BACHELOR END PROJECT

DRONE DOCUMENTATION

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– Solar Powered drones –
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Contents

1 Introduction

With renewables being on the rise, green solutions are being investigated for every market. This thesis revolves around the idea that the flight range and flight time of commercially available drones could possibly be elongated by the addition of solar panels. In order to do this, a drone is proposed which has the ability to accommodate solar panels and thus can provide its on board system with additional power to elongate the flight range.

This thesis is structured as follows. First the UAV type is selected, then the actual drone frame and the additional components are selected. Finally the drone is simulated and final results are elaborated on.

2

UAV selection

For the UAV selection, it is important to understand which types of UAVs there are. Four types of UAVs are considered and discussed: multi-rotor, single-rotor,fixed-wing and fixed-wing hybrid.

2.1. Multi-rotor

A quadcopter is what is generally thought of when thinking of a UAV, which is a subclass of the multi-rotor class. Typically it is driven by four rotors, where the direct opposite rotors spin in the opposite direction. This type of UAV is the easiest to engineer, since as long as the rotors are spaced in a symmetrical way it will fly without problems. Stability and flexibility are two of the main advantages of a quadcopter; it can suspend itself in the air and take photos from a still position. Furthermore, it can move very flexibly, in any direction at any given time, which may prevent crashes in tightly packed neighbourhoods. Finally it will not need a lot of space for take-off since it can take-off vertically. However, there are also some disadvantages to this design, among which is the fact that it is less-efficient than airplane solutions [6]. Secondly it is difficult to keep the camera angle compared to the ground constant, since the angle of the quadcopter changes when moving and hovering. One of the most important advantages is the fact that a quadcopter could have a large area available for the placement of PV panels, which would benefit the purpose of our project. An extensive overview of advantages and disadvantages of a quadcopter are listed in table 2.1.

Figure 2.1: Quadcopter example [8]

Table 2.1: Advantages and disadvantages of a quadcopter

Advantages	*Disadvantages*
Easy to engineer	Less energy efficient than airplane solutions
Can take still photos	Photos while moving changes camera angle
Very flexible movements	Simple square shape is more fragile
Possibly a lot of area for solar panels	Low payload

2.2. Single-rotor

A single-rotor, or helicopter, type of UAV is contrary to the fact that it is called a single-rotor type, two rotors. These rotors consist of a large rotor and a smaller, tail rotor. These types of UAVs are much more efficient than it's multi-rotor counterpart [10], but still less efficient than a fixed-wing solution according to [6]. Besides that, such a solution has little to no suitable room for solar solutions. Therefore, these types will not be further considered since they are not a suitable solution for solar powered UAVs.

Figure 2.2: Single rotor example [1]

2.3. Fixed-wing

Next to this distinction, another type of drone can also be investigated, the fixed-wing. Fixed-wing type UAVs are entirely different in build and using purposes. Where rotor types are able to suspend themselves in mid-air, fixed-wing UAVs are constantly moving at a certain horizontal speed. They remain at altitude by the lift force generated by the wings, which counteracts the gravitational force. This way, it moves in a more efficient way than a rotor type UAV. This, and the fact that it is always moving, is why it is very suitable for long distance operations, such as mapping. The main disadvantage of a fixed-wing solution is that it is less flexible in moving around mid-air and needs either a runway (a small grass field is usually enough) or some sort of launching base to propel it into the air

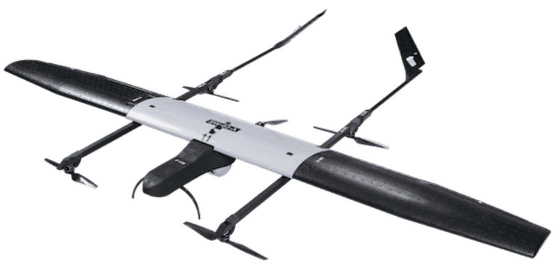
Table 2.2: Advantages and disadvantages of a fixed-wing UAV

Advantages	*Disadvantages*
More energy efficient	No photos from still position / cannot suspend in mid-air
Constant angle while moving (at equal altitude)	Only suitable area for solar panels is on the wings
More robust shape	Needs a runway or launching mechanism
Higher payload	

2.4. Fixed-wing hybrid

The final type researched is a fixed-wing hybrid UAV. This type of UAV has VTOL (Vertical Take-Off and Landing) capabilities and can take-off and land vertically as the name suggests, while in the air flies like a fixed-wing UAV. With this design the aim is to combine the benefits of a multi-rotor with the flying efficiency of a fixed-wing UAV. However this leads to a complex design and a bigger chance of complications during flying.

(a) Fixed wing drone [12]



(b) Fixed wing hybrid [7]

Figure 2.3: Fixed wing vs Fixed wing hybrid

2.5. UAV type selection

For the drone selection, a few criteria are important. The table on the next page shows these criteria per section for the four types of drones we distinguished. All the way on the right, the weight per criteria is indicated, with '10' being the most important and '1' being not important at all. From this table it becomes clear that a fixed wing is the best option, especially when the red factors are taken into account. The quadcopter has a low payload capacity and mounting the PV cells would be difficult. For the single-rotor UAV, the placement of the PV cells would also be difficult. The concept of a VTOL UAV is quite new, so the simulation would be difficult to make and the complexity of the design would make it more difficult to make it solar powered. Next to that, it would also be rather expensive.

UAV Types		Multi-rotor	Fixed-wing	Single-rotor	Fixed-wing hybrid	Importance
General specs	Range	short	long	short	long	10
	Speed	limited	variable	variable	variable	4
	Efficiency	low	high	medium	medium	10
	Flight time	20-30 min	couple of hours	higher than multi-rotor	higher than multi-rotor	10
	Payload capacity	small	medium	high	variable	8
Controllability	In air stability/ camera control	high	medium	high	high	8
	Runway	VTOL	yes	VTOL	VTOL	2
	Skill training	not needed	required	required	required	2
	Controllability	easy	medium	easy	easy	7
	Ability to stay at same height	oke	oke	oke	oke	8
Robustness	Maintenance	not often	not often	often	often	2
	Waterproof	per case	per case	per case	per case	2
	Shockproof	per case	per case	mostly not	per case	4
Adjustability	Possiblity changing casing	per case	per case	per case	per case	1
	Attachment solar cells	not easy (payload capacity)	easy	low	medium	10
	Impact of changes on efficiency	high	low	Low	low	6.5
	Efficiency optimalization	low	high	medium	high	10
	Rotor adjustability	high	Medium/High	high	medium	2
	PV potential/Area	High	Medium/High	None	Medium	8
Other	Risk of use	possibly	possibly	yes (strong big blades)	possibly	5
	Easily simulatable	medium	yes if drag constants are known	medium	no	8
	Costs	low	medium	high	high	7
	Datasheet	per case	Per case	per case	per case	5
	Remarks					
	Link					

2.6. UAV selection

In the last section, the decision was made to design a fixed-wing UAV. To optimize the performance of the drone all the components needed for the drone are chosen manually and described in chapter 3. To select a frame, the payload capacity has to be high enough to carry all the components and a decent camera for albedo mapping. Furthermore, it should be possible to attach PV cells on the frame. There are a lot of frames available, but in the end the frame of the Skywalker X8 was chosen as it was a frame that was commercially available, easily implemented for simulations and has a large wing area. Next to this, it was a relatively cheap UAV. Models of the frame have been found as well to analyse the aerodynamics of the frame needed for modeling of the entire UAV.

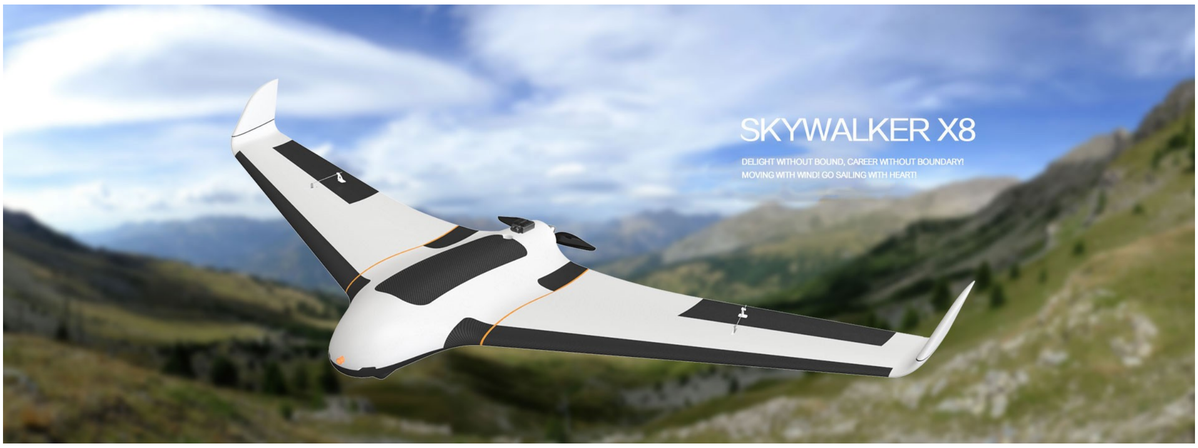


Figure 2.4: The Skywalker X8 [15]

The Skywalker X8 is a fixed wing, single rotor UAV. The specifications of the Skywalker X8 are as follows:

Model	Skywalker X8
Wingspan	2122 mm
Length	820 mm
Payload volume	9550 cm^3
Mean aerodynamic chord	357mm
Max wing curve	8.9 degrees
Typical cruising speed	65 km/hr
Maximum speed	85 km/hr
Body weight	880 g
Maximum take off weight	3200-4200 g

Table 2.3: Frame specifications

The specifications show a large payload volume and high payload capacity for all the components and equipment. Large wings to place the PV cells on, but with a wingspan of 2122mm and the possibility to detach the wings from the body, compact enough for transportation. Finally it is important that there are models available of the frame and aerodynamic specifications can be found or calculated to simulate the characteristics of the frame.

