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Demonstration of energetic potential, safety and regulatory compliance of Airborne Wind Energy systems in Switzerland on a pilot scale.

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Subsidy recipients:
Skypull SA
Via Aeroporto 4
CH-6527 Lodrino – Riviera
www.skypull.com

Authors:
Marcello Corongiu, Skypull SA, marcello.corongiu@skypull.com
Nicola Mona, Skypull SA, nicola.mona@skypull.com

SFOE project coordinators:
Nicola Mona, Skypull SA, nicola.mona@skypull.com
Corey Houle - corey.houle@twingtec.ch

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Zusammenfassung

Skypull zielt darauf ab, ein innovatives patentiertes Airborne Wind Energy (AWE)-System zur Erzeugung von Strom aus erneuerbaren Quellen zu schaffen: eine Lösung mit grösserer Verfügbarkeit, grösserer territorialer Energiedichte, geringeren Installationskosten, einfacherer Logistik und Demontage, grösserer Produktionskapazität, geringere Sicht- und Umweltbelastung, grössere Skalierbarkeit und schliesslich mit einem geschätzten LCoE (Levelized Cost of Energy), der mit den weltweit leistungsstärksten Windturbinen vergleichbar ist.

Die Skypull-Lösung besteht aus einer autonomen vertikalen Start- und Landedrohne (VTOL), die an einen Bodengenerator angebunden ist. Die Drohne ist mit dem innovativen Boxed-Wing-Design gebaut. Es erntet auch bei niedrigen Windgeschwindigkeiten mehr Energie und bleibt auch bei einem Tether-Ausfall einsatzbereit. Es wurde eine Kombination technischer Lösungen gewählt, um keine Bedrohung für Flugzeuge darzustellen. Eine proprietäre Steuerungssoftware integriert die Drohne und den Bodengenerator, um einen unterbrechungsfreien Betrieb, Stromversorgung und Produktion sicherzustellen.

Airborne Wind Energy (AWE) ist eine neue Technologie, die das Potenzial hat, den durch Wind erzeugten Gesamtanteil der globalen Energie deutlich zu erhöhen. Allein in Europa verfolgen derzeit über 10 private Unternehmen verschiedene Ansätze, um innerhalb der nächsten Jahre wirtschaftlich tragfähige Systeme zu realisieren. Zwei der führenden Entwickler, TwingTec AG und Skypull SA, haben ihren Sitz in der Schweiz und entwickeln ähnliche, aber differenzierte Systeme.

In diesem Projekt haben beide Unternehmen Pilotsysteme entwickelt und getestet. Jedes Unternehmen wollte die Leistung und Zuverlässigkeit seiner jeweiligen Systeme demonstrieren und gemeinsam relevante Themen für den sicheren und wirtschaftlichen Betrieb von AWE untersuchen.

Résumé

Skypull vise à créer un système breveté innovant d'énergie éolienne aéroportée (AWE) pour la production d'électricité à partir de sources renouvelables: une solution plus disponible, avec plus densité territoriale, coûts d'installation réduits, logistique et démantèlement facilités, plus grande capacité de production, production plus importante et plus stable, impact visuel et environnemental moindre, une plus grande évolutivité et enfin avec un LCoE (Levelized Cost of Energy) estimé comparable à les éoliennes les plus performantes au monde.

La solution Skypull consiste en un drone autonome à décollage et atterrissage verticaux (VTOL) relié à un générateur au sol. Le drone est construit avec la conception innovante des ailes en boîte. Il récolte plus d'énergie même à faible vitesse de vent et reste opérationnel même en cas de panne d'attache. Une combinaison de solutions techniques a été adoptée afin de ne représenter aucune menace pour les aéronefs. Le logiciel de contrôle personnalisé intègre le drone et le générateur au sol pour assurer des opérations, une alimentation et une production ininterrompues.

L'énergie éolienne aéroportée (AWE) est une nouvelle technologie qui a le potentiel d'augmenter considérablement la fraction globale de l'énergie mondiale produite par le vent. Rien qu'en Europe, plus de 10 entreprises privées poursuivent actuellement diverses approches pour réaliser des systèmes commercialement viables dans les prochaines années. Deux des principaux développeurs, TwingTec AG et Skypull SA, sont basés en Suisse et développent des systèmes similaires mais différenciés.

Dans ce projet, les deux sociétés ont développé et testé des systèmes pilotes. Chaque entreprise a visé à démontrer la performance et la fiabilité de leurs systèmes respectifs ainsi que d'enquêter conjointement sujets à l'exploitation économique de l'AWE.

Summary

Skypull aims at creating an innovative patented Airborne Wind Energy (AWE) system for the production of electricity from high altitude wind power: a solution with greater availability, greater territorial energy density, lower installation costs, easier logistics and dismantling, greater production capacity, greater and more stable production, lower visual and environmental impact, greater scalability and finally with a LCoE (Levelized Cost of Energy) estimated comparable with the worldwide best performing wind turbines.

The Skypull solution consists of an autonomous vertical take-off & landing (VTOL) drone tethered to a ground generator. The drone is built with the innovative boxed wing design. It harvests more energy even at low wind speeds and remains operational even in the case of tether failure. A combination of technical solutions has been adopted in order to represents no threat to aircraft. Custom control software integrates the drone & the ground generator to ensure uninterrupted operations, power supply & production.

Airborne Wind Energy (AWE) is a new technology which has the potential to significantly increase the overall fraction of global energy being produced by the wind. In Europe alone, over 10 private companies are currently pursuing various approaches to manufacture commercially viable systems within the next few years. Two of the leading developers, TwingTec AG and Skypull SA, are based in Switzerland and are developing similar yet differentiated systems.

In this project both companies have developed and tested pilot systems. Each company aimed to demonstrate the performance and reliability of their respective systems as well as to jointly investigate relevant topics to the safe and economic operation of AWE.

Main findings

The project demonstrated - within the possible extent given by the activities carried out - that, by exploiting the altitude wind in Switzerland, Airborne Wind Energy systems based on drones:

- can generate energy that could be used for off grid and on grid applications
- can operate in safe conditions, in compliance with current aviation regulation and – following the implementation of specific technical solutions – ensure an adequate level of safety in terms of collision avoidance in the airspace
- can operate in compliance with noise limits given by existing regulations

Contents

Abbreviations

Acronym	Explanation
AOA	Angle Of Attack
AWE	Airborne Wind Energy
CAD	Computer Aided Design
CS-23	Certification Specifications for Normal-Category Aeroplanes
ESC	Electronic Speed Controller
FCU	Flight Control Unit
FEM	Finite Element Analysis
GGS	Ground Generator System
GS	Ground Station
GUI	General User Interface
PDCA	Plan, Do, Check, Action
PWM	Pulse Width Modulation
RC	Remote Control (Unit)
R&D	Research and Development
SA	Società Anonima (Aktiengesellschaft)
SOC	State of Charge
SP/SKP	Skypull
SW	Software
UAV	Unmanned Aerial Vehicle
UAVCAN	Uncomplicated Application-level Vehicular Computing and Networking
VESC	Vedder Electronic Speed Controller

Introduction

Background information and current situation

AWE can represent a breakthrough technology in the energy transition from fossil fuel to a feasible RE based energy production scenario. Expected performances of Altitude Wind Energy Systems (AWES) allow envisaging their deployment in a much wider number of areas compared to traditional wind turbines. The areas where wind turbines are not deployable due to their specific wind endowment, or the high logistic costs implied can be served by AWES efficiently by providing electricity at sustainable cost (LCoE).

The Federal Energy Agency has stated that in Switzerland wind energy production must grow exponentially in the coming years: "*Swiss wind farms will have to produce six times more by 2020 compared to 2015 and by 2050 forty times more current than 2015*[1]".

In Switzerland 0.7% of the national surface present enough winds to enable wind turbines deployment, above all on the tops of the Jura and the Alps[2]. Most of the exploitable sites are nevertheless in fact inaccessible to traditional turbines, both for logistics and for the exorbitant cost to allow accessibility (roads of access for the transport of components). AWE systems can be designed to be placed in the mountains in locations impossible for traditional wind turbines.

The figure aside indicates the average specific windiness at 100 m a.g.l., where the largest wind turbines collect energy. The market potential for AWE in Switzerland could be conservatively assessed as representing 10% of the additional planned installed wind energy capacity between now and 2050. Based on the theoretical 1 MW system specifications presented in the next section, this would represent the installation of approximately 100 systems, representing 100 MW of installed capacity.

AWE targets to become the market leader for wind energy in logistically difficult terrain, where the installation of conventional wind turbines is prohibitively expensive.

Purpose of the project

The main goal of the project is to provide a roadmap to address key challenges to the commercial operation of AWE systems from a regulatory and permitting perspective and to assess the energetic potential of AWE technology.

The project work program has been focused on the development and implementation of all system functionalities and the execution of the system tests necessary to achieve the project objectives.

The first two work packages of the project:

- WP1 Maximising the visibly of AWE system for all airspace users
- WP2 Performance and noise assessment of AWE systems

[1] http://www.svizzeraenergia.ch/energierinnovabili/energia-eolica.aspx

[2] http://www.stromkennzeichnung.ch/en/fontienergetiche/energia-eolica

have been performed by both partners on a common planning framework with relevant results shareable with the AWE community in general, while the other work package:

- WP3 Development and testing of pilot system

has been performed individually by each partner.
While WP1 and WP2 were aimed at providing the results required to assess and allow the compliance of the AWE systems with the above mentioned relevant permitting perspective, WP3 was aimed at adapting the system in order to make it suitable for effectively and efficiently performing the tests foreseen in WP1-2 and to increase the reliability and soundness of project results.
This report summarises the activities performed by Skypull from the beginning of the project (May 2019) until the end of May 2022 and the approximate % of accomplishment for each task and related costs.
The project was mainly focused on ensuring the deployment of the AWES in Switzerland and potentially also abroad, with regards to the current and future aviation regulations related to aircraft visibility.

Objectives

The project objectives were:

- Define, test, and formalise a series of technical solutions, rules and procedures, specific to AWES, that would grant the system's compliance towards aircraft detection as envisaged within present aviation rules.
- Characterise the system in terms of power production and noise emissions.
- Present to FOCA the results of the testing and evaluation of visibility solutions adopted

Description of facility

To properly test the solutions envisaged for ensuring the visibility and the expected system's performances, 3 different drones (UAVs) were expected to be manufactured and tested, adopting different technical solutions. These UAVs were expected to have a wingspan of 125-200 cm and a power output of 5-12 kW.
Aside from the UAV also the Ground Generation System had to be revised and updated, to properly manage the forces and the dynamics exerted by the UAVs on the tether.

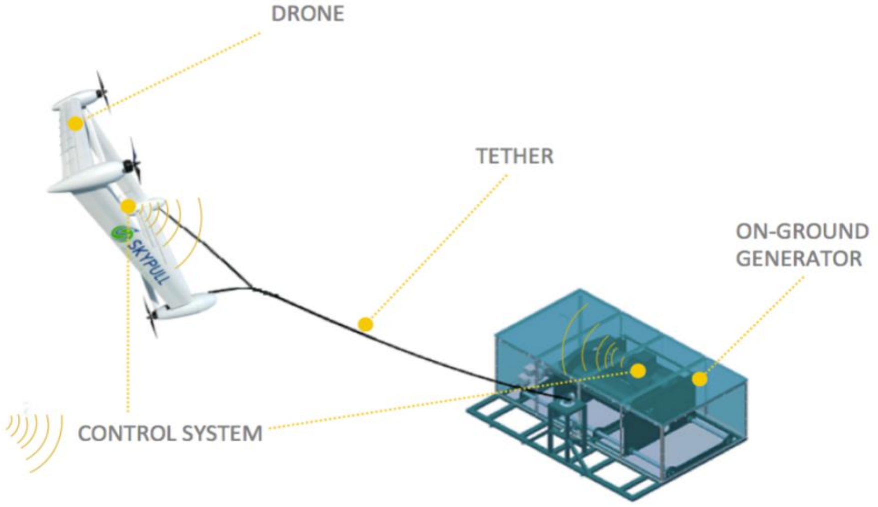

Figure 1: Overall Schematic diagram of Skypull Technology

Figure 2: The Skypull facility on the Mount Bar

Procedures and methodology

During the project execution, the Skypull followed some defined procedures and development methods. The former has been defined in the Standard Operating Procedures (SOP), while the latter in the Design and Development Plan (DDP) report. The SOP describes how to conduct safely, efficiently and legally the UAV operations. Safety, above all else, is the primary concern in each and every operation, regardless of the nature of the mission. On the other hand, the DDP describes the design and the development methods.
These documents are part of the Specific Operation Risk Assessment (SORA) which has been approved by FOCA in June 2020. In addition to SOP and DDP, Standard Operation Manual (SOM) is also attached. This document is a standard risk assessment process. It analyses the risks of UAV operations and defines possible mitigation strategies and robustness levels.

Results and discussion

Characterization of AWE system visibility for airspace users

A series of test have been performed on evaluating the current visibility of the Skypull system to a possible aircraft that enters the concerned airspace. A drone with a high-resolution camera was deployed, simulating different types of aircraft at different speeds. The drone used was a DJI Mavic 2 that can reach the maximum speed of 80 km/h, and as such can simulate both a para glider and an airplane. The UAVs used for tests (see hereafter the UAVs description on pag. 19 and ff.) had a main wingspan of 1.3 meters and lateral wingspan of 1 meter.
The performed visibility tests showed that it is necessary to increase the visibility of the entire system. There are many phases where it is not possible to detect the system, especially at higher speeds.

Figure 3: Lack of visibility of the UAV from a third flying object point of view

Following the analysis of relevant FAA and CAA anti-collision lights rules and meeting with FOCA, it has been decided to increase the system's capability both to be perceived by intruders and to detect intruders into the operation airspace (to deploy procedures that can minimise/avoid a risk of collision or accident). The solutions implemented were:

1. to add strobe lights on the drone and obstruction light on the Ground Station.
2. to add a combination between ADS-B receiver and FLARM to ensure the system detection of intruders.

Figure 4: The FLARM alert zone

Figure 5: Flashing strobo lights mounted on Skypull's UAV

The adopted solution in conjunction with the presence of NOTAM were declared as adequate by the FOCA.
A campaign of several tests in untethered and tethered mode were made with red and white ”Easylight” strobe lights ,”LUME CUBE” lights, FLARM and ADS-B devices. It has been concluded that the strobe lights should be at least 1000 lumen (with less than 1000 lumen the lights are visible only up to 150 meters), 2000 lumen lights are advisable (taking in account weight and power consumption) to ensure visual identification. As per CS-23 (23.2530), any position and anti-collision lights, if required by operational rules, must have the intensities, flash rate, colours, fields of coverage, and other characteristics to provide sufficient time for another aircraft to avoid a collision. Still some concerns remain on powering onboard hi power strobe lights, so that alternate solutions could be evaluated. FLARM and ADS-B devices to detect intruding aircraft are being also successfully implemented and an alarm system (siren) has been installed at the ground level activated soon as an intruder is detected by the UAV, but further tests are required to validate the active procedures to be implemented in case of intruder detection.

Power performance of AWE systems

A review of the existing standards for power performance measurements of electricity producing wind turbines (IEC 61400-12) has been done but it came out soon that standard methods and definitions related to other wind-based energy generation technologies appeared to be unfit to the purpose, due to the novelty of the AWE technologies and the peculiarities of their working principle. Discussions on power performance measurements methods and parameters have thus been started within the Airborne Wind Europe Association (https://airbornewindeurope.org/) where a set of terms, definitions and evaluation parameters have been elaborated, aimed to provide a common and shared significant set of rules to assess AWE system’s performances. One of the most important (and prone to misunderstanding) term is the *Electrical Average Power*, defined by the Group as *the net energy over one power cycle divided by the cycle time,* specifying also that it should be measured on the AWES side, i.e. before the transformer. The graphs represent this term as defined within AWEurope for a yo-yo based AWE generation system like the Skypull one.

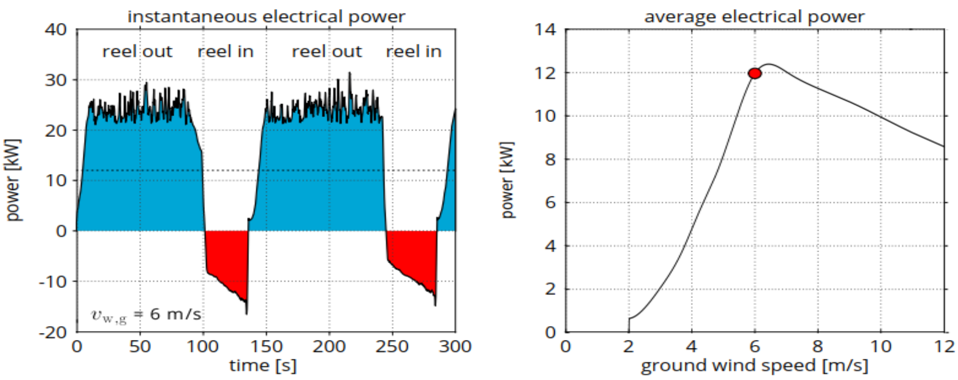

Figure 6: Electrical Average Power – AWEurope definition

Being the power generated by the system always precisely logged, the main problem to do an accurate measurement and characterization of the system resides in having reliable data on the wind speed. Not existing sufficiently precise on-board devices to this purpose, it has been decided to infer data from modelling. Simulations of a 10x10 km model of the dynamics of the local atmosphere flows were conducted, allowing some inferences about wind speed at UAVs operational altitude.

