Capacity: 3400 mAh
- Nominal voltage: 3,7 V
- Dimensions: 18mmx65mm
- Weight: 45g
- Max. Amps: 6,7 A
- Internal Resistance <=45 mOhm
- Max. Charge: 4,20 V
- Shut down: 2,75 V

Figure 30. Panasonic NCR18650B.

https://rc-innovations.es/shop/Panasonic-NCR18650B-Li-ion-3400mah-bateria-18650#attr=2028,619

3.2.2 LiPo Batteries

LiPo batteries are known for their high energy density, lightweight design, and ability to deliver high discharge rates. They can be manufactured in various sizes and shapes using a polymer.

The primary classification of LiPo batteries is based on their voltage. The voltage is determined by the number of cells used, with each LiPo cell having a voltage of 3.7V. The chemical components of these batteries allow for a maximum voltage storage of 4.2V, and the minimum cell voltage should never be below 3V if reusability is desired. Exceeding the voltage range described above would permanently damage the battery or, in certain circumstances, could lead to an explosion. For this reason, the use of special balance chargers is recommended to ensure safe charging of the battery.

If higher voltage is desired from LiPo batteries, the number of cells inside must be increased. The number of cells in a battery is indicated as 1S for a single-cell battery, 2S for a two-cell battery, and so on.

Using a higher voltage implies obtaining more power from the motors. However, some motors and electronic speed controllers (ESCs) have specific operating voltage limits that should not be exceeded to avoid damage.

In order to understand the operating voltage range for different numbers of cells in LiPo batteries, Table 16 is provided.

Cell numbers	Nominal Voltage	Min. Voltage	Max. Voltage
1S	3.7 V	3.0 V	4.2 V
2S	7.4 V	6.0 V	8.4 V
3S	11.1 V	9.0 V	12.6 V
4S	14.8 V	12.0 V	16.8 V
5S	18.5 V	15.0 V	21.0 V
6S	22.2 V	18.0 V	25.2 V

Table 2. Cell counts and Voltages in LiPo Batteries.

It is possible to see the cell count defined by a number such as '3S2P', where the first number (before the S) defines the number of cells connected in series (3S). The second number defines the configuration of how many cells are connected in parallel (2P). In order to obtain more capacity and higher discharge rates, some batteries have more cells connected in parallel, which increases the capacity and discharge rate while maintaining the voltage constant. In the example of a 3S 2P battery, the battery actually has six individual cells.

Another important parameter of LiPo batteries is the Milliampere-hour (mAh), which measures the amount of energy or capacity of a battery. If a longer flight time is desired, the battery should have a higher capacity. However, increasing the capacity of a battery also proportionally increases the weight. Therefore, the motors will have to work harder to keep the drone in flight.

3.3 Motors.

Firstly, in order to meet the design requirements, it has been considered to use sealed motors, which have some protection against water splashes and dust or tinny objects that may get inside. When choosing the motors for the quadcopter, the following general rule should be followed: it should assure that the motors produce enough thrust to be able to lift the drone in the air with a throttle position of around 50-60% of the maximum value. of acceleration, so for example, having a total weight of 1kg, as the quadcopter uses four motors, each motor would need to produce at least 500g of thrust, to give a total thrust of twice the weight (2kg = 4 x 0.5kg).

The most widely used motors in unmanned aircraft today are brushless motors, because they provide a large amount of power in relation to their low weight. These motors consist of a stator (non-moving part) and a rotor (moving part). The stator consists of coils arranged in a radial pattern, with copper wire wound around each coil, to form a bunch of electromagnets. The electromagnets are wound and connected in a very specific way depending on the desired characteristics of the motor.

These motors are relatively cheap, and could be used in a first prototype, the problem is that they are not very powerful and can get hotter than common motors because they are protected.

The rotor has magnets arranged around the inside of the motor housing. To spin the motor, power is applied to specific sets of coils at very precise intervals, so it is necessary to use an electronic motor controller to control their speed. This explains why brushless motors have three wires to connect them, since there are three sets of electromagnets connected in a typical brushless motor.

Table 3 shows a typical engine naming convention; the first four numbers are an indication of the size of the motor, the numbers followed by KV show how fast the motor will rotate, and the final numbers provide details of the stator and rotor configurations.

22	12	850 KV	12N	14P
Rotor Diameter	Rotor Height	Revolutions per Volt	Number of electromagnets in the stator	Number of permanent magnets in the rotor

Table 3. Brushless Motor Nomenclature.

From: "How to build your own Drone" by Alex Elliot

One of the important factors in motor performance is the KV rating, which represents the motor's revolutions per minute (RPM) per volt. Therefore, an 850KV motor will spin at 850 RPM when supplied with 1V of electrical voltage.

Motors with lower KV ratings spin slower but have more torque, while motors with higher KV ratings spin faster but have less torque. A lower KV motor is created using thinner copper wire around each electromagnet, which means it requires more volts for fewer amps. As a result, it spins slower but produces more power. On the other hand, a higher KV motor is built with thicker wire and fewer windings around each electromagnet, which means it draws more amps at lower voltages. This allows the motor to spin faster but with lower torque, making higher KV motors more suitable for smaller propellers

A very cost-efficient choice for a sealed motor, considering a relatively small quadcopter capable of carrying a small camera is to use BrotherHobby Venom 2206 motors with a KV rating of 1900. The main feature of these motors is that the coils are fully protected by the motor bell. Additionally, they have a specific shape that aids in cooling through convection. There are three different types of this motor available in the market: 1900KV, 2400KV, and 2600KV. As the project's intention is to carry a payload, like a camera, the best option is to use larger propellers. Therefore, it is advisable to choose the lower KV option.

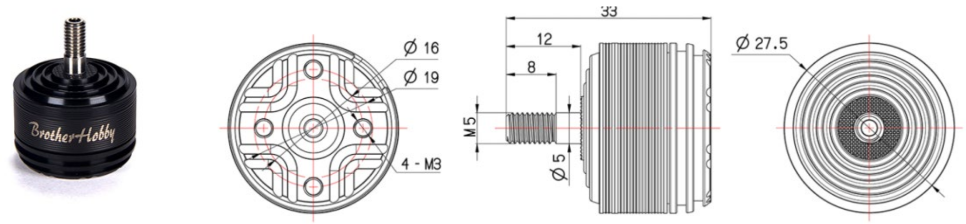


Figure 31. Motor Venom 2206 - 1900 KV

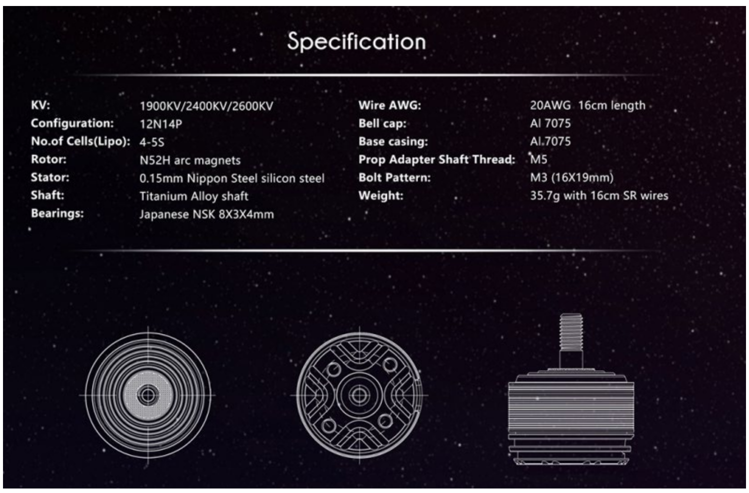


Figure 32. Venom 2206 Motor features

From: https://www.brotherhobbystore.com/venom-2206-motor-p0040.html

3.4 Propellers.

A propeller is a rotating aerodynamic profile composed of two or more blades attached to a support structure connected to the motor's rotor. Its purpose is to generate thrust or drag using the power transmitted by the motor.

Being a rotating aerodynamic profile, it achieves the same effect as that produced by the profile of a plane's wing when exposed to a moving airflow: it creates a difference in pressures and, therefore, lift. Since the same physical principles apply, a determining factor will be the air density, with higher density resulting in better propeller performance (generating more lift force).

Another characteristic of propellers is that the blade tips have a higher speed of movement in their plane of rotation compared to the parts near the hub (same angular velocity but different linear velocity). This allows them to reach speeds close to the speed of sound. When this happens, there is a significant decrease in their performance. To avoid this situation, propellers have limitations on their diameter and rotational speed. This difference in speed along the blades, increasing as we move away from the hub towards the tips, affects their design. The blades are twisted in such a way that they provide a significant blade angle near the hub and a slight blade angle at the ends. Additionally, the thickness and chord (length) of the profile vary. This way, the most effective angle of attack and aerodynamic profile is achieved for each section of the blade, while maintaining a constant value of the lift force generated along its entire length.

The main characteristics that describe a propeller are diameter, pitch, weight, shape, number of blades, and construction material (aluminum, plastic, carbon fiber, among others).

The common nomenclature used for drone propellers is shown in Table 15.

T	70t	56	C
Number of Blades	Diameter in inches	Pitch	Rotation´s Direction

Table 4. Nomenclature for Propellers

Fuente: " How to build your own Drone " by Alex Elliot

Figure 33. T7056C Propeller.

For example, for the propeller in Figure T7056C (Figure 92), the first letter "T" indicates the number of blades, which in this case would be a three-blade propeller. On the other hand, if we were referring to a four-blade propeller, the letter "Q" would be used.

The next two numbers "70" should be divided by 10 and indicate the diameter formed by the propeller when rotating, measured in inches. In this case, the propeller diameter would be 7 inches.

The next two numbers "56" refer to the pitch. This value, divided by 10, corresponds to the inches the propeller would advance during a complete 360° rotation, theoretically penetrating a solid substance (in practice, since air is a gaseous medium, the actual advance produced will always be much less).

3.4.1 Toroidal Propellers.

A new concept of propeller was recently studied by MIT; in 2019, MIT researcher Thomas Sebastian was assigned the task of studying the potential of using an electric field to generate thrust and propel an aircraft through electro aerodynamic thrust, or ionic wind. This promised quieter propulsion compared to traditional propellers. Sebastian explored different designs, particularly ring-shaped wings that were lighter, and proposed adopting a similar shape for a propeller by joining the blade tips to form a ring. This concept of toroidal propellers quickly caught attention and generated significant interest, further driven by an R&D award and videos released by MIT that detailed Sebastian's innovative work.

Figure 34. Foxxer Dalprop Donut 5145

When a traditional propeller like the one in shown in **Figure 33.** is spinning through the air, it creates high pressure underneath the propeller and low pressure on the top, the difference between pressures generates the thrust that pulls the propeller through the air.

If we take a closer look to the propeller tip, it can be observed that the high-pressure air underneath the propeller rushes around the tip to fill the low-pressure void above the propeller, this process generates a vortex that flows around the tip and generates noise.

Figure 35. Tip of a traditional Propeller

Instead, the toroidal propeller aims to remove the possibility for that vortex to be formed.

Figure 36. Tip of a Toroidal propeller.

In any kind of propeller, there is low-pressure at the top and high-pressure air underneath but when reaching to the tip of the propeller, there is no an easy path where the high-pressure air can rush round and fill in the low-pressure side. Moreover, at the tip of the propeller, there is a kind of twisted propeller shaped with some high to it that helps keep the low pressure-air on the top and the high-pressure air underneath apart from each other. In conclusion, vortices get generated in a toroidal propeller but they do not happen just in one place (on the tip) but, vortices get generated through the whole airflow profile and because those vortices are spread out across the propeller, they are smaller, they dissipate more quickly and they generate **less noise.** In addition, this means less energy is taken out of the propeller making toroidal propellers more efficient, generating more thrust for less drag and less power.

