Escuela Técnica Superior de Ingeniería del Diseño

Control of an electric Propulsion System for a Light Aircraft

Final Year Project

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Escola Tècnica Superior d'Enginyeria del Disseny
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Final year Project for the BACHELOR DEGREE IN AEROSPACE ENGINEERING

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Summary

In the future, aviation will most certainly tend to be electric, reason why there exists an increasing interest in developing electrically propelled aircrafts. An option is to replace traditional fuel engines with electrical motors where it is available, namely in light aircrafts. To be able to do so, a design process needs to be followed, which contemplates adapting an electric motor to suit its new task by designing and testing its control system, specially designed for its implementation on the aircraft. Likewise, said modifications will also involve the installation of batteries and, lastly, flight testing to prove the performance of the aircraft has not been negatively affected, except for the fact the autonomy is reduced substantially in spite of the differences in energy provision by batteries and by traditional aviation fuels.

Keywords: electric aircraft, control, light aircraft, propulsion

Agraïments

Estic agraïda al tutor d'aquest treball, Ramón Blasco, per tota l'ajuda rebuda, i als meus pares, sense els quals no haguera pogut fer mai el present projecte.

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REPORT

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Chapter 1

State of the art

The annual increase of 9% in passenger traffic since the 1960's [1], linked to spread of public concern about environmental issues has created the necessity for the aerospace industry to find solutions to the problem of fossil fuel burning. While attempts to reduce these emissions have been made by changing the fuel composition [2], there is an increasing interest in developing electrical propulsion systems.

In the current times, it is possible to find in the market a number of choices to buy an aircraft with electric motor as its form of propulsion. Nevertheless, it is usual to discover these aircrafts part from a piston engine version to which slight changes have been made to implement the electrical motor and its batteries; this means private companies have proven it possible to perform these substitutions. This project intends to prove this same thing, whilst working in a simulation environment with a theoretical aircraft.

Analysis of the technologies used in electrical propulsion (batteries and motor) is performed in subsequent chapters. This project addresses the current state of development of these technologies as well as its theoretical background to ultimately demonstrate the plausibility of completing these modifications to light aircrafts in a inexpensive, easy manner.

The fact that the future is coming near fast and it will be greener served as a motivation to develop this project.

Chapter 2

Objectives of this project

This document has a total of three parts to it, each clearly separated from each other and with a grade of independence although of course connected at topic level. The connexion between all the parts is stated in the next paragraphs, as they all obey the same objective and have ultimately the same purpose.

2.1 Objectives

The present document's main objective is to design the propulsion system and its control of an electric powered vehicle and implementing it to a light aircraft model to analyse its performance and capabilities. In order to be able to do so, an extensive research of the current state of development of the technologies used in these type of vehicles was carried out, paying special attention to the improvements made in the last few years given the relative novelty of this electric propulsion technology.

The topic is a conjunction of a tool of ever-growing importance in the industry (simulation) and an emerging technology with a bright future ahead (electric propulsion). The latter gains importance in the current political and historical situation, where air pollution and its associated global-scale problems are being addressed by environmentalist organizations and the scientific community alike, increasing the pressures on the industry to find a solution. A plausible way of solving the matter has been designing electrical propulsion aircrafts, which, due to the relatively recent technology being handled, present certain differences with respect to their fossil-fuel powered counterparts. The aim of this document is to analyse the possibility of implementing an electric propulsion system to a light aircraft and discussing the matters that should be further modified, if any, for its performance to match as closely as possible the unmodified model. In order to achieve this, a simulation program by *MathWorks* will be used, the infamous *Simulink*. This program provides a model of a light aircraft, named the *SkyHogg*, which will serve as a base for this project.

The project covers the points of implementing a custom designed propeller, a suitable electric motor, appropriate batteries and control to all of it. The fact that the project is carried out as a simulation allows for further elaboration. The aircraft in which the project is based upon can be modified with appropriate DATCOM files to extend the concept to other light aircrafts, although this would involve the redesign and tuning of controllers in the simulation and further studies about aerodynamics, which are outside of the scope of this project.

2.2 Procedure

The procedure followed to develop this project started by investigating the possibilities in the commercial program *Matlab* to do an aircraft simulation. Upon finding the complete model of an aircraft had already been developed in *Simulink* by *Mathworks*, the whole project revolved around it.

Once this has been made clear, here is how the project was structured and the order in which it was completed:

1. In order to be able to carry out the completion of this project, it was necessary to start off with an exhaustive bibliographic and literature revision to find the technological limitations of different components up to the date of starting the project.

2. Nearly simultaneously, the *Simulink* model and all the documentation about it was studied to assure a complete understanding of the it for further modifications. It was found little data exists about the actual aircraft, but the model workspace incorporates a great number of variables from which information can be extracted.

3. Next, because information from the propeller in the model was not available and it was a fundamental part from which to extract data that had to be used in the simulation of the propulsion plant, it was designed from scratch using an on-line tool named *JavaProp*. The design was based upon propellers found in light aircrafts available at the moment in the market.

4. Afterwards, the connections and relations of the propeller with the rest of the propulsion components were implemented in *Simulink* to test out its performance. It was an iterative process and the propeller had to be redesigned a few times until a definitive model was

produced. Its performance parameters were studied and graphed for reference and visual easiness.

5. Once this was all set out, the electric motor control was designed. It started off as a DC motor control which evolved to be AC. A *Simulink* block with the actual motor functioning was provided already made. The batteries were simultaneously designed, and further on implemented in the simulation.

6. Finally, an analysis of the performance was carried out to prove the viability of the modifications. Different missions were taken into account and tested, while monitoring various parameters for the sake of analysis. This allowed to examine the correct working of all the designed components as well as extracting conclusions about the feasibility of performing the modification on an actual aircraft of identical characteristics.

CHAPTER 3

PROPULSION IN LIGHT AIRCRAFTS

What nowadays falls into the definition of light aircraft is what first allowed humanity to soar the skies in 1903 for the very first time and has allowed us to do so since then. Of course, more than a century later many things regarding aviation have changed, but the focus of this chapter will be on the propulsion aspect, which has probably undergone the most noticeable changes since that first flight ever.

3.1 Introduction to propulsion

Propelling is the act of pushing or driving an object forward and any machine that produces thrust, enabling said object to move forward, is a propulsion system. In aviation, Newton's third law (action and reaction) is taken advantage from to generate thrust. This is done by accelerating a gas in the engine, producing a force. [3]
In origin, all propulsion systems take the energy from burning fuel. The principal traditional airborne propulsion systems would be: gas turbines, propellers, rocket engines, and ramjets.

Gas turbines are by far the type of propulsion system for aircrafts best known by the lay person. The core of gas turbines is the gas generator, which has the aim to achieve a gas which has high temperature and pressure. The gas generator is basically formed by the compressor, combustor and turbine. Air enters through the inlet and is compressed at the compressor before reaching the combustor, where it is mixed with fuel and burnt, creating hot exhaust gasses. These gasses enter the turbine, which is coupled to the compressor though a shaft, and power said shaft to turn the compressor. The exhaust gasses exit the turbine to enter the nozzle, where they are expanded in order to achieve the highest possible speed at the outlet of the engine.

Propellers fall in the category known as 'screw propulsion' [4], this is: a propeller driven by a shaft. Different engines serve as different solutions to turn the shaft which results in the propeller rotating. Two common systems are piston engines and jet engines; the latter system may be a turboprop or a turboshaft. Piston engines work taking in the surrounding air, mixing it with fuel and burning it, using the heated gas to move a number of pistons attached to a shaft. Finally, the shaft causes the propeller to move and ultimately propel the aircraft. Similarly, turboshafts employ the engine based on a gas generator to power the rotation of the shaft. Alternatively, in turboprops the gas generator is used to directly drive the propeller [5].
The fundamentals of propellers are based on momentum theory. The propeller acts as a wing, thus creating lift. The vast majority of thrust is created by the propeller and the exhaust gasses from the engine provide few thrust [6].