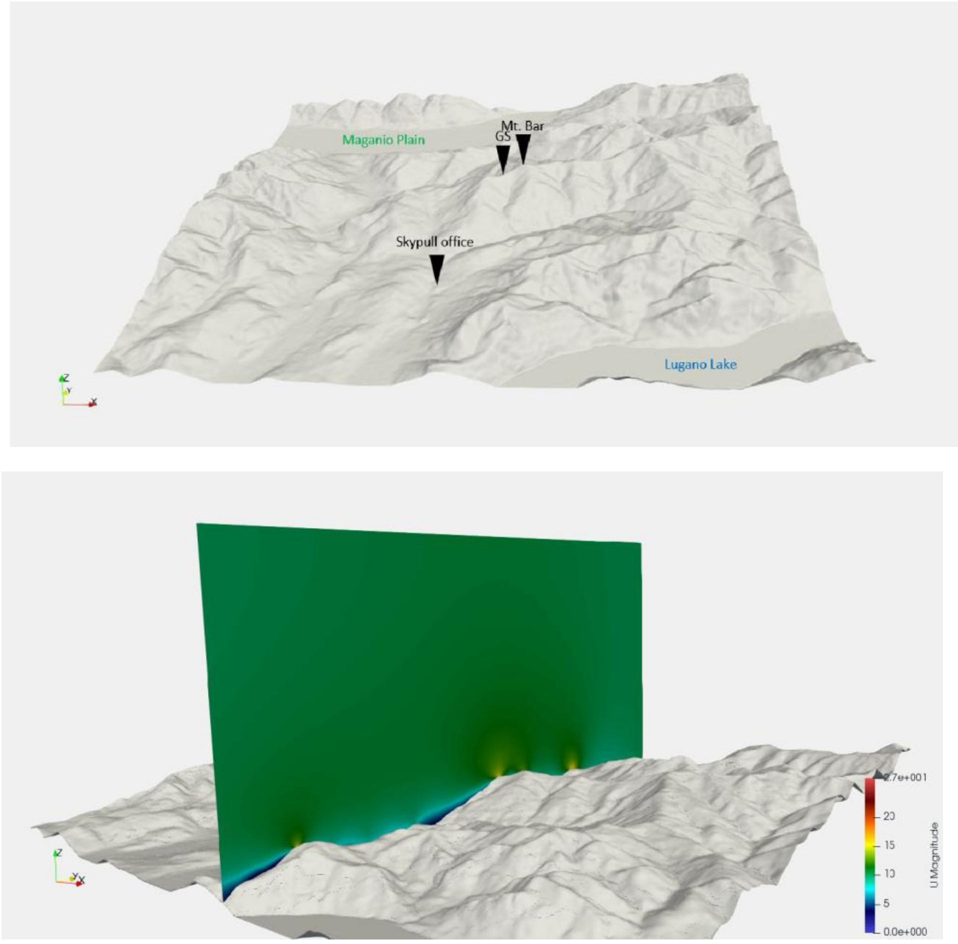

Figure 8: Discretized region in grey and a slice in north-south direction of the flow field in m/s.

A complete simulation model of the system based on the computational fluid dynamics (CFD) has been conducted, including a numerical model of the terrain (to consider the wind speed different intensity and directions on the test field).

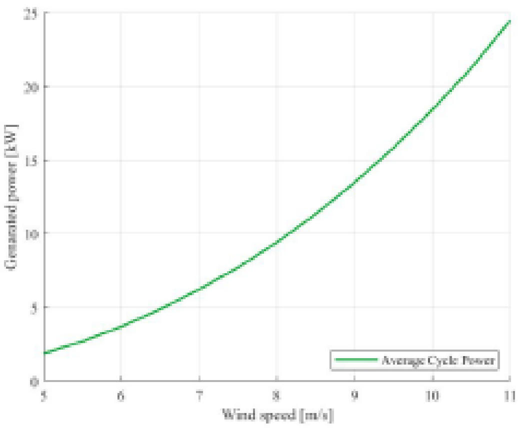

Figure 10:Computed power curve of a 3.2m UAV

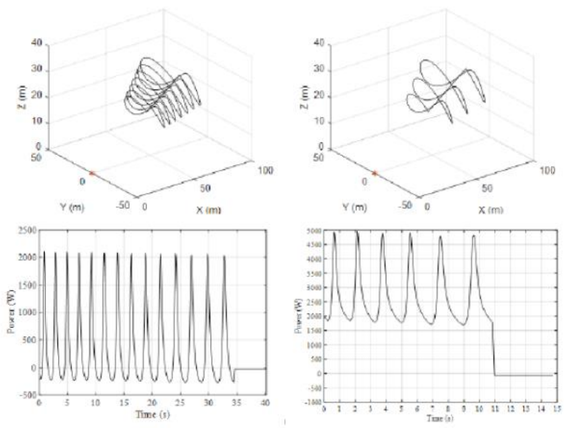

Figure 10: example of computed pumping cycle

From the initial wind data analysis performed it came out that the region where the UAV produces electricity is less windy than at the GS level. This is the opposite case than a normal situation, i.e. over a flat terrain. Usually increasing the altitude, it increases the wind speed as well. The numerical tests reported a wind speed drop of ~21% at UAV1 point, which is 100 m far away and 25 m higher than the GS. While at UAV2 point, which is 200 m far away and 50 m higher than the GS, the drop is around ~25%.

To increase the meaningfulness of the model output data, a higher resolution anemometer (up to 5 Hz) has been installed, while a set of new communication protocols and log SW have been implemented, while the model of the local atmosphere has been upgraded and adapted to the new data flow. A more precise anemometer has been also installed on board the UAVs. A power performance prediction study has been conducted to compute a first approximation of operational feasibility and power production of the system. A measurement campaign has been performed, adopting AWEurope power definition and the wind speed average at 5 m a.g.l.

Figure 11:The new weather station implemented

13 flight tests have been performed and a set data has been than collected thanks to the higher resolution of the new anemometers implemented and the developed SW and FW tools and to the correlations made with the system's power output. The most interesting data are related to the average electrical power over the ground wind speed. It is depicted on the figure hereunder, here, the average power is negative but there is a positive trend (red line).
This result should be further improved with the next prototypes, leading to a positive power curve. Within the test performed some significant results have been also improved by reaching a peak power of 4.6 kW and an overall flight time of 5 min and 17 secs with 5 complete cycles of generation/re-traction.

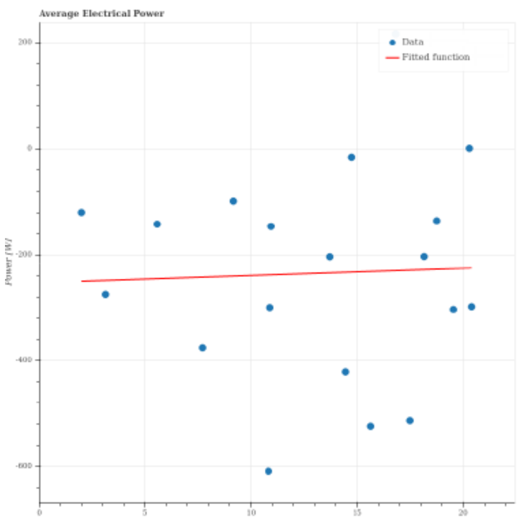

Figure 12:

Average electrical power over the GS wind speed

Noise emissions of AWE systems

In order to characterize the noise emissions of the system contacts have been preliminary taken with FOE, with local (Tessin) authorities and with the Department of Environment, Transport, Energy and Communication of FOCA to gather information about the relevant regulations in terms of noise emissions measurement and regulation methodologies and parameters for similar generation devices, like Noise Abatement Ordinance (NAO) 15.12.1986, Ermittlung und Beurteilung von Industrie - und Gewerbelärm (Bundesamt für Umwelt BAFU 2016) and EMPA noise assessment guidelines.

After the analysis of the relevant literature a noise measurements system test campaign has been performed.
The noise generated by the UAV during take-off and landing has been registered at different distances. 25 different tests have been performed by using the SP130-02 and the SP130-03 UAVs. Hereunder the SP130-03 results.

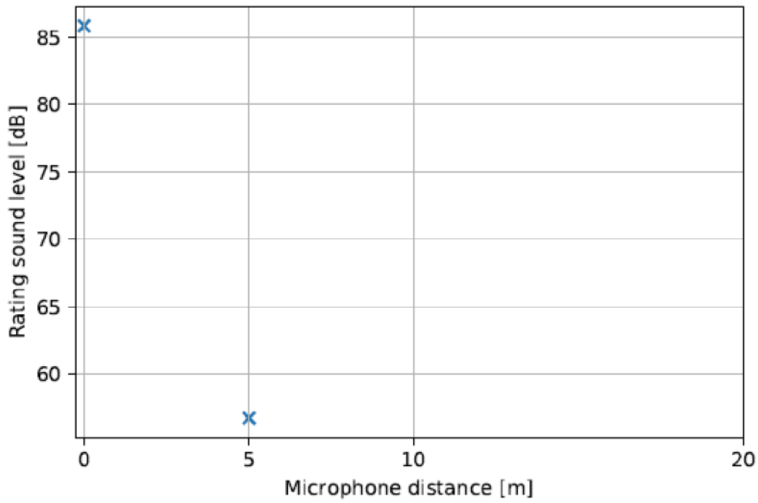

Figure 13: TO&L UAV recorded sound levels

The noise generated by the ground station has been registered at different distances and regarding the different operational phases. 3 different tests have been performed. Hereunder the results related to the most impacting operational phase.

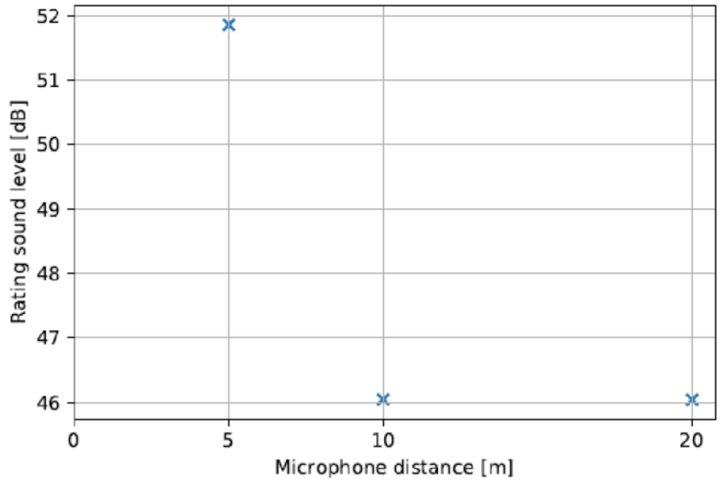

Figure 14: GS recorded sound levels

The noise generated by the system during tethered flights were registered at different distances with regards to the standard generation/recovery operational phases. 2 different test campaigns have been performed by using the SP130-02 UAV. Hereunder the results.

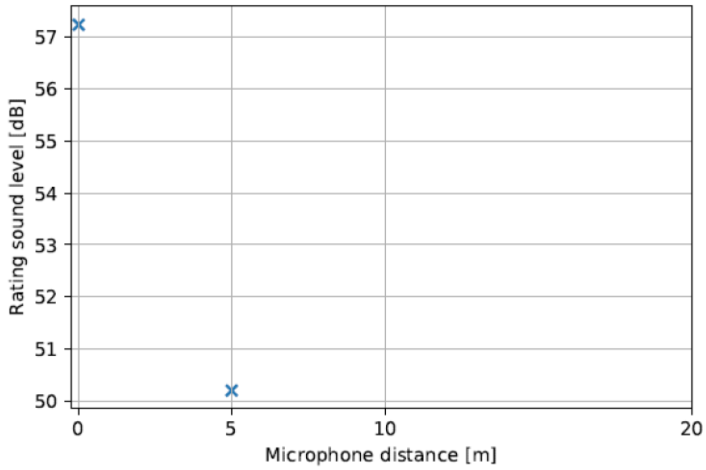

Figure 15: GS recorded sound levels

The first set of tests unveiled that the UAV noise emissions were always inside the NAO specifications. In one case (UAV take-off) the result was over the threshold because of the microphone was placed right below the taking-off UAV, an unrealistic position for a person in normal operations.
The second set of tests reported UAV noise emissions (UAV take-off and landing) higher, so that this aspect should be considered in the design phase.
The GS noise emissions were much lower: the field tests demonstrated that the noise emissions are significant during the UAV take-off and landing phases (due to the UAV motors) while the noise generated during the normal flight operation phases, at ground level, mainly due to the tether unwinding/rewinding, the motor/alternator and the generator sledge, was essentially neglectable and even hard to measure and distinguish from the wind noise. Furthermore, the noise scales with a 6 dB reduction by doubling the distance and the area swept by the drone during an operational phase was big enough to neglect the different position of the microphone.

Development and testing of UAV pilot systems

Within the project activities have been also focused on the execution and optimization of continuous generation tests in fully autonomous flight control mode. To reach this objective, it has been necessary to:

- Develop and test a tailored on-board generation system
- Manufacture a set of up-scaled Skypull UAVs, with all features required to host and operate the devices needed to ensure compliancy with aviation regulation

a. The on-board generation system

A tailored on-board generation system had to be preliminary developed and tested, to ensure an on-board power production coherent with the defined system's requirements.

UAV have been equipped with a specific ESC technology, named "VESC", that allow bidirectional current flows, to use the motors as generators during phases of the flight. This development has been particularly complex due to the need of these components to be highly reliable under different flight phases and conditions. Follow to a lengthy phase of development and test of such systems, on board the UAV has been generated energy reaching peak power up to around 80W, far above both the needed and the expected values. The graph hereunder shows the consumption of the 4 UAV motors along a 100” flight test (negative values represent energy generation).

A big effort has been required to achieve reliable performances from the VESC system, that has been pursued thanks to the cooperation with the company that provides the VESC hardware.

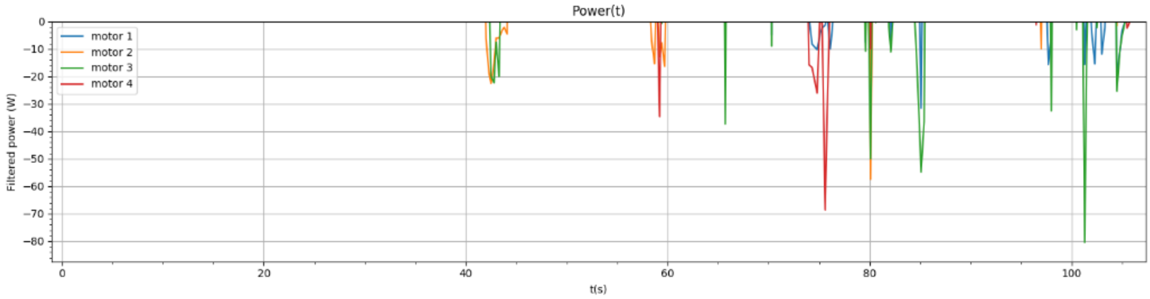

Figure 16: VESC power consumption plot (negative values represent power generation)

An extended study has been done on different VESC boards, VESC parameters, motors and propeller combinations: hundreds of bench tests have been performed in order to achieve a reliable performance from said system. Different motor drive technologies were also considered, studied, and tested, such as BLDC and FOC. It also meant at times building the bench tests as well as developing the testing methodologies required. System identification work as also been done to characterize the performance of all components of this section.
This culminated in a reliable system with VESC, which has already been successfully flown multiple times, in which onboard regenerative braking can be studied and tested on a flying system. Furthermore, another separate system was also developed in order to study the effect of regenerative braking during flight, in this case a testing system on top of a moving car. The main purpose of this is to gather data and ultimately obtain the relationship between the maximum regenerated current and the wind speed, and the conditions required for this to occur. It was concluded that regenerative power increases with incoming air speed and that the choice of propeller has a big effect on this scenario. This can easily be seen in the image below where the regenerative current is plotted for different propeller speeds and for different incoming air speeds.

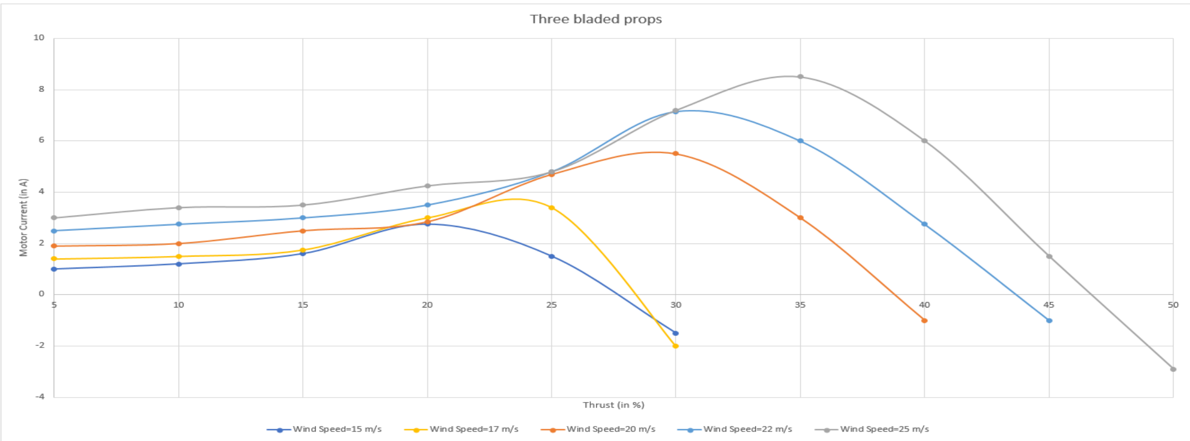

Figure 17: Regeneration curves at multiple air speeds

In addition, several autonomous regeneration tests have been made on a car setup, where it was demonstrated that given favourable conditions, long term generation is indeed possible.

Before implementing this feature in tethered flights, untethered tests have been performed in what is called the diving tests. These tests consisted in bringing the UAV up to 100-150 m a.g.l., capsize it and let it fall straight towards the ground for a few seconds. These tests have validated the ability of the system to generate and break during flight and lastly the ability for the UAV to maintain stability in such conditions. The software development has already been done, and it has been tested in simulation. No real flight tests have been made though. Still validation in down loops must be implemented in tethered flight tests with regenerative braking, which should yield improvements in the UAVs efficiency mostly in terms of flight time duration but also an increase in energy production.

Figure 18: The system used on car to test regeneration performances

Since VESC and ESC were not reaching the same thrust, the max values of VESC parameters have been increased to reach the same output. After several tests the same trust has been reached but during flights VESC have been found out giving high current spikes that were aiming to sudden short shut down of VESC for autonomous safe, that were giving instability to the drone flight. Due to these continues problems, the VESC company took in charge the problem and the result was that VESC was completely redesigned relative to hardware and software to reach the desired specifications. Finally, VESC and ESC had the same trust with no spikes, while the weight of VESC specially designed for Skypull UAV had been decreased substantially.

b. The flight control system

The autonomous control system was developed in such a way that both the UAV and the GS can perform all phases of the operation autonomously and in sync. The real-time communication between the two systems (UAV and GS) was also developed.