3

Component selection

In this chapter the different components that were chosen for the implementation of our system are discussed. To complete the skywalker X8, an Auto-pilot, propeller, motor, speed controller, battery and a camera needed to be selected.

3.1. Auto-pilot

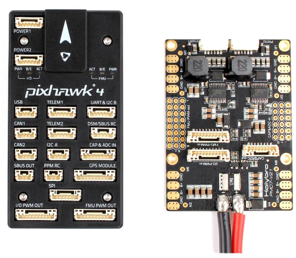


Figure 3.1: Chosen Auto-pilot [3]

The autopilot is a mini computer that controls the motor and servos during the flight using sensor and telecommunication hardware. The requirements for our autopilot are the following:

1. It is commercially available product.
2. Works with other selected components and is easy to implement.
3. Can fly stand-alone.
4. Easy to set way points/flight route to fly.
5. Functionality to implement safety instructions.

Because the the auto-pilot will not be simulated in Simulink and no physical implementation will be made. Little research was done for this component. The above mentioned requirements were taken into account but no comparison was made between all the available auto-pilots on the commercial market. For our application we have chosen the Holybro Pixhawk 4, because this device is affordable and meets our requirements. See the appendix A.2 for the further specifications.

3.2. Propeller

The propeller is able to convert the rotational energy into thrust force. Generally, the greater the propeller area, the higher the thrust force and propeller efficiency, as long as the motor is able to supply the required torque. Also, the propeller needs to fit on the UAV. The recommended maximum propeller size for the frame that was chosen, is 11" x 7", so for the propeller this size is taken. To have useful propeller data, a Graupner Nylon 11" x 7", which is covered in PropCalc [17], was used. The test data provided by this program is shown in figure 3.3, where efficiency is plotted against the speed.

Figure 3.2: Chosen Propeller [5]

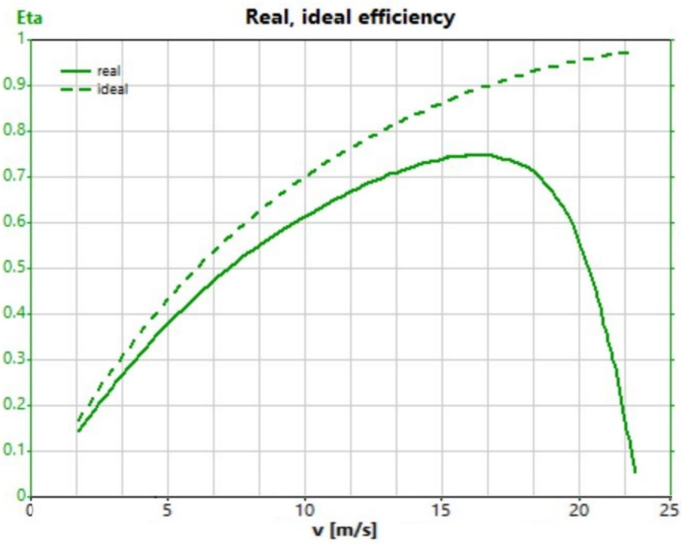


Figure 3.3: Propeller efficiency of the Graupner Nylon 11" x 7"[17]

3.3. Motor

For the motor, the goal is not to create the most efficient drone but to prolong the flight time as long as possible. The most important consideration that is taken into account is the KV. The KV, or RPM/V, depicts how much the RPM of the motor will increase per volt. The KV is linearly dependent on the torque, as is seen in Equation 3.1, where K_t is the torque constant. Furthermore, it is beneficial to have the motor operate at a higher voltage, as this results in a higher efficiency [13].

$$K_V = \frac{1}{K_t} \tag{3.1}$$

Figure 3.4: Chosen Motor [2]

Subsequently, higher torque is needed to drive a higher diameter propeller as a higher diameter propeller has more air resistance or, in other words, can propell more air around. This is why the lowest recommended KV motor was chosen, which is the Turnigy Aerodrive 4250 KV500. However, next to this, the motor should also be able to deliver a power of at least 200W, as this is the expected consummated power by keeping the UAV in the air. The chosen model's specifications are shown in table 3.1.

Specification	Unit
Motor model	Turnigy Aerodrive 4250 KV500
KV	500 RPM/V
Maximum power (5S)	1350W
Maximum current	57A
Burst current	70A
Weight	269g

Table 3.1: Motor specifications

3.4. Speed controller

A speed controller is responsible for the three-phase control of the motor. Therefore it must be able to handle the maximum rated current of the motor, which is 60 A. Other requirements regarding the selection of the speed controller is that it should be light weighted and commercially available.

Figure 3.5: Chosen Speed controller[11]

For the selection of the speed controller the following speed controllers were condisered; the Aerostar RVS 60A Electronic Speed Controller w/Reverse Function 5A BEC, YEP 60A (2 6S) SBEC Brushless Speed Controller, Turnigy Plush-32 60A Speed Controller w/BEC and the HobbyKing 60A ESC 4A SBEC. From these options, the Aerostar RVS speed controller was chosen for a number of reasons. First, this controller is able to handle a 60A motor rating that is able to handle the voltage of a five series battery cell configuration. It is also light weight in comparison with the Yep en Turnigy speed controllers, namely 20 gram. Furthermore, it has a build-in Battery Eliminator Circuit (BEC) and the efficiency is known.

The specifications of the chosen speed controller can be found in table 3.2

Specification	Unit
Motor model	Aerostar RVS 60A Electronic Speed Controller w/Reverse Function 5A BEC
Maximum current	60A
Weight	44g
Size	56 x 30 x 14mm
Efficiency	83-87% (Higher efficiency at lower voltages)

Table 3.2: ESC specifications

3.5. Battery

When choosing a battery, a trade-off regarding the battery size should be made. A bigger battery capacity will not always extend the flight range because the weight will also impact the payload and so the power consumption. Therefore, a light weighted but high capacity battery is preferred and a high energy to mass ratio is wanted. The battery also needs to be sufficient for the high current demands of the motor, it must be commercial available and the characteristics of the battery need to be specified for the simulations.

Figure 3.6: Chosen battery[14]

When taking these specifications into consideration, it can be found that li-ion batteries offer the highest energy density and have a storage efficiency close to 100%. The lithium nickel cobalt manganese-oxide (NCM) compound meets the requirements for high specific capacity (mAh/g) and this technology is commercial available.

Within the different commercial NCM li-ion cells, the following types are compared; the Sanyo NCR2070C, Molicel INR21700-P42A, the Samsung INR21700-40T, the Samsung INR21700-30T and the Molicel INR20700A. There was found a good energy/mass ratio of 0.224wh per gram for the Molicel INR21700-P42A. This cell is also able to deliver a high maximum output current of 45A.

After comparing different configurations of this battery cell, the configuration with 5 cells in series and 3 of these series configurations in parallel meets the required capacity, input voltage and the continues current.

Also the weight, volume and expected price fits in the range of the drone specifications. Therefore, this configuration is chosen. The specification of this battery pack can be found in table 3.3. For every series string, a safety component is added that prevents high charge and discharge currents flowing trough the battery. The specifications of this safety component can be found in the appendix.

Specification	unit
Battery model	Molicel INR21700-P42A
Voltage	18.5V
Capacity	12000 mAh
Max continues current	135 A
Weight	990 gr
Volume	115.8 cm3

Table 3.3: Battery Pack specs

3.6. Camera

To be able to create Albedo maps, a camera is needed that is able to create high quality images. Since there are flight-height restrictions imposed by the Dutch government that withholds UAV's to fly higher than certain heights, the camera should be able to create quality images around 120m. To be able to do this it should have a maximum ground spatial distance (GSD) of 20cm at a shutter time less or equal to 1/1000s. Another requirement is that the camera should be able to create RAW linear images to make sure the images are easily edited for Albedo map creating. The camera should have stabilisation in order to be less affected by the turbulence of the UAV and lastly, it should be lightweight and as cheap as possible. The options that were considered were the GoPro MAX, HERO8 Black, AKASO V50, Insta360 ONE X, HERO 7 Black and the Sony Alpha-6000 because these camera's are all compact while having considerably good specifications. However, based on above mentioned specifications the The Sony Alpha-6000 camera with SELP1650 lens is chosen.

Figure 3.7: Chosen Camera [4]

The specifications of the chosen camera can be found in table 3.4

Specification	unit
Camera model	Sony Alpha-6000 camera with SELP1650 lens
Weight	460 gr
Pixels	24.3 MP
Frames per second	11 (in burst mode)
Shutter time	1/4000 s
Maximum field of view	83 degree
Aperture	f/2.8
ISO	100-25600
focal point	15-60mm
focal length	35-75mm
Image output	RAW and JPEG

Table 3.4: Camera specifications

4
System overview

4.1. Introduction

This chapter describes the system overview. First an overview of the weight and cost of the UAV is given. Then the selected components and the selected drone are 3D modeled to show the fit of the described system. Then the inter-component wiring is described and the total system overview is explained.

4.2. Costs

To ensure that the UAV will fly as efficiently as possible, the system needs to be optimized for weight. Next to this, as a business plan has to be generated, the system also has to be optimized for cost. The total weight and cost of all the components and the UAV are described in table 4.1.