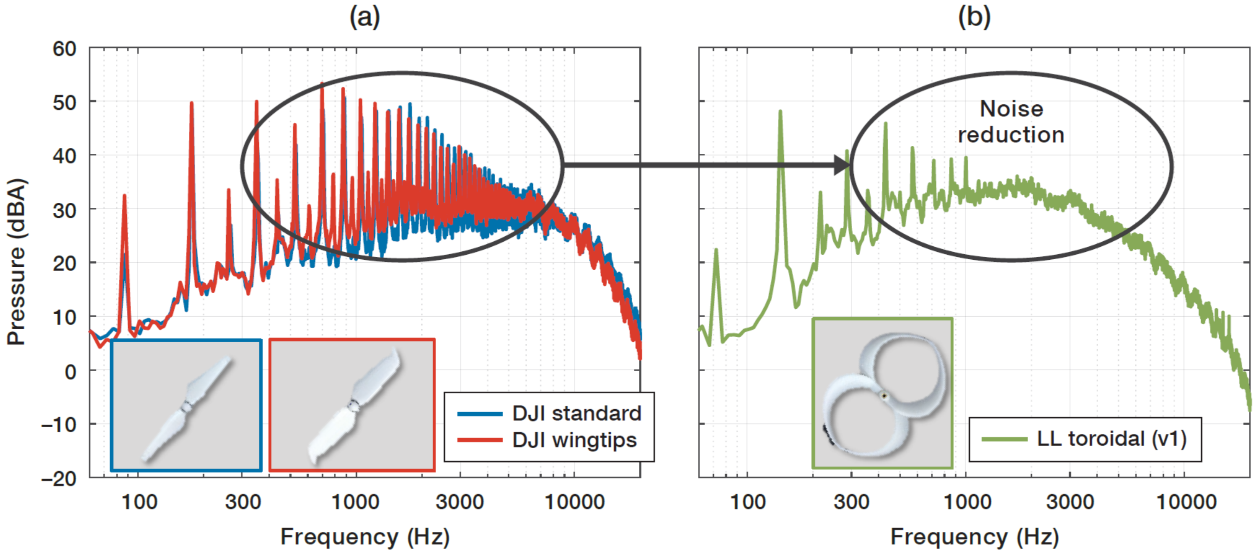


Figure 37. Comparison between conventional propellers and toroidal propeller.

https://www.ll.mit.edu/sites/default/files/other/doc/2022-09/TVO_Technology_Highlight_41_Toroidal_Propeller.pdf

In some experiments performed in MIT Lincoln Laboratory, the comparison between conventional propellers (a) used on DJI drones and the toroidal propeller (b), shows the significant reduction of noticeable noise achieved by the toroidal propeller.

4 ANALYTICAL CALCULATIONS.

To begin, it will be needed to calculate the link budged for entire system in order to assure that the system will maintain a safe connection within the competition area. Teams will deploy their Solutions from a Base Station located at a maximum of 200 meters outside of the Competition Area. The maximum testing area is 100 hectares. Distribution of team competition areas will be strategically coordinated and sufficiently distanced to avoid interference, within a homogeneous, undisturbed lowland tropical rainforest landscape.

Considering that the competition area is a square surface, the maximum distance from the base station area to the furthest point to reach in the competition is:

$$d = 200 + 1000 \cdot \sqrt{2} = 1614\, meters$$

The link budget is the clearest and most intuitive way of computing the required transmitter (TX) power. All the equations that connect the TX power to the receiver Signal-to-noise ratio (SNR) are written in a tabular form. The Signal-to-Noise Ratio is a measure of the strength of the desired signal compared to the level of background noise of interference present in the communication channel.

The SNR is expressed as a ratio of the power of the signal to the power of the noise. A higher SNR indicates a stronger and cleaner signal, which generally leads to better communication performance and higher data transmission rates. Conversely, a lower SNR means that the signal is weaker in comparison to the noise, increasing the likelihood of errors and degradation in communication quality

SNR is an essential parameter in evaluating the performance and reliability of wireless communication systems. It is influenced by factors such as distance, environmental conditions, interference sources, and the quality of the transmitting and receiving equipment. In wireless networks, maintaining an adequate SNR level is crucial for achieving satisfactory signal quality and ensuring reliable data transmission.

As most factors influencing the SNR enter in a multiplicative way, it is convenient to write all equations in logarithmic form, specifically in dB (decibels). Since this calculation is theorical, the link budget gives only an approximation (often the worst-case estimate) for the total SNR, because some interactions between different effects are not taken into account. Therefore, experimental measurements for comparing the results from this calculous will be necessary.

4.1 Link Margin for the Analog Video

Based on the specifications provided in 3.1.1.1 Analog video system. It will be presented the procedure to calculate the link margin for this system.

The Link Margin is the difference between the real receive power and the minimum receive power required (which is the sensitivity) plus some extra room to cover extra attenuations. A good Link Margin should be above 12 dB.

As it was explained previously, the Rapidfire module receiver use diversity reception, that means that the system will pick the signal out of two different antennas depending on the situation to prevent video signal loss. Therefore, two calculations will be required for both types of antennas installed on the module, one omnidirectional and the other, directional or patch. The most restrictive will provide the most critical link margin giving the information required to judge whether the system is capable enough or not.

In the following calculations, the link margin of the analog video system will be calculated by comparing the performance of different video receiver antennas, listing the components to be compared below:

<table>
<tr>
<td>Analog Video System</td>
<td>Antenna set on the Aircraft:

Lumenier AXII 2 Long Range:
Gain: 2,2 dBi</td>
<td>VTX used for the comparison:

Reaper Infinity
Max Power: 5W</td>
<td rowspan="2">Receiver Module used for the comparison:

ImmersionRC Rapidfire Analog Video receiver.
Sensitivity: -96 dBm</td>
</tr>
<tr>
<td>Antenna´s to be compared set on the receiver module:</td>
<td>Patch Antenna:

Lumenier DUO
Gain: 12.2 dBi</td>
<td>Omnidirectional Antenna:

Lumenier AXII2
Gain: 4,7 dBi</td>
</tr>
</table>

Table 5. Comparison of the two antennas set on the analog video receiver.

For further details of each component from **Table 5** it is recommendable to check section 3.1.1.1

Link Margin Calculation for the Analog Video with Patch Antenna (Lumenier AXII DUO Patch):

First, relevant data must be tabulated in order to gain awareness of the important parameters necessary to proceed.

Parameter	5,8 GHz radio
Sensitivity (dBm)	- 96
Transmit power (dBm)	**37**
Maximum distance (m)	1614
Ground station antenna gain (dBi)	12,2
Aircraft antenna gain (dBi)	2,2
Maximum pointing error	3
Maximum bank angle (°)	45
Radio to antenna cable losses at each end (dB)	0,5

Table 6. Relevant data - Link Margin Calculation for analog video with Patch antenna

Notes: The values of Maximum pointing error, maximum bank angle and Radio antenna cable losses are not provided by the manufacturer, so default values have been assumed to perform the calculations.

Free Space Losses:

$$5,8\ GHz \ \rightarrow solve\ for\ 5800\ MHz:$$

$$L_{FS}(dB) = 20 \cdot log\left(\frac{4\pi \cdot 5800 \cdot\ 1,614}{0,3}\right) = 111,87\ dB$$

Polarization loss:

$$L_{pol} = -20 \cdot log\ [cos(45^{\underline{o}})] = 3,01\ dB$$

Calculating the transmitter power in dBm: The radio can go up to 1W as maximum power, therefore for the calculus in this example, this value will be taken:

$$P_{TX}[dBm] = 10 \cdot log(5000mW) \approx 37\ dBm$$

Calculating the Receiver Power:

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2\right]$$

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot f \cdot d}{c}\right)^2\right]$$

$$P_{RX} = 29,2\ +\ 2.2 - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot 5800 \cdot 10^6 \cdot 1614}{3 \cdot 10^8}\right)^2\right]$$

$$P_{RX} = -80,47\ \ dBm$$

Calculating the Power Loss due to propagation of the wave under Free Space conditions.

$$L_{FS}(dB) = 32,44 + 20 \cdot log(f[MHz]) + 20 \cdot log(d[km])$$
$$L_{FS}(dB) = 32,44 + 20 \cdot log(5800[MHz]) + 20 \cdot log(1,614[km])$$
$$L_{FS}(dB) = 111,87\ dB$$

$$P_{RX} = P_{TX} + \sum G_i - \sum L_i$$
$$Link\ margin = P_{RX} - P_{RX,required}$$

At this point, it is possible to complete the parameter table for this case:

$$Link\ margin = P_{RX} - P_{RX,required}$$

Parameter	5800 MHz (maximum range)
Power transmit *(P_{TX})*	37 dBm
Ground cabling loss *(L_{TX})*	0,5 dB
Ground station antenna gain *(G_{TX})*	12,2 dB
Ground positioning loss *(half power)*	3 dB
Free space propagation loss *(L_{FS})*	111,87 dB
Polarization loss (L_{pol})	3,01 dB
Aircraft pointing loss (half power)	3,00 dB
Aircraft antenna gain (G_{RX})	2,2 dB
Aircraft cabling loss (L_{RX})	0,5 dB
Power receiver (P_{RX})	**-70,48dBm**
Required receiver Power ($P_{RX, required}$)	**-96 dBm**
Link Margin	**25,52 dB**

Table 7. Link Margin Calculation for analog video with Patch antenna

In the case of the Patch Antenna, it seems have a very good link margin and it also would be still more than enough even much less transmit power, with a 2 W of VTX power the link margin is about 14,03, so it is higher than the minimum recommended value for the maximum distance required. However, it is important to keep in mind that the radiation pattern of a patch antenna very directional, it means that if the drone is located out of the range of the radiation pattern, the signal can be affected dramatically.

Link Margin Calculation for the Analog Video with the Omnidirectional Antenna (Lumenier AXXI2):

Parameter	5,8 GHz radio
Sensitivity (dBm)	- 96
Transmit power (dBm)	**37**
Maximum distance (m)	1614
Ground station antenna gain (dBi)	4,7
Aircraft antenna gain (dBi)	2,2
Maximum pointing error	3
Maximum bank angle (°)	45
Radio to antenna cable losses at each end (dB)	0,5

Table 8. Relevant data - Link Margin Calculation for analog video with Omnidirectional Antenna

Notes: The values of Maximum pointing error, maximum bank angle and Radio antenna cable losses are not provided by the manufacturer, so default values have been assumed to perform the calculations.