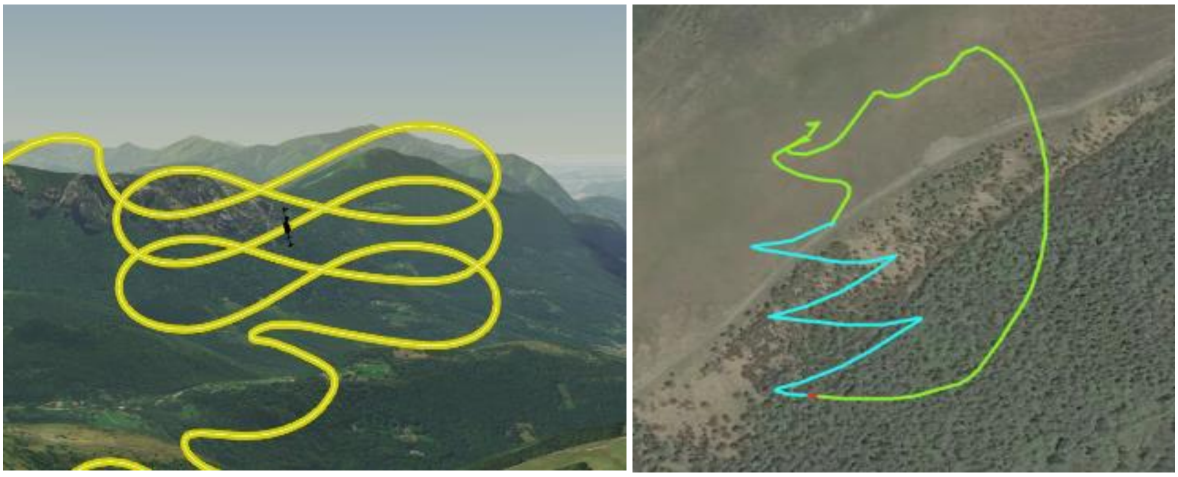

Figure 19: screenshots of a drone flight log (on the right screenshot autonomous flight is in light blue)

During the project great progress has been achieved in this field: fully autonomous flight from all systems has been achieved several times and is now part of the standard operation. This means that from take-off to landing, or in other words from arming to disarm, the UAV goes through all the phases of flight, including traction and retraction, autonomously without any input from the operators past the initial setup. During flight both systems are in communication to sync the different flight phases. One of these flights' trajectory is shown in the image below. This achievement was out of the present scope and marks a very important milestone for the project.

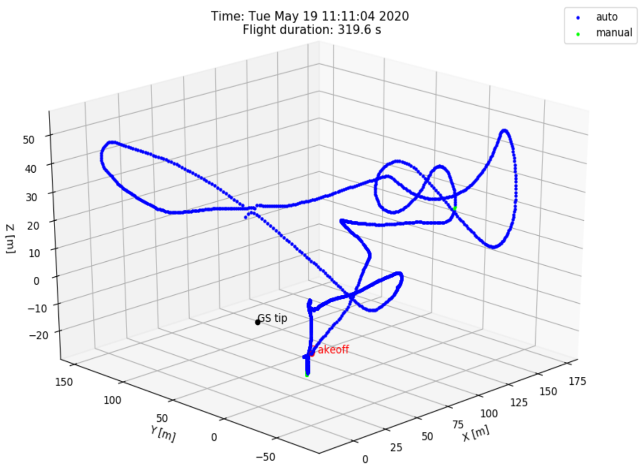

Figure 20: UAV trajectory during fully autonomous flight

The system performed multiple full cycles of generation (take-off, ascent up to 65 m tether length, traction phase: up loops and retraction phases, descent and landing) in fully autonomous flight mode with a flight duration of multiple minutes and by generating power with peaks registered up to 6 kW.

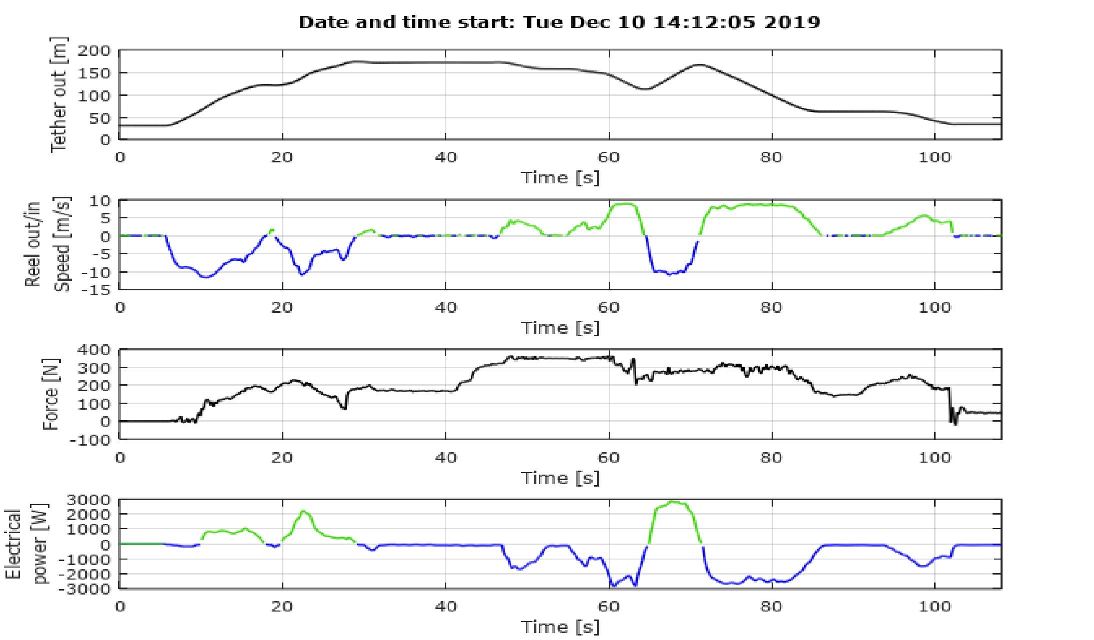

Figure 21: A flight log (example)

c. Upscaled UAV development – Structures and aerodynamic design

A set of upscaled Skypull UAVs have been designed and manufactured, compliant with aviation regulation equipment and increased in dimensions to reach higher power output.
The UAVs made and used within the project were 3, as expected, with increasing dimensions and different specifications and technical solutions to be adopted and checked.
The first UAV is the so called **SP130-02**[3]**,** designed mainly to test and validate the theoretical aerodynamic development done starting from literature review and ending with CFD analysis and become a cost-effective solution with fast manufacturing and repairing, with good performances.
The second UAV is the **SP130-03,** mainly developed to validate the aerodynamic results given by the multi element airfoil. The third UAV is the **SP180-01,** with the same geometry of SP130-03, mainly the same aerodynamic airfoil but with an increased wingspan, to be able to have higher payload onboard and to produce more traction (converted in higher energy output of the GS). Here after is a more detailed description of the above-mentioned UAVs.

SP130-02 has a box-wing shaped airframe without a fuselage. The aircraft is under the category of rotorcraft drone. It has four thrust producing devices (propellers with electric motors) driven electrically.

[3] UAVs have been denominated as SPXXX-YY, where SP stands for SkyPull, XXX for the specific UAV wingspan length in centimeters, YY for the UAV version (progressive number) with the same wingspan.

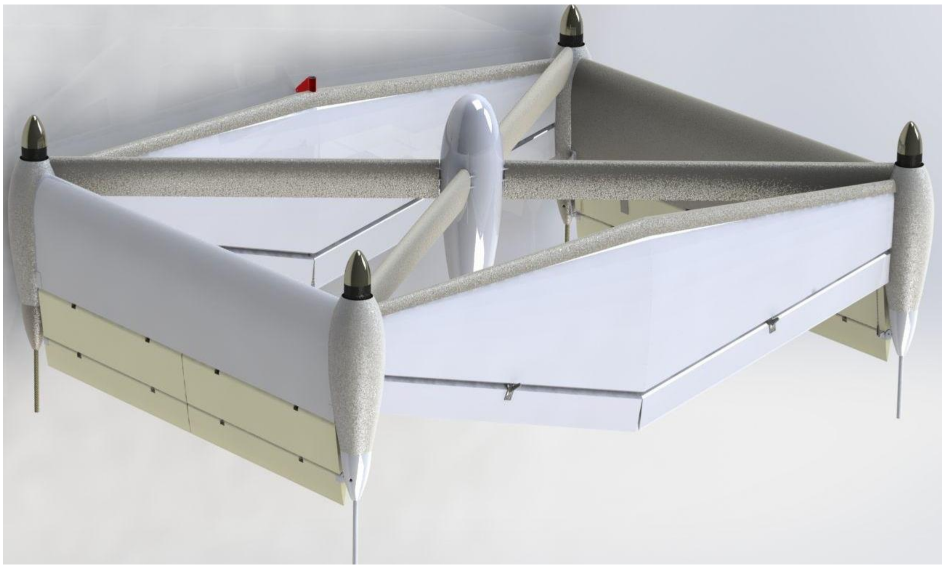

Figure 22: SP130-02 UAV

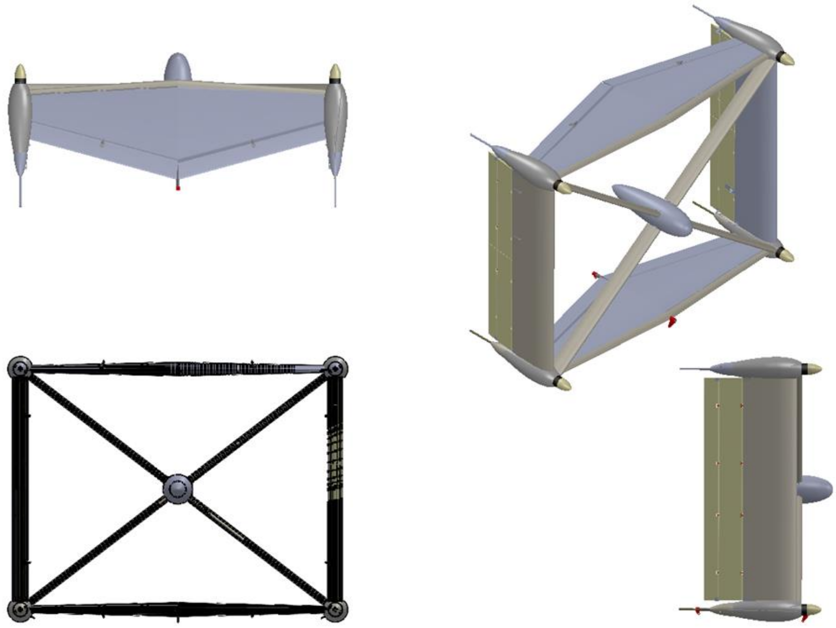

Figure 23: Different Views of SP130-02

Wingspan (in m)	Width (in m)	Height (in m)
1.3	1.033	0.664

Table 1: Dimensions of the drone

Static and dynamic stability of the UAV was ensured by means of the software XFLR5. Analyses were also made to define and determine the suitability of the proposed design. The aerodynamic load analysis was carried out using SU2 and OpenFoam software. Figure 24 shows the flow lines and the pressure field based on CFD analysis with infinite airfoil for the Skypull systems with four propellers.

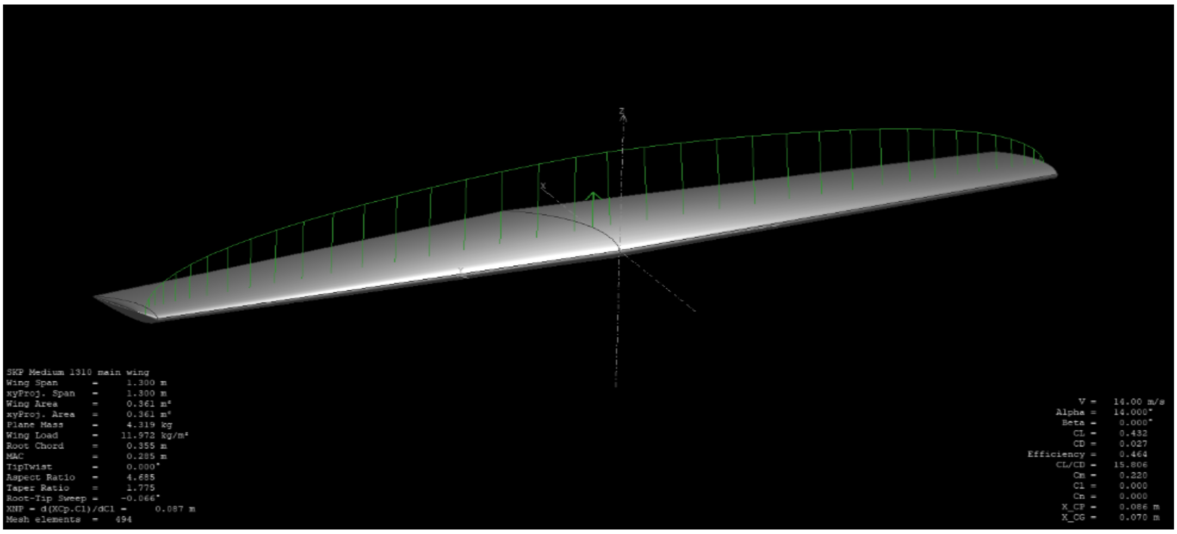

Figure 24: Load Distribution in the Main Wing

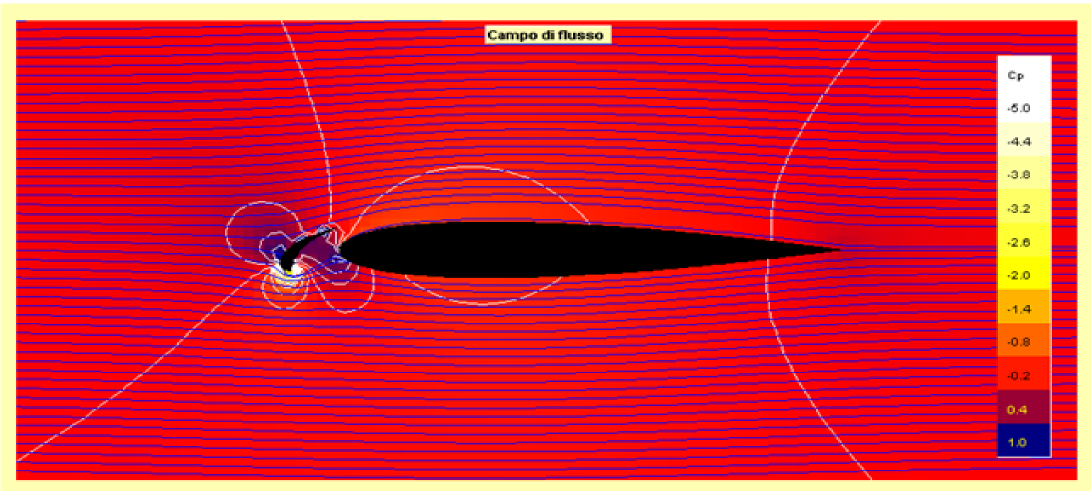

Figure 25: CFD analysis with infinite airfoil for four propellers

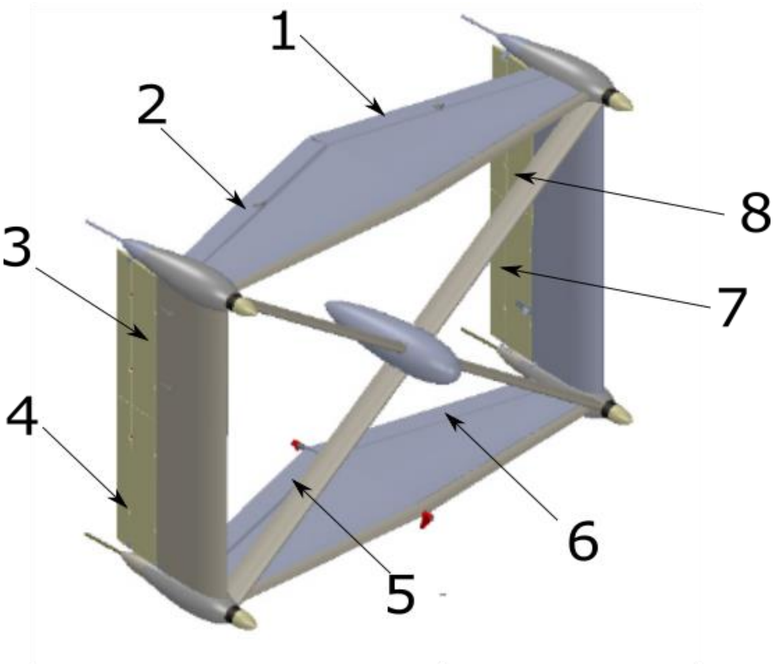

Figure 26: Flight Control Surfaces of SP130-02

SP130 03 has a box-wing shaped airframe without a fuselage. The aircraft falls under the category of rotorcraft drone.

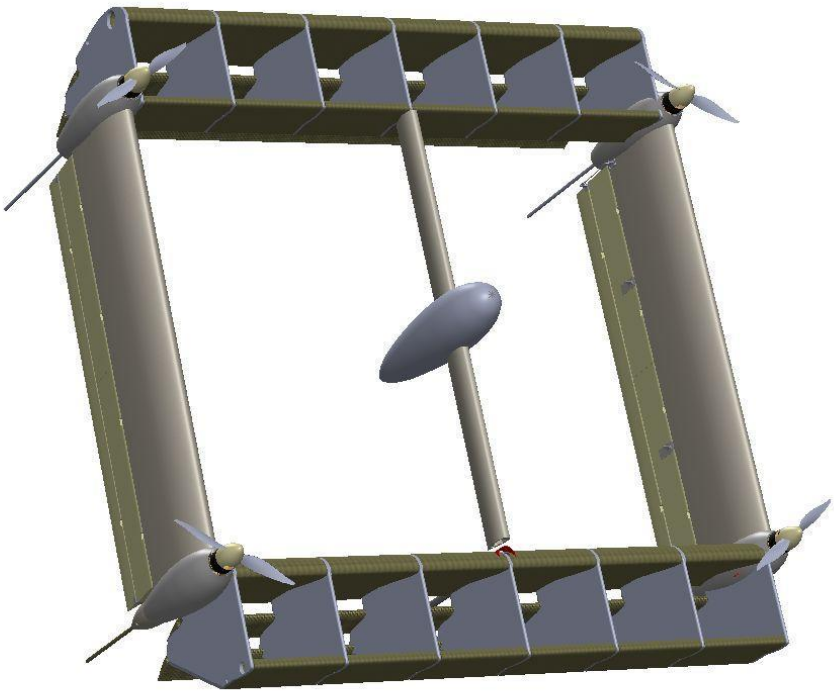

Figure 27: SP130 03 UAV final design

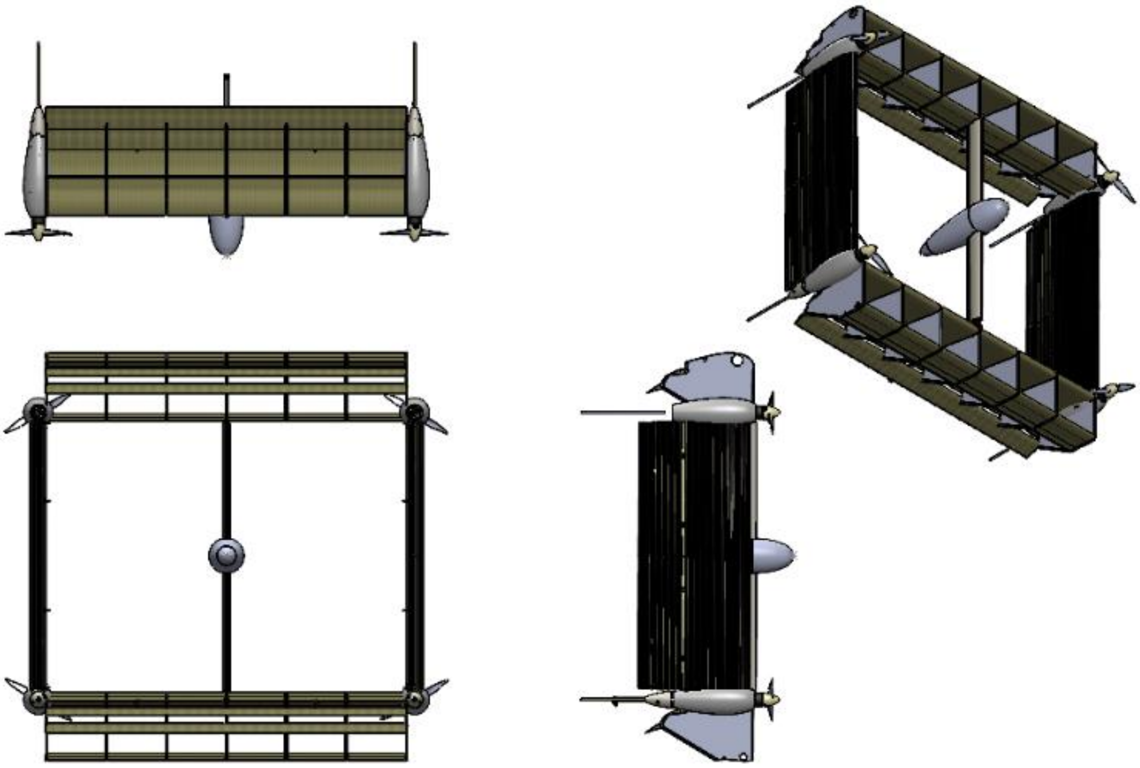

Figure 28: Different Views of SP130 03

Wingspan (in m)	Width (in m)	Height (in m)
1.3	1.033	0.664

Table 2: Dimensions of the drone

Studies of Bombardieri et. al and Chau, Zingg observed that box-wing structured are not prone to any flutter phenomenon throughout its operational (wind) speed range. Moreover, the four bridles attached to the tether attached to the drones increase the flutter speed making it impossible for flutter phenomenon to occur.