Table 4.1: Total weight and cost of UAV

Component	**Weight (grams)**	**Estimation (€)**	**Costs incl. tax (€)**
Body	880	140	239.9
Motor	269	40	38.37
ESC	60	30	30.74
Servo (2x)	40	15	14.22
Propellor	20	15	8.95
Auto pilot/controller	37	180	159.3
Gps for auto pilot	32		
Receiver FrSky R9	5.8	30	29.95
Camera	344	550	650
lens for camera	116		
Battery (18V, 12Ah = 216Wh)	1050	86	123
3x Battery protection	45		45
Wiring and mounting	100		
FrSky Taranis X9 Lite remote ctrl	nvt	120	109
PV panels	616.6	nvt	213.32
Total	**3615.4**	1206	1661.75

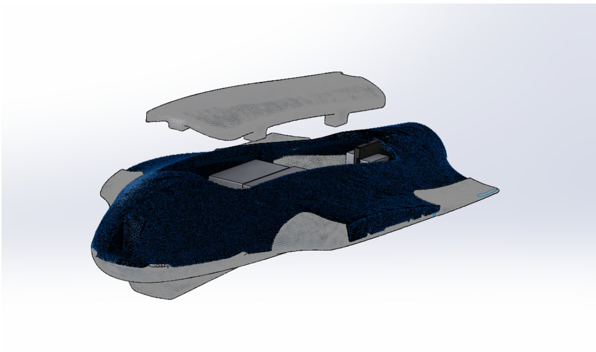
4.3. Component fit

After the selection of all the components and the drone, a model of the components can be fitted into the drone. Although the physical UAV will not be created, an estimate of the component fit and thus the weight distribution can be made. Table 4.2 shows the components referenced in chapter 3 and their respective dimensions.

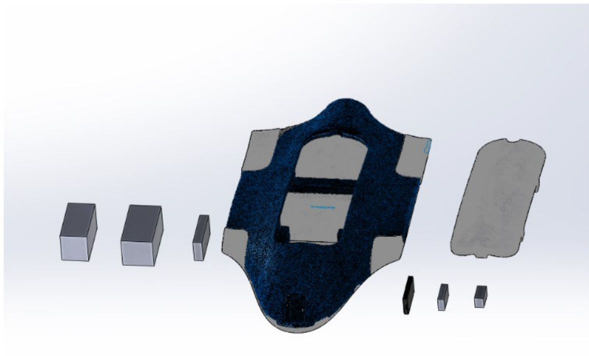
Table 4.2: Overview of the component dimensions

Component	**Length (cm)**	**Width (cm)**	**Height (cm)**	**Total volume** (cm^2)	**Total volume + 2cm marge** (cm^2)
Battery	13,2	6,6	7	609.84	1176.48
Camera	12.0	6.7	4.5	361.8	791.7
Motor	not relevant (own space)	not relevant(own space)	not relevant(own space)		
Speed controller	5.6	3.0cm	1.4	23.52	129.2
Propellor	not relevant (own space)	not relevant (own space)	not relevant (own space)		
**DC-DC controller(power management solar panels)	4.5	2.5	2.0	22.5	117
*micro controller - power management	10.16	5.33	2.0	108.3056	356.5312
flight controller(+ auto pilot)	5.5	3.8	1.55	32.395	154.425
**power system	10	5	2	100	336
GPS Module	5.0	5.0	2.5	62.5	220.5
TOTAL				1320.8606	3281.8362

Figure 4.1 shows the 3D fit of the components in the UAV in solid works. Here, the battery is placed more towards the front (the main box visible) to center the weight of the components around the center of mass of the UAV. Thus stabilizing the UAV.



(a) Top view of components in UAV



(b) From Left to right: Camera, Battery, Power system, Autopilot, Speed Controller, DC-DC

Figure 4.1: Top view and closed view of components in the uav

4.4. Inter-Component relationship

Figure 4.2 shows the general overview of the total system. The power supplies are displayed in blue. On the left, the battery cells are connected to the battery management system. This manages the internal cell voltage and ensures enough power is supplied to the secondary systems, such as the ESC and BEC, which is actually integrated inside the ESC but is displayed separately for the completeness of the model. Below, the PV system is interconnected with the power converter. The power converter, subsequently, is supplied with the necessary control data from the (MPPT) micro controller.

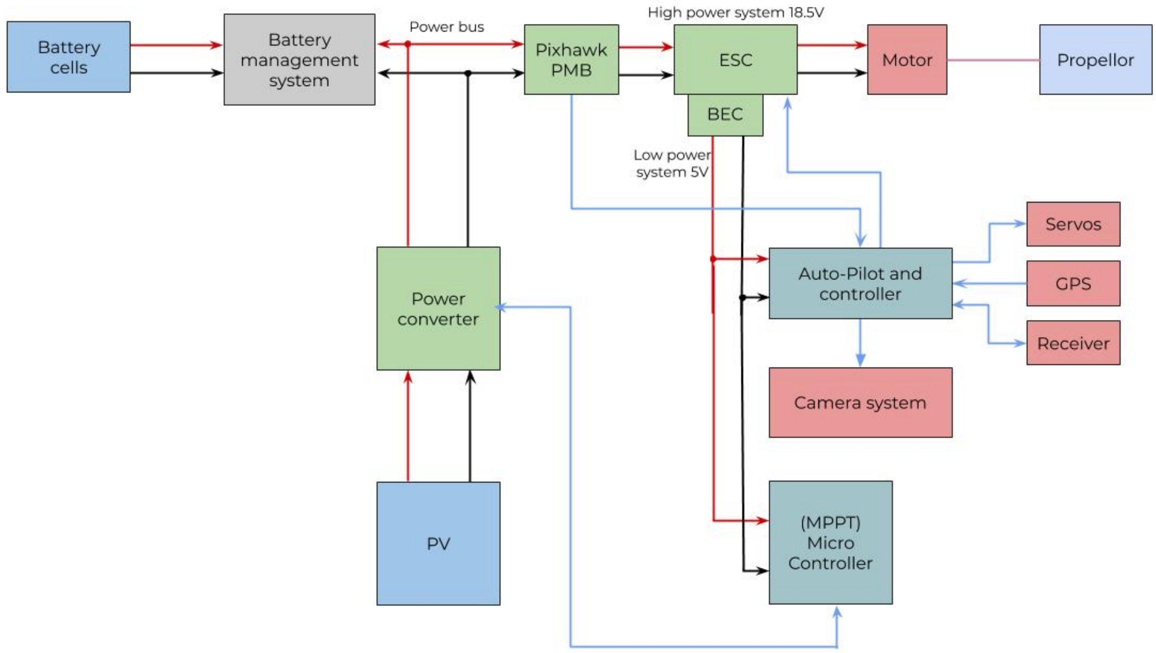


Figure 4.2: System overview diagram

5 Flight simulation

5.1. Introduction

This chapter describes the modelling of the drone. To accurately represent the drone the aerodynamic forces need to be modelled as they influence the power and energy needed for flight. First the general modelling of an air vehicle is explained, then the implementation of the Aerodynamic model in simulink is elaborated on. Next the integration of the electrical And Aerodynamic model is explained. At last, the effect of the aircraft mass and aircraft angle is investigated with the implementation of a mass sweep and an angle sweep.

5.2. Aerodynamic model

When looking at an aircraft, 4 main forces can be identified. The Lift, Drag, Thrust and gravitation force indicate the way the aircraft will fly. Figure 5.1 shows these four forces and their respective orientation with the UAV.

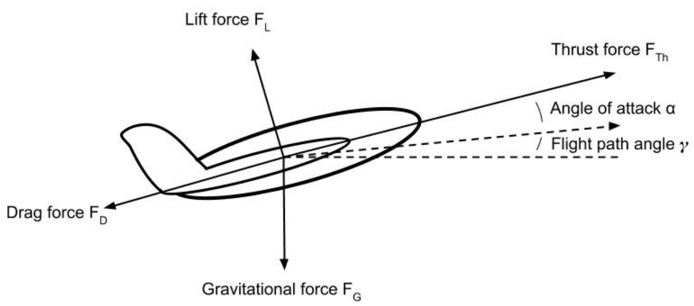


Figure 5.1: Forces on the plane

The Lift force is the result of the airflow above and over the wing lowering the air pressure on the top of the wing, which pulls the wing up-wards and will thus push the aircraft up-wards. It is generally seen as the force which counteracts gravity.

The drag force is the result of the air resistance which the UAV encounters whilst moving through the air. This can be viewed as the amount of force it takes to move the UAV through air. The counteract force to drag is the thrust force. The thrust force indicates the force the motor provides to move the aircraft forward.

Figure 5.1 also shows the angle of attack and the flight path angle. The flight path angle (γ) is the angle of the aircraft path with respect to the ground. The angle of attack (α) is the angle between the incoming air the aircraft experiences with respect to the angle of the aircraft.

The aerodynamic model of the airplane is based on the measurement results and aerodynamic simulations presented in [9] and the electric aircraft Model in Simscape [18].

Simulink implementation of the aerodynamics

The main goal of the aerodynamic model is to determine the power that the motor should provide. The architecture of the model is similar to the implementation of [18] however our model does take the angle of attack into account for determining the lift and drag coefficients as seen in Figure 5.2.