Rocket engines, contrary to the other mentioned propulsion technologies, are non-air-breathing systems and carry both fuel and oxidizer in the vehicle, allowing the engines to work in space as well as in the atmosphere. The working principle is both the fuel and oxidizer, known as propellants, are introduced into the combustion chamber where they are ignited by some system. The resulting gasses are then accelerated in the nozzle and expelled, driving the vehicle forward [5].

The **ramjet** develops thrust through a process similar to the jet engine, but it does not involve a compressor. The process is as follows: air enters the inlet, is compressed and it goes into the combustion zone, where fuel is injected, mixed with the air and finally burned. The gases produced in this combustion are then expelled through the nozzle.
Compression is achieved by the inlet decelerating incoming air, which results in a raise in pressure in the combustion zone. This pressure raise is higher with greater velocity of the incoming air, which makes the ramjet suitable for supersonic flights but not so at subsonic velocities, where air at a higher velocity must enter the inlet in order to start the ramjet. However, the combustion in the ramjet does occur at subsonic velocities [5].

These technologies precede all more recently developed propulsive systems. Advances and changes have been made, specially regarding fuel-related improvements. The aforementioned systems, except for the rocket engine, are all air-breathing and work differently at different altitudes. This determines the actuation of pilots when flying them, to optimize the engine's thrust and the fuel consumption.

In the late years, due to the renascence of interest for non-fuel-burning alternatives in propulsion, propellers are once again gaining importance and popularity, given the reach of this electrical propulsion technology still has not gone as far as having developed machines comparable to any of the other mentioned propulsion system and been proven to work all right.

3.2 Approaches for light aircrafts

Light aircrafts are those with a maximum gross take-off weight of no more than 12,500 lb or 5,670 kg [7]. This kind of aircrafts are pushed forward by propellers rotated by some kind of engine or motor.

Traditionally, this type of aircrafts used to be powered by reciprocating internal combustion engines, otherwise known as RICE, but recent developments in propulsion technology have interested companies in incorporating electric propulsion motors to aviation.

Propellers need systems which will be able to turn the shaft at high rates and give the blades rotatory movement. Due to aerodynamic limitations, such as the appearance of transonic effects at the tip of the blade, aircrafts using propellers must not go faster than Mach 0.6, which is a speed lower than typical airliners'. This speed limitation allowed for light aircrafts to continue to be powered by internal combustion engines even after jet propulsion was invented. In the last decades, an increase in interest to reduce air pollution has pushed forward the investigation of electric motors, and the fact light aircrafts did not need as much power as other air transports made them ideal to try out new powering technologies.

3.2.1 Traditional - Combustion engines and turboprops

The first-ever powered flight, achieved by the Wright brothers in 1903, used a propeller driven by a 9kW, four-cylinder engine [8]. This accomplishment marked the very start of aviation and employed reciprocating internal combustion engine, and so did every aircraft designed until jet engine was invented in the early decades of the twentieth century. RICE technology underwent multiple changes since the patent of the first reciprocating internal combustion engine was completed 1876 by Nicolaus Otto [9].

Internal combustion engines are divided into two main categories: spark-ignition (SI) and compression-ignition (CI). These categories describe whether the ignition of the mixture of fuel and air in the chamber is started by an external rise in temperature, typically a spark, or by itself, in a spontaneous manner due to the high temperature [10]. These differences are achieved by using different fuels: petrol for SI and diesel for CI. The internal working process of a RICE engine describes a cycle which depends on the type of engine: Otto cycle for SI and Diesel cycle for CI.

RICEs work by intaking air into the combustion chamber, compressing it, adding fuel to create a mixture and having this mixture ignited (by either method). The expansion of the gasses applies force to the piston, thus converting chemical energy into usable, mechanical energy.

The preferred designs of RICEs for their application to aviation have changed over time and the fact that the World Wars were fought in the air, specially WWII, rocketed their development and lead to improvement, such as the reduction of mass or settling for a certain number of cylinders (figures 3.1 and 3.2 respectively).

In figure 3.3 it can be seen how the RICE technology is in fact a consolidated, mature technology and has experienced hardly any evolution over the decades concerning specific power as a function of weight, which happens to be a parameter of utmost importance in engines.

Although this information is not reflected in the figures below because they contain information only up to the seventies, the tendency as of the last two decades is developing piston engines which are horizontally opposed, otherwise known as flat engines.