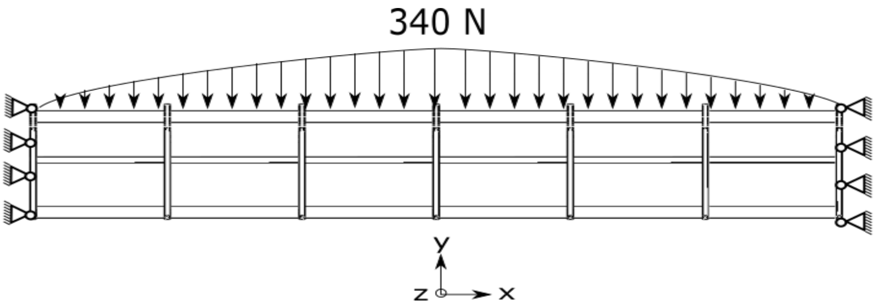

Figure 29: static load simulation

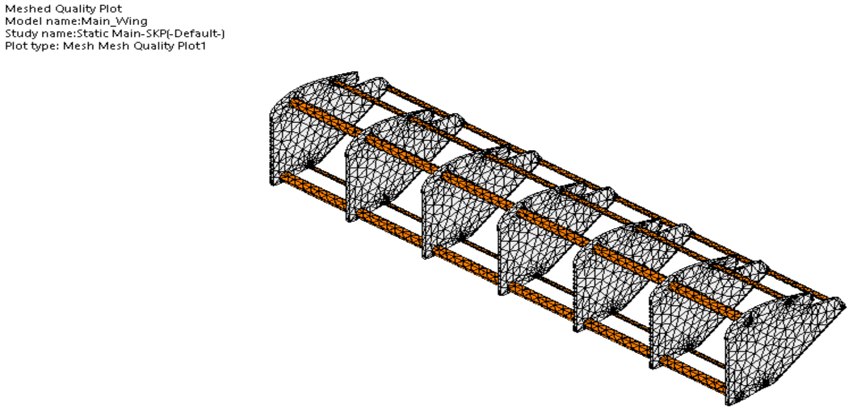

Figure 30: Main wing meshed component

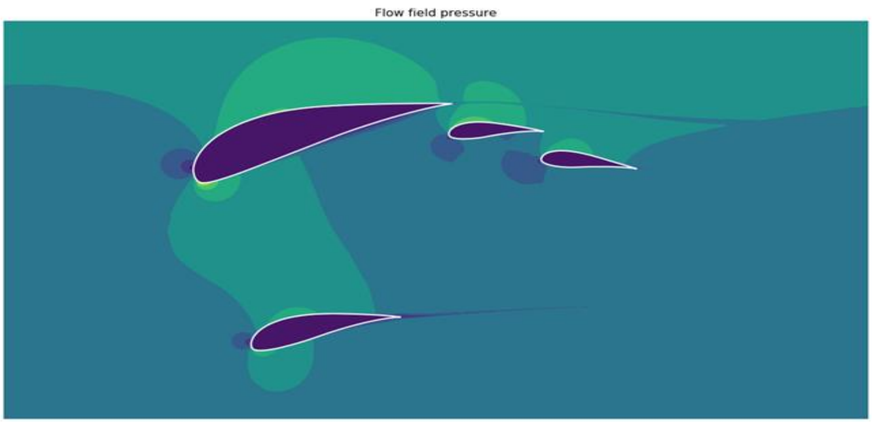

Figure 31: Boundary conditions and Loading case for main wing

Several analyses were made to define and determine the suitability of the proposed design. The aerodynamic load analysis was carried out using SU2 and Open Foam software.

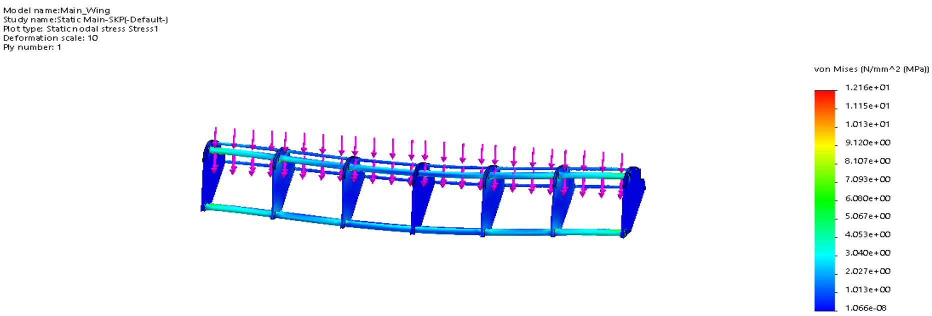

Figure 32: Von Mises Stress distribution for loading conditions

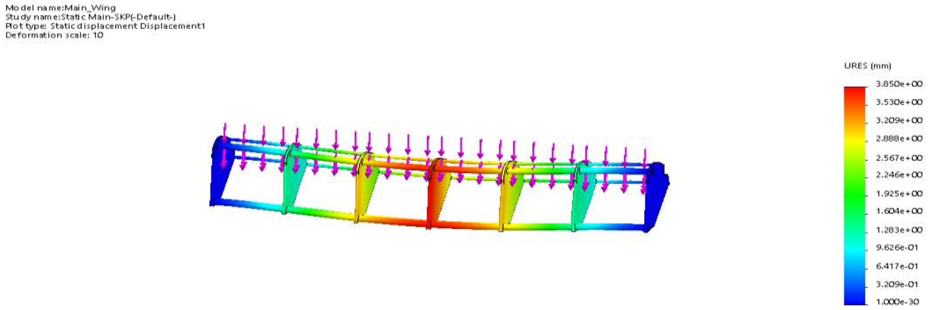

Figure 33: Maximum Displacement for loading condition

The above figure shows the flow lines and the pressure field based on CFD analysis with infinite airfoil for the Skypull proprietary multi element airfoil.

SP 180- 01 has a box-wing shaped airframe without fuselage. The aircraft is under the category of rotorcraft drone. It has eight thrust producing devices (propellers with electric motors) driven electrically.

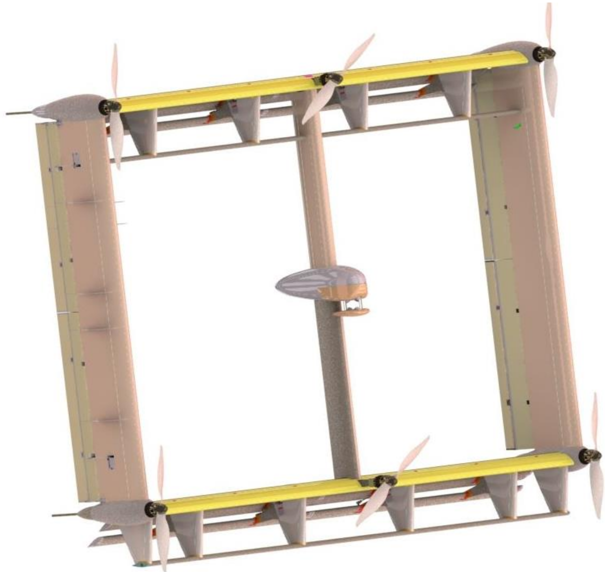

Figure 34: SP 180- 01 UAV

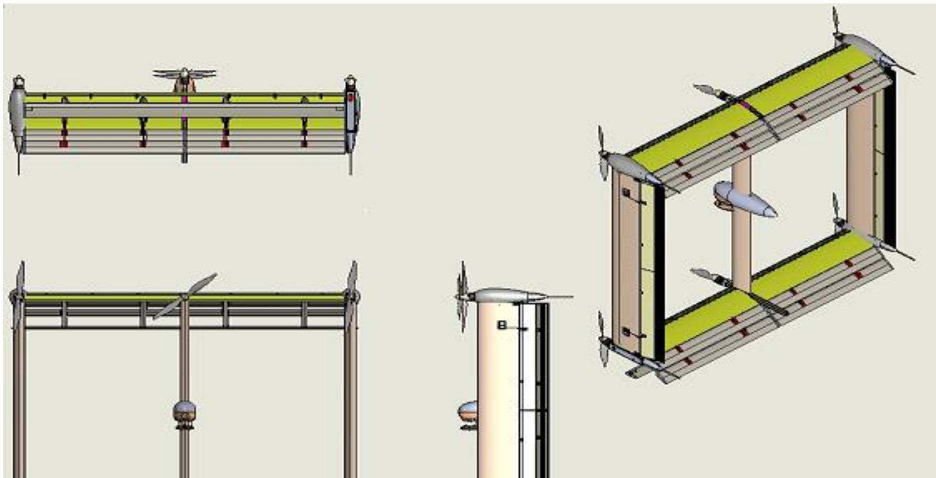

Figure 35: SP 180- 01 different views

Wingspan (in m)	Width (in m)	Height (in m)
1.800	1.42	0.634

Table 3: Dimensions of e SP180 UAV

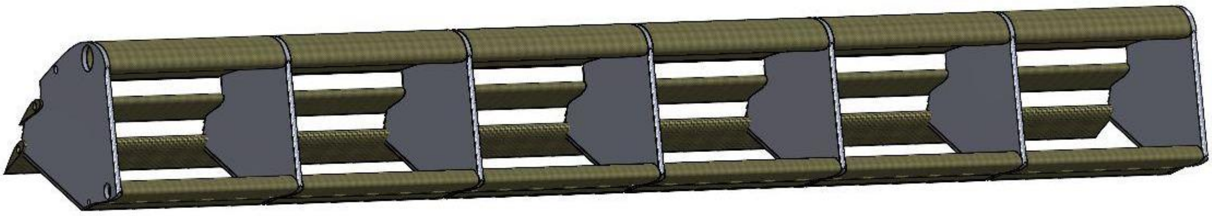

Figure 36: SP 180- 01 Main Wing

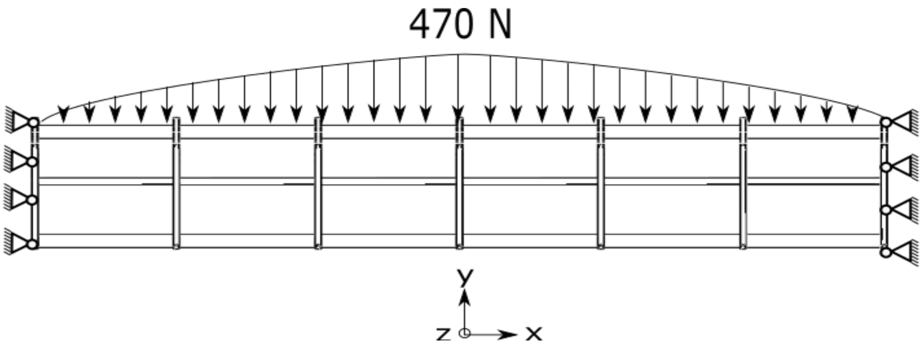

Figure 37 SP 180- 01 Main Wing boundary and loading conditions

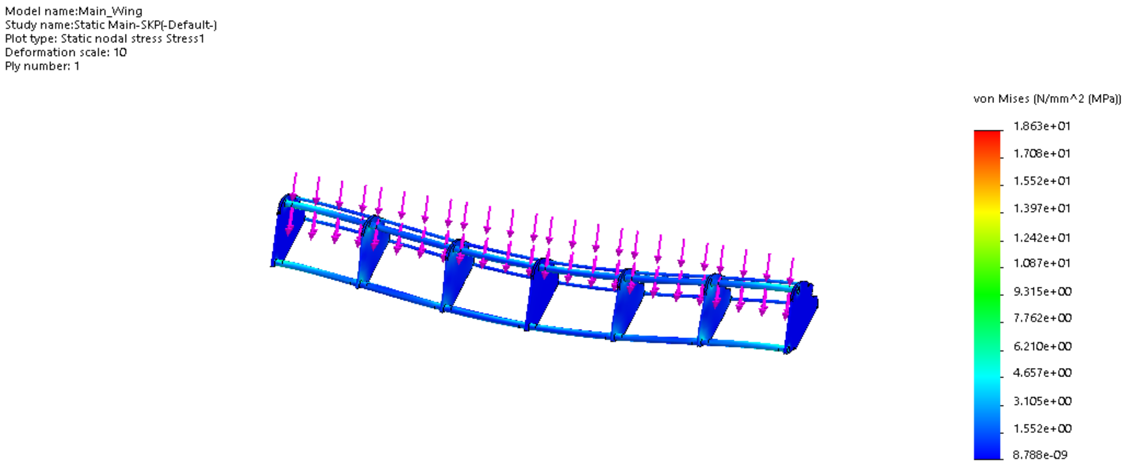

Figure 38: SP 180- 01 Main Wing Von Mises Stress distribution for loading conditions

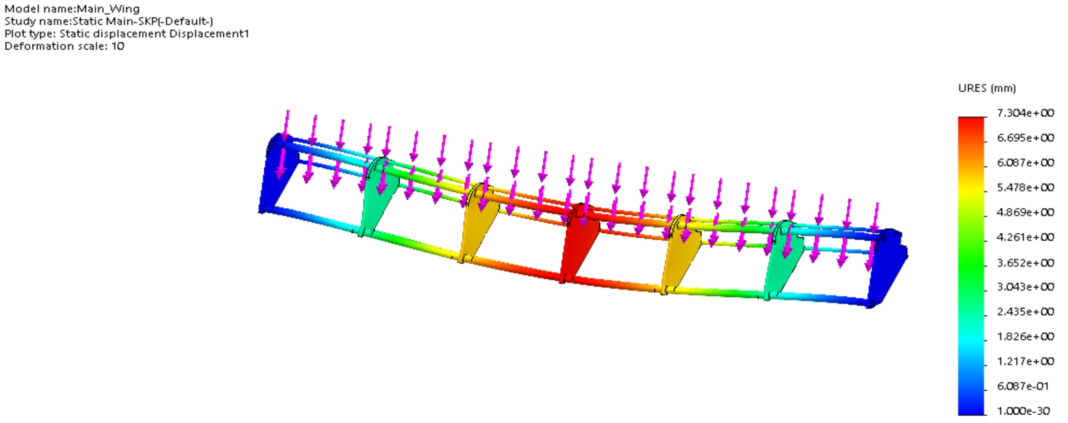

Figure 39 Maximum Displacement for loading conditions

SP180-01 main wing design has been precisely dimensioned and weighted with an improved composite layup to be sure to get the same values of theory. It passed through a series of refinements to increase its performances and several modifications have been introduced and tested along the project.

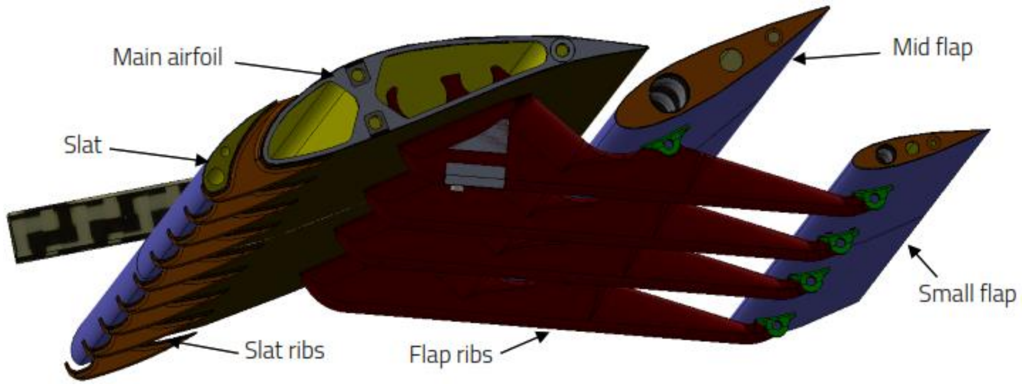

Figure 40 Modified SP180 main wing design

SP180 UAV frame also went through a series of design improvements and modifications, mainly aimed at increasing its stiffness also by mean of a series of FEM analysis. In parallel to the FEM - to the same purpose - also a structural analysis has been carried on: several structural issues have been identified and corrected by selecting the appropriate material/manufacturing solution.