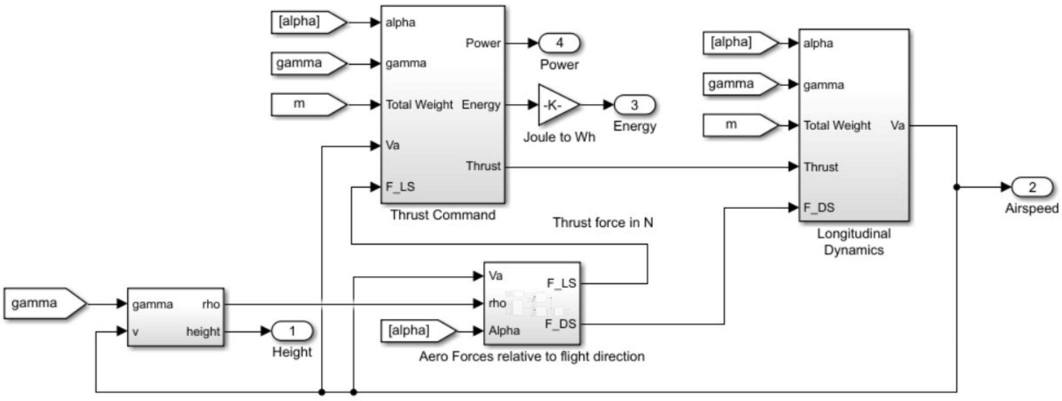


Figure 5.2: Aerodynamics overview

Aerodynamic forces

Table 5.1: Aerodynamic coefficients used as measured by [9]

C_{L_0}	0.0867
C_{L_α}	4.0203
C_{D_0}	0.0197
$C_{D_{\alpha 1}}$	0.0791
$C_{D_{\alpha 2}}$	1.0555

First, the lift and drag coefficients, C_L and C_D respectively, are derived from the angle of attack α according to Equation 5.1 and 5.2.

$$C_L = C_{L_0} + C_{L_\alpha}\alpha \tag{5.1}$$

$$C_D = C_{D_0} + C_{D_{\alpha 1}}\alpha + C_{D_{\alpha 2}}\alpha^2; \tag{5.2}$$

The lift and drag forces, F_L and F_D respectively, are then calculated using the airspeed V_a, air pressure ρ, wing area S_{wing} and the coefficients described above.

$$F_L = \frac{1}{2}\rho V_a^2 S_{wing} C_L \tag{5.3}$$

$$F_D = \frac{1}{2}\rho V_a^2 S_{wing} C_D \tag{5.4}$$

Forces reference system

Three reference frames are present in the simulation as seen in Figure 5.3. Firstly the inertial frame (green) is relative to the ground. This is used for the gravity that is always pointing down. The stability frame (blue) is in the orientation that the airplane is flying. This is the orientation that is relevant to calculate if the airplane accelerates/decelerates and if the lift and motor force counteract the gravity. The third reference frame is the body frame (black) pointing in the same direction as the airplane. This differs from the stability frame because of the angle of attack of the airplane.

The forces of lift, drag and the motor are in the body frame reference. These are therefore rotated by the angle α to go from the body frame to the stability frame.

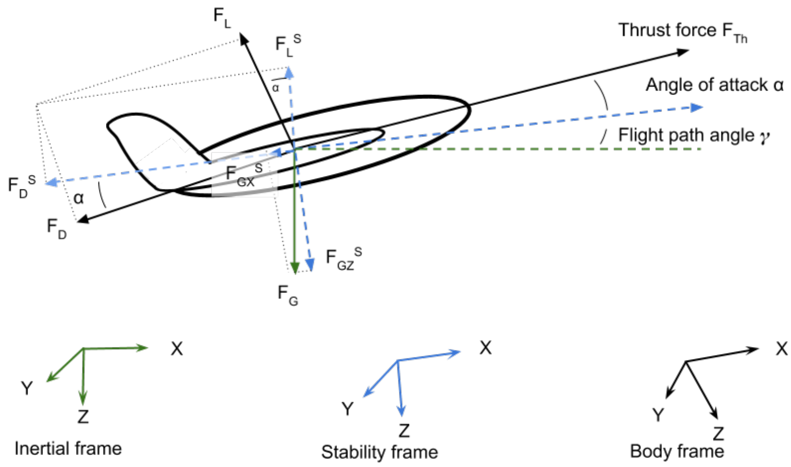


Figure 5.3: Reference systems of Aerodynamic forces

Thrust command and longitudal dynamics
The required thrust F_{th}, is calculated based on the difference between aerodynamic lift and opposing force of the weight. The propulsion power P, is determined by multiplying the thrust force by the airspeed.

$$F_{th} = \frac{1}{\sin(\alpha)}(F_G^S - F_L^S) \tag{5.5}$$

$$P = F_{th} V_a \tag{5.6}$$

Where F_G^S F_L^S are the gravitational force with respect to the stability frame visible in 5.3. From this thrust, the drag and gravitational forces in the stability reference frame, F_{Gx}^S and F_D^S respectively and the total airplane mass m, the acceleration $\dot{v}$ is determined. The airspeed is determined by integrating this acceleration.

$$\dot{v} = -F_{Gx}^S - \frac{F_D^S}{m} + \frac{F_{th_x}^S}{m} \tag{5.7}$$

By integrating the airspeed and taking the flightpath angle into account the height of the plane is tracked and the corresponding air density is determined.

If the airplane didn't had enough lift to counteract the gravity the motor thrust will become larger, this will increase the airplane velocity and this results in more lift generated. This feedback loop ensures that the aircraft will acquire a steady state, ascending or descending according to the flight path angle.

Mass and angle of attack sweep
Figure 5.4 was obtained by simulating the airplane model. On the vertical axis the Maximum flight range, the maximum flight duration the cruising speed and the cruising power draw is shown. In each simulation the airplane starts off thrown at a height of 2 meter and an airspeed of 2 m/s. The plane is instructed to climb to a height of 120m and than to maintain level flight until the battery is empty.

This simulation is performed for different airplane weights and different alpha values to obtain the maximum range for all weight configurations.

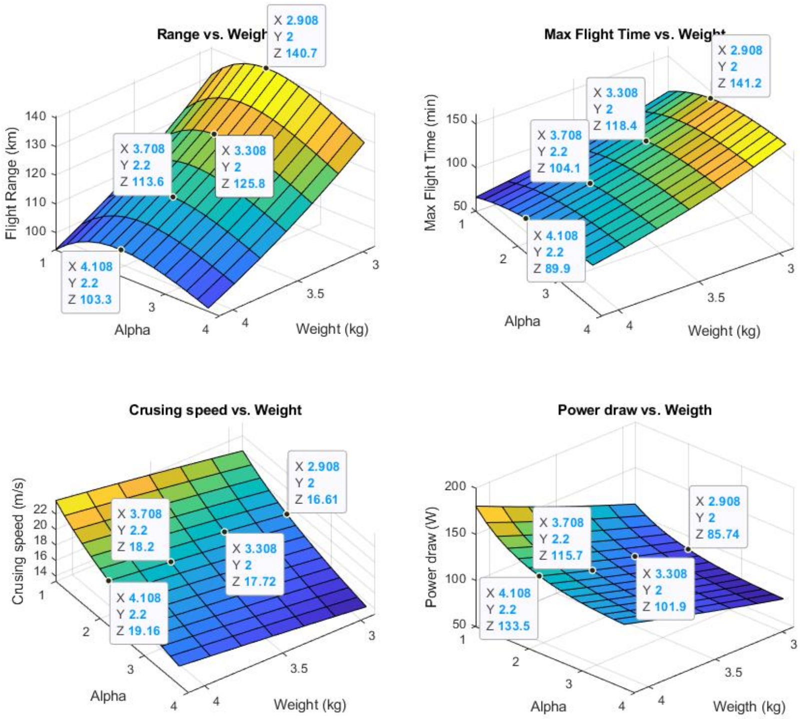


Figure 5.4: Simulation results under varying weight and angle of attack (alpha in degrees)

6

Final simulation

6.1. Introduction

This chapter elaborates on the final simulation done. In this simulation, all the sub-systems were integrated into one big simulation. Fist the simulink is explained after which the results are discussed.

6.2. Simulink Implementation

The overview of the final simulation can be viewed in 6.1. Here, on the left, the battery and the PV power are inputted which provide power to the system. The PV power can be turned on or off to simulate a cloudy day or a sunny day. The on the top right, the flight controller and the aerodynamic model can be found. These simulate the take-off, level flight and landing by adjusting the flight path angle in the aerodynamic model.

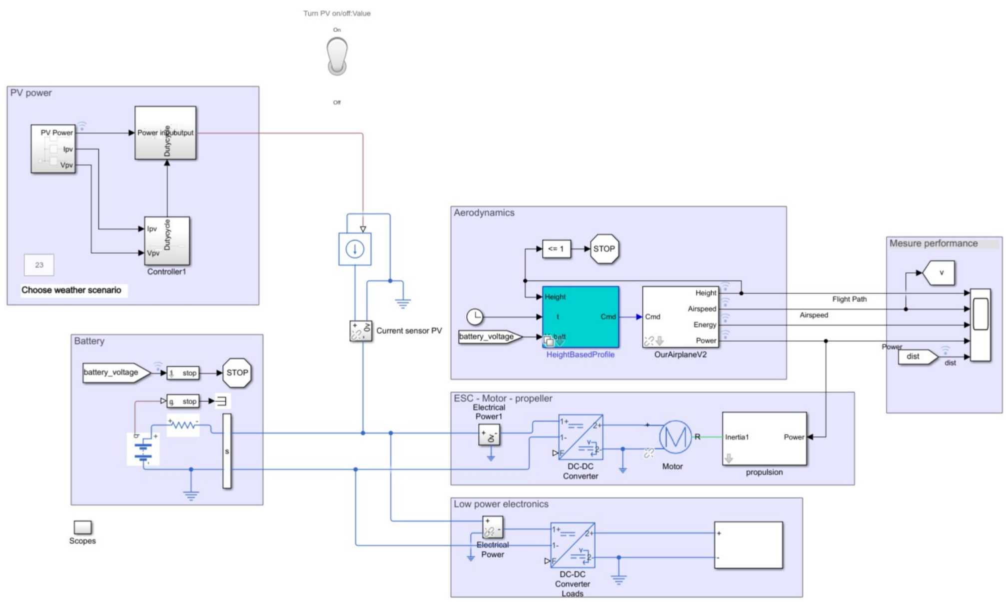


Figure 6.1: Final electrical simulation of the aircraft

The middle block shows the propeller and the motor. The aerodynamic model output the power needed to stay in the air. The propeller and motor then adjust accordingly to provide the necessary torque. Lastly, the bottom block, represents all the secondary systems which need power like the auto-pilot or the speed controller.