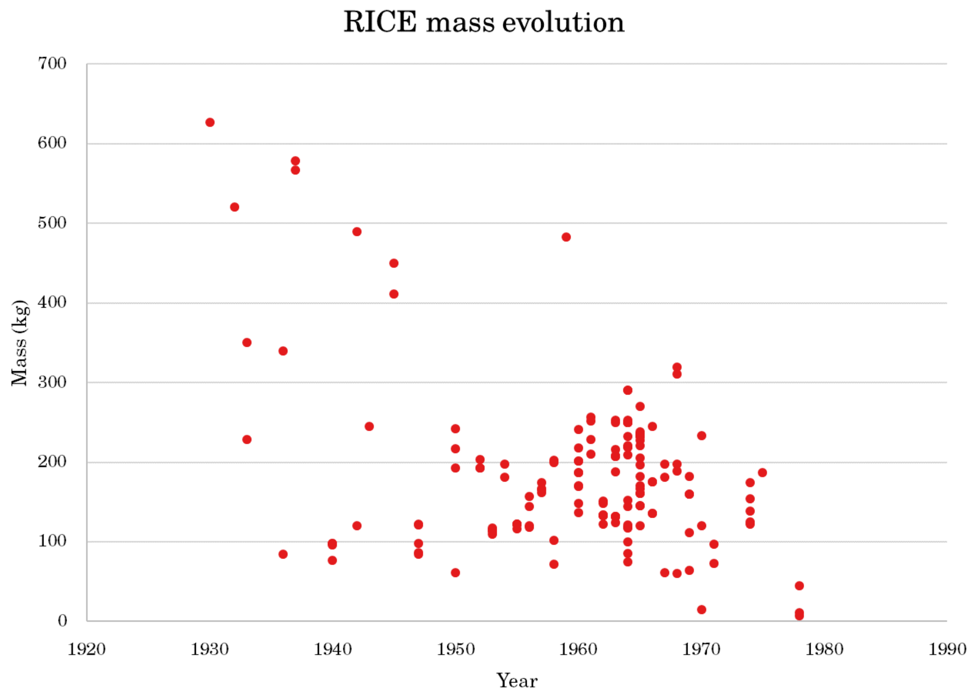


FIGURE 3.1. Evolution of RICE mass over the years

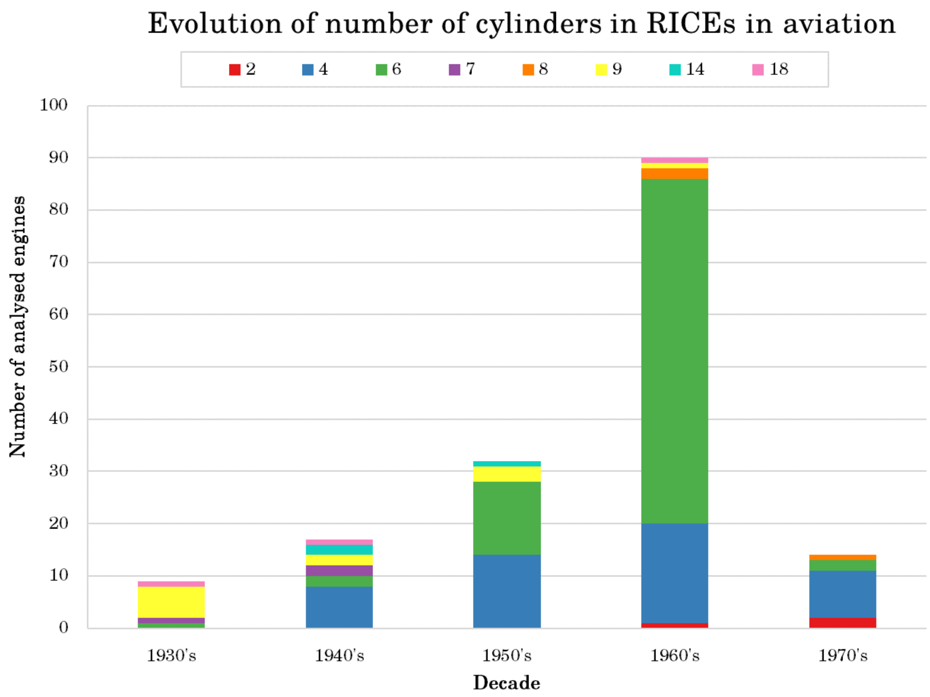


FIGURE 3.2. Evolution of RICE number of cylinders over the decades

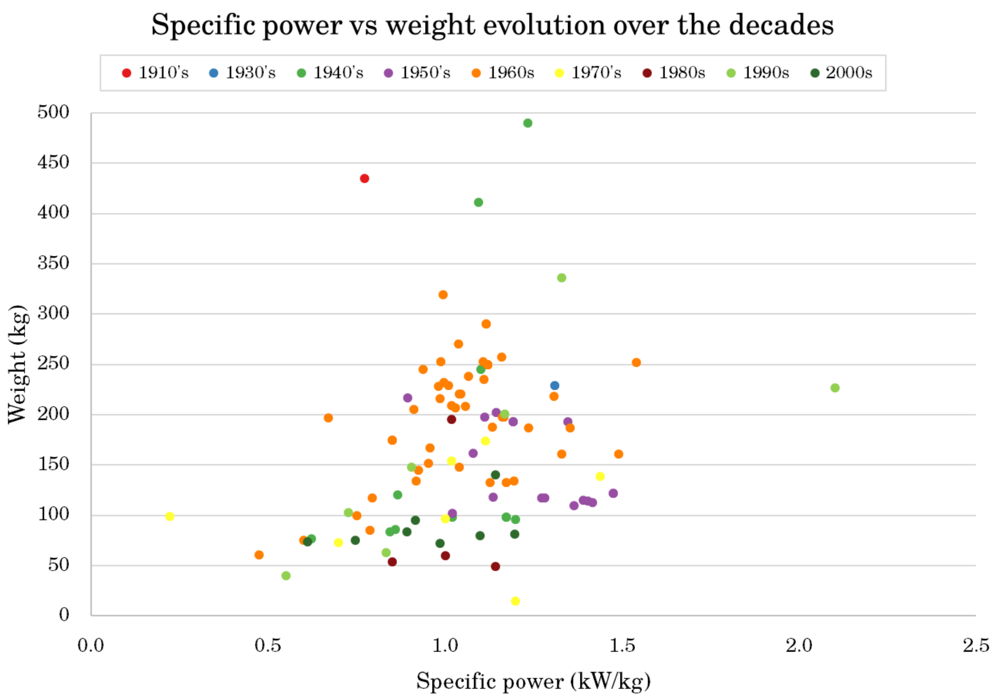


FIGURE 3.3. Specific power versus weight over the decades

On the the topic of traditional means of powering electric aircraft, another technology is worthy of mentioning: turboprops. The idea of this technology dates back to 1925, but it was not until 1945 when the first turboprop aircraft flew [8]. This technology basically consists of a turbojet which drives a shaft with a prop on its end. The turn of the shaft is achieved by the energy supplied by the expansion of gas. On a side note, the advantages and disadvantages of the turboprop are the same as for the propeller: speed is limited by compressibility effects at the blade tips when approaching high velocities [5].

3.2.2 Modern - Electric

Despite being perceived as modern and innovative, electric propulsive motors date back to the early nineteenth century, where examples of electric motors to power boats or cars can be found as early as 1838 and 1851, respectively [11]. The development of electric motors was interrupted because they were dependant on batteries which lacked the necessary energy supply to operate at a sensible cost [11].

In opposition to internal combustion engines, electric motors convert electrical power into magnetic power and finally into mechanical power. Hence, electromagnetism acquires utmost importance in electric motor operation by generating the necessary magnetic forces to produce motion, whether linear o rotational [12].

Given there are two types of current, direct (DC) and alternating (AC), the consequence is there are two matching types of electric motors. Whilst there is a reduced number of DC motor kinds, there exists a great amount of important AC motor types: synchronous, induction, repulsion... [11]

The kind electric motor to be chosen for a propulsive task depends on a number of factors, including vehicle limitations, energy source available and expectations such as acceleration, maximum speed, etcetera [13].

The sort of motor being most widely used actually for light aircraft propulsion is permanent magnet motor, which falls into the category of brushless motors; more specifically, permanent magnet brushless DC motors are commonly being used. The main interest of this type of motor is it allows to control speed and torque while being lightweight and having fewer moving parts [14]. Also, the popularity of the aforementioned kind of motors in propulsive applications is partly because it is a mature technology and simple to control [13].

3.3 General requirements for propulsion

To understand what is required from a propulsion system to power light aircrafts, a table with engine characteristics of a number of light aircrafts has been put together. Table 3.3 shows relevant data from internal combustion engines and mentions some aircraft in which said engine was applied. For the sake of comparison, on table 3.2 a collection of electric motor characteristics was also put together, although because it is a comparison between a fairly old technology versus a new one, the electric motor table is sparser.

It is easy to notice how the electric options have lower revolution speeds but are comparable in terms of the specific power and even greater, in some cases, than the traditional reciprocating engines.

TABLE 3.1. RICE motor data over the years (ref. [15],)