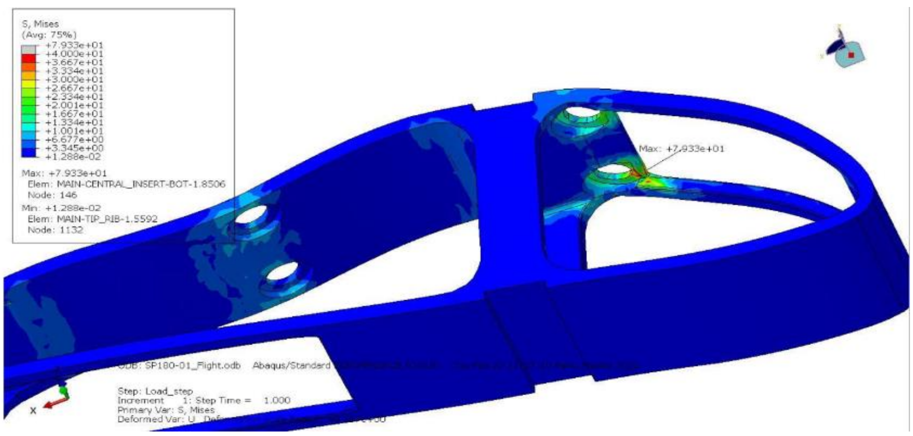

Figure 41 FEM analysis on Mises stress on central insert of lower main wing

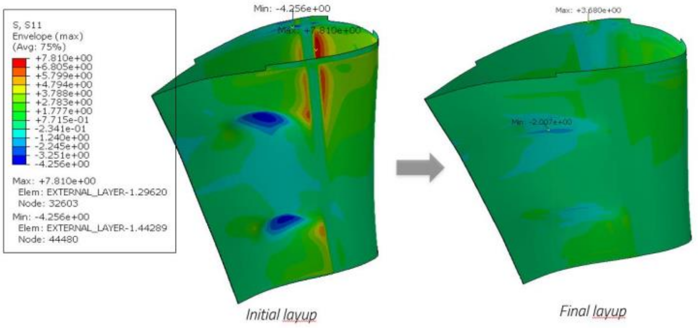

Figure 42 Study on reduction of stresses on external fibres layers on the SP180 main wing due a new layup

During the development of the 3 UAVs, continuous reviews were performed to the existing UAVs to understand the improvements needed to comply with requirements. Reviews have been based mainly on static and dynamic aerodynamic analysis on wings.

The first idea was to upscale the SP130 only through increasing the wing dimensions. After further review, it was decided to improve the geometry by moving the wing from an initial H-shape geometry to a box-shape geometry for an added increase in the aerodynamic efficiency. A review of the aerodynamic design has been finally done to improve its performance. The design difference between the SP130-01 and SP130-02 were:

- UAV dynamically stable in roll attitude thanks to new side wings.
- UAV geometry: from H-shape to box wing in order to decrease induced drag.
- Main wing slat position to increase the lift coefficient and so the overall traction

After testing the 130-02 a new design review of the main wings has been also done, so that the multi element airfoil has been adopted for UAV 130-03.
The reviews of the SP130-02 have been based mainly on static and dynamic aerodynamic analysis on wings and flight tests using also webcam on the wings to better understand the wing flow. Thanks to these studies we could move to the aerodynamic study and analysis of 130-03. It was decided to improve the geometry by moving the wing from a box-shape geometry with a x section to a single middle vertical strut to decrease drag and increase overall efficiency.
A review of the aerodynamic design has been finally done to improve its performance. The design difference between the SP130-02 and SP130-03 were:

- UAV fast responding in yaw attitude thanks to more rigid structure and control surfaces.
- UAV geometry: from box wing with X to and I drone support structure to decrease induced drag and overall weight without reducing the stability.
- Multi element wing on main wings to improve lift and decrease drag

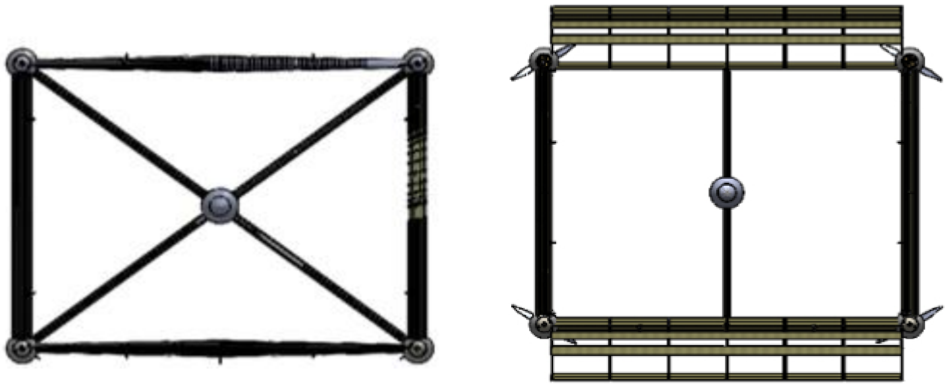

Figure 43: SP130-02 and SP130-03 final drawings

Further review activities, together with the aerodynamic analysis and wind tunnel test above mentioned led to a deep UAV redesign for the SP180-01. Its design, as already mentioned, went through a complete ad iterative modification, due to a series of analysis of both the airfoil – notably through the collaboration with Rapperswil and ZHAW Universities – and of the UAV frame too, through extensive FEM and structural analysis. This activity has not still reached an end, since the SP180 still needs to be furtherly refined under a structural point of view.

CAD drawings have been made for producing components, assembling them altogether in an accurate and repeatable way, in case of necessity of repairing. The main wings, for all the UAVs have been statically tested.

As far as the SP130-02 is concerned, since the main wing is the primary load bearing structure, an equivalent distributed load of 27 kg was placed on the wing as shown below. Hence in the static test, the maximum load equivalent to 27kg was placed on the wing.

Figure 44: Polystyrene slabs placed on main wings of 130-02

The SP130-03 statical test reached a maximum load of 35 kg and was compared with FEM analysis showing that we could reach 73 kg of maximum wing load without structural damage.

Figure 45: Static test on the main wing of SP130-03

A tailored test bench has been designed and implemented to ensure appropriate and sound procedure in determining strength limits of the SP180-01 main wing. The statical test performed showed 60 kg of maximum wing load without break.

Figure 46: Static test on the main wing of SP180-01 on the new test bench

SP180 wings design has also been based on a series of intense and extended activities of aerodynamic analysis of the wing's airfoil, performed in collaboration with the University of Applied Science of Rapperswil (HSR) and the University of Applied Science of Winterthur ZHAW. The first one performed a series of studies on the wing profile by analytical methods and computational fluid dynamics, while ZHAW conducted a series of real-world measurements, mainly in a wind tunnel but also within real flight and other experimental tests conducted by Skypull. The activities performed by the two partners has been paid by the Innosuisse project no. 43730.1. After the wind tunnel campaign, the airfoil profile has been modified substantially, with consequent changes in the structural parts and kinematics.

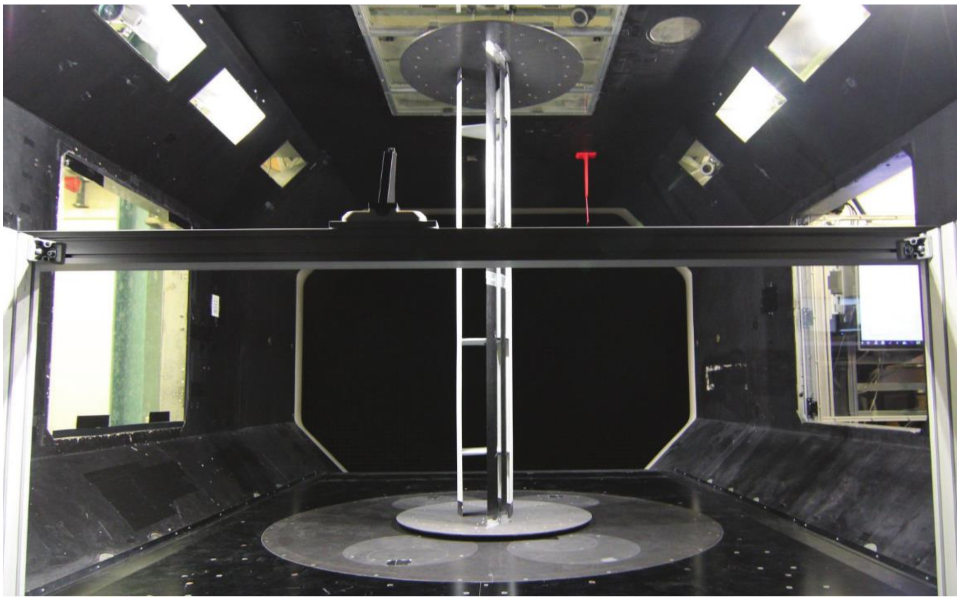

Figure 47: Aerodynamic test of the Skypull SP180 airfoil within the ETH wind tunnel facility

d. Upscaled UAV development – Electronic Design

Also, UAV electronic systems, including propulsion, avionics and electricals has been thoroughly redesigned. The overall system architecture diagram of the UAV is described in the picture below:

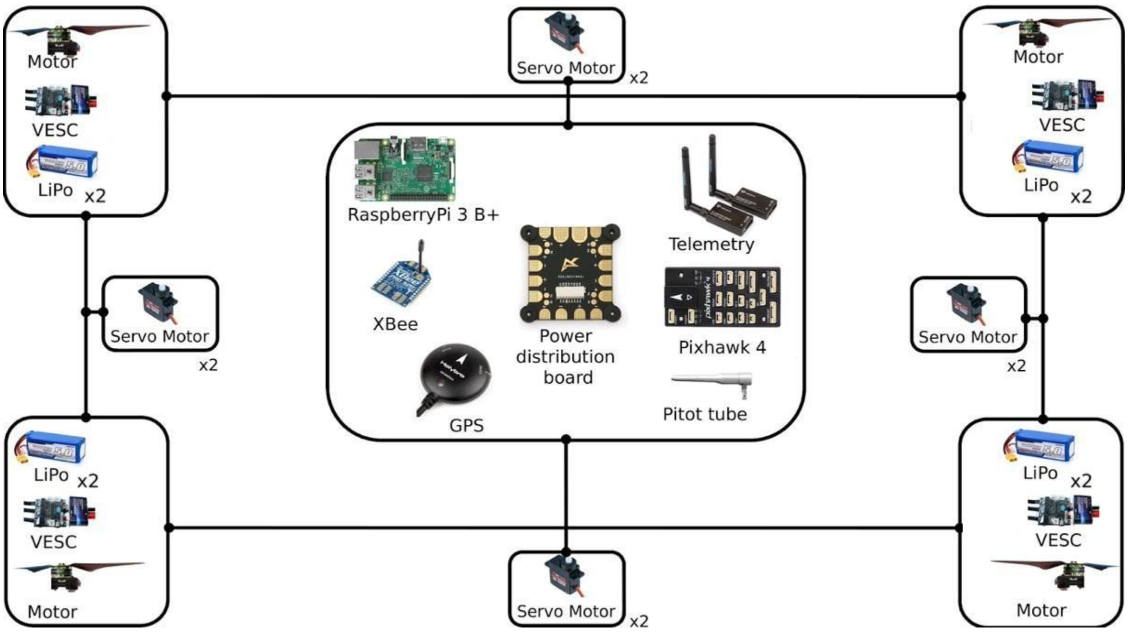

Figure 48: System Architecture

The new specs of the UAV required a review and adaptation of the propulsion system. The design of components and their corresponding model types of propulsion system are listed below:

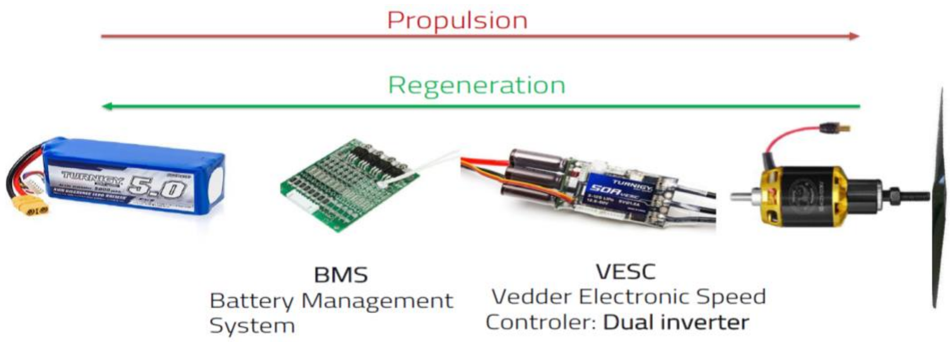

Figure 49: Propulsion Systems

The propulsion system is based on identical electrical motors. Since each motor is controlled by using a VESC (Vedder Electronic System Controller), during the drive the propellers act as in-flight generators in the recovery phase to recharge the batteries.
The power system is composed of two independent circuits. In particular, the first circuit is composed of battery pack sub-systems connected in parallel in order to obtain backup power (i.e. to power the controller board).

Motor Type	BLDC motor
Number of motors	4
Max Continuous Power Output	1850 W
Current Range of motor	-85 A to 85 A

Table 4: Motor Characteristics

The UAV electric diagrams and avionic systems have been thoroughly redesigned in view of the implementation of the different UAVs. The new system layout granted the following features:

- The power system has redundant feeding loop, that can provide energy to the motors by all the batteries onboard, meaning it can still fly with a malfunction of one of the batteries, possibly more, even if with degraded performance. Also, if the loop is interrupted on one side, the motors will always be powered.
- The on-board BECs that power the servomotors and raspberry are configurable and already have a double redundant power supply circuit inside them.
- The FCU and onboard computer are powered via two different power sources which allows both controllers to remain online even during a general power outage (of one of the systems).
- The system has also redundant control surface actuation, by having a total of eight control surfaces, meaning it can still fly with a malfunction of one of the servos.
- The UAVCAN bus system has redundant communicating loop, where all the VESC's are connected in parallel. It means that offer the same safety level of the power loop circuit.
- All other components here are connected via serial ports or controlled via PWM signals.

The electronic systems needed to be redesigned thoroughly for each UAV to adapt them to the new geometries.

The UAV autopilot, flight control & GUI went also through a complete redesign and optimization phase.

The control system architecture diagram is shown in the figure below and includes informational or data flows. Industry standards for signal processing and link security (POSIX, MAVLink, UAVCAN) are employed and work with low latency for ultra-quick response (9ms)

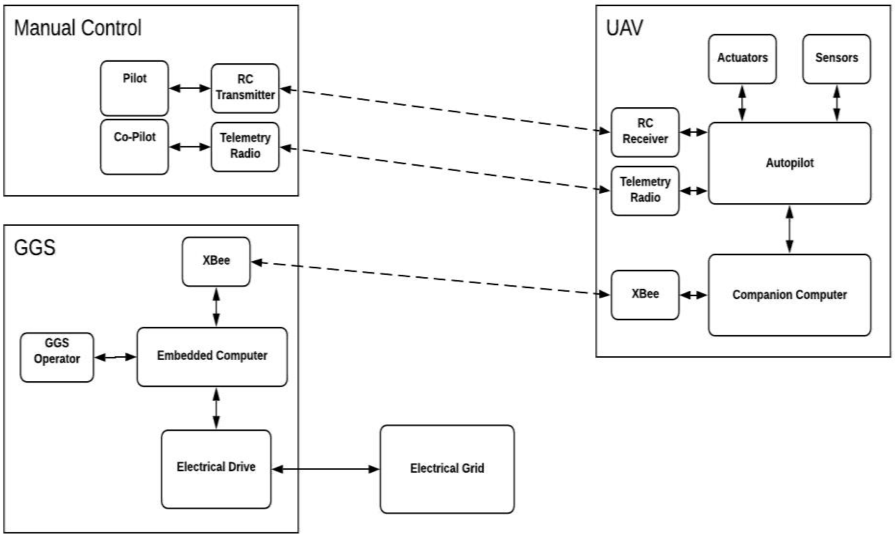

Figure 50: Flight Controller

RC transmitter and receiver communicate at 2.4 GHz, whereas telemetry communication occurs at 915 MHz. These spectrums are specifically chosen because they are approved to be used in Europe. A different spectrum shall be used if required to fly in an area of the world with different regulations. In the CS there is a display with RSSI and packet loss regarding the connection to the drone. If there is any packet loss or data loss the operator is informed immediately by the CS. The same signal displays are present directly in the RC. If there is a failure the respective emergency procedure will be performed as required. Link degradation and link lost due to distance or obstacles is considered highly improbable and not further investigated. All devices used are rated for much higher distances than the ones present during any Skypull procedure.

The autopilot or Flight Control Unit (FCU) used is the Pixhawk 4 shown aside. It was developed in conjunction with the PX4 team and based on the Pixhawk project FMUv5 open hardware design. The autopilot runs on NuttX OS which is a real-time operating system (RTOS) with an emphasis on standards compliance and small footprint. As such it is a mature system overall which is currently used in both academic and commercial products worldwide.

Figure 51: Flight Controller

The FCU is responsible for the low-level processing and control of the UAV. The embedded IMU sensors, such as Accelerometer, Gyroscope, Magnetometer, and barometer are handled directly by the NuttX OS. External sensors such as wind speed sensors, GPS, distance sensors and others, are directly wired to the FCU and its data is handled by different communication protocols such as UART, I2C, SPI and UAVCAN according to each sensor.

The onboard computer is responsible for the high-level control such as trajectory and path planning, mode switching and selection of emergency procedure. It has wired communication to the FCU which enables communication between the two units, not just of data but also of commands. This means that any desired data that is available on the FCU can also be accessed by the onboard computer, which in turn can send commands to be executed by the FCU. The onboard computer is also responsible for the communication with the Ground Generator System to synchronize the phases between both systems. The flight modes used more frequently are stabilized, altitude, position and offboard.

- **Stabilized Modes:** In stabilized flight mode (can also be called manual) the Pilot commands the attitude and thrust of the UAV via the RC. With no input of the Pilot the UAV will keep the last thrust value and automatically stabilize itself to maintain a level hovering attitude.
- **Altitude Modes:** Altitude flight mode is as above with the difference that with no Pilot input the UAV will still control the thrust value to keep altitude or maintain the desired ascent/descent rate.
- **Position Modes:** In position flight mode the RC inputs from the pilot map directly to the position of the UAV and not the attitude. The UAV will automatically compute the desired attitude at any point to maintain position or horizontal velocity. In this mode with no RC input from the pilot the RC will maintain position, even in the presence of winds, and it will still control the thrust value to keep altitude or maintain the desired ascent/descent rate.
- **Offboard Modes:** In offboard flight mode the FCU receives commands from the onboard computer which can be attitude or position setpoints.

The Control Station (CS) is based on the established QGround Control software and permits highly customized parameterization of control and normal/abnormal operating procedures.