6.3. Results of final simulation

Figure 6.2 shows the additional flight range that the PV panels provide. On the left, the worst case scenario is displayed in which the solar irradiance is 129 W/m^2 and the temp equals 21.1 degrees Celsius. Here the flight range is decreased with 4% by the addition of PV as the PV panels add more weight and dus more power is needed than the PV panels deliver. On the Right, the best case scenario is displayed. In this case, the the solar irradiance is 782 W/m^2 and the temp equals 18.5 degrees Celsius. Here the flight range is increased by 83%.

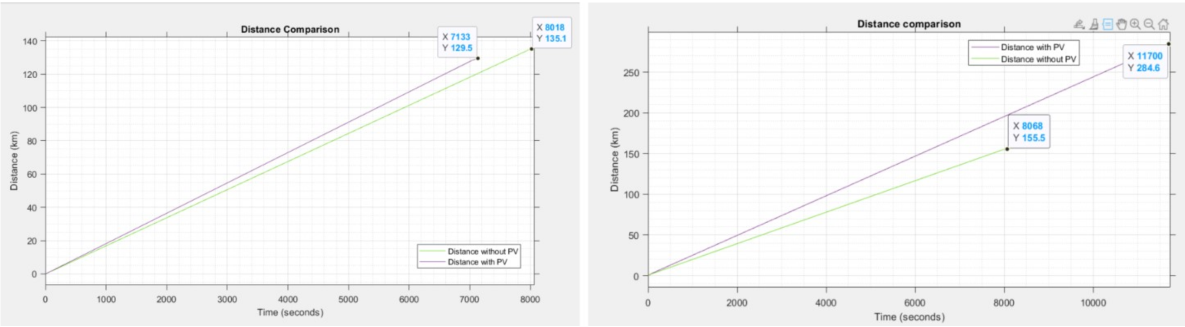


Figure 6.2: Addition to flight range from PV under different weather scenario's

Figure 6.3 shows the overall results of he total simulation, this figure can be found as a larger figure in appendix B.2. In the figure, the purple line represents the simulation in which PV panels are used. The green line represents the simulation without the PV panels. The right On he top left, the increased flight time becomes visible. We can see that the drone will fly for a long period of time before it lands. On the bottom left, it becomes visible that the discharging of the battery goes slower when PV panels are added.

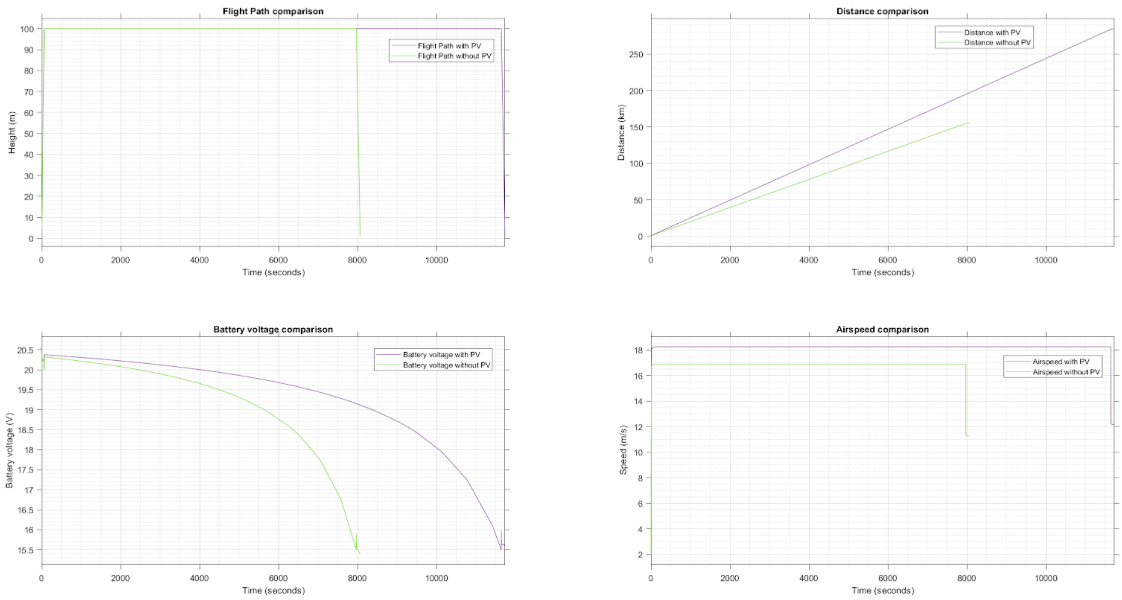


Figure 6.3: Comparison of flight path with and without PV

On the left, the difference in range becomes clear. In this particular situation, as mentioned in 6.2, the solar panels added 83% increase in range.

6.4. Flight path calculation

The flight path of the UAV is dependent on UAV and camera specifications based on the program of requirements, its path should be able generate high quality images while being time efficient. The image will have a good quality when the ground sampling distance (GSD) is lower than 20 cm [16]. The GSD can be calculated using formula 6.1.

$$GSD = \frac{p * H * 1000}{f * cosd(0.5 * FOV)} \tag{6.1}$$

Here p is the pixel size (micron), H is the flight height (m), f is the focal length (mm) and FOV is the field of view (degrees). The camera specifications can be found in section 3.6. The pixel size can be calculated using formula 6.2

$$p = \frac{s_w}{p_w} + \frac{\frac{s_h}{p_h}}{2} \tag{6.2}$$

Here s_w and s_h are the sensor width and sensor height respectively and p_w and p_h are the pixel width and pixel height respectively. Based on these calculations, the GSD is 17.93cm when flying at a height of 120m, which is sufficient. Now, another specification that is needed to guarantee the quality of the generated albedo map is image overlapping. There is a forward overlap of images needed of 65% and a sideward overlap of 40% [16]. The following formula's are used.

$$d_f max = \frac{v}{fps * 3600} \tag{6.3}$$

$$d_s need = \frac{\frac{(1-o_side)*H*s_w}{f}}{1000} \tag{6.4}$$

In formula 6.3 the forward distance between every picture d_{fmax} (m) is calculated based on the speed v of the UAV (m/s) and the frames per second fps (1/s), and is 1.6 meter. The needed side overlap d_{sneed} is calculated in formula 6.4 to be 48.5 meters. Lastly, in order to create a flight path, the turning radius of the UAV needs to be calculated. This is done via the following formula's.

$$R_f = \frac{(0.54 * v)^2}{11.26 * tand(30)} \tag{6.5}$$

$$R = \frac{\frac{R_f}{3.28}}{1000} \tag{6.6}$$

$$l_c = 0.5 * \pi * R \tag{6.7}$$

Here R_f is the possible radius in foot, which is dependent of the velocity v of the UAV. In formula 6.6, the radius is transformed from foot to kilometer. In formula 6.7 the minimum length of the turn is calculated. This is 363 meter. Based on previously mentioned outcomes, a flight path is chosen. This can be seen in figure 6.4.

The total flight range is calculated via formula 6.8. Here l_{fl} is the length of the flight lines, which is based on the length of the TU Delft and is 2.1km. l_{ctop} and l_{cdown} are the lengths of the turning circles for the top part of the figure and bottom part of the figure respectively, which are 686m and 609m . n_{rtop} and n_{rdown} are the number of turns for the top and bottom part respectively, which are 9 and 8. l_{to} and l_l are the take-off length and the length for landing respectively. They are both chosen to be 1 km to be on the safe side.

$$d_{tot} = (n_{fl} * l_{fl}) + (l_{ctop} * n_{rtop}) + (l_{cdown} * n_{rdown}) + l_t o + l_l \tag{6.8}$$

This gives a total flight path length of 48.75 km. The corresponding flight time, given that the speed of the UAV is 65km/h is 00:45 hours.

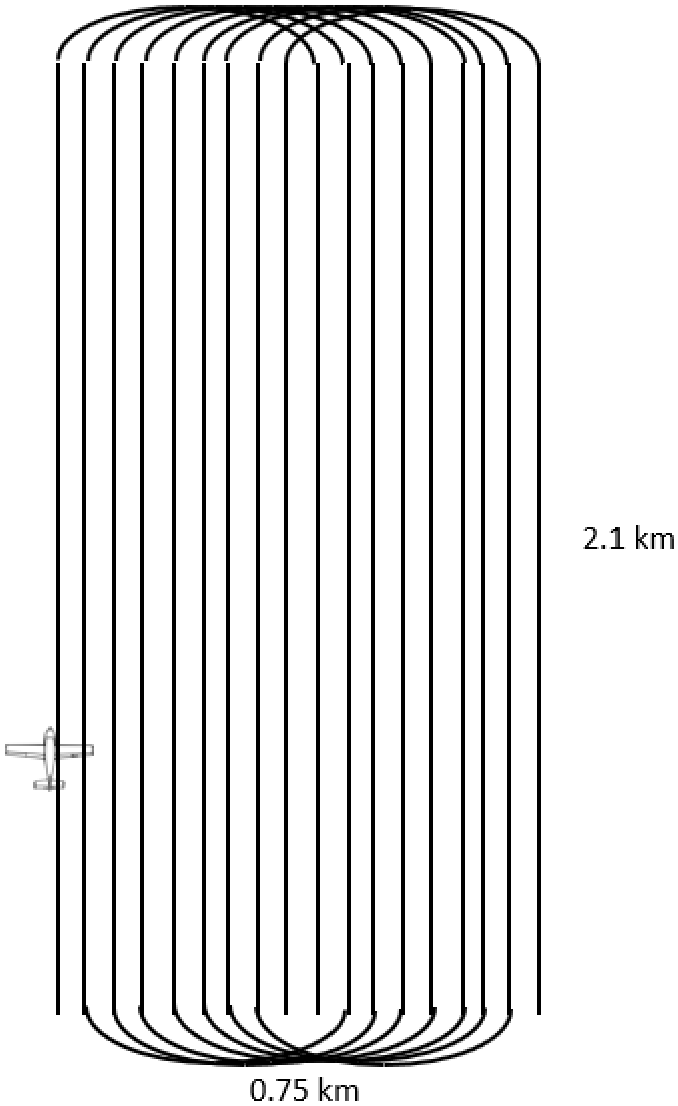


Figure 6.4: Flight path of the area of the TU Delft

6.5. Power consumption in flight

Figure 6.5 shows the power consumption by the system and the power generated from the battery and PV in the best case scenario. The Solar irradiation equals 887 W/m^2 and the temperature equals 21.2 degrees. From this graph, it becomes visible that the solar panels generate about 50W, the battery generates about 60W and the motor + secondary system consume about 110W. Figure 6.6 shows the power consumption by the system