YEAR	REMARKS	AIRCRAFT	N° ENGINES	MANUFACTURER	MODEL	TAKE OFF POWER (kW)	RPM (thousands)	WEIGHT (kg)	SPECIFIC POWER(kW/kg)
1917	broad arrow	Vickers Vernon	2	NAPIER	Lion	336	2.2	435	0.8
1933	radial	Cessna 195	1	JACOBS	R-755-A	300	2.2	229	1.3
1940	horizontally opposed	Cessna 152	1	LYCOMING	0-235C	115	2.7	98	1.2
1940	horizontally opposed	Cessna 152	1	LYCOMING	0-235H	115	2.6	96	1.2
1940	horizontally opposed	Cessna 152	1	LYCOMING	O-235-L	115	2.7	98	1.2
1940	radial	Lavochkin La-9	1	ASH	ASH-82V	1380	2.4	1070	1.3
1940	horizontally opposed	Piper J-4	1	CONTINENTAL	A65	48	2.3	77	0.6
1942	horizontally opposed	Cessna 152	1	LYCOMING	O290-D2C	104	2.8	120	0.9
1942	air-cooled supercharged radial	North American T-28 Trojan	1	LYCOM	R1300-3	605	2.6	490	1.2
1943	radial	Culp Special	1	VEDENEYEV	M14V26	270	2.8	245	1.1
1945	radial	PZL-106 Kruk	1	PZLRZE	PZL-3S	450	2.1	411	1.1
1947	horizontally opposed	Cessna 150	1	CONTINENTAL	C-90	71	2.6	84	0.8
1947	horizontally opposed	Cessna 150	1	CONTINENTAL	O-200-A	100	2.8	98	1.0
1947		Cessna 150	1	ROLSRO	CO-O-200	74	2.7	86	0.9
1947	horizontally opposed	Cessna 170	1	CONTINENTAL	O-300-A	108	2.7	121	0.9
1950	radial	PZL-101 Gawron	1	IVCHEN	AI-14RT	190	1.9	61	3.1
1950	fuel injection, flat	Cessna 180	1	TELDYNE	IO-470-D	260	2.6	193	1.3
1950	radial	PZL-104 Wilga	1	IVCHEN	AI-14RT	194	2.4	217	0.9
1952	horizontally opposed	Cessna 182	1	CONTINENTAL	O-470-R	230	2.6	193	1.2
1952	horizontally opposed	Cessna 180	1	CONTINENTAL	O-470-S	230	2.6	193	1.2
1953	horizontally opposed	Cessna 172	1	LYCOMING	AEO320-E	150	2.7	117	1.3
1953	horizontally opposed	Piper PA-18 Super Cub	1	LYCOMING	O-320-A	150	2.7	110	1.4
1953	horizontally opposed	Cessna 172	1	LYCOMING	O-320-D	160	2.7	114	1.4
1953	horizontally opposed	Cessna 172	1	LYCOMING	O-320-E	160	2.7	113	1.4
1953	horizontally opposed	Cessna 172	1	SALYCO	O-320-H	160	2.7	115	1.4
1954	gearbox & flat	Beechacraft Twin Bonanza	2	LYCOMING	GO-480	220	3.4	198	1.1
1955	flat ; left-hand rotating crankshaft	Beechcraft Duchess	2	LYCOMING	LO-360-E	180	2.7	122	1.5
1955	horizontally opposed	Robin DR400	1	LYCOMING	O-360-F	180	2.7	122	1.5
1956	horizontally opposed	Piper Cherokee	1	LYCOMING	O-360-A	134	2.7	118	1.1
1957	flat	Cessna 182	1	LYCOMING	O-540-J	175	2.4	162	1.1
1958	inverted in line	Aero 145	2	WALTER	AVIA M332	104	2.4	102	1.0
1958	flat	Piper PA-31 Navajo	2	LYCOMING	VO-540-A	231	3.2	202	1.1
1960	gearbox, fuel injection & flat	Dornier Do 28-2	2	LYCOMING	IGSO540	285	3.4	218	1.3
1960	inverted in line	Let L-200D Morava	2	WALTER	AVIA M337	154	2.6	148	1.0
1960	flat	Piper PA-31 Navajo	2	LYCOMING	IO-540-E	231	2.6	187	1.2
1960	turbocharged, flat	Robin HR100	1	TELDYN	T6-320	253	4	187	1.4
1961	horizontally opposed	Beagle B206	2	CONTINENTAL	GIO470A	231	3.2	229	1.0
1961	horizontally opposed	Northwest Ranger C-6	1	LYCOMING	IO-720-B	388	2.7	252	1.5
1961	horizontally opposed	Northwest Ranger C-6	1	LYCOMING	IO-720-A	298	2.7	257	1.2
1962	horizontally opposed	Beechcraft Musketeer Custom III	1	CONTINENTAL	IO-346	123	2.7	134	0.9
1962	horizontally opposed	Cessna 336 Skymaster	2	LYCOMING	IO-360-C	160	2.8	134	1.2

YEAR	REMARKS	AIRCRAFT	N° ENGINES	MANUFACTURER	MODEL	TAKE OFF POWER (kW)	RPM (thousands)	WEIGHT (kg)	SPECIFIC POWER(kW/kg)
1962	horizontally opposed	Beechcraft Musketeer Super III	1	LYCOMING	IO-360-A	150	2.7	133	1.1
1962	horizontally opposed	Mooney M20	1	CONTINENTAL	IO-360-A	156	2.8	133	1.2
1963	fuel injection, flat	Cessna P206	1	TELDYN	IO-520-A	213	2.7	216	1.0
1963	fuel injection, flat	Cessna 210F	1	TELDYN	IO-520-C	213	2.7	207	1.0
1963	fuel injection, flat	Cessna 185 II landplane	1	TELDYN	IO-520-D	220	2.7	208	1.1
1963	fuel injection, flat	Cessna 310R	2	TELDYN	IO-520-M	213	2.7	188	1.1
1963	gearing, flat	Cessna 404	2	TELDYN	GTSIO-520D	280	3.4	250	1.1
1963	gearing, flat	Cessna 421	2	TELDYN	GTSIO-520Hs	280	3.4	253	1.1
1964		Bellanca 7ACA Champion	1	FRANKLIN	2A-120C	45	3.2	75	0.6
1964	gearing, flat	Cessna 150	1	CONTINENTAL	O-200-A	75	2.8	100	0.8
1964	gearing, flat	Cessna TU206	1	TELDYN	TSIO-520-C	213	2.7	209	1.0
1964	gearing, flat	Cessna 210M	1	CONTINENTAL	TSIO-520-R	231	2.7	221	1.0
1964	turbo-charging, flat	Beagle B.206	2	CONTINENTAL	GTSI-520-C	250	3.2	253	1.0
1964	turbo-charging, flat	Bellanca Skyrocket II	1	CONTINENTAL	GTSI-520-F	324	3.4	290	1.1
1964	turbo-charging, flat	Aero Commander 500 family	2	CONTINENTAL	GTSI-520-K	324	3.4	290	1.1
1964	gearing, flat	Cessna 421B	2	CONTINENTAL	GTSI-520-H	280	3.4	250	1.1
1964	gearing, flat	Cessna 421C	2	CONTINENTAL	GTSI-520-L	280	3.4	250	1.1
1964	gearing, flat	Cessna 421C	2	CONTINENTAL	GTSIO-520-M	280	3.4	250	1.1
1964	flat	SOCATA Rallye family	1	FRANKLIN	O-235	93	2.8	117	0.8
1964	gearing, flat	Mooney M10 Cadet	1	CONTINENTAL	C90-16F	67	2.5	85	0.8
1964	gearing, flat	Cessna 336 Skymaster	2	CONTINENTAL	TSIO-360-A	145	2.8	152	1.0
1965	horizontally opposed	Beechcraft Baron 56TC	2	LYCOMING	TIO-541-E	280	2.9	270	1.0
1965	gearing, flat	Cessna 414	2	TELDYN	TSIO520-N	230	2.7	221	1.0
1965	horizontally opposed	Piper PA-31 Navajo	2	LYCOMING	TIO540-A	231	2.7	232	1.0
1965	horizontally opposed	Piper PA-23 Aztec C	2	LYCOMING	TIO540-C	187	2.6	205	0.9
1965	horizontally opposed	Piper PA-31-350	2	LYCOMING	TIO540-J	261	2.6	235	1.1
1965	horizontally opposed	Cessna R340L	2	LYCOMING	TIO540-R	254	2.5	238	1.1
1965	horizontally opposed	Sequoia 300 Sequoia	1	LYCOMING	TIO540-S	224	2.7	228	1.0
1965	flat	Piper PA-36	1	CONTINENTAL	6-285A	214	3.7	161	1.3
1965	flat	Trident TR-1 Trigull 320	1	CONTINENTAL	6-320	240	4	161	1.5
1965	flat	Socata Rallye MS 894	1	FRANKLIN	6A-350C	160	2.8	167	1.0
1965	flat	Bushcaddy L-164	1	FRANKLIN	6A-350	134	2.8	145	0.9
1965		PZL-104 Wilga 80	1	PZL	AI-14RA	132	1.7	197	0.7
1966	gearing, flat	Beechcraft 58TC Baron	2	CONTINENTAL	TSIO-520-L	230	2.7	245	0.9
1966	horizontally opposed	Piper PA-34 Seneca	2	CONTINENTAL	TSIO-360-E	149	2.6	175	0.9
1966	horizontally opposed	Piper PA-28-201T Turbo Dakota	1	CONTINENTAL	TSIO-360-F	149	2.6	175	0.9
1967	gearing, flat	Cessna TU206G	1	CONTINENTAL	TSIO-520-M	230	2.6	198	1.2
1967	horizontally opposed	Fournier RF-4D	1	RECTIMO	4AR1200	29	3.6	61	0.5
1968	gearing, flat	Cessna T210N Turbo Centurion II	1	CONTINENTAL	TSIO-520-R	231	2.6	198	1.2
1968	horizontally opposed	Piper PA-31P-425 Navajo	2	LYCOMING	TIGO541E	317	3.2	319	1.0