Free Space Losses:

$$5,8\ GHz\ \rightarrow solve\ for\ 5800\ MHz:$$

$$L_{FS}(dB) = 20 \cdot log\left(\frac{4\pi \cdot 5800 \cdot\ 1,614}{0,3}\right) = 111,87\ dB$$

Polarization loss:

$$L_{pol} = -20 \cdot log\ [cos(45º)] = 3,01\ dB$$

Calculating the transmitter power in dBm: The radio can go up to 1W as maximum power, therefore for the calculus in this example, this value will be taken:

$$P_{TX}[dBm] = 10 \cdot log(5000mW) = 37\ dBm$$

Calculating the Receiver Power:

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2\right]$$

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot f \cdot d}{c}\right)^2\right]$$

$$P_{RX} = 31,68 + 2,2 - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot 5800 \cdot 10^6 \cdot 1614}{3 \cdot 10^8}\right)^2\right]$$

$$P_{RX} = -77,99\ dBm$$

Calculating the Power Loss due to propagation of the wave under Free Space conditions.

$$L_{FS}(dB) = 32,44 + 20 \cdot log(f[MHz]) + 20 \cdot log(d[km])$$

$$L_{FS}(dB) = 32,44 + 20 \cdot log(5800[MHz]) + 20 \cdot log(1,614[km])$$

$$L_{FS}(dB) = 111,87\ dB$$

$$P_{RX} = P_{TX} + \sum G_i - \sum L_i$$

$$Link\ margin = P_{RX} - P_{RX,required}$$

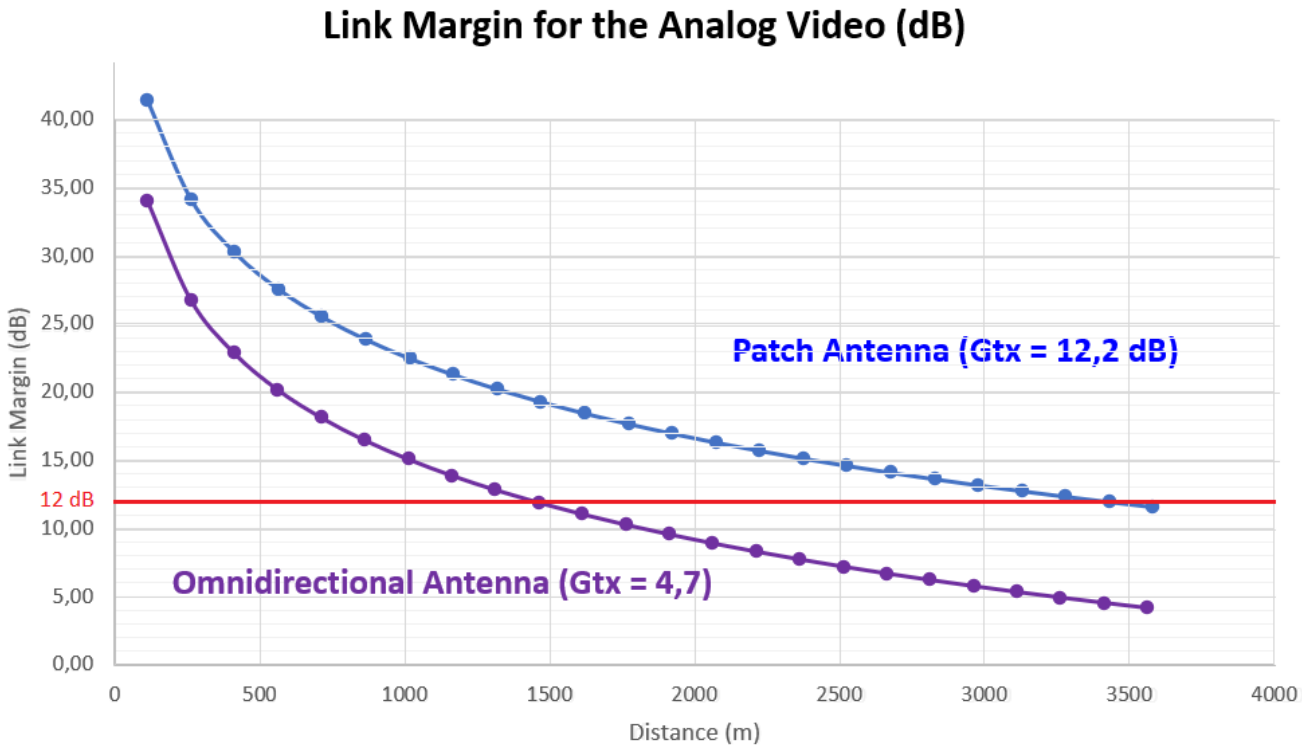
At this point, it is possible to complete the parameter table for this example:

$$Link\ margin = P_{RX} - P_{RX,required}$$

Parameter	5800 MHz (maximum range)
Power transmit *(P_{TX})*	36,99 dBm
Ground cabling loss *(L_{TX})*	0,5 dB
Ground station antenna gain *(G_{TX})*	4,7 dB
Ground positioning loss *(half power)*	3 dB
Free space propagation loss *(L_{FS})*	111,87 dB
Polarization loss (L_{pol})	3,01 dB
Aircraft pointing loss (half power)	3,00 dB
Aircraft antenna gain (G_{RX})	2,2 dB
Aircraft cabling loss (L_{RX})	0,5 dB
Power receiver (P_{RX})	**-77,99 dBm**
Required receiver Power ($P_{RX, required}$)	**-96 dBm**
Link Margin	**18,01 dB**

Table 9. Link Margin Calculation for analog video with Omnidirectional Antenna

In the case of the Omnidirectional Antenna, the ***Link Margin*** for the distance imposed by the competition area is about 18,01 dB, that means that the signal is pretty strong, it seems to be stable at the maximum range at 5W power since this is the highest power reached on this system.



Graph 1. Link Margin for the Analog Video

The Graph 1 shows the link margin obtained for different distances when using two types of reception antennas with the Rapid-fire diversity module in the analog video transmission system.

The maximum safe range is defined as the distance at which the link margin is equal to 12 dB. According to this definition, the range achieved with the omnidirectional antenna is approximately 1443 meters. On the other hand, with the directional patch antenna, a safe distance of approximately 3414 meters can be reached.

Considering the defined maximum distance of 1614 meters imposed by the Xprize Rainforest challenge, it can be concluded that the directional antenna should be primarily pointed towards the farthest point of the competition area from the base to ensure a secure video reception at all times.

While in the comparison of the analog video system, the aim was to compare components within the same system, in the following radio link comparison, the intention is to compare completely independent systems with each other, in order to objectively determine the most suitable system for the mission.

Comparison between two Radio Controller Module Systems for Drones		
	ExpressELRS	TBS Crossfire
Frequencies used	2.4 GHz	915 MHz
TX Modules:	Radiomaster Ranger: Max. Power Output: 1W	TBS Crossfire: Max. Power Output: 2W
TX Antennas Modules:	Radiomaster Moxon: Gain: 5,98 dB	TBS Diamond: Gain: 2,88 dB
RX Receiver	Radiomaster RP3 Diversity: Sensitivity: -132 dBm	TBS Crossfire Nano RX: Sensitivity:
RX Antennas:	ExpressELRS 2 T antennas: Gain: 2dBi	TBS Immortal T V2: Gain: 2dBi

Table 10. Comparison of the two Radio Module Systems for the RC communication

For further details of each component from **Table 10** it is recommendable to check section **3.1.2.**

4.2 Comparison between different radio link systems.

In order to compare ExpressElrs control link with the TBS Crossfire control link, it will be required to calculate the link budget from both systems.

Link Margin Calculation for Express ELRS:

First, relevant data must be tabulated in order to gain awareness of the important parameters necessary to proceed.

Link budget definition (uplink)

Parameter	2.4 GHz radio
Sensitivity (dBm)	-132
Transmit power (dBm)	**30**
Maximum distance (mile)	31,068 (50.000m)
Ground station antenna gain (dBi)	5,98
Aircraft antenna gain (dBi)	2
Maximum pointing error	Half power beamwidth
Maximum bank angle (°)	45
Radio to antenna cable losses at each end (dB)	2.3

Table 11. Relevant data for Express ELRS

Notes: The values of Maximum pointing error, maximum bank angle and Radio antenna cable losses are not provided by the manufacturer, so default values have been assumed to perform the calculations. The maximum range for Express ELRS listed by the manufacturer is around 50 kilometers.

Free Space Losses:

$$\mathbf{2.4\ GHz\ \rightarrow solve\ for\ 2400MHz:}$$

$$L_{FS}(dB) = 20 \cdot log\left(\frac{4\pi \cdot 50.000}{0.328}\right) = 125.65\ dB$$

Polarization loss:

$$L_{pol} = -20 \cdot log\,[cos(45º)] = 3.01\,dB$$

Calculating the transmitter power in dBm: The radio can go up to 1W as maximum power, therefore for the calculus in this example, this value will be taken:

$$P_{TX}[dBm] = 10 \cdot log(1000mW) = 30\,dBm$$

Calculating the Receiver Power:

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2\right]$$

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot f \cdot d}{c}\right)^2\right]$$

$$P_{RX} = 35,98 + 2 - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot 2400 \cdot 10^6 \cdot 50000}{3 \cdot 10^8}\right)^2\right]$$

$$P_{RX} = -96,05\,dBm$$

Calculating the Power Loss due to propagation of the wave under Free Space conditions.

$$L_{FS}(dB) = 32,44 + 20 \cdot log(f[MHz]) + 20 \cdot log(d[km])$$

$$L_{FS}(dB) = 32,44 + 20 \cdot log(f[2400]) + 20 \cdot log(50[km])$$

$$L_{FS}(dB) = 134.02\,dB$$

$$P_{RX} = P_{TX} + \sum G_i - \sum L_i$$

$$Link\ margin = P_{RX} - P_{RX,required}$$

At this point, it is possible to complete the parameter table for this example:

$$\boldsymbol{Link\ margin} = \boldsymbol{P_{RX}} - \boldsymbol{P_{RX,required}}$$

Parameter	915 MHz (maximum range)
Power transmit *(P_{TX})*	30 dBm
Ground cabling loss *(L_{TX})*	2,3 dB
Ground station antenna gain *(G_{TX})*	5,98 dB
Ground positioning loss *(half power)*	6,2 dB
Free space propagation loss *(L_{FS})*	125,65 dB
Polarization loss (L_{pol})	3,01 dB
Aircraft pointing loss (half power)	6,18 dB
Aircraft antenna gain (G_{RX})	2 dB
Aircraft cabling loss (L_{RX})	2,3 dB
Power receiver (P_{RX})	**-116,04 dBm**
Required receiver Power ($P_{RX,required}$)	**-132 dBm**
Link Margin	**15,96 dB**

Table 12. Link Margin for Express ELRS

The ***Link Margin*** for the maximum range listed by the manufacturer is about 15,96 dB, that means that the signal is pretty strong, it seems to be stable at the maximum range at 1W power since this is the highest power reached by this system.