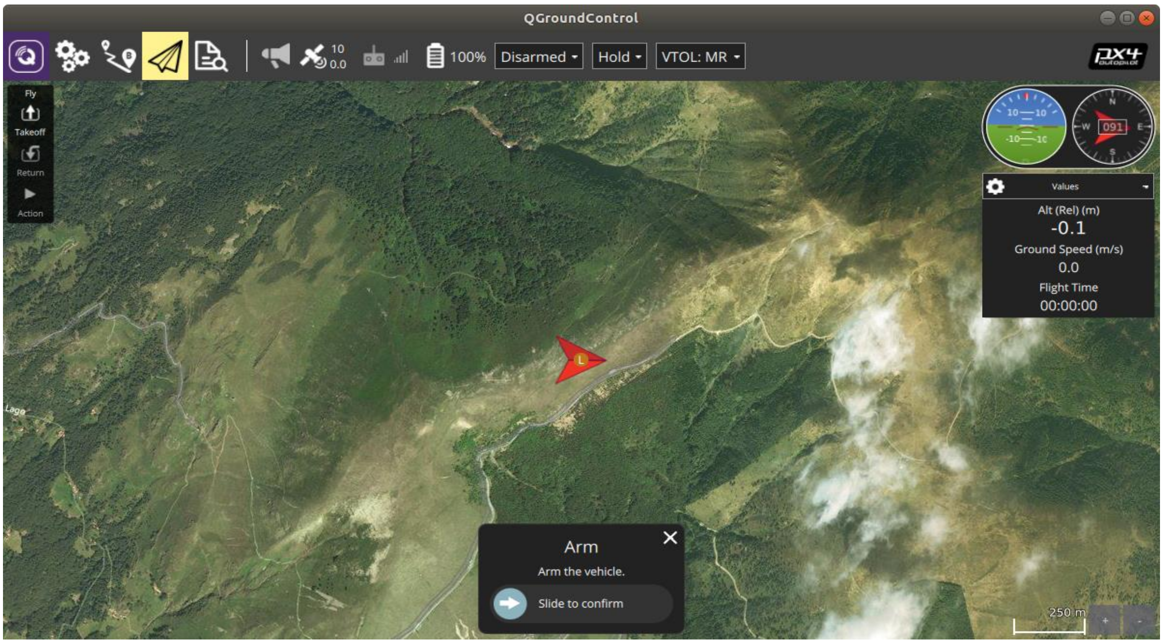

Figure 52: QGround control

The CS displays all sensor and actuator data from the data, so the level or precision is the same as determined by the UAV. However, the data is streamed at a lower frequency than the one being computed in the FCU which is much higher than required for display purposes (Up to several hundred Hz). The CS software runs on a laptop or computer that is dedicated for this purpose.

A big emphasis was placed on consolidating the work done thus far, including the reworking of some features in order to facilitate the scaling and development expected in the future. As such the control

protocol of the UAV was improved with added communication from the companion computer to the autopilot. In turn this allows a much easier deployment of new features, especially in the early development stages. Moreover, virtually all phases of the UAVs flight were further improved, some to consolidate the already existing logic while others with slight improvements that rose from continuous flight test feedback. The two main goals were to improve flight performance most of all, and to make the logic more comprehensible to make future tuning and development easier.
New features such as bidirectional communication between the GS and UAV systems have been developed: this means that data will be streamed continuously between both systems, allowing for more efficient control strategies and higher performances of both systems. Other examples of such features are the new sensors that are being integrated on the UAV namely LIDAR distance sensors, high precision GPS such as RTK, or ultrasonic wind speed sensors. With the added data from such sensors, new strategies can be developed and deployed, overall improving flight performance. For example, using the distance sensor a more precise and faster landing strategy is being developed and in the testing phase. With the RTK the overall position of the UAV is massively improved and so is performance or at the very least the data gathered from flights which always has a positive effect on all parts of development. The same is also true for the ultrasonic sensor wind speed sensor adding to the fact that it can have a very direct and positive effect on the UAV trajectory, improving aerodynamic performance.
Lastly the simulation environment has been massively improved with further information being added to the simulator to match the real flight test scenario more closely, such as wind conditions, control and communication protocols and a more realistic GS model.
An anemometer on the ground station was installed with data logging that was giving information of wind speed and direction to the drone so that the drone will always be centred in the correct wind direction. This allows the drone to produce more traction during generation phase and consume less energy at the GGS during retraction. The take-off can be always in the same space, but as soon as the drone is 5 mt above ground it will first move to the centre of wind direction so that the wind and tether are aligned and then it will start reel out.
Reel out trajectory was improved so that reel out phase is shorter and generation phase is longer.
Parameters of all phases can now be changed in a fast way using only one board with all parameters together.
We improved the maximum load that the tether can withstand as there is an added parameter that control the maximum load applied to the tether and over that the generator will start to reel out or will increase reel out speed. In this way the safety factor of the tether will be maintained in all different wind conditions.
The tether was changed as we reached more than 120 kg of traction, so we moved from 0.81 mm to 1.2 mm diameter of tether and reach a max traction load of 200 kg before breaking, anyway the parameter of max load on tether was always less than 100 kg so that safety factor was always more than 2.
A new control station with added features was added so that a GUI on a screen was not anymore necessary, to improve safety and reliability of the system.
The communication between drone and ground station was improved using new protocol in x-bee antenna system, new software inside Xbee antenna.
We found a new type of antenna to communicate between Pixhawk and PC on the GGS to check drone parameters during flight to improve stable communication.
The drone trajectory in take-off and landing was improved adding a proximity sensor for precise and fast take-off and landing and it was tested in tethered and untethered flights several times.

The drone trajectory during flight was improved adding an ultrasonic wind sensor (to measure 2D wind speed and direction of wind) for precise trajectory so that the angle of attack of side wings is always in the best condition to withstand the weight of drone and not to generate additional drag. It was tested in tethered and untethered flights several times to get and log data, the software to use these data was developed. The complete system was simulated but still waiting to try the software for perfect AOA of side wings in tethered flight, since the new software directly measures the AOA used in UAV autopilot.

Figure 53: UAV ultrasonic wind sensor implemented

Finally, with reference to the overall control system architecture, thanks to the improvements made now the GGS can perform continuously comparison between position of drone through its GPS information (data are passed from drone to GGS through XBEE antenna connection) and correlate them with tether length and speed so that there is always tension on tether. The actual GPS on the drone has a precision of 1-2 m with some spikes in between so a special Kalman filter was applied to receiving data so that only average data are used to compute the GPS data. We decided to pass from low precision GPS on drone to RTK GPS that has a precision of 20 cm so that also the control of tether tension will be much more precise. The only disadvantage is that the RTK component is weighing 150 gr compared to the previous sensor that was only 40 g.

e. Upscaled UAV development – Manufacturing

As far as the manufacturing of the UAVs was concerned, the production methods on were developed with the following aims:

- The first UAV had to be fast in production
- The second UAV had to be stiff in structure and with good aerodynamic performances
- The third UAV had to be stiff and light and have good aerodynamic performances.

To manufacture the different UAVs, carbon tubes covered by polystyrene foam and by a thin plastic film were used, leading to a sandwich construction (foam + carbon fibre multiaxial and pultrusion strips).

The SP130-02 UAV entered into service in May 2020.

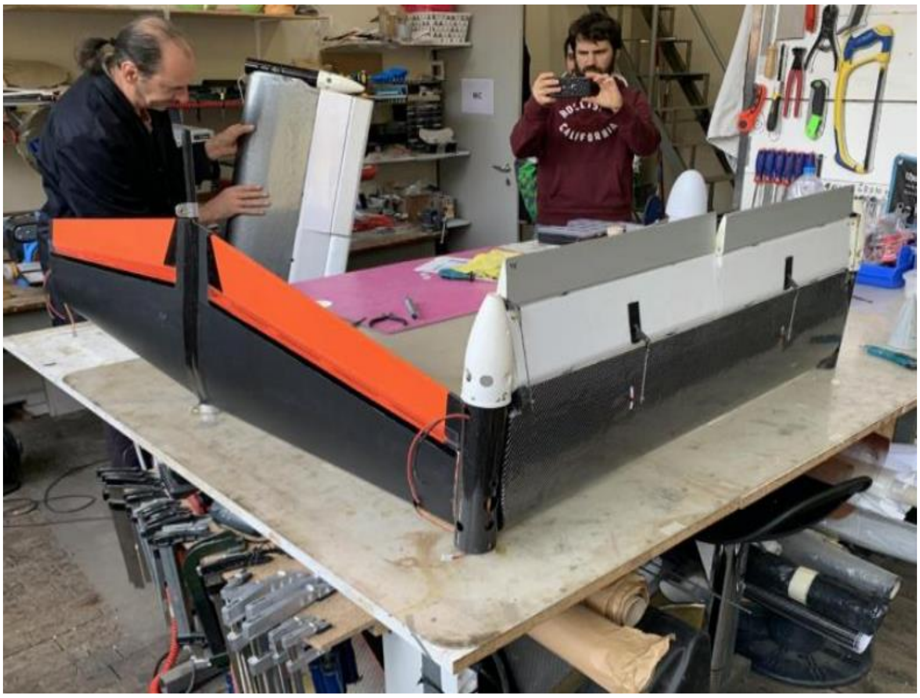

Figure 54: SP130-02 Under construction

The SP130-02 has been tested as of Summer 2020 with good results both from the point of view of aerodynamic efficiency and power production.

Figure 55: SP130-02 in flight

The construction of the SP130-03 UAV started in April and has been completed in October 2020.

Figure 56: SP130-03 Main wing construction

Figure 57: The SP130-03

The production of the SP180 (wingspan 180 cm) started in December 2020 with the main wings, also to be used in wind tunnel tests. A video of the construction of a SP180 wing is available at this link

Figure 58: The SP180 first main wing (close-up)

SP180 has been built on summer 2021. A first preliminary series of untethered tests of the UAV showed that the UAV wasn't enough stiff to properly operate. This required a series of interventions in re-design and re-production under a PDCA approach. A series of modifications have been therefore made on the SP180 components to improve its characteristics and performances.

Figure 59-60: SP180 in Summer 2021

The development of the SP180 continued until April 2022. During that period, the SP180 increased progressively its structural performances but, due to the less favourable operational scenario and to other technical issues (drive control system), it was not possible to engage the SP180 in all planned test phases.

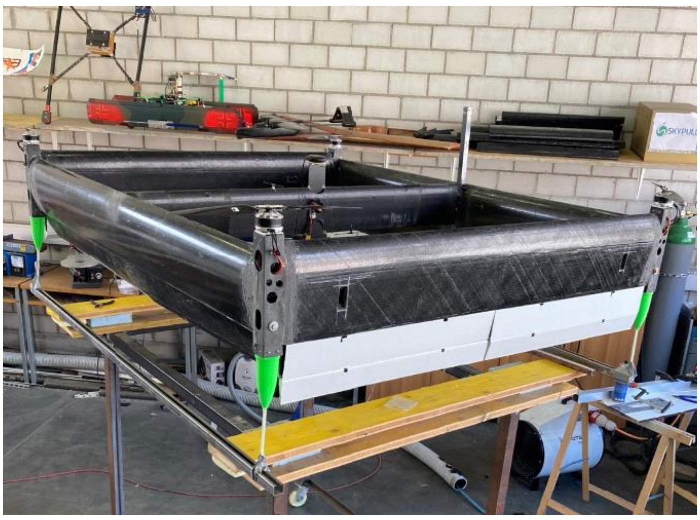

Figure 61: A structurally improved version of the SP180 aerodynamical frame

Optimization of the Ground Station

a. Definition of requirements & specifications - Design Layout

Aside the development of the UAV, it has been necessary to develop a newly featured Skypull GS with all features required to operate the new UAVs and be closer to the future marketable system. Requirements have been reviewed and redefined according to the envisaged increased performances in terms of management of forces on tether, winding/rewinding speed, inertia and reactivity. The given requirements led to the redesign and refurbishing of the GS to fulfil the needs of the new UAVs. The data flows and the main components of the GS are represented hereunder.

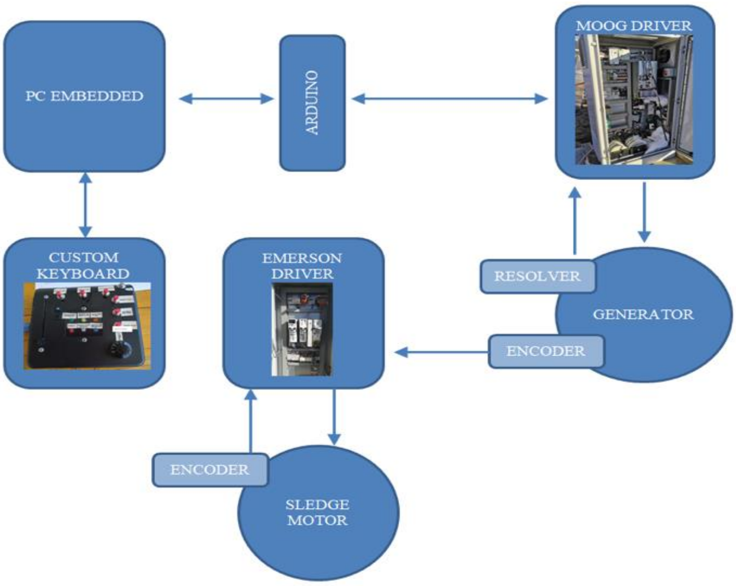

Figure 62: Ground Generation System Scheme

The GS redesign has been focused on the following requirements:

- A stiffer and more reliable tether out sub-system.
- Reducing inertia and increasing speed performances.
- Management of forces on tether, winding/rewinding speed, inertia and reactivity
- Withstand higher UAV traction load expected.
- Increased safety features
- landing platform

Since the Skypull GGS is a single tether system, to avoid the tether jamming, the drum had to be mounted on a slide and energized by screw actuator to ensure that the tether roll-up is guided back and forth over the totally available drum width. This avoids cross-layers and guarantees a smooth unrolling and rolling-up. In particular, the screw actuator had to ensures a correct tether unwinding and rewinding. Moreover, the motor had to be equipped with an absolute encoder to measure and record all tether movements.

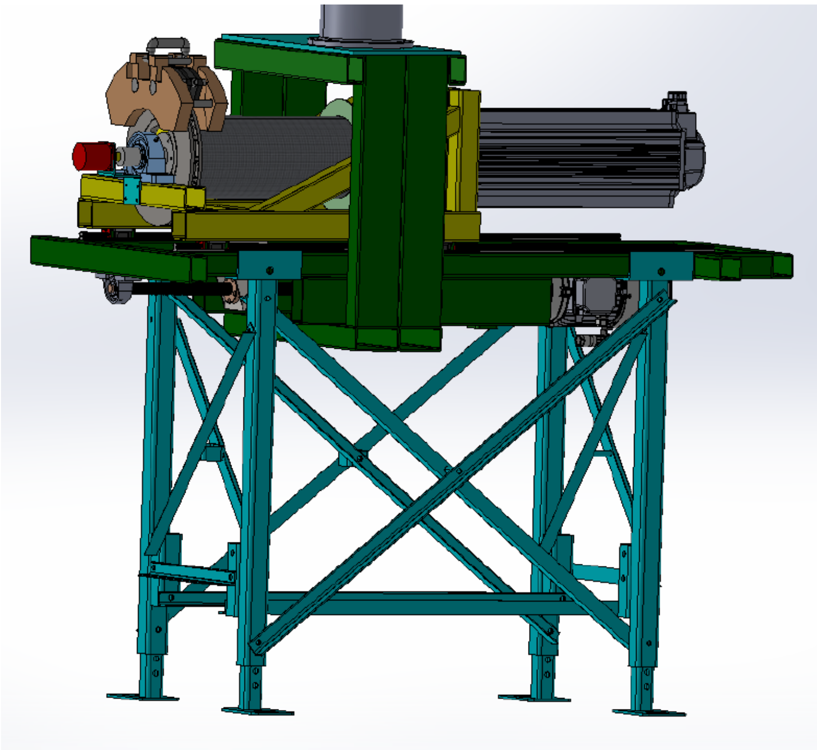

Figure 63: GGS 10-02 design

After a series of flight tests, it has been decided that retraction phase had to have an increased tether speed so the best and more efficient way was to increase the drum outer diameter that passed from 170 to 212 mm. With this improvement the max tether speed during rewinding phase increased from 8.9 till 11.5 m/s, thus reducing the time length of the passive phase of the cycle and improving the duty cycle efficiency. It was first performed a redesign of the drum assembly and subcomponents, then a structural analysis was performed, the system has been purchased while the construction assembly and calibration activities have been attentively monitored in collaboration with the supplier. A new model simulator has been developed, including UAV, tether and GGS, thus obtaining a simulation closer to the reality and optimizing the control system.

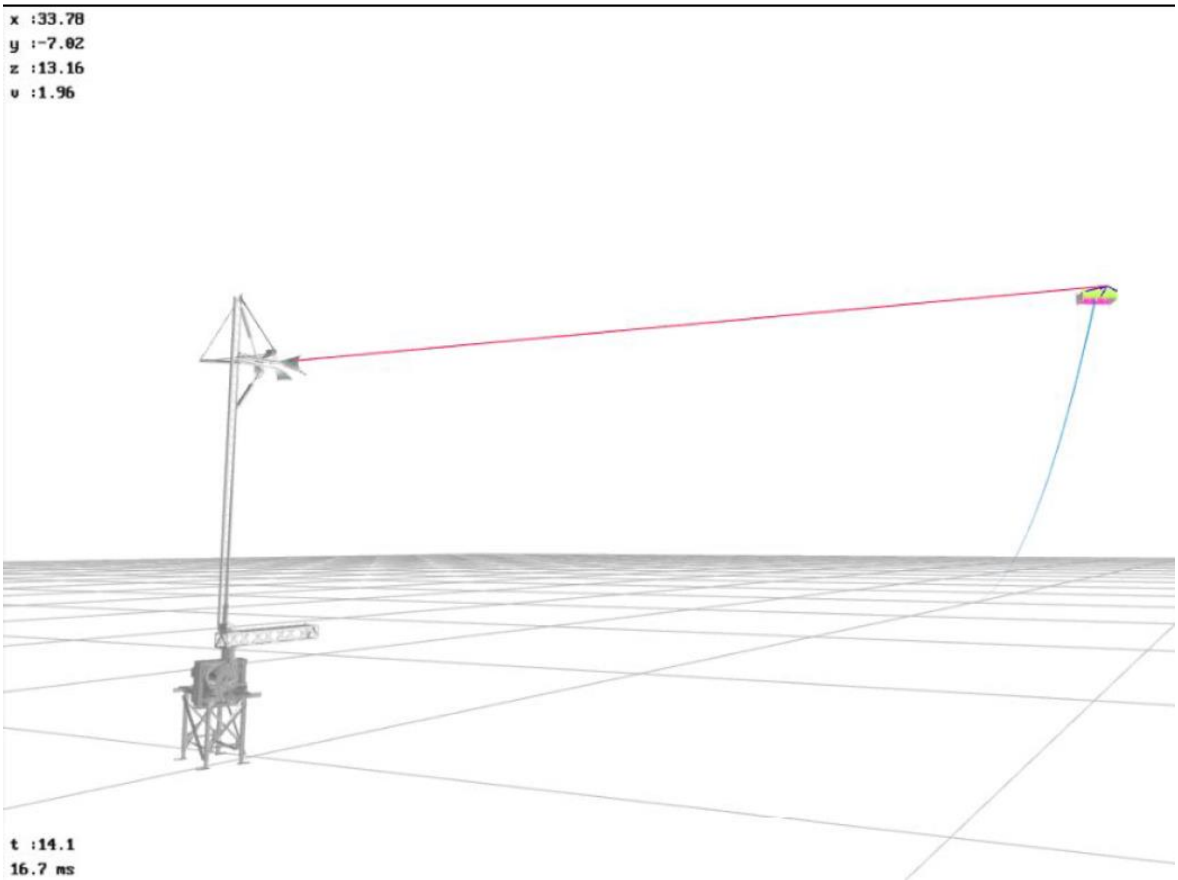

Figure 64: The complete Simulator model implemented

In order to implement the new simulator, we started from the previous standard model, implementing the equations in python and increasing their resolution. The system has been resolved using a RUNGE-KUTTA 4 scheme that gave good results, then MATPLOTLIB have provided the flight animation of the system. Minimalist animation using Python IT was then considered to move the model on C++ and a simulator has been created by using OpenGL (a graphic library) in order to have a model in real time. The simulator visuals using OpenGL A wind field was also introduced using the data from an anemometer at our test site. The global wind field has been obtained by an extrapolation in altitude using the wind gradient. A realistic model for the tether has been also defined, using a quasi-static tether approximation to consider the catenary curve effect caused by the tether mass and for optimization considerations. Next refining steps still to be done are related to the implementation of a MPC (model predictive control) of the model.
The ground station is conceived to have a platform for take-off and landing of drone connected to it. This platform will self-align with the wind in a passive way (as a flag thanks to proper aerodynamic surfaces).
The platform can lift the drone until the tip of carbon tube (used as damping system) so that the drone is out of wind gusts that are normal in the vicinity of ground due to turbulence.
After the preliminary design of the platform has been completed, it has been compared with the take-off platform of present competitors, while a comprehensive and complete survey of all those platforms has been made. Follow to that analysis some changes and some new features have been decided and a new design with fewer moving parts is being implemented.