YEAR	REMARKS	AIRCRAFT	N° ENGINES	MANUFACTURER	MODEL	TAKE OFF POWER (kW)	RPM (thousands)	WEIGHT (kg)	SPECIFIC POWER(kW/kg)
1970	horizontally opposed	Borzecki Alto-Stratus	1	BORZEC	2RB	18	4.5	15	1.2
1971	horizontally opposed	Fournier RF-5	1	LIMBAC	SL-1700-E	51	3.2	73	0.7
1971	horizontally opposed	Cessna FRA150M	1	ROLLS ROYCE	O-240A	97	2.8	97	1.0
1974	flat	Pitts Special S-2B	1	LYCOMING	AEIO-540-D	194	2.7	174	1.1
1974	flat	Slick Aircraft Slick 360	1	LYCOMING	AEIO-360-A	200	2.7	139	1.4
1974	horizontally opposed	Scaled Composites Catbird	1	LYCOMING	TO-360-C	157	2.6	154	1.0
1979	direct drive; two stroke	Hovey Delta Bird	1	CUYUNA	430	22		99	0.2
1983	horizontally opposed	Extra EA-400	1	CONTINENTAL	IO-550	224	2.7	195	1.0
1985		ARV Super2	1	HEWLAND	AE75	56	6.75	49	1.1
1985	horizontally opposed	Partenavia P.86 Mosquito	1	KFM	112M	46	3.4	54	0.9
1989	horizontally opposed	Foxcon Terrier 200	1	ROTAX	912 UL	60	5.8	60	1.0
1990	V	Papa 51 Thunder Mustang	1	RYAN FALCONER	FALCONER V12	477	4.5	227	2.1
1990	V-block	de Havilland Canada DHC-2 Beaver	1	ORENDA	OE600	447	4.4	336	1.3
1993	twin cylinder	Milholland Legal Eagle	1	BETTER HALF	HALF VW	22		40	0.6
1995	four stroke	Murphy Rebel	1	FIREWALL	CAM 100	75	2.5	103	0.7
1995	flat	Just SuperSTOL	1	JABIRU	2200	60	3.3	63	0.8
1996	horizontally opposed	Found Expedition E350	1	LYCOMING	IO-580	235	2.5	201	1.2
1997	V	Cirrus SR20	1	DELTAHAWK	DH180	134	3.6	148	0.9
2002	horizontally opposed	Cirrus SR20	1	LYCOMING	IO-390	160	2.7	140	1.1
2004	in-line			VIJA	J-10Si	75	6.6	84	0.9
2005	horizontally opposed			VAXELL	60i	45	3.2	73.5	0.6
2005		Just Highlander	1	VIKING	130	97		81	1.2
2005	horizontally opposed	Zenair CH650	1	ULPOWER	UL260i	71	3.3	72	1.0
2008	horizontally opposed	Tecnam P92	1	LYCOMING	IO-233	87	2.8	95	0.9
2008	horizontally opposed	BRM Aero Bristell	1	ULPOWER	UL350i	88	3.3	80	1.1
2009	in-line	Rans S-6 Coyote II	1	LORAVIA	LOR 75	56		75	0.7

TABLE 3.2. Characteristics of different electric motors (ref. [16], [17], [18], [19], [20], [21], [22], [23], [24], [25])

ID	YEAR	TYPE	APPLICATION	N° MOTORS	MOTOR MANU-FACTURER	MODEL
1	2002	permanent magnet	Pipistrel Taurus Electro	1	SIEMENS	
2	2003	brushless-electric	Large Antares	1	LANGE	EM 42
3	2009	brushless-electric	Yuneec International E430	1	YUNEEC	SP55D
4	2010	electric	E-Flight electric Sport Aircraft	1	SONEX	
5	2011	brushless-electric	Elektra One	1	PC-AERO	
6	2013	hybrid electric	DA36 eStar Gen.2	1	SIEMENS	
7	2015	electric	Extra 330LE	1	SIEMENS	SP260D
8	2015	permanent magnet	Sora-e	2	ENSTROJ	EMRAX188
9	2017	electric	CityAirbus	1	SIEMENS	SP200D
10	2017	electric	NASA X-57 Maxwell	2 (+12 high-lift)	JOBY	
11	2017	electric	Pipistrel Alpha electro	1	SIEMENS	
12	2018	brushless-electric	Bye Aerospace Sun Flyer 4	1	BYE AERO	

ID	TAKE-OFF POWER (Kw)	RPM (thousands)	MOTOR WEIGHT (KG)	CONTINUOUS TORQUE (NM)	NOMINAL VOLTAGE (V)	BATTERIES (kWh)	SPECIFIC POWER (kWh/kg)
1	260	2.5	50	1000	580		
2	40	2.4	19		133		
3	105		20				
4	204	1.3	49	1500			
5	16	1.4					
6	60					17	
7	60		26		461	69 (47 usable)	1.8
8	38.2		29				
9	70	6	7	50	400	14.5	2.1
10	50	2.2	14			17	1.2
11	40		11			7,1 (5,7 usable)	0.5
12	105	2.4	13	70			

3.4 Electric Aircrafts

The term ‘electric aircraft’ might be prone to confusion due to the fact there are two different approaches to this term, depending on which cases are being considered. These two terms are ‘All electric aircraft’ and ‘More electric aircraft’ and are going to be further discussed in this part.

More electric aircraft, broadly known as MEA, are those aircrafts based on using electric power in the aircraft subsystems. This approach still involves fuel being used, given it powers the propulsion system. Remainder forms of power which in conventional aircrafts would be using fuel too, namely pneumatic, mechanical, hydraulic and electrical power, are substituted by systems of electric nature [26].

All electric aircraft, known by the initials AEA, is an aircraft concept in which all systems are substituted by electrical-powered systems. The difference it bears with the MEA is that this design is powered by an electric system. This is the type of aircraft of interest in this document.

The problematic of these systems arises from the fact the flight safety characteristics still have to be met. However, the electric aircraft has been proven to present advantages such as reducing the empty weight of commercial aircrafts by about 10% [27]. In the case of MEA, where propulsion is still based on fuels, a reduction of similar magnitude in specific fuel consumption (SFC) has also been proved, among other conveniences [28].

In electric aircrafts, it is noticeable the majority of the electrical system's weight are electric cables, generators and motors and even though the losses due to Joule's law in electrical cables are smaller than the losses of traditional systems, said energy waste still limits the electrical system [29] .

3.4.1 Electric Motors for propulsion

Whether or not the electric motors are for airborne applications, there are seven general properties common to all of this kind of motors [30]:

1. The output of a motor is mostly determined by the cooling arrangement
2. The rated torque is toughly proportional to the rotor volume in motors with comparable cooling systems
3. Speed is directly proportional to output power per unit volume
4. Large motors have a higher specific torque and are also more efficient than small motors
5. Motor efficiency improves with speed
6. Any voltage may suit a motor without affecting its performance
7. Overloading for short periods of time will not damage most motors

In the case of electric aircrafts, the type of propulsive motor being currently developed for most prototypes is the permanent magnet motor. They are designed to be specially lightweight and in many cases are brushless DC motors, which is just another way of saying permanent magnet excited synchronous motors [13].

The most basic configuration for a brushless DC motor is a triphasic stator winding with permanent magnets attached to the rotor. The position of the rotor is controlled by transducers which inform the electronic controller. The controller shifts the DC voltage in the stator windings and causes the rotor to turn [14]. The magnets used in this kind of motors are usually an alloy of aluminium, nickel and copper, being known as Alnico alloys, due to their high suitability for the purpose [31].