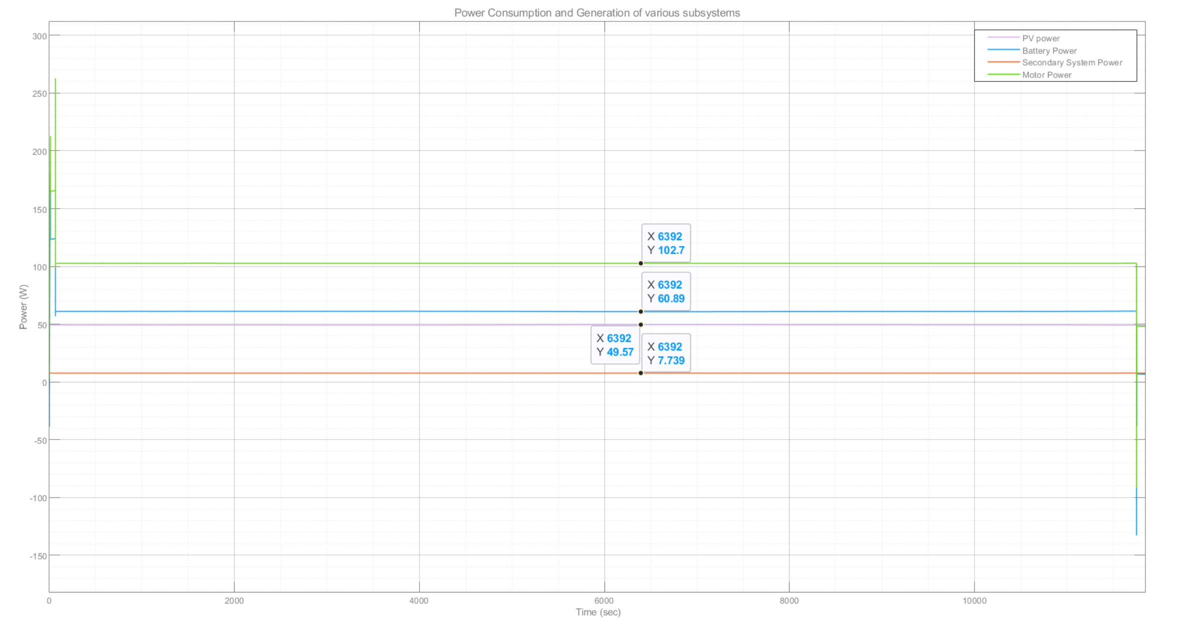


Figure 6.5: Power consumption of the system in the best case scenario

and the power generated from the battery and PV in the worst case scenario. The Solar irradiation equals 0 W/m^2 and the temperature equals 4.4 degrees. From this graph, it becomes visible that the solar panels generate 0W, the battery generates about 100W and the motor + secondary system consume about 110W.

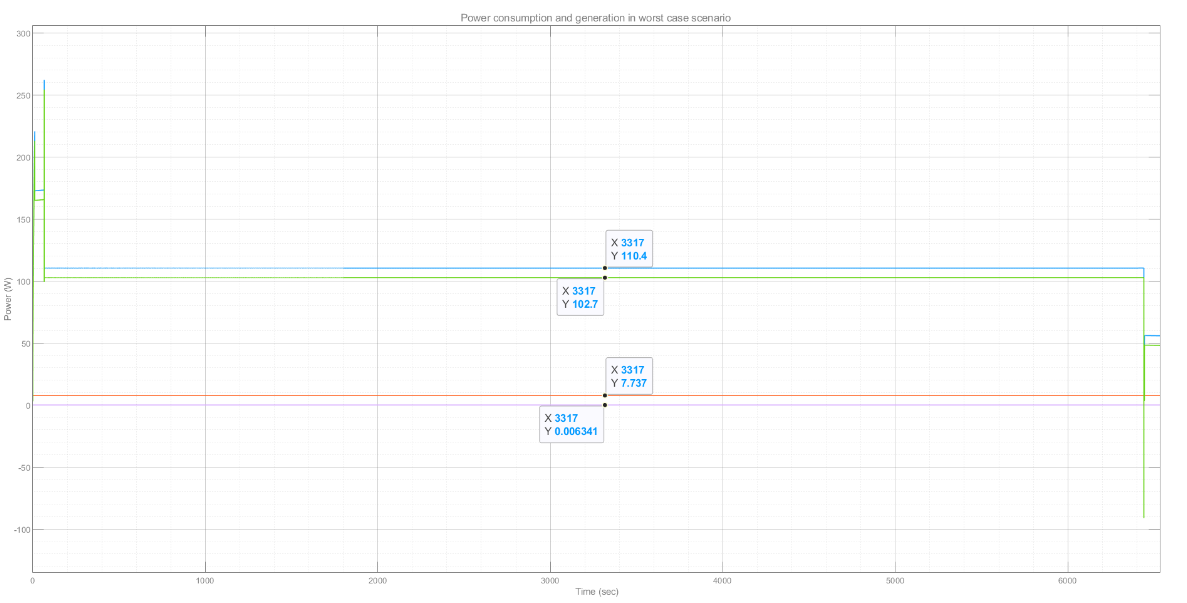


Figure 6.6: Power consumption of the system in the worst case scenario

Figure 6.6 shows the power consumption by the system and the power generated from the battery when no PV panels are added. From this graph, the battery generates about 82W and the motor + secondary system consume about 89W.

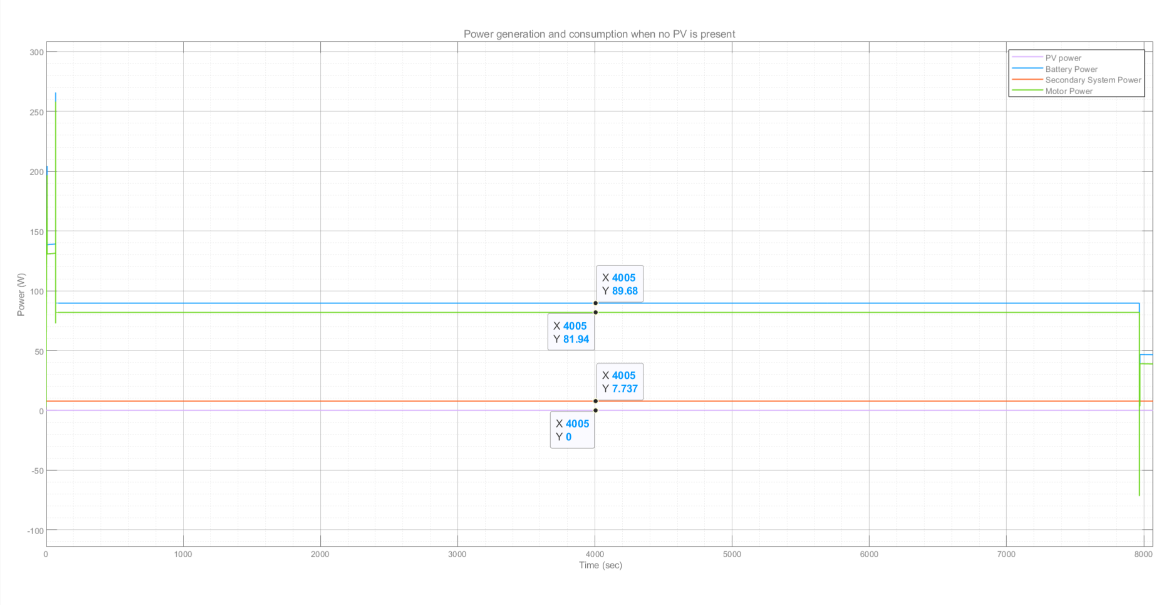


Figure 6.7: Power consumption of the system when no PV panels are added

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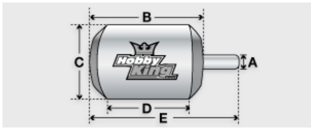
A

Components

Turnigy Aerodrive SK3 - 4250-500kv Brushless Outrunner Motor



SKU: SK3-4250-500

425 g

Config Table

K_v	500 RPM/V
Weight	269 g
Max Current	57 A
Max Voltage	19 V
Power	1350 W
Internal resistance	18 mohm
Shaft (A)	5 mm
Length (B)	58 mm
Diameter (C)	42 mm
Can Length (D)	34 mm
Total Length (E)	80 mm

Figure A.1: Motor - Turnigy Aerodrive SK3 - 4250-500kv specifications

The power of Pixhawk® 4 in a compact form

Product Features

- Half the footprint of the *Pixhawk® 4*
- The same FMU processor and memory resources as the *Pixhawk 4*
- Aluminum casing for great thermal performance
- Easy to connect to commercial ESCs
- The latest sensor technology from Bosch® and InvenSense®
- Redundant IMUs for reliable performance
- NuttX real-time operating system
- Pre-installed with the most recent PX4 firmware

The *Pixhawk® 4* Mini autopilot is designed for engineers and hobbyists who are looking to tap into the power of *Pixhawk 4* but are working with smaller drones. *Pixhawk 4 Mini* takes the FMU processor and memory resources from the *Pixhawk 4* while eliminating normally unused interfaces. This allows the *Pixhawk 4 Mini* to be small enough to fit in a 250mm racer drone. The *Pixhawk 4 Mini* is easy to install; the 2.54mm (0.1in) pitch connector makes it easier to connect the 8 PWM outputs to commercially available ESCs.