Link Margin for TBS CROSSFIRE:

Proceeding to the calculations similarly to the previous case:

Link budget definition (uplink)

Parameter	915 MHz radio
Sensitivity (dBm)	-130
Transmit power (dBm)	**33,01**
Maximum distance (mile)	30 (48,270m)
Ground station antenna gain (dBi)	2,88
Aircraft antenna gain (dBi)	2
Maximum pointing error	Half power beamwidth
Maximum bank angle (°)	45
Radio to antenna cable losses at each end (dB)	2.3

Table 13. Relevant data for TBS Crossfire

Notes: The values of Maximum pointing error, maximum bank angle and Radio antenna cable losses are not provided by the manufacturer, so default values have been assumed to perform the calculations. The maximum range for TBS Crossfire listed by the manufacturer is 30 miles (around 48,270m)

Free Space Losses:

$$900\ MHz\ \rightarrow solve\ for\ 915MHz:$$

$$L_{FS}(dB) = 20 \cdot log\left(\frac{4\pi \cdot 48.270}{0.328}\right) = 125,34\ dB$$

Polarization loss:

$$L_{pol} = -20 \cdot log\ [cos(45^{º})] = 3,01\ dB$$

Calculating the transmitter power in dBm: The radio can go up to 2W as maximum power, therefore for the calculus in this example, this value will be considered:

$$P_{TX}[dBm] = 10 \cdot log(2000mW) = 33,01\ dBm$$

Calculating the Receiver Power:

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2\right]$$

$$P_{RX} = EIPR + G_{RX} - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot f \cdot d}{c}\right)^2\right]$$

$$P_{RX} = 15,9 + 2 - 10 \cdot log\left[\left(\frac{4 \cdot \pi \cdot 915 \cdot 10^6 \cdot 48270}{3 \cdot 10^8}\right)^2\right]$$

$$P_{RX} = -107,44\ dBm$$

Calculating the Power Loss due to propagation of the wave under Free Space conditions.

$$L_{FS}(dB) = 32,44 + 20 \cdot log(f[MHz]) + 20 \cdot log(d[km])$$
$$L_{FS}(dB) = 32,44 + 20 \cdot log(f[915]) + 20 \cdot log(48.27[km])$$
$$L_{FS}(dB) = 125,34\ dB$$
$$P_{RX} = P_{TX} + \sum G_i - \sum L_i$$
$$Link\ margin = P_{RX} - P_{RX,required}$$

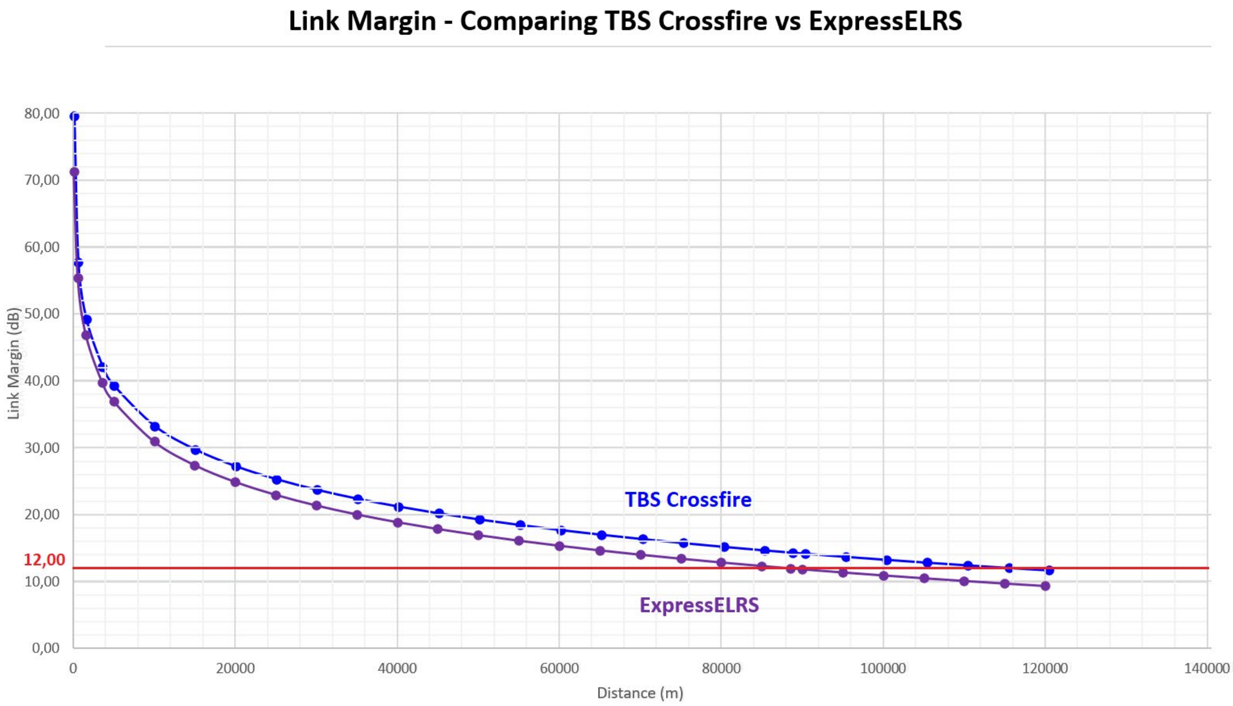
At this point, it is possible to complete the parameter table for this example:

$$Link\ margin = P_{RX} - P_{RX,required}$$

Parameter	915 MHz (maximum range)
Power transmit *(P_{TX})*	33,01dBm
Ground cabling loss *(L_{TX})*	2,3 dB
Ground station antenna gain *(G_{TX})*	2,88 dB
Ground positioning loss *(half power)*	6,2 dB
Free space propagation loss *(L_{FS})*	125,34 dB
Polarization loss (L_{pol})	3,01 dB
Aircraft pointing loss (half power)	6,18 dB
Aircraft antenna gain (G_{RX})	2 dB
Aircraft cabling loss (L_{RX})	2,3 dB
Power receiver (P_{RX})	**-107,44 dBm**
Required receiver Power ($P_{RX, required}$)	**-130 dBm**
Link Margin	**22,56 dB**

Table 14. Link Margin for TBS Crossfire

For TBS Crossfire, the ***Link Margin*** for the maximum range indicated by the manufacturer is about 22,56dB, that means that the signal is very strong and TBS Crossfire proved to be more robust than ExpressELRS.



Graph 2. Link Margin TBS Crossfire vs Express ELRS

On balance, as the crossfire system operates in a different scale of frequencies and it also have more output power capabilities, despite the fact that the sensitivity is inferior than the ExpressELRS system, TBS Crossfire perform around 30% better in these conditions.

The free space model has been taken as a reference for calculating signal propagation attenuation to provide an initial approximation for overflight in wooded areas. This reference model has also been experimentally verified through measurements performed on the received signal power when flying over open spaces above forests, outside controlled airspace, as detailed in section 5.1.

For a more detailed analysis of vegetation-induced attenuation under other conditions, it is necessary to have a detailed understanding of the specific characteristics of the environment between the transmitter and receiver under the specific conditions being explored. More precise approximations can be used for this purpose, as indicated in *[2] J. M. Hernando Rábanos, J.M. Riera, L. Mendo, "Radio Transmission" (section 3.12 Vegetation Attenuation, pages 173-175)* which are detailed in ITU-R Recommendation P.833-10.

In particular, in the case of a radio path where one terminal is located in a forest or similar vegetation, and the other end is outside of it, the additional loss due to vegetation can be characterized by two parameters:

- The specific attenuation rate (dB/m) mainly due to energy scattering outside the radio path.
- The maximum additional total attenuation due to vegetation in a radio path (dB), limited by the effect of other mechanisms, including surface wave propagation over the top of the vegetation medium and front scattering within it.

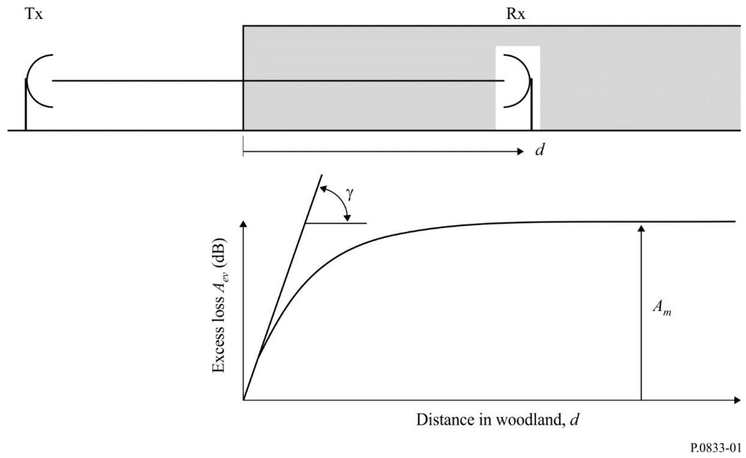


Figure 38. Representative radio path in woodland.

Figure 38 shows the scenario where the transmitter is outside the forest and the receiver is at a certain distance, d, inside it. The excess attenuation, Aev, due to the presence of vegetation could be approximated by x:

$$A_{ev} = A_m [1 - \exp(- d \gamma / A_m)]$$

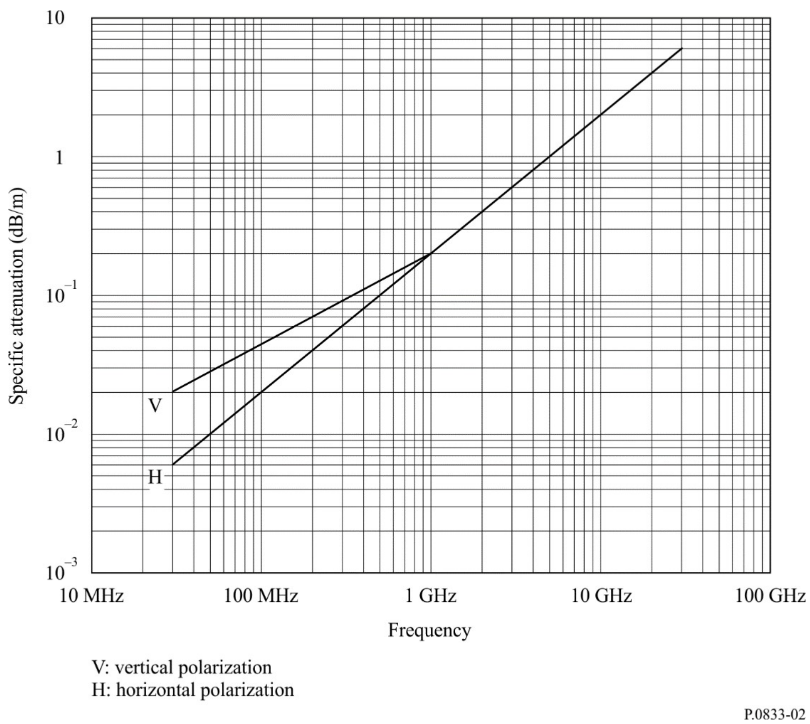
where:

- d : length of path within woodland (m)
- γ : specific attenuation for very short vegetative paths (dB/m)
- A_m : maximum attenuation for one terminal within a specific type and depth of vegetation (dB).

The excess attenuation, Aev, is defined as the excess over all other mechanisms, not just free space loss.

It can also be noted that Am is equivalent to the loss due to multipath echoes often mentioned for a terminal obstructed by some form of ground cover or parasitic echoes.

The value of specific attenuation due to vegetation, γ dB/m, depends on the species and density of the vegetation. Approximate values are provided in **Graph 3** as a function of frequency. That figure displays typical values for specific attenuation derived from various measurements in the frequency range of 30 MHz to approximately 30 GHz in forests. Below approximately 1 GHz, there is a tendency for vertically polarized signals to experience higher attenuation than horizontally polarized signals, believed to be due to the scattering from tree trunks.



Graph 3. Specific attenuation due to woodland

Attenuation due to vegetation varies widely due to the irregular nature of the mediumand the wide range of species, densities, and water content obtained in practice. The values shown in Graph 3 should be viewed as only typical.

At frequencies of the order of 1 GHz the specific attenuation through trees in leaf appears to be about 20% greater (dB/m) than for leafless trees. There can also be variations of attenuation due to the movement of foliage, such as due to wind.

The maximum attenuation, A_m, as limited by scattering from the surface wave, depends on the speciesand density of the vegetation, plus the antenna pattern of the terminal within the vegetation and the vertical distance between the antenna and the top of the vegetation.

5 EXPERIMENTAL TESTS.

5.1 Real Flights compared with previous link margin calculations

TBS Crossfire:

For the experimental flight, the first step is planning the mission, in order to do that, it is mandatory to be aware of the actual rules and regulations for unmanned aerial vehicles in the specific location. Therefore, for the experimental flight a non-regulated airspace location was selected to carry out the experiment and considering that the flight area is clear was and uninhabited.