The distribution of the magnets is of great importance to avoid unwanted effects, such as torque ripple. The Halbach array is an arrangement which combines one radial magnet array and one azimuthal magnet array. This arrangement focuses the flux to the desired direction and allows reaching a higher magnetic potential [32]. Implementing a Halbach array to the rotor has been confirmed to deliver high torque density, better stability [33] and reducing torque ripple due to near-perfect sinusoidal field distribution [32].

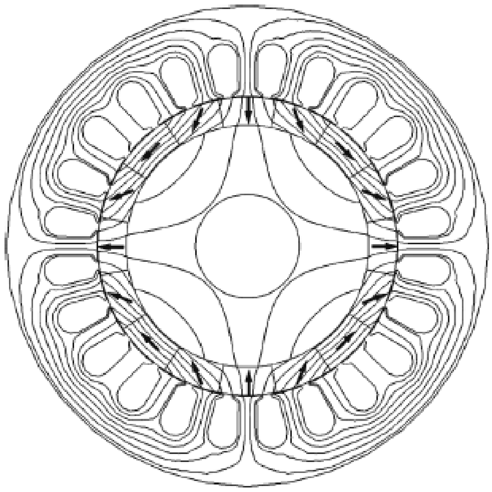


FIGURE 3.4. Halbach magnet array rotor flux distribution (Image from [32])

One of the attractions of brushless motors is they erase the need for rotating contacts and thus do not have the problems linked to them, such as wearing [14] and because there is no current circulation in the rotor it does not heat up [13]. To increase reliability and performance, motors with higher number of phases may be used [34]. However, this involves increasing the complexity of the motor, which might not be desirable.

3.4.2 Energy supply and storage

Nowadays, three main approaches are considered in electric aircrafts when it comes to energy supply: either batteries, fuel cells or solar panels.Because the lower power density of the latter compromise the maximum achievable speed of the aircraft [35] to the present day, manufacturers do not opt for them, although some projects with solar panels such as *Solar Impulse 2* or *Sunseeker* have proven to solar panels to be a feasible technology [36] , [37]. Fuel cells, contrary to solar panels, resemble batteries but store the fluid outside the battery. Some prototypes such as *SkySpark* and *ENFICA-FC* have flown, but the technology of fuel cells is still not a common choice for manufacturers [38], [39].

Focusing on batteries, batteries are devices which transform chemical energy into electrical energy and vice-versa, depending on whether charging or discharging. The most extended in use for electrical vehicle applications are Li-ion, given it has been proven to display high energy density and efficiency when compared to other types of batteries [40] [41]. For airborne propulsion systems, high energy density batteries are required and lithium based batteries present this advantage as well as low weight and low cost [31].

To the present day, the truth is the specific energy of Li-io batteries is nothing comparable to that of aviation gasoline, as can be observed in table 3.3. Even to the best of their performance, Li-io batteries of present-day technology are only theoretically capable of reaching 387 $\frac{\text{Wh}}{\text{kg}}$ [42].

TABLE 3.3. Comparison of specific energy of aviation gasoline and Li-io batteries (refs. [43], [44], [45], [42], [46])

	Energy content	
	MJ/kg	KWh/kg
Aviation gasoline	43.7	12.1
	46.4	12.9
	43.5	12.1
Li-io batteries	0.36-0.54	0.1-0.15
	0.36-0.569	0.1-0.158

This compromises the possible applications of electric light aircrafts to missions where great autonomy is needed. Because the total energy available on the aircraft will depend on the battery weight, it is in some cases possible to renounce some payload weight to incorporate more batteries, thus increasing autonomy

3.4.3 Safety considerations and redundancy

Aircrafts are subject to very strict regulations regarding safety and electric aircrafts are no exception. Introducing electric propulsion systems introduce new hazards which have to be taken into account and minimized.

When using brushless DC motors, the main faults that can occur in the machine are short-circuit due to insulation failure and open-circuit of a winding [34]. For a motor that can continue to be operative after suffering any of these faults, the motor must necessarily follow a modular approach treating each phase as a separate module, assuring complete electrical isolation between phases [34].

To assure no malfunctioning will impede the motor to work correctly, two redundant wiring systems are applied to some prototypes as well as redundant control systems [47]

When implementing brushless motors, given there was a wreck, the motor could still be excited by its magnets and be dangerous to people nearby due to its high voltage difference in the terminals [13].

CHAPTER 4

SIMULATION ENVIRONMENT AND APPROACH

This chapter presents the model developed by *Mathworks* on which the whole simulation is based. The parts other than propulsion system and pilot control are left mostly untouched, meaning nothing about the aircraft design and functioning will be altered at a big scale. The modifications performed to the model are closely related to the fact light aircrafts have the possibility of being adapted to be propelled by electric systems even though they might have originally been powered by fossil fuel engines.

4.1 *Simulink* Light Aircraft Model

MATLAB® provides a broad set of utilities related to Aerospace Engineering in its toolbox '*Aerospace toolbox*'. Contained in this package, a complete model of a light aircraft can be found under the name *asbSkyHogg*. When opened, this model looks like what is seen in figure 4.2. Out of the displayed subsystems, the one of interest for the matter being is the one under the 'Vehicle System model' label. To further understand this model, some of its most important parameters can be found in the Appendix.

The *Simulink* model has many levels, all of which are represented in a visual manner in figure 4.1. The modified version of this simulation will have more levels in the 'Propulsion' block, which is the subsystem of ultimate interest. Otherwise, the model stays virtually untouched.

Minor modifications are also carried on the model when changing the initial conditions. This does not affect the model other than by changing some of the model variables.

FIGURE 4.1. Diagram of the *asbSkyHogg Simulink* model

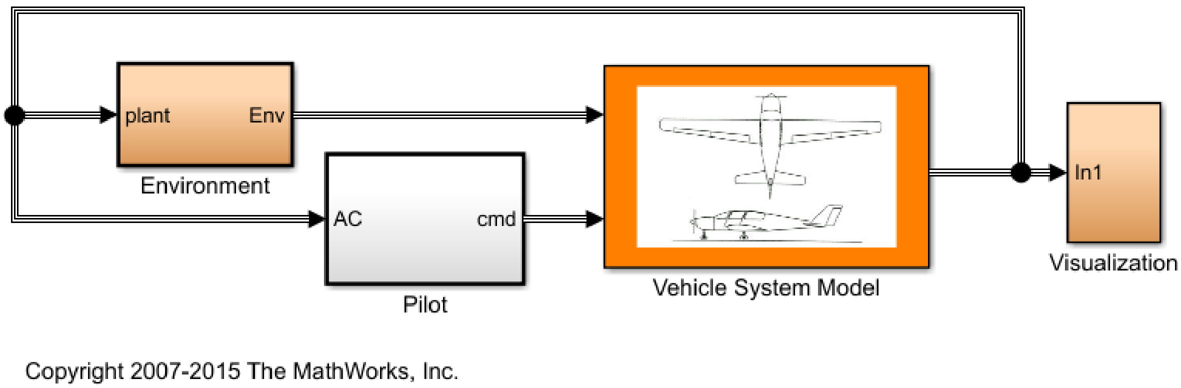


FIGURE 4.2. View of the light aircraft model *asbSkyHogg* in *Simulink*

4.1.1 Environment

This system contains all necessary information about the surroundings of the aircraft in the situation in which the simulation will take place. It includes information about the terrain elevation and shape, the wind behaviour at the specified altitude and it also uses the WGS84 geoid model to define the gravity at the specified coordinates at which the aircraft is situated. Other than this, the block also includes an atmosphere model to compute the outside temperature, pressure, air density and speed of sound. The atmosphere model being used in this particular simulation is the COESA atmosphere model.