Pixhawk 4 Mini was designed and developed in collaboration with Holybro® and Auterion®. It is based on the Pixhawk FMUv5 design standard and is optimized to run PX4 flight control software.

Pixhawk® 4 Mini Technical Data Sheet (August 2018) Page 1 of 3

Figure A.2: Auto pilot - Pixhawk 4 mini specifications

TURNIGY Manual for Brushless Motor Speed Controller

Thank you for purchasing our Electronic Speed Controller (ESC). High power systems for RC model can be very dangerous; we strongly suggest you read this manual carefully. We have no control over the correct use, installation, application, or maintenance of our products, no liability shall be assumed nor accepted for any damages, losses or costs resulting from the use of the product. Any claims arising from the operating, failure or malfunctioning etc. will be denied. We assume no liability for personal injury, property damage or consequential loss resulting from our product or our workmanship. As far as is legally permitted, the obligation to compensation is limited to the invoice amount of the affected product.

Features:

- **Lithium battery Balance Discharge Monitoring and Protecting (BDMP) Design**, monitors in real time the discharge voltage of each lithium (Li-ion/Li-poly) cell in a battery pack. Don't worry about the over discharge problem again, your lithium battery pack will have a much longer life. **(Remark: This BDMP function is ONLY available for "SENTRY" series ESC)**
- Extreme low resistance, high current endurance.
- Full protection features: Low-voltage cutoff protection / Over-heat protection / Throttle signal lost protection
- 3 startup modes: Normal / Soft / Super-Soft, can be used for both fixed-wing aircraft or helicopter models
- Throttle range can be configured, fully compatible with all kinds of available transmitters.
- Smooth and accurate speed control, excellent throttle linearity.
- Microprocessor uses separate voltage regulator IC (except PULSAR-6A and PULSAR-10A), with high anti-jamming capability.
- Supports up to: 210000 RPM (2 poles), 70000 RPM (6 poles), 35000 RPM (12 poles) motors.
- The program card is a very small device which can be purchased additionally for easy programming the ESC in the field.
- With a program card, you can activate the music playing function of ESC, and there are 15 songs can be selected.

Specifications:

PLUSH Series

Class	Model	Cont. Current	Burst Current (>10s)	BEC Mode	BEC Output	Battery Cell Li-ion Li-poly	Battery Cell NiMH NiCd	User Programmable	Balance Discharge Protection	Weight	Size L*W*H
6A	PLUSH-6	6A	8A	Linear	5V/0.8	2	5-6	Available	N/A	6g	24*12*6
10A	PLUSH-10	10A	12A	Linear	5V/2A	2-4	5-12	Available	N/A	9g	27*17*6
12A	PLUSH-12	12A	15A	Linear	5V/1A	2-4	5-12	Available	N/A	12g	32*24*8
	PLUSH-12E	12A	15A	Linear	5V/2A	2-4	5-12	Available	N/A	13g	32*24*10
18A	PLUSH-18	18A	22A	Linear	5V/2A	2-4	5-12	Available	N/A	19g	45*24*11
25A	PLUSH-25	25A	35A	Linear	5V/2A	2-4	5-12	Available	N/A	22g	45*24*11
	PLUSH-25-OPTO	25A	35A	N/A	N/A	2-4	5-12	Available	N/A	21g	45*24*11
30A	PLUSH-30	30A	40A	Linear	5V/2A	2-4	5-12	Available	N/A	25g	45*24*11
40A	PLUSH-40	40A	55A	Switch	5V/3A	2-6	5-18	Available	N/A	35g	55*28*12
	PLUSH-40-OPTO	40A	55A	N/A	N/A	2-6	5-18	Available	N/A	32g	55*28*11
60A	PLUSH-60	60A	80A	Switch	5V/3A	2-6	5-18	Available	N/A	60g	70*31*14
	PLUSH-60-OPTO	60A	80A	N/A	N/A	2-6	5-18	Available	N/A	56g	70*31*13
80A	PLUSH-80	80A	100A	Switch	5V/3A	2-6	5-18	Available	N/A	62g	70*31*14
	PLUSH-80-OPTO	80A	100A	N/A	N/A	2-6	5-18	Available	N/A	58g	70*31*13

SENTRY Series

Class	Model	Cont. Current	Burst Current (>10s)	BEC Mode	BEC Output	Battery Cell Li-ion Li-poly	Battery Cell NiMH NiCd	User Programmable	Balance Discharge Protection	Weight	Size L*W*H
18A	SENTRY-18	18A	22A	Linear	5V/2A	2-4	5-12	Available	Available	24g	45*26*11
25A	SENTRY-25	25A	35A	Linear	5V/2A	2-4	5-12	Available	Available	27g	45*26*12
30A	SENTRY-30	30A	40A	Linear	5V/2A	2-4	5-12	Available	Available	29g	45*26*12
40A	SENTRY-40	40A	55A	Switch	5V/3A	2-6	5-18	Available	Available	40g	55*28*15
60A	SENTRY-60	60A	80A	Switch	5V/3A	2-6	5-18	Available	Available	65g	70*31*14
80A	SENTRY-80	80A	100A	Switch	5V/3A	2-6	5-18	Available	Available	67g	70*31*14

BASIC Series

Class	Model	Cont. Current	Burst Current (>10s)	BEC Mode	BEC Output	Battery Cell Li-ion Li-poly	Battery Cell NiMH NiCd	User Programmable	Balance Discharge Protection	Weight	Size L*W*H
18A	BASIC-18	18A	22A	Linear	5V/2A	2-4	5-12	Available	Available	24g	45*26*11
25A	BASIC-25	25A	35A	Linear	5V/2A	2-4	5-12	Available	Available	27g	45*26*12

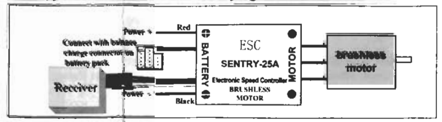
BEC Output Capability	Linear Mode BEC(5V/2A)				Switch Mode BEC(5V/3A)	
	2S Li-Poly	3S Li-Poly	4S Li-Poly	5S Li-Poly	2S — 4S Li-Poly	5S Li-Poly
Standard micro servos(Max.)	5	4	3	2	5	4

IMPORTANT! The ESC named "xxx-xxx-OPTO" hasn't a built-in BEC, so an UBEC (Ultimate-BEC) or an individual battery pack should be used to power the receiver. And an individual battery pack is needed to power the program card when setting the

TURNIGY Manual for Brushless Motor Speed Controller

programmable value of ESC, please read the user manual of program card for reference.

Wiring Diagram:

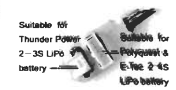


Lithium Battery Balance Discharge Monitoring and Protecting Adapter For "SENTRY" Series ESC:

We provide 2 kinds of Lithium Battery Balance Discharge Monitoring and Protecting Adapters for user to choose.

Adapter #1

Adapter #2



VERY IMPORTANT! You MUST connect the adapter with the balance charge connector on battery pack BEFORE connecting the main power to ESC. And if you use banana-shape connectors on main power wires (input wires), please connect the black wire (negative polarity) BEFORE red wire (positive polarity). So the right sequence is:

Balance discharge adapter → BLACK wire of main power → RED wire of main power

Feature Explanation:

1. **Brake Settings:** Brake Enabled / Brake Disabled, default is Brake Disabled
2. **Battery Type:** Li-xx(Li-ion or Li-poly) / Ni-xx(NiMh or Nicd), default is Li-xx.
3. **Low Voltage Protection Mode(Cutoff Mode):** Reduce / Cutoff Output Power, default is Reduce the output power gradually.
4. **Low Voltage Protection Threshold(Cutoff Threshold):** Low / Medium / High, default is Medium.
   - **When NOT using balance discharge monitoring and protecting function** (i.e. **Do Not** plug the balance charge connector into the balance discharge protecting socket on ESC, in this case , the ESC only monitors the voltage of whole battery pack)
     1) For Li-xx battery, number of battery cells are calculated automatically, low / medium / high cutoff voltage for each cell are: 2.6V/2.85V/3.1V. For example: 3 cells Li-Poly, when medium cutoff voltage is set, the cutoff voltage is: 2.85*3=8.55V.
     2) For Ni-xx battery, low / medium / high cutoff voltages are 0%/45%/60% of the startup voltage (i.e. the initial voltage of battery pack), and 0% means low voltage cutoff function is disabled. For example: 10 cells NiMH battery, fully charged voltage is 1.44*10=14.4V, when "medium" cutoff voltage is set, the cutoff voltage is : 14.4*45%=6.5V.
   - **When using balance discharge monitoring and protecting function** (i.e. Plug the balance charge connector on battery pack into the balance discharge protecting socket on ESC, in this case, the ESC monitors not only the voltage of whole battery pack but also the voltage of each cell). For Li-xx battery, low / medium / high cut off voltage for each cell are: 2.6V/2.85V/3.1V. When the voltage of any cell in battery pack is lower than the cutoff threshold, the protecting program is activated.
5. **Startup Mode:** Normal /Soft /Super-soft, default is Normal startup.
   Normal is good for fixed-wing aircraft. Soft and Super-soft are good for helicopters. The initial speed of soft / super-soft mode is very slow, 1 second (soft startup) / 2 seconds (super-soft startup) from startup to full speed. But if throttle is closed (throttle stick is moved to bottom) and opened again (throttle stick is moved upwards) within 3 seconds after the first startup, the restart will be temporarily changed to normal mode to get rid of the chances of crash caused by slow throttle response in aerobatic fly.
6. **Timing:** Low / Medium / High, default is Low.
   In normal cases, low timing can be used for most motors. But for high efficiency, we recommend the **Low** timing for 2 poles motor and **Medium timing for 6 poles and above.** For higher speed, **High** timing can be chosen.
   Important! After you changing the timing setting, please test your RC model on ground firstly!