Finally, a new design of a take-off/landing platform to be retrofitted on the GS has been developed, to be developed and built for future applications.

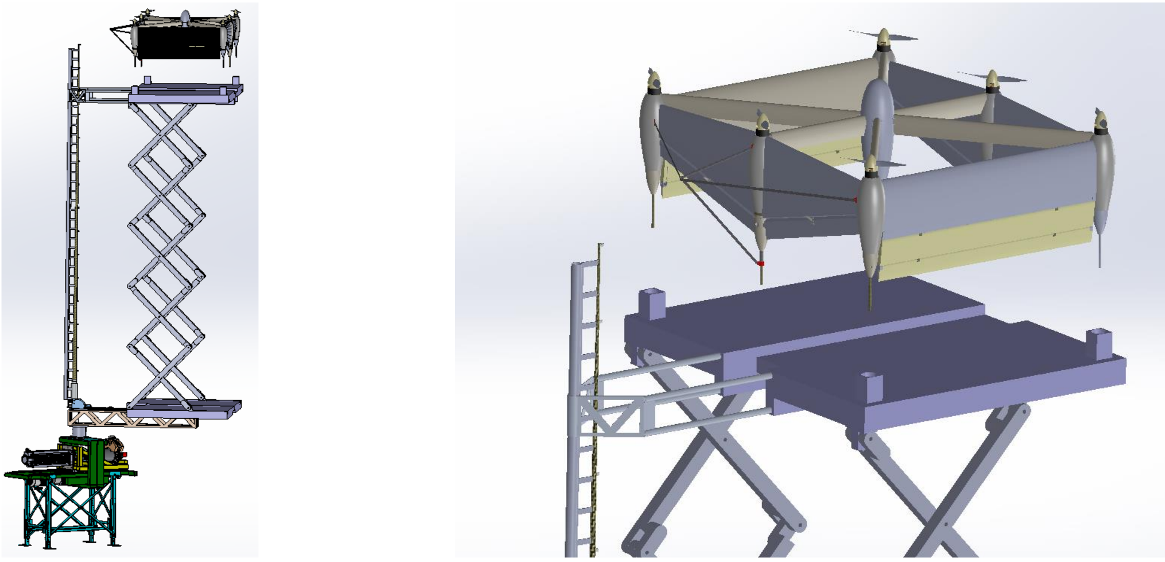

Figure 65: Study of a Ground Station with take-off /landing platform

b. Mechanical, electrical, electronics, COM and GS control system design

The GGS has been modified to align with the newly defined requirements and specs. The new GGS has been named GGS 10-02.

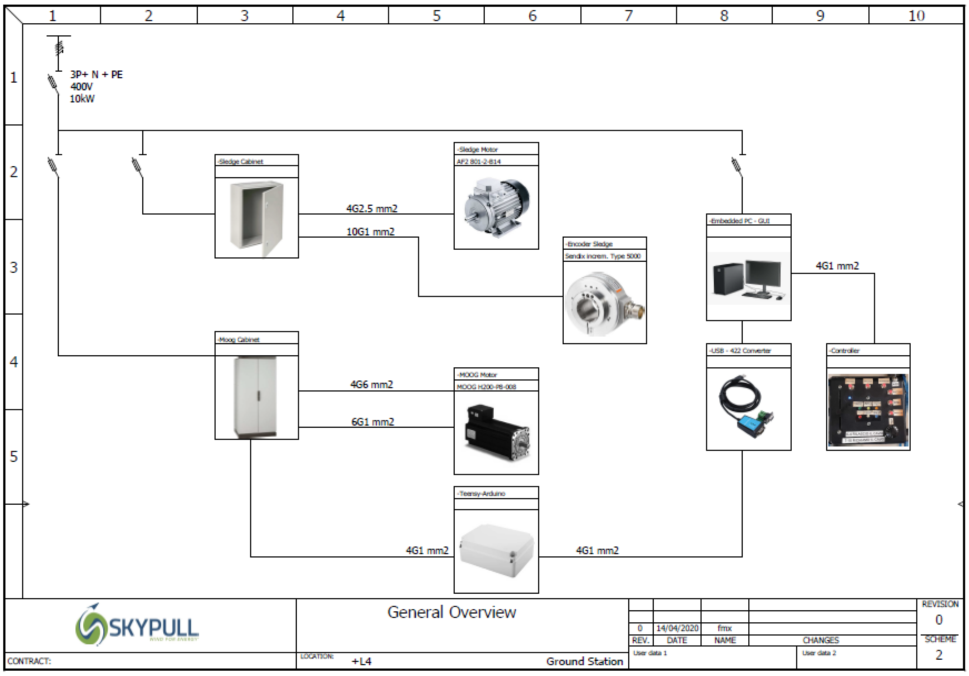

Figure 66: GGS 10-02 layout

From a mechanical perspective it has been thoroughly analysed, modelized and revised in order to optimize masses and weight by maintaining the stiffness and strength required reducing at the same time, whereas possible, the inertia of moving parts.

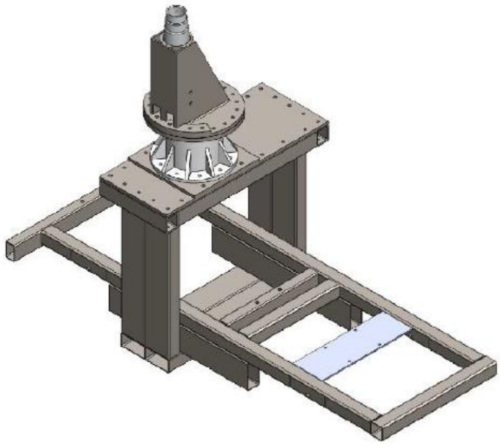

Figure 67: GGS 10-02 model

The GS control firmware has been radically changed to deal with the oscillation issue. To solve this problem, it was necessary to obtain the mathematical model of the Ground Station (GS) that was also able to capture the effect of both dynamic and static friction. To find a motor-winch system model was needed to apply the rotational equilibrium principle, while for the friction model the Least Square Method (LSM) was used. To use the LSM, it was necessary to conduct many dynamic tests on our electric motor. Once the GS mathematical model was obtained, it was possible to design the new control firmware. The latter introduces great improvements from the GS control point of view. In fact, this new firmware relies on more phases for the return phase to minimize the electrical energy spent during the retraction phase. By doing so, in addition to having solved the oscillations issue, it was possible to reach the goal of net positive energy production.
The previous GS control was characterized by sudden oscillations which could lead to dangerous situations such as the instability of the entire system with a paramount effect on the overall efficiency. This issue was due to the non-linearity introduced by the previous control strategy. Follow to the new control logic, the amount of net positive energy output increased significantly.

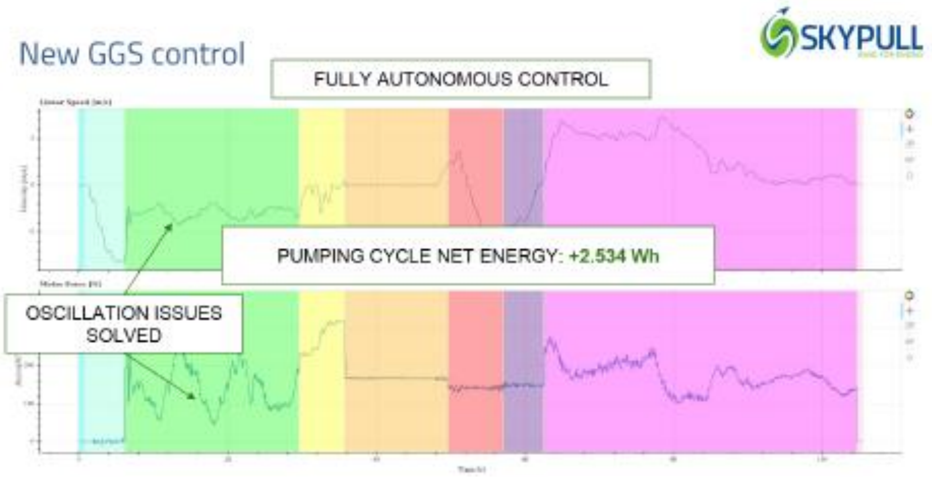

Figure 68: Result obtained by using the new GS control strategy

Regarding the GS GUI optimization, the main reason is that we would like to add the possibility to have graphs in the GUI that allow you to immediately understand the trend of the electricity produced and / or consumed. The GUI has been redone from scratch to that purpose using Python.

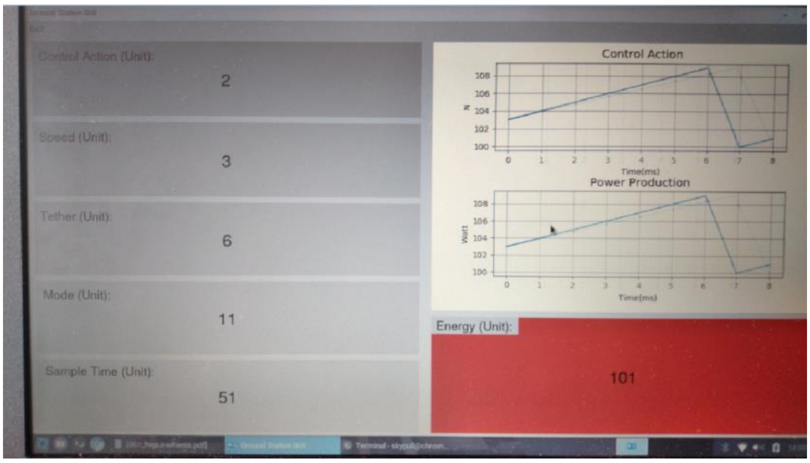

Figure 69: New GUI Prototype

After the GUI implementation the way of controlling the GS has been thoroughly modified. Data are not anymore conveyed by an Arduino board to the GUI that send commands to the driver of the generator. Before the control was passing through the GUI, now the GUI is only showing data so that the clock time for passing packages through the 2 systems passed from 6 Hertz to 400 Hertz and the control is much more precise and uniform. A new GUI is presently being developed to better adapt to the new command logic and will soon be completed.
A new joystick has been developed to let the pilot have all needed information on the screen of the joystick. Another important newly added feature is relative to the fact that now autonomous control command can be launched with the joystick (before only manual control could be performed through joystick and the autonomous launch had to be started through the keyboard connected to the GUI.

c. GS - Energy management design

Together with the new GUI implementation also the way of controlling the GS driver has been thoroughly modified. Data are not anymore conveyed through the GUI to the GS driver and all the control is done inside the added embedded PC that talks directly to the inverter through MAVROS communication format. This ensures much more efficient and prompt driver commands and consequently an overall increased efficiency in the energy management system.
A study on energy backup system dimensioning has been made by determining the type, dimensions, and relative cost of a system able to grant the system to operate in order to be set in idle mode in case of lack of power from the grid. The envisaged system entails a pack of Lion batteries coupled with a diesel generator. For the SP300 system (25kW) it has been defined a 500 Wh Lion battery pack coupled with a 6 kW genset, for an overall expected cost of about 5000 CHF. Normally the battery pack should be sufficient while the gen-set would be used in case the system would require to be powered for an exceptionally long-time window (that could happen in case of high wind conditions and the UAV at the max distance from the GS).
Several offers have been collected by multiple suppliers from several countries to that purpose, but due to the specific requirements (especially of the Diesel gen-set) the cost appeared to be much

higher than expected (more than 2-4x), making the solution inconsistent with the envisaged market constraints. In the end has been decided to use the renewed system within the project, postponing the development of the scaled-up gen system.

d. GS development & test

Ground Station components have been defined according to the results of the previous subtask activities. New parts of the GS have been developed and implemented and tested.

GGS 10-02 has been equipped with a brushless permanent magnet motor (MOOG H200-P8-008) and digital servo drive for controlling multi-axis systems the (DM2020). The modular platform, high performance control card and advanced control software allow to improve performance levels in terms of energy conversion (from mechanical energy into electrical energy), system integration and tracking of reference torque. This last is generated from the real time controller embedded on the Arduino. The controller governs rotating speed and torque of the drum to maintain the desired tether tension and thus guarantee the maximization of the energy production. Furthermore, Arduino acts as an interface between the MOOG driver and the embedded PC where the Graphical User Interface is installed. The firmware inside the Arduino provides the possibility to choose whether to control the GSS automatically or manually. The manual-automatic transition and vice versa is achieved by a special switch located on the controller. In addition, in case of an emergency, a special button (quick stop) is installed on the controller which activates the static brake that stops the motion of the motor instantly.

The tether is made of a DSM Dyneema SK75 12 strand rope, 0.83 mm section. Dyneema is an Ultra High Molecular Weight Polyethylene (UHMWPE) and offers maximum strength with minimum weight. It is resistant to UV, abrasion, moisture, and chemicals, with very low elasticity and is up to 15 times stronger than steel and up to 40% stronger than aramid fibres, on a weight-for weight basis. The UHMWPE also present the advantage of less scatter in the mechanical behaviour, which means more predictable, linear and safer behaviour in case of break. The tether is designed to withstand up to a maximum safety factor of 3.

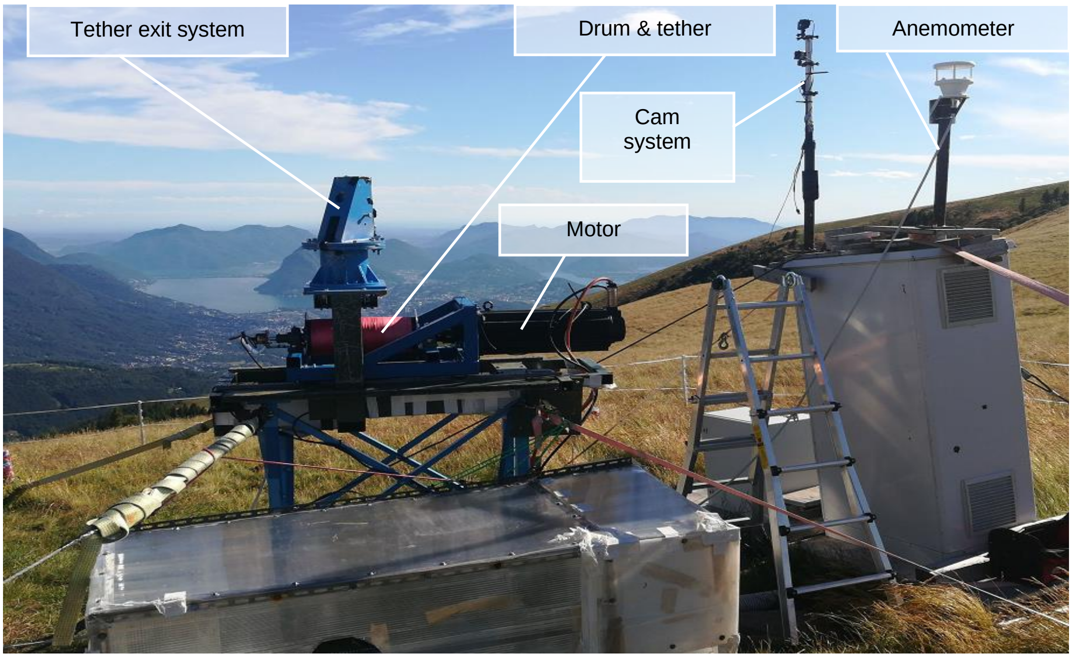

Figure 70: GGS 10-02

Due to the greater complexity of the new control systems and logic, the GGS electronic hardware has been also improved to cope with. Thus, a new PCB equipped by a new microcontroller with more computing power (Teensy 3.6) has been installed and implemented.

Figure 71: Teensy 3.6 Control Board

Moreover, to increase the efficiency of the entire system (GS + UAV), a new ultrasonic anemometer mounted on the GS was bought, setup both in hardware and software terms and tested.
Besides, to have better manual control on our electric drive both GS joystick and GUI have been rebuilt.
After testing the joystick has been tested, it was decided to update it with several new features, to improve the overall reliability of the system and by including also the commands and information related to autonomous flight mode operations.

Figure 72: The new Anemometer

Figure 73: The new GS Joystick

The new drum system has been manufactured and assembled. After having changed the dumping system and the drum system the GS is fit for being used both with the SP130-03 and for the SP180 system, while further upgrades will be requested to operate the SP300 system.

Figure 74: The new drum

Testing activities

Multiple tests have been conducted within the project. Before testing the UAV tethered, several tests have been conducted to ensure safe tethered flight tests. These tests are:

- Autonomous bench test: the UAV is fixed to a ground fixed frame. The test is aimed to assess the correct operation and performances of the hardware/software components (Raspberry Pi, Pixhawk and all the sensors involved) as well as the UAV structure stiffness and motors behaviour.

Figure 75: Bench test of a UAV used to test electronic components

- Controller tuning procedure: It regards the tuning of the Pixhawk controller. This test allows the improvement of the flight performances in terms of trajectory and flight stability.
- Autonomous straight line flight test: This test is important to understand UAV aerodynamics performances to gather data about the UAV for the autonomous tethered flight.
- Return to home procedure: This test is a safety procedure. It is important to have all UAV capable of returning to the take-off position in case of tether rupture.

Figure 76: Autonomous return to home (straight line) flight test of a UAV

The tests above depicted represent maybe the biggest amount of testing activities performed since they had to be made every time a change occurred in the UAV's components, structure, etc.
Where no changes were implemented in the UAV, a different set of pre-flight check had to be implemented to ensure its operability.