4.1.2 Pilot

It is in this block where any human actions that were to be applied to the aircraft to control its behaviour.
This block has the capability to control the actuators (elevator, rudder and aileron) manually, but as it will be explained in the paragraphs following, the model does not make it strictly necessary to control the elevator by hand because it is the autopilot who is in charge of doing so. For this reason, the inputs for all three actuators are set to zero. On the other hand, this block allows to control the throttle applied to the motor. For the sake of simplicity, it is set as a constant value throughout the simulation for the totality of this project.
The final part one is able to control in this system is the altitude command. This is: one is able to describe the desired vertical movement for the aircraft and the autopilot will follow it closely. The command is defined as a step, but for the comfort of those who would be flying on the *SkyHogg*, the vertical profile of the ascent is of 500 meters every 3 minutes.

4.1.3 Vehicle System Model

This system contains the totality of the information regarding the vehicle functioning and geometry. If the aircraft model was to be changed, it is this block which should be modified to include the essential information which differentiates the functioning of one aircraft to another. This information can be broken down into three main categories, which happen to be the three subsystems which the 'Vehicle System Model' contains: avionics, vehicle and flight sensors.

4.1.3.1 Avionics

It is inside this block where the Inertial Measurement Unit, indispensable tool to further calculate the aircraft dynamics, is set. It also includes the air data computer, which takes information from the aircraft sensors, and the guidance system. The latter combines the information provided by the other two with the pilot's commands in order to create a reference signal, in this case for altitude, which will be of utmost importance in the last block inside this subsystem: the autopilot block. This block takes the outputs of all three previous blocks (IMU, air data computer and guidance) as input data. As a result of longitudinal controller which aims to follow the altitude reference signal created in the 'Guidance' subsystem, this autopilot controls the elevator in an automated way to demand the aircraft to follow the reference as closely as possible.
The actual appearance of said 'Autopilot' controller is shown in figure 4.3. It is important to note the controller was tuned for the initial conditions which were predefined for the model and thus it works best at these conditions.

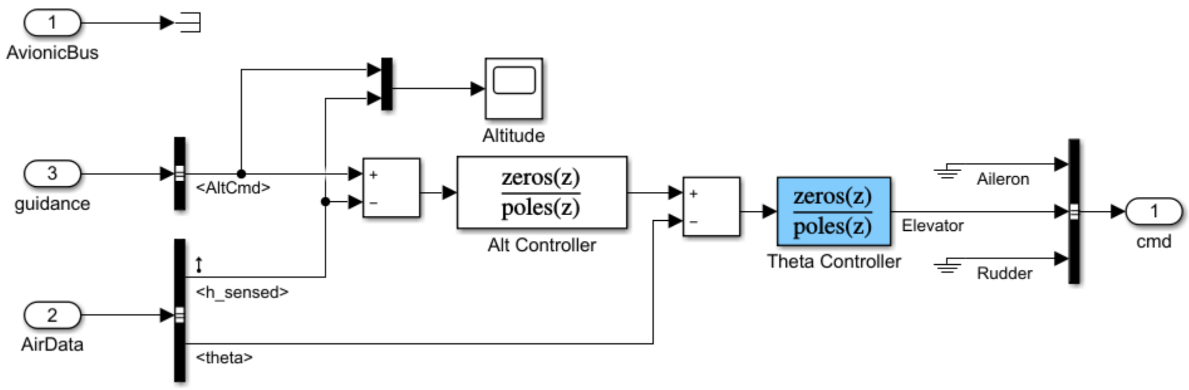


FIGURE 4.3. Default Autopilot block in *asbSkyHogg* which controls the elevator position

4.1.3.2 Flight Sensors

This system takes the data from the environment and the aircraft plant conditions (such as aircraft velocity) and passes it as input to some blocks which act as aircraft sensors, such as Pitot tubes. It is considerable part of this subsystem remains incomplete and performs no action upon the input data. It was done this way by the *MathWorks* developers whom left the transducer and noise models for its development later on, as it is stated in an annotation inside both blocks.

4.1.3.3 Vehicle

This block will be the one suffering modifications throughout this project, as it contains the propulsion subsystem. The interior of this block is, untouched, what can be seen in figure 4.5. Its most important component is an input, *cmd*, coming from the 'Pilot' system, which directs the amount of throttle applied. This throttle leads to a corresponding thrust which is extracted in the *ThrustX* block. This thrust is part of the output of the propulsion subsystem, along with the thrust in Y and Z axes (null thrust) and moments in all three axes (again, null).
Besides the propulsion block, this system also contains other necessary components which describe the vehicle. The 'Airframe Actuators' block uses as input data the information provided by the 'Autopilot' and transmits to the aileron, rudder and elevator the demanded position commands. The 'Aerodynamics' block then uses the data outputted from the 'Airframes Actuators' block, alongside with environmental and plant data, to compute the wind in different axes an the forces and moments being produced by the actuators.
As it is known, the resultant forces and moments on a body are the sum of the forces and moments acting on said body. The outputs of the 'Aerodynamics' and 'Propulsion' block are condensed into a single total force and total moment for the aircraft, which serves as input for the '3DOF to 6DOF' block, that then uses mechanical equations to extract all variables of interest for the aircraft, namely velocity, longitudinal rotation speed, or body angles.

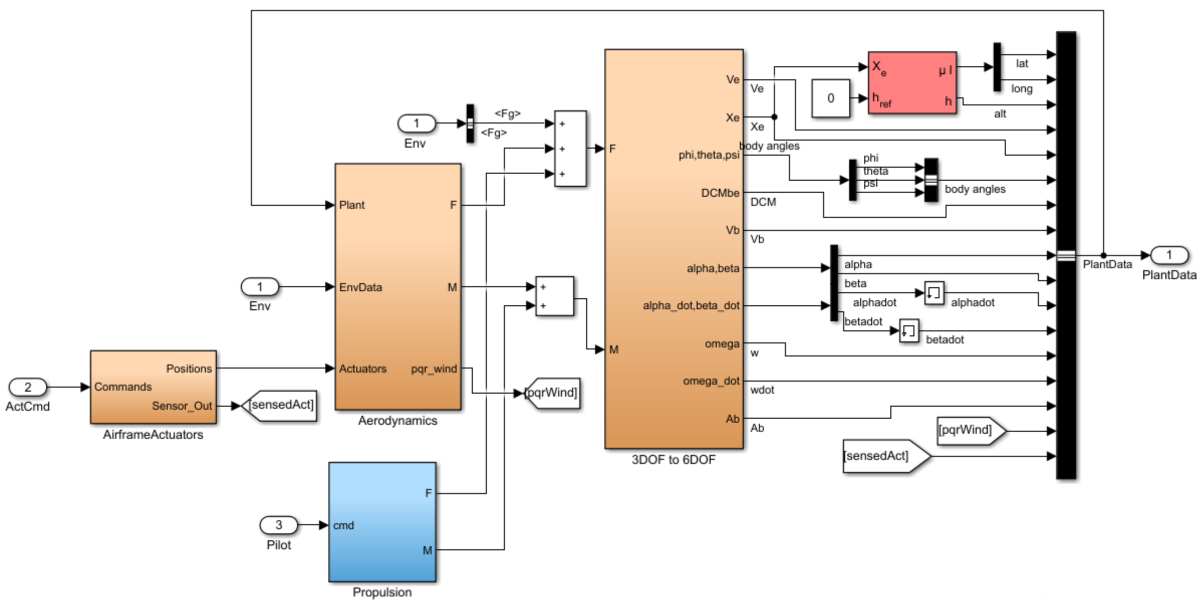


FIGURE 4.4. View of the Vehicle block in *asbSkyHogg* with the propulsion block in blue