Special Hint

Some high KV out-runner motors have very special configuration, the space between each alnico is very large, and lots of ESCs can't drive these motors. After updating the program, our ESCs have very good compatibility with them. But some RC fans still have several questions about the programmable value for some special motors. So we just give some suggestions as follows:

Motor \ Programmable Value Suggestion	Timing	Startup Mode
General in-runner motor	Low	Usually, aircraft uses "normal" startup mode helicopter uses "super-soft" startup mode
General out-runner motor	Low or Medium	
Align 420LF (Made in TAIWAN, out-runner)	High (MUST)	
450TH (Made in TAIWAN, out-runner)	Low	Soft (MUST)

Begin To Use Your New ESC

Please start up the ESC in the following sequence:

1. Move the throttle stick to bottom position and then switch on the transmitter.
2. Connect battery pack to ESC, the ESC begins the self-test process, a special tone " ♪123" is emitted, which means the voltage of battery pack is in normal range, and then N "beep" tones will be emitted, means the quantity of lithium battery cells. Finally a long "beep-----" tone will be emitted, which means self-test is OK, the aircraft/helicopter is ready to go flying.
   - If nothing is happened, please check the battery pack and all the connections;

Figure A.3: Speed controller - Turnigy Plush 60

MOLICEL®

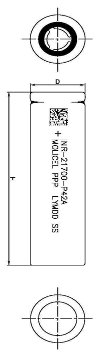
LITHIUM-ION RECHARGEABLE BATTERY

PRODUCT DATA SHEET
MODEL **INR-21700-P42A**

■ **CELL CHARACTERISTICS**

Capacity	Typical	4200 mAh 15.5 Wh
	Minimum	4000 mAh 14.7 Wh
Cell Voltage	Nominal	3.6 V
	Charge	4.2 V
	Discharge	2.5 V
Charge Current	Standard	4.2 A
Charge Time	Standard	1.5 hr
Discharge Current	Continuous	45 A
Typical Impedance	AC (1 KHz)	10 mΩ
	DC (10A/1s)	16 mΩ
Temperature	Charge	0°C to 60°C
	Discharge	-40°C to 60°C
Energy Density	Volumetric	615 Wh/l
	Gravimetric	230 Wh/kg

■ **PHYSICAL CHARACTERISTICS**

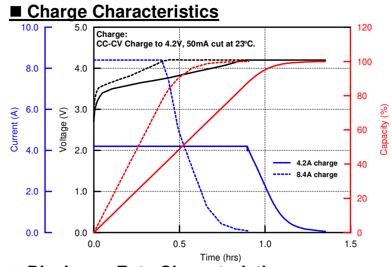


Shape	Cylindrical
Can	Steel
Diameter	21.7 mm (Max)
Height	70.2 mm (Max)
Weight	70 g (Max)

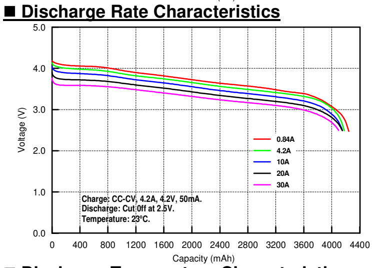
The information contained herein is for reference only and does not imply a performance guarantee or a product warranty. Specifications and characteristics are subject to change without prior notice.

For application specific information, please contact E-One Moli Energy Sales and Applications or the nearest MOLICEL® recognized agent.

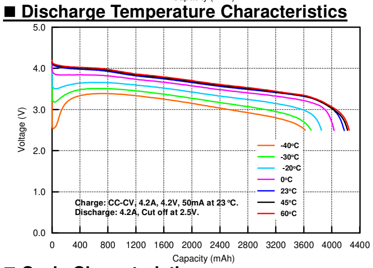
■ **Charge Characteristics**



■ **Discharge Rate Characteristics**



■ **Discharge Temperature Characteristics**



■ **Cycle Characteristics**

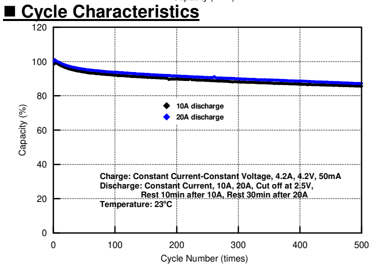


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Figure A.4: Battery cel - Molicel P42A specifications

BMS Specifications For 5S /18.5V Li-ion Battery Pack			
Model: LIM-5S1045LI606			
No.	**Test item**		**Criterion**
1	Voltage	Charging voltage	DC:21V CC/CV
		Balance voltage for single cell	4.180V ± 50 mV
2	Current	Balance current for single cell	80mA±10mA
		Current consumption for single cell	≤6μA
		Maximal continuous Charging current	10A
		Maximal continuous Discharging current	45A
3	Over charge Protection	Over charge detection voltage	4.25V≤±0.025V
		Over charge delay time	1S
		Over charge recovery voltage	4.15V≤±0.025V
4	Over discharge protection	Over discharge detection voltage	2.8V≤±0.1V
		Over discharge delay time	128ms
		Over discharge release voltage	3.0V≤±0.1V
5	Over current protection	Over current testing voltage	150mv ≤± 15mv
		Over current detection current	90A± 10A
		Over current delay time	12MS
		Release condition	Automatic Recovery
6	Short protection	Detection condition	Exterior short circuit
		Detection delay time	≤300us
		Release condition	Automatic Recovery
7	Resistance	Protection circuitry (MOSFET)	≤20mΩ
8	Temperature	Operating Temperature Range	-40~+65°C
		Storage Temperature Range	-40~+ 125°C
9	Size		L60*W60*T9mm
10	Weight		30g

Figure A.5: Specifications battery protection component

B
Results

Figure B.1: Power distribution during flight

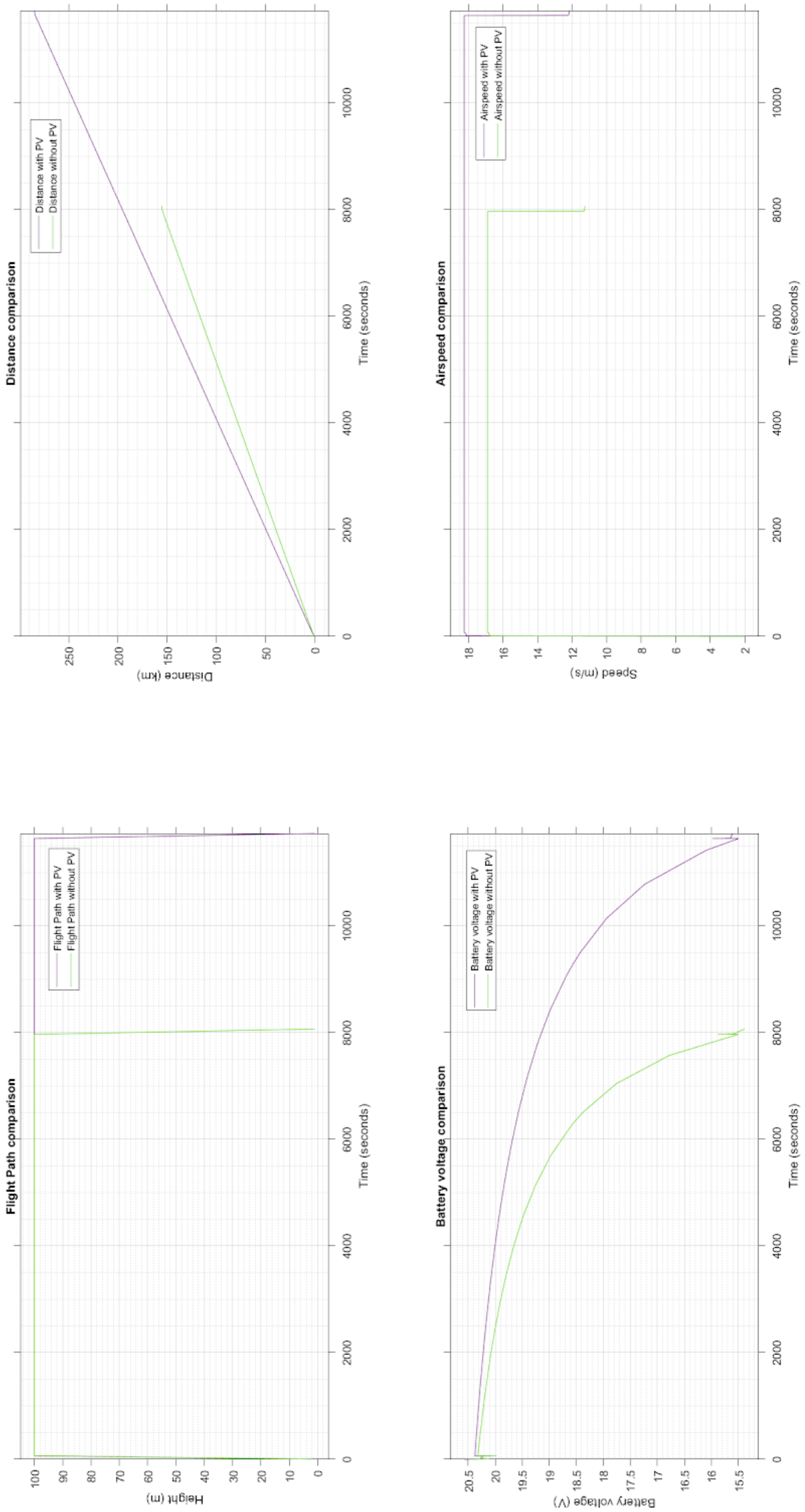

Figure B.2: Comparison between using PV panels and not using PV panels at a Solar irradiance of 782 W/m^2 and a Temp: 18.5 deg