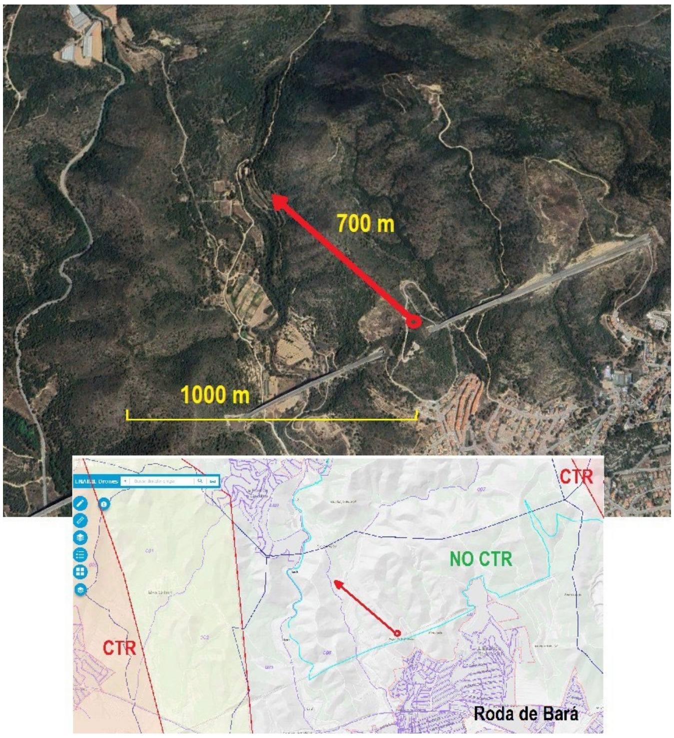


Figure 39. Flight planning for the TBS Crossfire test

Experimental flights have been carried out to check the behavior of the drone signal loss from the TBS Crossfire system. In addition, the graphs of this theoretical behavior have been superimposed along with the real behavior.

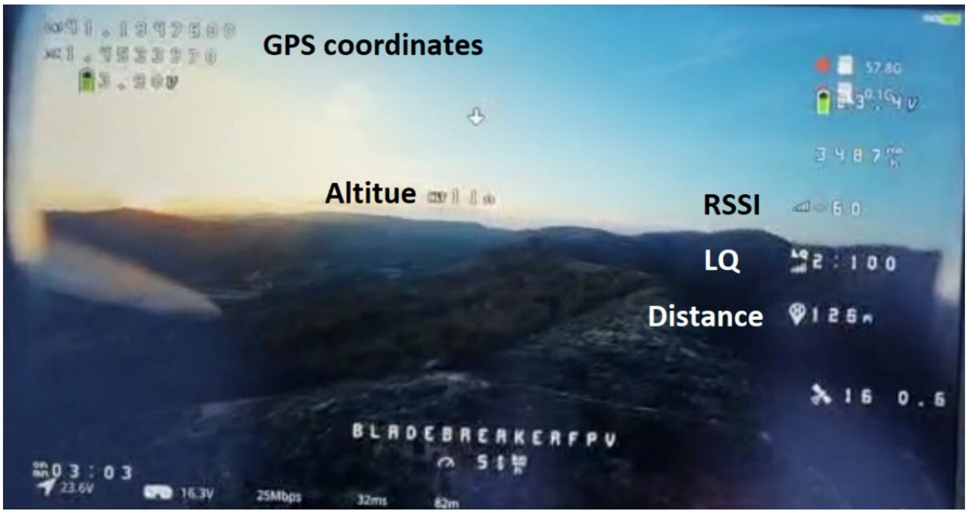
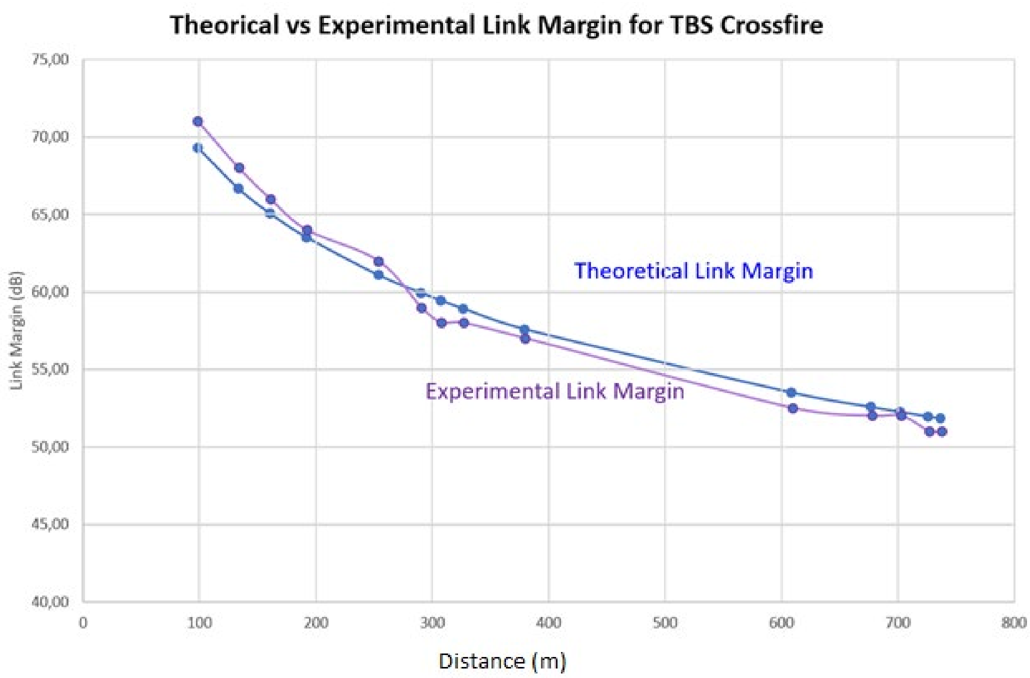


Figure 40. TBS Crossfire Real Mission

To assess the link margin behavior of TBS Crossfire in a real flight, it was conducted a controlled experiment. A drone equipped with the TBS Crossfire system was flown at different distances while monitoring the RSSI values. The Link Margin experimental values were obtained by measuring the signal strength and comparing it to the minimum required signal strength for a reliable communication.

The experiment yielded consistent and reliable results, showcasing the effectiveness of the TBS Crossfire radio control system. The link margin values recorded during the experiment closely matched those reported in previous theorical calculations and can be visualized in the Graph 2.



Graph 4. Theorical vs Experimental Link Margin for TBS Crossfire

Even though, I could not fly for a real long-range distance because legal restrictions, I could demonstrate the behavior of the theorical link margin compared with the values obtained in my experiment. It would allow me to predict the point where I could experiment some connection problems or even be able to know how far it can be expected to keep a safe connection link.

ExpressELRS:

Since I do not own the system yet, I referred to the missions performed by other enthusiast pilots competing in an international ExpressELRS Long-Range contest, taking similar data from the OSD (On-Screen Display) recorded during the flight, that I used in my experiment.

https://www.expresslrs.org/info/long-range/

The On-Screen Display (OSD) enables the visualization of different kind of data received and processed by the flight controller. One of its most useful applications is the ability to display alarms or notifications during flight, providing awareness of the remaining flight time, as well as the quality and strength of the signal to prevent telemetry loss, or in this case, taking measurements to compare different parameters from real missions with the ones previously calculated.

The data used for this experimental test was acquired by Leslie Yagin, a month ago, reaching a maximum distance of 31,56 km with a 2,4 GHz ExpressELRS receiver. Tx Power was around 50 mW and the aircraft was a fixed-wing type.

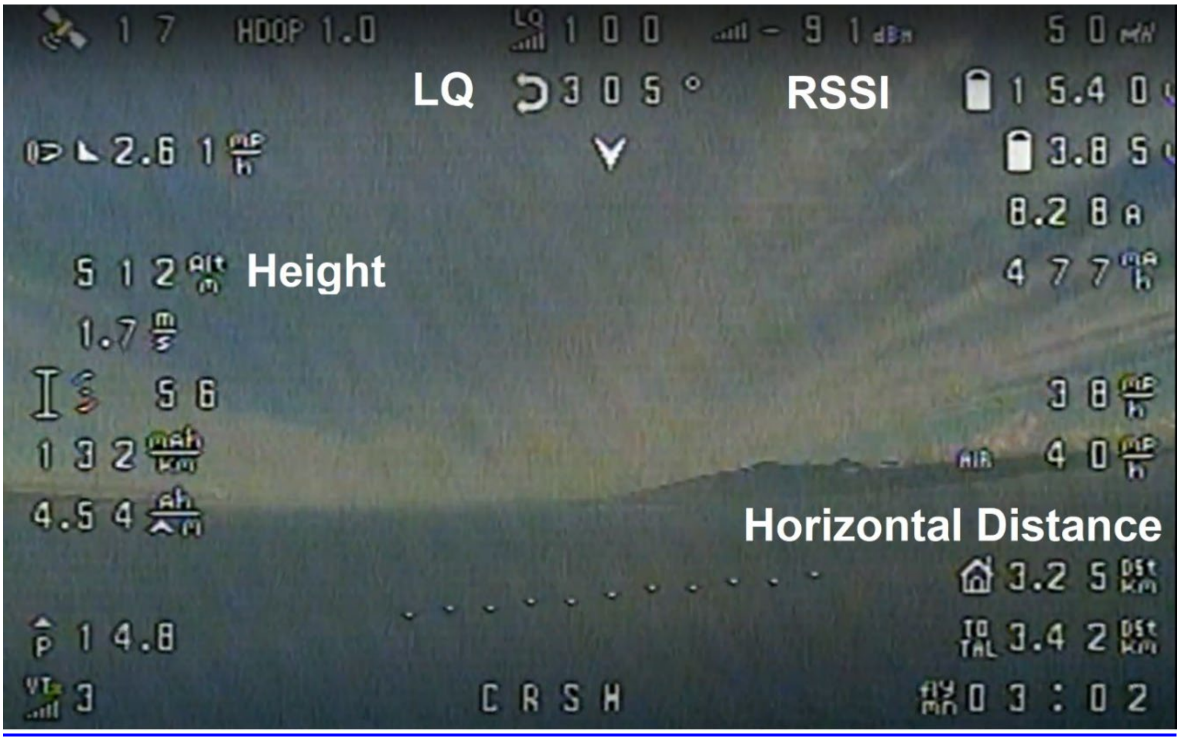
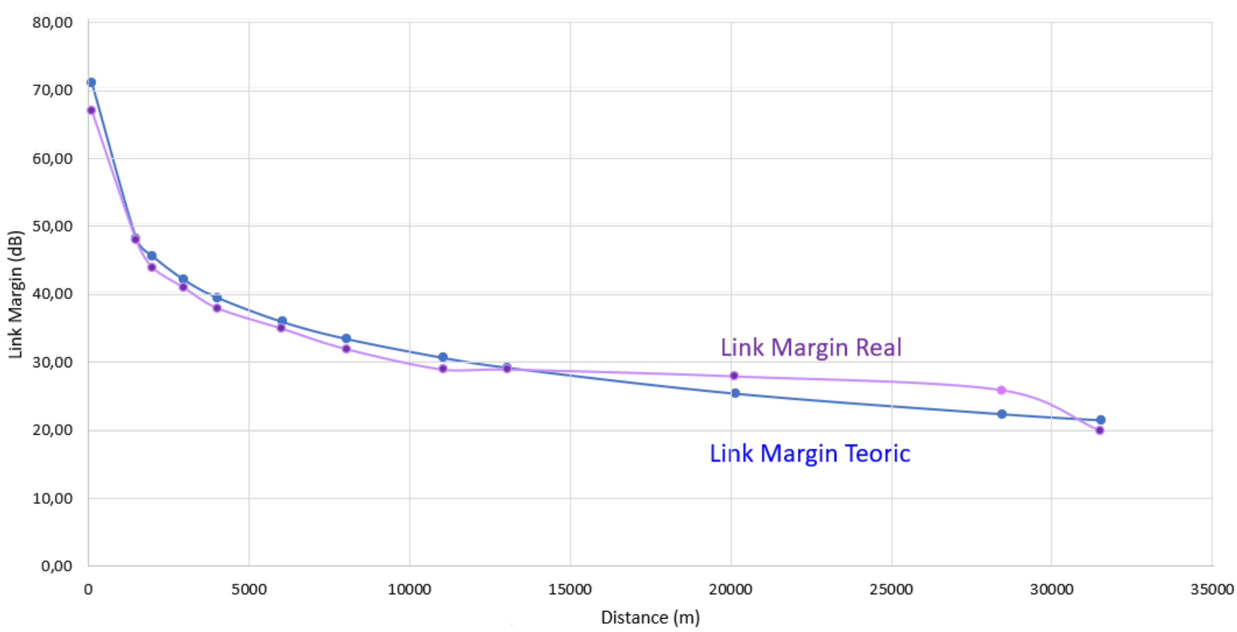