After the preliminary test (mainly performed by or near the Skypull premises) the UAVs were brought on the test site (most of them occurred on top of the Mount Bar, near Lugano) where the GS had been installed and the tethered test could be performed.

As above already mentioned SP180 has never been tested in tethered mode, because of the extended time required for re-design and production of the UAV aimed at increasing its stiffness and eventually because of some problems in having an available test site under good wind condition at proper time. Some tests have already been conducted though, but only in untethered mode.

Figure 77: SP180-1 hovering test in February 2022

During the timeframe of the project execution 37 flight tests have been conducted in tethered mode, 9 of them in fully autonomous control mode, with a total time of tethered flight of around 5 hours. For each flight has been made a report indicating the people and systems involved, the objectives, results, etc. Here is a video showing the SP130-02 UAV in operation

System Functional, Failure Tree and Mode Effects analysis

With the collaboration of the Polytechnic of Milan analysis has been performed on the system. After a concise description of the system under study and its working principle, a functional analysis and an architectural one has been performed, followed by an analysis of the main operating modes.

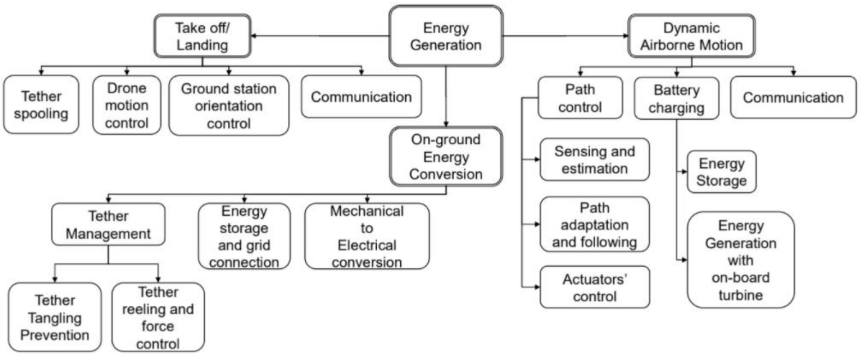

Figure 78: Functional analysis (example)

A Preliminary Hazard Analysis (PHA) of the whole system and a Failure Tree Analysis (FTA) followed. This last analysis is focused on the drone subsystem. In compiling the analysis, the employed quantitative information (e.g. probability of occurrence of faults) was not supported by actual figures derived e.g. from statistical evidence, since these are difficult or impossible to derive at the current development stage. Therefore, the quantitative data are to be intended as a quantification of relative likelihood among the considered faults, rather than as precise probabilities

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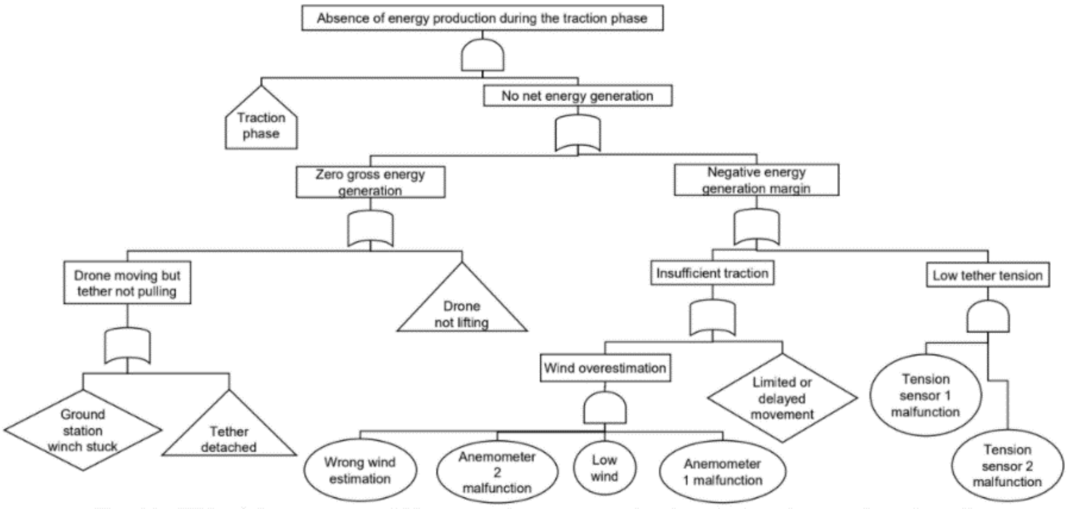

Figure 79: FTA analysis (example)

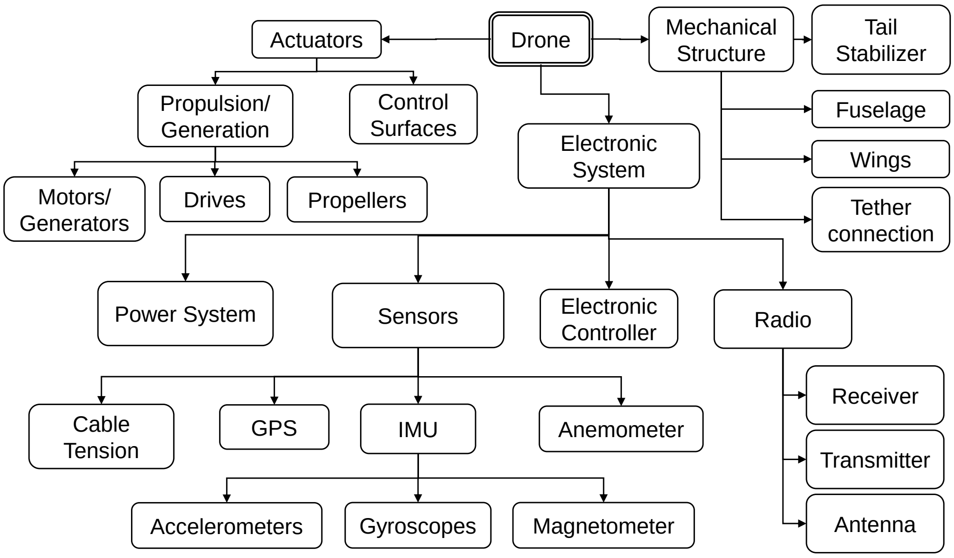

Figure 80: Drone structure considered for the FMECA

Failure Modes Effects and Criticality Analysis (FMECA) has been performed. The set of results obtained will be kept updated all along the project.

The safety analysis performed highlights some of the most critical elements of the considered system, primarily the onboard power supply system and propellers, and points out several potential faults together with possible countermeasures. The analysis is not exhaustive of all possible risks, rather it shall serve as a starting base for a more in-depth study, as the system is developed towards industrialization, and as an example of possible general approach that can be adopted for the system hazard analysis.

Organization and Management

The PM activities were managed with the help of a dedicated IT tool (Jira SW). Coordination of technical activities and the overall technical coherence of the system components specifications and performances is granted by the development plan as following the specific requirements defined to produce the expected deliverables and to reach the identified milestones. The entire process has also been defined in the SORA, that specifies how to edit and manage the related technical documentation.

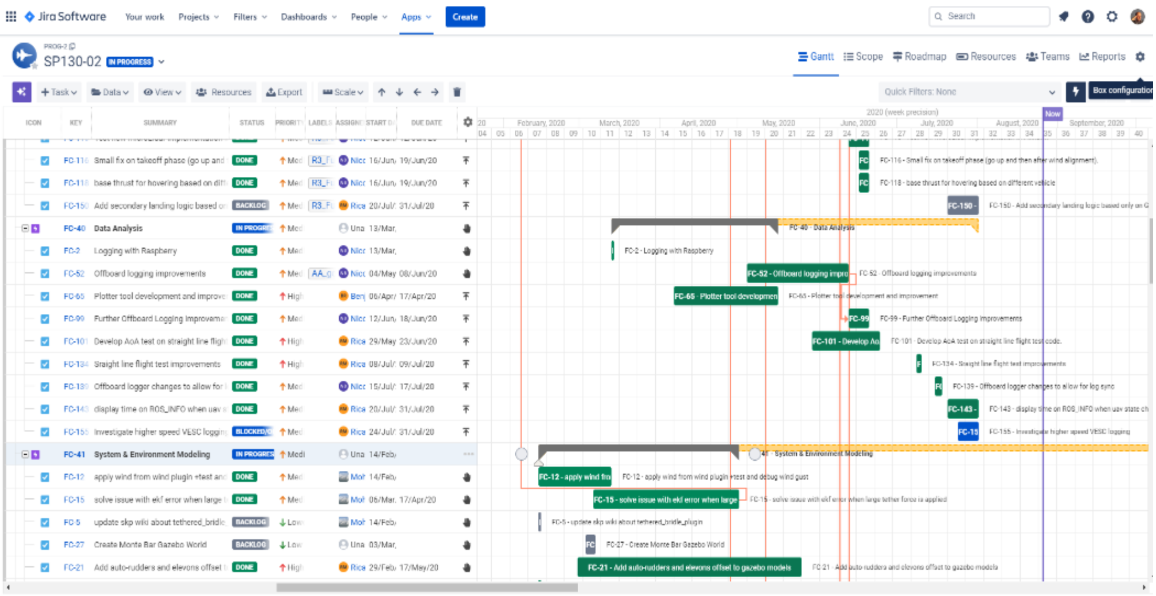

Figure 81: Jira MP tool (detail)

Finally, as far as the test site is concerned, some activities have been aimed to ensure the continuous viability and the accessibility of the site for the tests. These activities were conducted by Skypull with the support of AEM, that has supported the project in particular by taking care of the overall test site safety and operability (specifically by checking and maintaining the power cable, providing special transportation means and security and safety measures like fencing and signals). Moreover, AEM has ensured the maintenance of the premises, by repairing either the protection hull that cover the cable powering the test site (subject to wearing and damages along time) and by repairing the premises, damaged by hail during summer 2019.

Conclusions

The project has accumulated significant delays, due to multiple reasons, such as:

1. Several reviews in the technical solutions to be adopted during the tech development to grant the operability of the systems and their compliance with the requirements
2. Reduced number of good wind/weather conditions required to perform flight tests on the test site along time and the difficulty in finding an alternative and more performing test site
3. Delays due to COVID restrictions

This delay impeded the project to reach all the expected results, as far the SP180 UAV tethered test is concerned. Thus, as from the above depicted activities, the project results can be considered the following ones:

- First campaign of system's visibility assessment completed
- First campaign of system's power performance assessment completed
- First campaign of system's noise assessment completed
- 3 UAV components and subsystem design.
- Full autonomous control SW (full operational cycle + some emergency procedures)
- 3 UAV with increased performances manufactured
- 2 UAV with increased performances fully tested
- 1 UAV (SP180) preliminary tested (untethered)
- VESC adaptation to UAV
- On board UAV regeneration system by motors/propellers
- On board UAV fight control by motors/propellers braking attitude
- New GS (GS-02) designed and built
- Optimization of GS features and performances
- New GS/AUV control system protocol implemented
- PHA, FTA, FMECA completed

Even though the SP180 UAV was not thoroughly tested as planned to fully determine its performances, the obtained results can be considered of extreme significance. In particular:

1. Visibility and identification tests have led to significant results and allowed to improve the visibility and detection of intruders to a level expected to be compliant with the requirements set by aviation authorities in standard operations.
2. Noise tests have identified criticalities that could be of potential threats for future market introduction and large-scale deployment. Areas of intervention have been determined.
3. Power performance tests have been instrumental to define a sound measurement system and methodology. These contributed significantly to advance in the system characterization and definition of power curves to be compared with other wind-based generation technologies.
4. Generation tests brought significant results, with peak power of 6 kW and positive balance of the duty cycle (traction/recovery) in the scale of several Wh (with 1.3m wingspan UAVs).
5. The development and test of a fully featured and reliable autonomous flight control system - covering all the duty cycle phases and some emergency phases as well - represent an outstanding result in the AWE sector, where very few players worldwide are known to have flown the system in full autonomous mode, especially considering the number and the type of control features of the Skypull UAV (required to ensure the expected safety levels and

higher manoeuvrability in all wind conditions). These features require more complex control SW compared to other more “standard” flying devices.

6. The usage of braking propellers as energy generators and, at the same time, flight trajectory controllers (a concept that has been patented by Skypull), represent an innovation in our sector.
7. Improvement in the GS performances have been quite significant.

Project costs

The expenditure related to the project is reported to be CHF 727'478, corresponding to the 88% of originally forecasted expenditure, most of them related to WP 3, as represented in the following table:

	Total reported costs	%	% on forecasted costs
1. Ensuring compliancy to aereonautical regulation on aircraft detection	57.566	8%	49%
2. Performance and noise assessment of AWE systems	54.490	7%	60%
3. Development and testing of pilot system	526.622	72%	99%
0. Organization and Management	88.800	12%	100%
TOTAL	***727.478***	***100%***	***88%***

The total of CHF 727'780 corresponds to the total of the costs related to the activities necessary to accomplish the project tasks. The following table illustrates the distribution of the overall costs among the different project tasks:

	SUBTASK	Total reported costs	%
1. Ensuring compliancy to aereonautical regulation on aircraft detection	*1.1.1 – Organization of characterization tests*	3.440	50%
	1.1.2 – Execution of tests	12.924	50%
	1.1.3 – Review and analysis of results	1.720	50%
	1.2.1 – Review and analysis of existing guidelines and standards for detection of	3.690	50%
	1.2.2 – Development / procurement of solutions	11.328	60%
	1.2.3 – Implementation of solutions	12.192	60%
	1.3.1 – Testing of solutions	10.208	40%
	1.3.2 – Evaluation of test results	2.064	40%
	1.3.3 – Dissemination of learnings to FOCA	-	0%
2. Performance and noise assessment of AWE systems	*2.1.1 – Review and analysis of existing guidelines and standards for the*	6.880	100%
	2.1.2 – Definition of measurement concept and first measurement period	19.224	100%
	2.1.3 – Refinement of measurement concept and second measurement period	622	10%
	2.1.4 – Data analysis and reporting	2.064	60%
	2.2.1 – Background and literature analysis	12.800	80%
	2.2.2 – LnL phase measurements	3.440	40%
	2.2.3 – Ground station measurements	2.564	40%
	2.2.4 – Field measurements	5.440	40%
	2.2.5 – Data analysis and reporting	1.456	40%
	2.3.1 – Drafting and review of guidelines	-	0%
	2.3.2 – Dissemination of guideline	-	0%
3. Development and testing of pilot system	*3.1.1 - Definition of requirements & specifications - Design Layout*	16.320	120%
	3.1.2 - UAV - Structures, wings, propulsion, avionics, electricals, electronics and	61.600	200%
	3.1.3 - UAV autopilot, flight control & GUI optimization	43.200	90%
	3.1.4 - Design Review	12.384	180%
	3.1.5 - UAV realization and test	133.334	120%
	3.2.1 - Definition of requirements & specifications - Design Layout optimization	12.192	120%
	3.2.2 - On board energy production and management design optimization	10.128	120%
	3.2.3 - OPGS realization	14.256	120%
	3.2.4 - OPGS test and validation	12.720	120%
	3.3.1 - Definition of requirements & specifications - Design Layout	9.242	80%
	3.3.2 - GS Mechanical Electrical, electronics, COM and GS control system design	9.144	90%
	3.3.3 - GS - Energy management design	6.931	60%
	3.3.4 - GS Realization & test	153.515	90%
	3.4.1 - Mechanical integration	5.012	70%
	3.4.2 - Electrical and electronic integration	8.624	70%
	3.4.3 - System Hazard Analysis: Failure Tree analysis and Failure Mode Effects and	18.020	95%
0. Organization and Management	*0.1 Project planning and management*	34.400	100%
	0.2 - Technical coordination	25.800	100%
	0.3 - Test site setup, maintenance, security, logistics	28.600	100%

The amount of CHF 705’478 (which corresponds to the reported project expenditure minus the cost supported by the partner AEM of CHF 22’000) represents roughly 44% of the overall Skypull expenditure recorded between May 2019 and May 2022 (CHF 1’600’000).
The total work performed during the project accounts for a total of 97 man-months (equivalent for the period to 2,7 FTE), representing 78% of the reported costs, the rest (around 151 kCHF) consisting in other direct costs (mostly system components).
These values are in line with the overall costs’ distribution for Skypull, where approximately 80% are costs related to HR.

Unfortunately, due to significant changes in the organisational structure of the company and the lack of continued funding, the project has not been completed as expected.
Nonetheless we would like to underline that most of the important activities have been performed and key learnings have been gathered. In particular, the positive results in terms of energy generation (up to 6 kW peak power with an only 1.3 wingspan drone) and system control are important insights for the entire industry. It shall be noted that Skypull is presently one of the few operators worldwide to have successfully tested a fully featured autonomous control software, covering all phases of the system operations.

Outlook and next steps

Notwithstanding the multiple and relevant results obtained, still some further research is needed to thoroughly reach the project objectives. In particular:

1. Development and implementation of solutions to improve the system identification and in particular:
   - Evaluate and test more powerful strobe lights on board the UAV (or alternate solutions) to grant the desired visibility in direct sunlight conditions
   - Develop, test, and assess a full range of anti-collision and emergency procedures to be implemented after active or passive FLARM/ADS-B identification of airspace intruders
   - Gather further test results and share with FOCA and Twingtec to standardize and disseminate guidelines

2. Further characterization of power and noise performances of the system and in particular:
   - Test noise emissions of bigger (SP180 and SP300) UAVs – especially in take-off and landing phases and during emergency procedures to assess their compliance with current regulations
   - Continue power characterizations of bigger (SP180 and SP300) UAVs to better evaluate their market introduction and competitiveness, as well as in various operating conditions.

3. Continue the upscaling of UAV development, with reference to aerodynamic, structural, power system and flight control performances required to reach the expected operational results.

National and international cooperation

The main partners/suppliers that have been activated within the project are:

- Azienda Elettrica di Massagno - AEM – Switzerland (project partner)

Massagno Electric Company SA, has been supporting the project both from a logistic and technologic perspective (AEM is also the first potential customer of the SP systems), by granting the operability of the test site, providing logistic and assets (vehicles and other transportation means) and technical support.

- Polytechnic University of Milan – DEIB – Italy (supplier)

Polytechnic University of Milan – DEIB (supplier) https://www.deib.polimi.it/ita/home, (Prof. L. Fagiano) collaborates with Skypull since 2016 in analyzing and developing the SP system's model. Within the project the Polytechnic is supporting Skypull in the execution of the FTA / FME system assessment

- OST - Ostschweizer Fachhochschule Rapperswil (HSR) / Zürcher Hochschule für Angewandte Wissenschaften (ZHAW)

HSR (https://www.ost.ch/en/) has performed a series of studies on the Skypull wing profile by analytical methods and computational fluid dynamics. ZAHW (https://www.zhaw.ch/de/hochschule/) has conducted a series of real-world measurements, mainly in a wind tunnel. The activities have been paid by the Innosuisse project no. 43730.1