Figure 41. Express ELRS Real Mission

https://www.youtube.com/watch?v=sK-OAQUwgyU

Theorical vs Experimental Link Margin for ExpressELRS



Graph 5. Theorical vs Experimental Link Margin for ExpressELRS

In the experiment mentioned from the ExpressELRS system, the maximum distance reached was limited mostly by the video transmission, watching at the mission, it was clear that the video was having issues from early moments. Nevertheless, it seems to keep a reliable connection from the Radio Link. What is most important, is that even in higher distances, the behave from the theorical calculations matches with reality in most of the trajectory. What it can be observed at the maximum distance reached by the fixed-wing is that the signal strength was decreasing dramatically at the final moments before turning home. Despite of that, reaching an incredible distance of 31,56 km with a 2,4 GHz controller link and full analog video system, is a remarkable achievement.

5.2 Test Bench with multiple batteries and multiple propellers for the 2206 Venom Motor

An experiment has been conducted to test the performance of the recommended engine in **Figure 31**. In order to fulfill this purpose, the necessary electronics have been installed on a test bench specifically prepared for testing brushless motors.

In order to take the data needed of the motor in real time, it was required in this case, to solder the motor to an ESC and connect everything to a Flight Controller in order to have real time data to transmit it on the OSD.

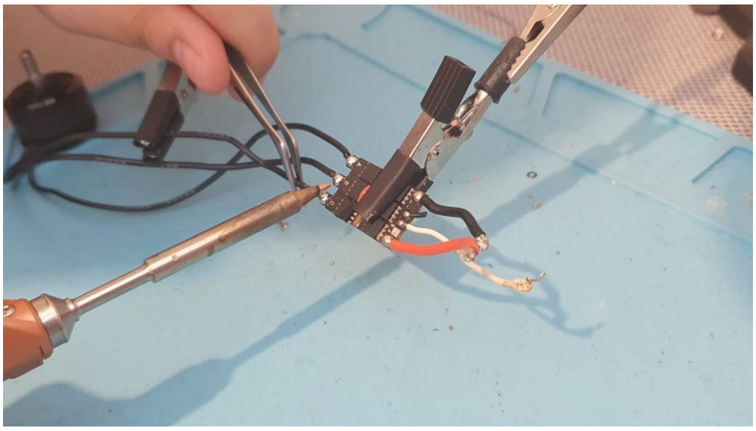


Figure 42. Setting the electronics for the motor experiment

A static thrust test has been conducted to verify the previously proposed general rule when selecting a motor.

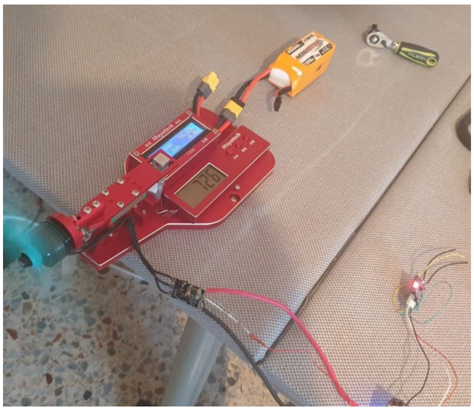


Figure 43. Venom 2206 Motor test

To this setup, a video transmitter (VTX) was added in order to obtain the required data (current and voltage) for each scenario through the On-Screen Display (OSD). These data were then combined with the thrust measurements generated by the motor using various types of propellers, as observed in **Figure 40.**

Table 13 displays the results obtained from static thrust tests using different propellers with a range of batteries, from 3S to 6S.

90m	Static Thrust Test: BrotherHobby Venom 2206-1900KV (-1900KV Medido)																								
	Voltaje: 3S – 6S / ESC: HobbyWing XR40A BLHeli R14.4																								
	6S GF 5045BN (PROP 1)					6S HQ 5045x3 V1S (PROP2)					4S dys XT5045x3 (PROP 3)					4S HQ 6045BN (PROP 4)					4S DAL T6040Cx3 (PROP 5)				
Propeller	Thrust[g]	Load[A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Load [A]	Volts [V]	Power W]	Eff [g/W]	Thrust [g]	Load [A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Load [A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Load A]	Volts [V]	Power [W]	Eff [g/W]
	300	3.1	23,0	72	4,2	300	3,2	23,0	73	4,1	300	4,2	16,1	68	4,4	300	1,1	16,6	18	16,8	300	3.8	16.1	60	5.0
	500	5.9	23.0	136	3.7	500	6.1	23.0	139	3.6	500	7.9	16.0	127	3.9	500	6.8	16.0	110	4.6	500	7.0	16.1	113	4.4
6S	700	9.5	22.9	217	3.2	700	9.6	22.9	220	3.2	700	3.1	16.7	52	13.6	700	11.0	16.0	176	4.0	700	11.1	16.0	178	3.9
	1000	15.3	22.9	351	2.9	1000	15.8	22.9	361	2.8	1000	21.3	15.9	339	2.9	1000	18.7	15.9	298	3.4	1000	18.5	15.9	296	3.4
	1779	35.9	22.7	813	2.2	1863	40.3	22.6	911	2.0	1188	26.6	15.9	422	2.8	1422	31.4	15.8	49.5	2.9	1391	29.5	15.8	467	3.0
5S	1340	26.9	18.7	505	2.7	1443	30.6	18.7	573	2.5															
4S	1024	21.1	15.9	335	3.1	1124	24.2	15.9	385	2.9															

	4S KK 6040 (PROP 6)					5S KK 6040 (PROP 7)					6S KK 6040 (PROP 8)					4S GF 7042 (PROP 9)					4S HQ 7045 (PROP 10)				
Propeller	Thrust [g]	Load [A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Carga [A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Load [A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Load [A]	Volts [V]	Power [W]	Eff [g/W]	Thrust [g]	Load [A]	Volts [V]	Power [W]	Eff [g/W]
	300	3.8	16.1	61	4.9	300	3.3	19.0	63	4.8	300	2.9	23.0	66	4.6	300	3.9	16.1	62	4.8	300	3.7	16.1	60	5.0
	500	7.4	16.1	118	4.2	500	6.2	19.0	118	4.2	500	5.6	23.0	128	3.9	500	6.6	16.1	105	4.7	500	6.5	16.1	104	4.8
	700	11.5	16.0	185	3.8	700	10.0	18.9	190	3.7	700	8.6	22.9	196	3.6	700	10.6	16.0	173	4.0	700	11.4	16.0	183	3.8
	1000	19.1	15.9	304	3.3	1000	16.7	18.9	314	3.2	1000	14.2	22.9	326	3.1	1000	20.3	15.9	324	3.1	1000	19.7	15.9	314	3.2
	1392	29.4	15.8	466	3.0	1769	37.3	18.6	696	2.5	2173	48.8	22.5	1098	2.0	1684	47.0	15.7	735	2.3	1680	43.4	15.7	681	2.5
3S																1259	33.9	12.0	406	3.1	1208	31.0	12.0	372	3.3

Table 15. Motor experimental results for different popellers and batteries

From the conducted experiment, the power used by the motor for different thrust values has been obtained. It is important to note that each table corresponds to a different battery configuration with varying cell counts, as well as different propeller sizes and pitches.

The final decision of what propeller and batteries to pick will depend on the full design of the aircraft since it is important to know the weight and the intended flight time.

6 CRITERIA ANALISIS.

Comparison between Crossfire and ExpressELRS.

Note that in the previous calculations, the power and frequency conditions of both systems were not the same, therefore, to make a fairer comparison, the calculations will be made under similar conditions. For this purpose, comparative tables of results for both control links are presented next:

Comparing the maximum theorical distance of both ExpressELRS and TBSCrossfire systems.

Parameter	ExpressELRS 2,4 GHz (88500 meters)	TBSCrossfire 915 MHz (115100 meters)
Power transmit *(P_{TX})*	30 dBm	30 dBm
Ground cabling loss *(L_{TX})*	2,3 dB	2,3 dB
Ground station antenna gain *(G_{TX})*	5,98 dB	2,88 dB
Ground positioning loss *(half power)*	6,2 dB	6,2 dB
Free space propagation loss *(L_{FS})*	138,98 dB	129,88 dB
Polarization loss (L_{pol})	3 dB	3 dB
Aircraft pointing loss (half power)	6,18 dB	6,18 dB
Aircraft antenna gain (G_{RX})	3 dB	2 dB
Aircraft cabling loss (L_{RX})	2,3 dB	2,3 dB
Power receiver (P_{RX})	**-120 dBm**	**-118 dBm**
Required receiver Power ($P_{RX, required}$)	**-132 dBm**	**-130 dBm**
Link Margin	**12,00 dB**	**12,00 dB**

Table 16. Maximum theorical distance of both ExpressELRS and TBSCrossfire

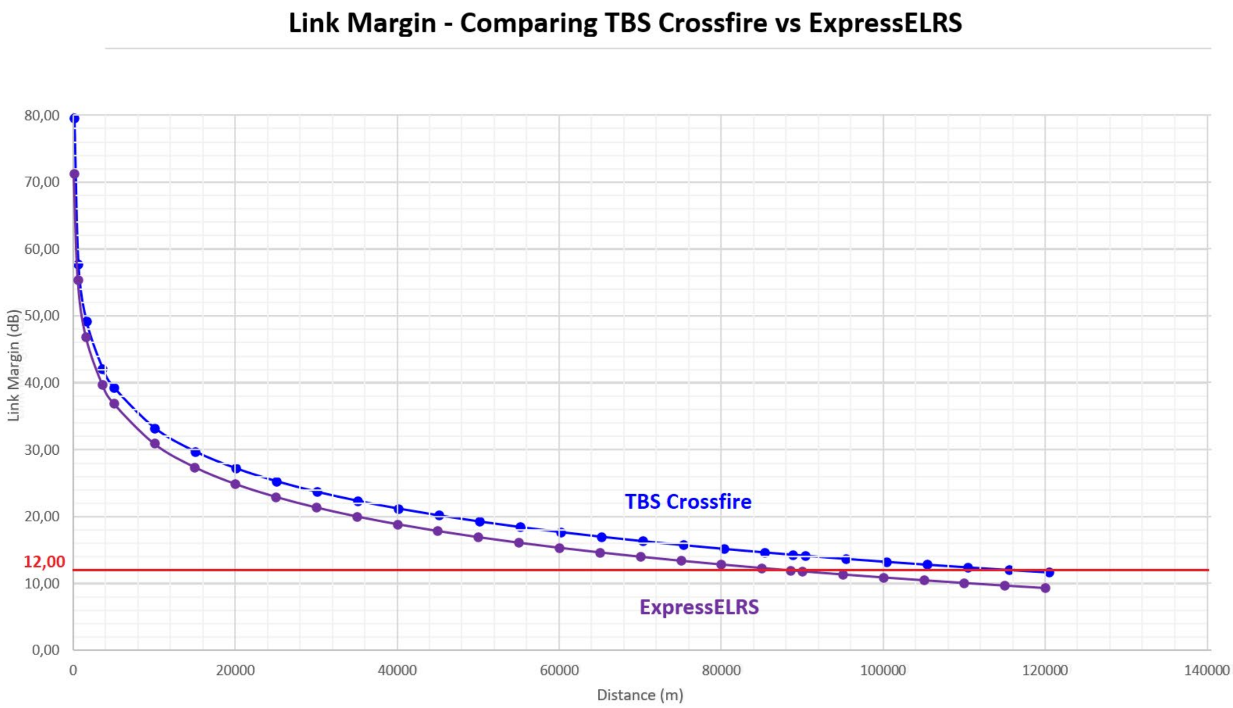
The **Table 14** is intended to show the maximum distance at which the 12 dB threshold is reached in both systems, resulting in 88500 meters for the ExpressELRS system and 115100 meters for the TBS Crossfire system.
The winner is TBS Crossfire with a maximum distance of 30% greater than the Express ELRS under the same conditions.

In order to graphically visualize the behavior of the Link Margin for both systems, the data of RSSI and Link Margin values for different distances are collected in the Table 15.

Distance (m)	RSSI (dBm) ExpressELRS	Link Margin (dB) ExpressELRS	Distance (m)	RSSI (dBm) TBSCrossfire	Link Margin (dB) TBSCrossfire
100	-60,68	71,32	100	-50,40	79,60
600	-76,62	55,38	600	-72,34	57,66
1600	-85,14	46,86	1600	-80,86	49,14
3600	-92,18	39,82	3600	-87,91	42,09
5000	-95,04	36,96	5000	-90,76	39,24
10000	-101,06	30,94	10000	-96,78	33,22
20000	-107,08	24,92	20000	-102,80	27,20
30000	-110,60	21,40	30000	-106,32	23,68
40000	-113,10	18,90	40000	-108,82	21,18
50000	-115,04	16,96	50000	-110,76	19,24
60000	-116,62	15,38	60000	-112,34	17,66
70000	-117,96	14,04	70000	-113,68	16,32
80000	-119,12	12,88	80000	-114,84	15,16
88500	-120,00	12,00	88500	-115,72	14,28
90000	-120,14	11,86	90000	-116,33	14,13
100000	-121,06	10,94	100000	-117,20	13,22
115000	-122,27	9,73	115100	-118,36	12,00
120000	-122,64	9,36	120000	-118,36	11,64

Table 17. Link Margin ExpressELRS and Crossfire for different distances

Taking the data from **Table 15** a comparison of how link margin behaves for both systems is graphically represented.



Graph 6. Link Margin ExpressELRS and TBS Crossfire

In the **Graph 5** it can be seen that in both cases the signal drops rapidly at the beginning and after 20,000 meters it decreases more slowly following the pattern of a negative exponential function. As previously verified, the distance that can be reached safely is greater with the ExpressELRS system being almost double that of the TBS Crossfire system.

The delay in most of the digital systems is a dynamic parameter, it means it increases as distance between RX and TX increase. Therefore, to compare some of the systems listed

To measure the quality from different digital systems,

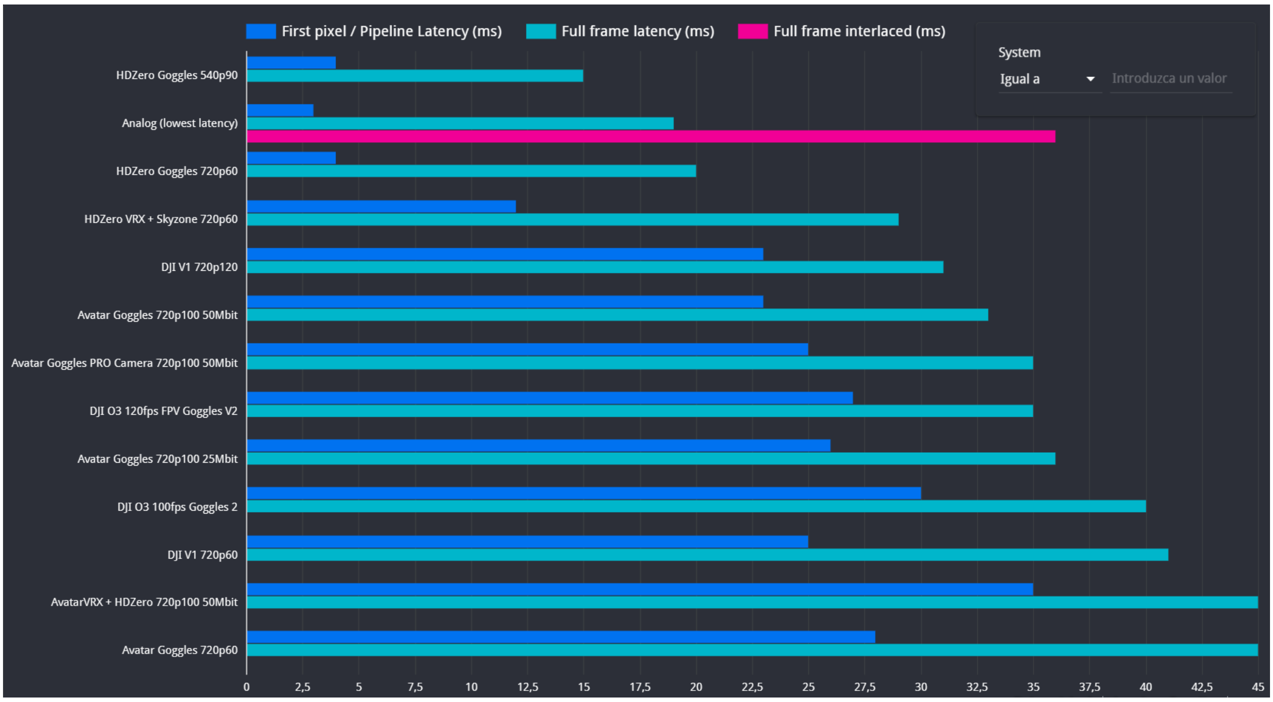


Figure 44. Different latency behavior for digital systems.

https://www.aos-rc.com/aos-labs

If we carefully count the frames in the high-speed footage and knowing that at a thousand frames per second each frame is one millisecond it is possible to easily calculate the latency of all of the systems on the test. Taking this parameter into account it can be seen that the HD Zero system is the one having the less latency. However, it is not really intended for long range operations since its penetration and distance are not comparable with the rest of systems.

7 PROCEDURES FOR ADAPTING THE DRONE TO THE ENVIRONMENT.

7.1 Video Signal Repeater.

One of the main challenges when flying through the rainforest regarding video link, is keeping a safe connection behind the dense vegetation of the environment.

To carry out any of the operations with drones needed for the Xprize Rainforest challenge, it is necessary to maintain a stable connection at all times with the drone, even if it has autonomous piloting functions, for security reasons.

One alternative to overcome the connectivity problem when having a considerable number of obstacles in between the drone and the base station is using a signal booster or a signal repeater. The second option will be considered in this work to propose a totally feasible solution.

The proposal consists of an analog video signal repeater which receives the drone signal in one channel, and transmits this same signal in a different channel. This system would also require a receiving system with multiple directional antennas and a switching mechanism.

The new concept of the repeater in this solution differs from any other by having this repeater on board another aircraft, since in the Xprize Rainforest competition it is not possible to access the competition area to install any device. Therefore, the solution must have omnidirectional antennas for each part of the system as the drone carrying the device will be changing its angle dynamically.

The first prototype of the repeater aims to prove that the concept of receiving the signal from one channel and retransmitting it in a different channel is possible to at least be able to transmit enough signal to still be able to operate the drone behind an obstacle that otherwise could represent a signal breaker.

For this purpose, a special piece of electronics will be introduced to be able to receive input video transmission and transmit as a video output but in a different channel. First a light weight video receiver is necessary to be able to catch the video from the main aircraft.

Even though this is not the final solution, the concept may be a feasible solution for the video signal possible loss when flying above the canopy and we do not have line of sight view from the drone intended to fly under the canopy.

Taking as an example a simple video receiver:

Figure 45. Skydroid 5.8 Ghz Dual Antenna FPV Video Receiver

https://rc-innovations.es/shop/skydroid-receptor-video-5-8g-fpv-para-android-uvc-otg-usb#attr=

Considering a flight controller capable of having more than one input as video and switching between them, basically to be able to switch the video input from a camera to the previously mentioned video receiver onboard:

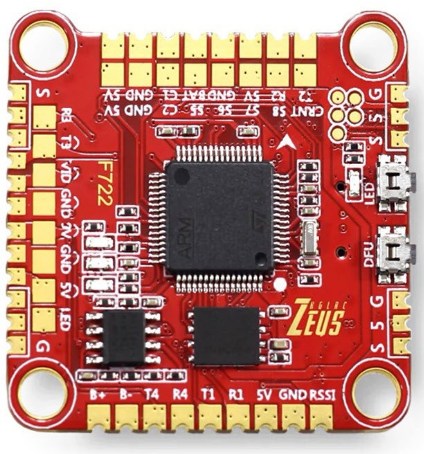


Figure 46. HGLRC Zeus F722 Flight Controller

https://iha-race.com/producto/controlador-de-vuelo-hglrc-zeus-f722-3-6s-con-conector-dji-3030-mm/

Apart from having two video inputs, this flight controller has full support and functionality in the INAV environment, this means that the aircraft not only can be very maneuverable but it also counts with some auto pilot functionalities as holding altitude and position.

Connecting this video receiver to one of the video inputs of a flight controller intended to go in one of the drones dedicated to repeat the video signal to the main explorer drone:

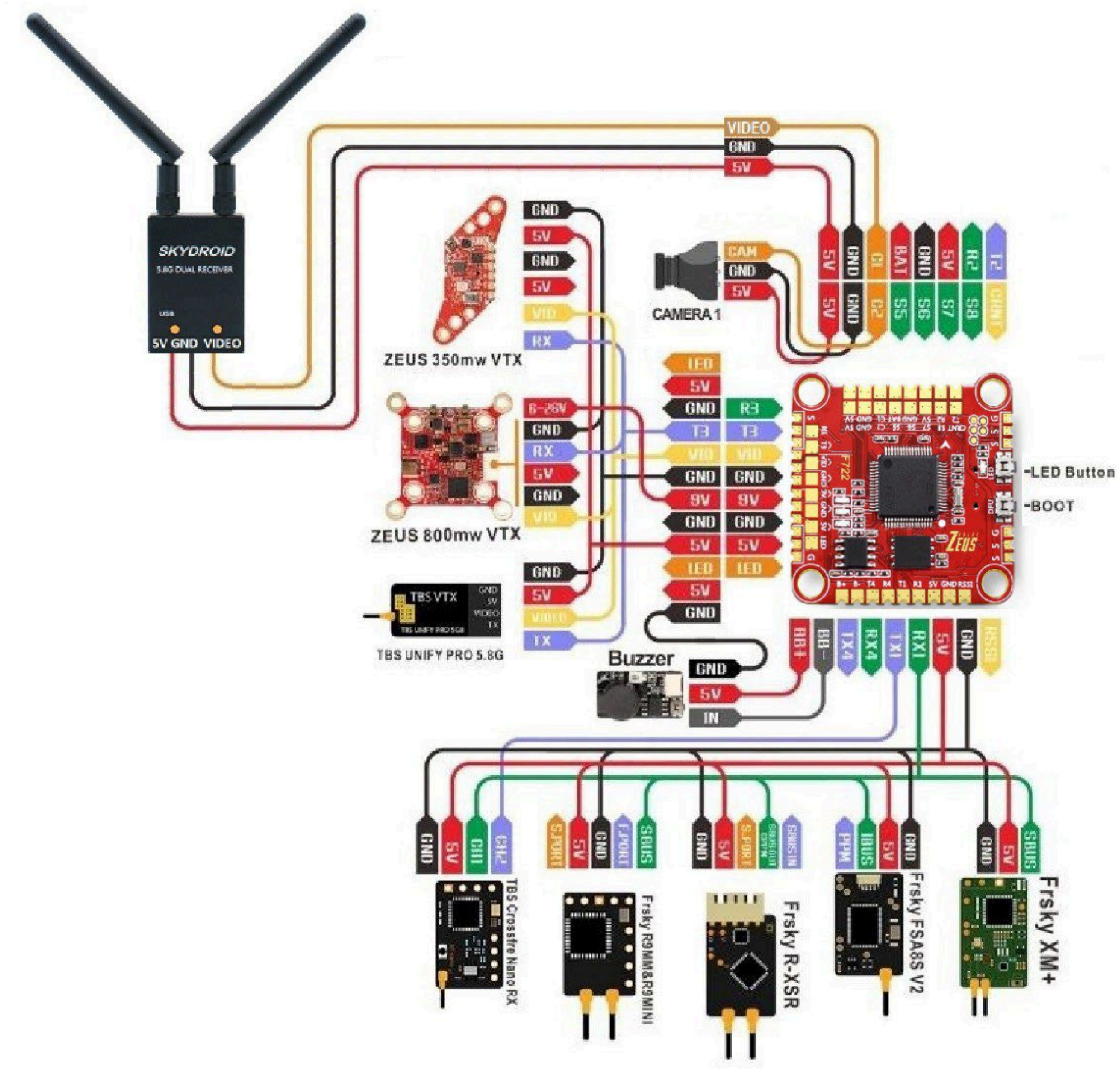


Figure 47. Repeater connection diagram

In the Figure 44 it is shown the full wiring diagram for the flight controller, connecting it to a camera and to the video receiver to be able not to have FPV capabilities but to have a repeater on board.

Having the same frequency band in both, receiver and transmitter, it may be necessary to use a screen or shield in order to separate both systems to avoid interference between each other.

7.2 Water Protection.

In order to apply a protective coating to safeguard the electronics against potential water splashes during operation, it is essential to first ensure the complete removal of any traces of dust or dirt from each electronic component to be protected.

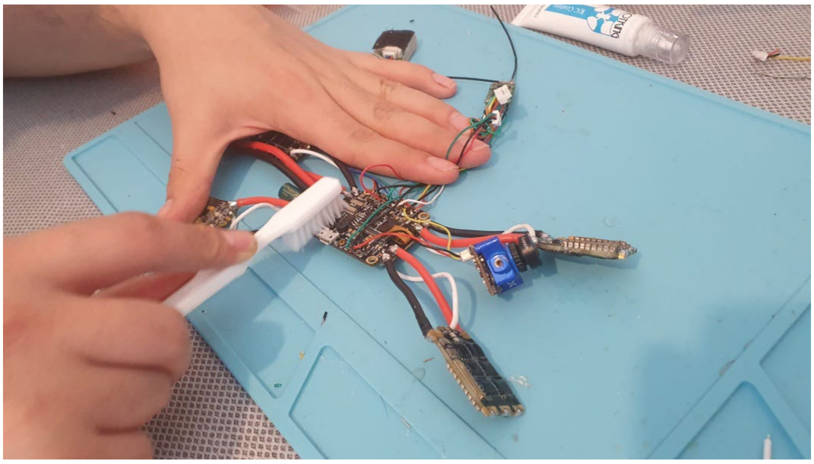


Figure 48. Cleaning out the impurities from the electronics.

Therefore, using a toothbrush, any residues or impurities that may have remained on the electronics are gently cleaned to prepare them for the application of the protective coating, ensuring resistance against water splashes.

Figure 49. KOTKING Coating

From: *https://www.phaserfpv.com.au/products/kotking-rc-waterproof-coating-for-drones*

The KotKing electronic protection coating is designed using a special silicone that enables heat dissipation, which is crucial for the application on aircraft electronics that may generate significant heat. KotKing is not only water-resistant but also heat-resistant, ensuring it does not melt due to the heat generated by critical electronic components such as ESCs (Electronic Speed Controllers) or the video transmitter (VTX).

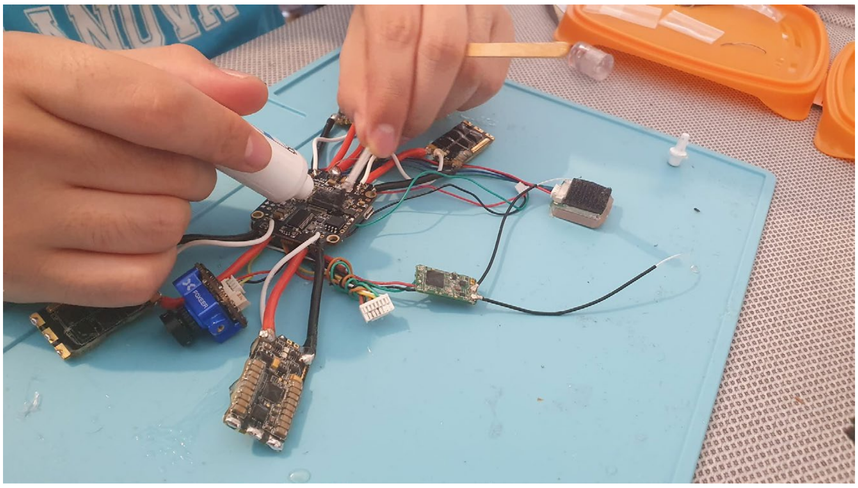


Figure 50. Appliying Kotking coating

When applying the KotKing coating (which will provide a certain level of waterproofing for the drone's electronics), special care must be taken to cover every part of the circuit of each individual electronic component. To ensure that the electronic components are fully coated with the protective substance, it is advisable to apply at least two layers, waiting at least 15 minutes after each application.

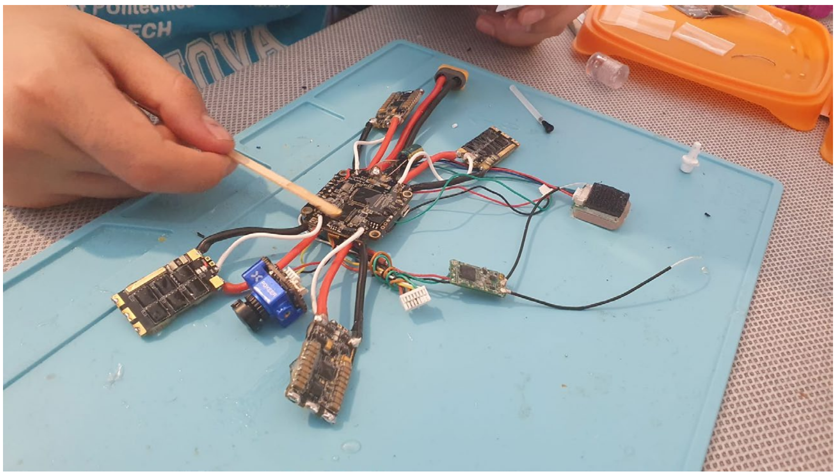


Figure 51. Using a stick to make sure every part of electronics is covered

In each application of the KotKing coating, it should be spread thoroughly using a wooden spatula or a brush to ensure that no solder joints are left uncovered.

8 FUTURE IMPROVEMENTS.

- Implement a video signal repeater functioning in different radiofrequency scales in order to avoid self-interference at the moment of receiving and sending back the signal to the base camp.
- Alternatively, to the previous point, it might be possible the use of satellite networks to receive and send information and commands from the drone.
- As battery technology continues evolving, solid-stage lithium batteries could be implemented in drone applications in a near future providing much higher efficiency and therefore much longer flight time.
- Apart from capturing video, a future version for the drone intended for capturing insides of the Rainforest can be a drone dedicated to recollect eDNA samples from the environment.
- The new toroidal propellers may be adapted for a large range of applications changing their shape and pitch to match different kind of aircraft. Giving the possibility to increase efficiency at the same time of reducing disturbing noise generated by traditional propellers.
- In case of needing to carry a heavier load, more powerful motors must be used.

9 CONCLUSIONS.

- ✓ This work has successfully provided various useful recommendations to overcome the challenge imposed by the Xprize Rainforest competition, specifying the procedures and selection of recommended components based on their capabilities.
- ✓ The recommendations that are listed in this work are a compromise between advantages and disadvantages of the different characteristics of the components. However, the technologies mentioned are cutting-edge technology from the actual date.
- ✓ On balance, TBS Crossfire since it uses lower frequency than ExpressELRS it proves that even though having less sensitivity and using only one antenna, it is more reliable more capable than ExpressELRS. However, both systems may be good enough for the challenge.
- ✓ Real flight missions demonstrated that the Link Margin calculated and the experimental one taken from those missions behave in a similar way.
- ✓ Even though the analog system may not be the most innovative technology, thanks to its simplicity it is easier to create signal repeaters to improve its performance.
- ✓ Li-Ion batteries would be more suitable for the application intended on this project. The main reason for choosing Li-Ion batteries is that a high discharge capacity is not required since the drone does not require aggressive handling, resulting in lower energy consumption during the flight. Li-Ion batteries, due to their higher power density, offer longer flight times for a lower battery weight.

  The use of toroidal propellers would be highly recommended, mainly due to its noise reduction, since the project involves entering a Rainforest area where many species of animals live that could be disturbed by noise. Besides that these propellers are more efficient since they provide more thrust per unit of energy consumed.

10 ACKNOWLEDGEMENTS.

First and foremost, I would like to express my gratitude to my Academic Advisor, Lluis, who provided me with valuable advice at the beginning of the project, helping to define and refine many crucial aspects of this work. He has always been positive, offering different perspectives and bringing forth new ideas for project development. I would also like to thank Miguel Valero, the director of the Drone Master's program, for proposing this multidisciplinary project and connecting me with the XPrize team through the IRI (Industrial Robotics Institute).

I would like to extend my thanks to Mishel André, and the rest of Prvidencers, who have shown meticulous attention to detail and thorough preparation to ensure the best participation and representation of Spain in this international project, which aims to ultimately help preserve the world's nature at a time when it is most needed.

I am also grateful to Toni, whom I consider to be like a father figure to me. Without his help and advice, the project would not have been completed within the planned timeframe. He has shown tremendous motivation and collaboration, especially during moments when I felt overwhelmed by multiple simultaneous activities and unexpected personal challenges. I would also like to express my appreciation to Patty, who has always been there to encourage and support me through both the good and difficult times.

Lastly, I would like to express my heartfelt gratitude to the entire community of drone pilots I have had the pleasure of getting to know in recent years. Your keen interest in this work has been truly inspiring. I would also like to thank the Catalan Aerial Federation and the Catalan drone racing leagues, including Lligueta and the Whoops league, where I actively participate as one of the pilots. Thank you once again to all the pilots I have had the pleasure of meeting and sharing those flights where we have learned so much and had an incredible time together.

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