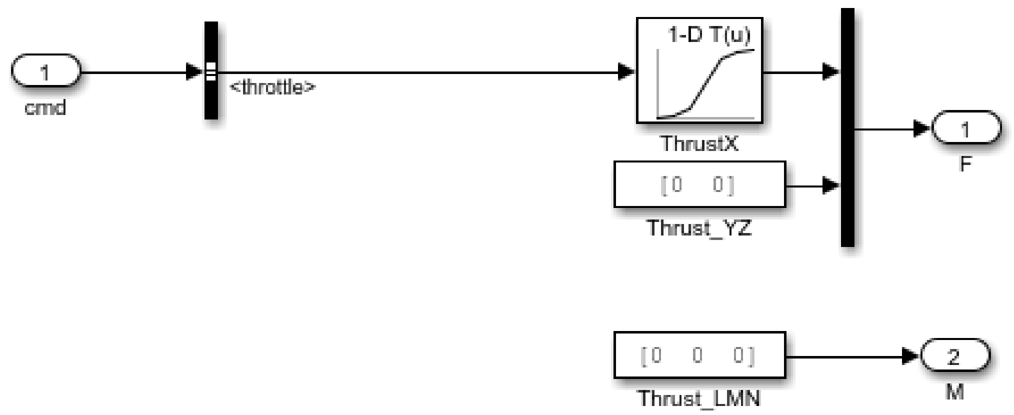


FIGURE 4.5. Default propulsion block in *asbSkyHogg*

4.2 Propulsion block layout

The default propulsion block in this model overlooks the fact the thrust in light aircrafts is mainly produced by its propellers, which is at the same time driven by the motor. The aim is to introduce in this block the dependency that thrust bears with the propeller and, consequently, with the electric motor drive which will be implemented. This dependency relies on the input to the electric motor drive: the desired torque, which comes given by the pilot input in the form of throttle.
Taking all different aspects into account, the propulsion block will be formed by three main parts: propeller, electric motor and batteries.

4.2.1 Propeller

The propeller generates the vast majority of the thrust which propels the aircraft. Its design must be detailed and focused on achieving as much thrust as possible with as little power as it can be; that is the same as saying the propeller designed must be as efficient as possible for the conditions in which it will work. A detailed explanation of the design process for the propeller can be found in chapter 5.

4.2.2 Electric motor

The design of this component will follow the requirements of the resultant propeller. It will be required to provide more power than the propeller might be needing to compensate for power losses in the shaft.
As it was analysed in table 3.2, the majority of the motors used are brushless electric (also noted as 'permanent magnet'), which are the norm for electric vehicles. The motor simulated will be of

these characteristics and furthermore will be AC.

The propeller and the motor will be intimately related by the torque provided to the propeller shaft by the motor. The following diagram in figure 4.6 describes in a visual manner this relationship, which will be studied in detail further on.

Because of the close relationship the electric motor bears with the batteries, these will be included inside the electric motor block for the sake of simplicity.

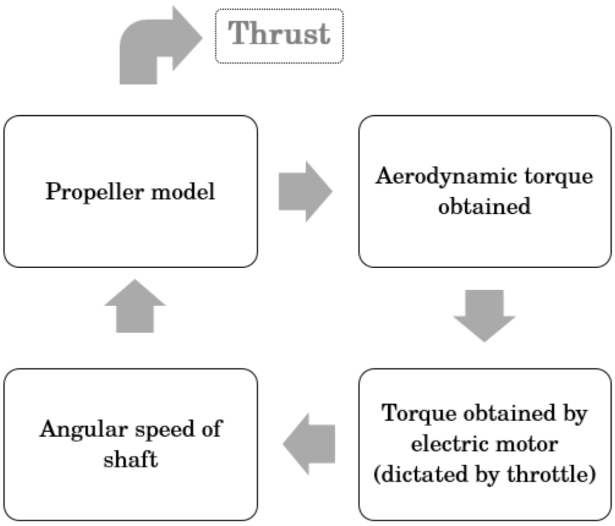


FIGURE 4.6. Flowchart of approximate steps in propulsion block

4.2.3 Batteries

An aspect of utmost importance is batteries, which need to be taken into account when designing an electric motor to make the aircraft able to complete its mission. The duration of a flight using batteries to power its propulsion system is, up to date, not comparable to the duration of a flight consuming fossil fuel because, as shown in subsection 3.4.2 in part I, the energy density of batteries is still really low compared to that of aviation gasoline.

One popular choice for pilot training schools to train new pilots flight hours are light aircrafts. Due to the fact these classes occur in the immediacies of an airport and have a short duration, electric powered light aircrafts manufacturers aim to make the electric aircraft option attractive to these schools. This is so because, up to date, the low energy density of batteries being used only allow for about 60 minutes of flight [25], keeping electric propulsion systems away from being ubiquitous and applied all types of missions.

A crucial thing to take into account when considering batteries is the weight they add to the aircraft. While the electric motor actually helps bringing down the total gross weight of the aircraft, it is the batteries which make it skyrocket. The autonomy of the aircraft will be greatly limited by the fact there is only a certain amount of battery weight it can carry. A parameter to be considered when choosing the batteries must be their energy density, as for, as the name indicates, a bigger energy density will allow a grater energy for the same weight. The matter of choosing the right batteries is addressed further on in the document.

CHAPTER 5

PROPELLER DESIGN AND IMPLEMENTATION

As it has been said, the propeller accounts for the majority of the thrust produced in a light aircraft. For this reason, its design must be carried out in a careful way and bearing in mind the characteristics of the *SkyHogg* and the requirements for the mission.
In this section, the design of the propeller in the program *JavaProp*, created by Martin Hepperle and available on-line [48], is described, along with the analysis of the needs of the aircraft and, ultimately, its limitations.

5.1 Design of a propeller with *JavaProp*

JavaProp is an inestimably useful tool when it comes to designing propeller blades. It offers a considerable number of possibilities and configurations for detailed designs. Nevertheless, there exist some limitations when it comes to employing this application. The way in which this applet carries out its calculations is based on the blade element theory, working by dividing the propeller blades into smaller sections. This has the advantage of simplicity and rapidness, although it implies some downsides and limitations. Quoting the author: "*The theory makes no provision for three dimensional effects, like sweep angle or cross flow. But it is able to find the additional axial and circumferential velocity added to the incoming flow by each blade segment. This additional velocity results in an acceleration of the flow and thus thrust. Usually this simplified model works very well, when the power and thrust loading of the propeller (power per disk area) are relatively small, as it is the case for most aircraft propellers* [48]".

Limitations were acknowledged during the whole process and are commented when necessary, although as the author stated, mostly the limitations do not have a great influence because of the characteristics of the aircraft.

The *Simulink* model provides no information regarding the propeller which is originally coupled to the aircraft. For this reason, the design of the propeller will be done from the very beginning to fit the aircraft's needs.

5.1.1 Thrust requirements of the *Sky Hogg*

To start off, an analysis of the original propulsion plant had to be executed. The propeller, along with the electric motor, should aim to reach approximately the levels of thrust which were attained by the previous engine. Ideally, the modified aircraft should bear no differences with the original model.

It can be checked how the thrust of the original model of the *Sky Hogg* ranges from 0 to 5000N at the given initial conditions. By running the model in *Simulink*, it can be seen how for these conditions, specified for the default mission and shown in table 5.1, the minimum thrust required to achieve a stabilised flight (that is: to compensate the drag) is about 1500N. Even though the mission is not necessarily the one which will be implemented, this should serve as a minimal requirement when designing the propeller, meaning the *SkyHogg* should be able to reach said value at reasonable speeds and propeller angular velocity. That way, the aircraft will be known to be capable of reaching the same conditions as the unmodified model's initial condition, at least.

TABLE 5.1. Flight initial conditions

Altitude (m)	**Absolute temperature (K)**	**Absolute pressure (Pa)**	**Air density (kg/m3)**	**TAS (m/s)**
2000	275.15	79495	1.006	93.1

The comparison between the sufficient and with deficient thrusts should be clearly different, as the insufficient thrust would imply the aircraft to start loosing height in a steady way, until reaching an altitude which it could bear or until the thrust was incremented.
The behaviour with said different thrusts can be observed in figure 5.1, where the yellow line represents the commanded altitude and the blue line represents the altitude measured by the on-board equipment.

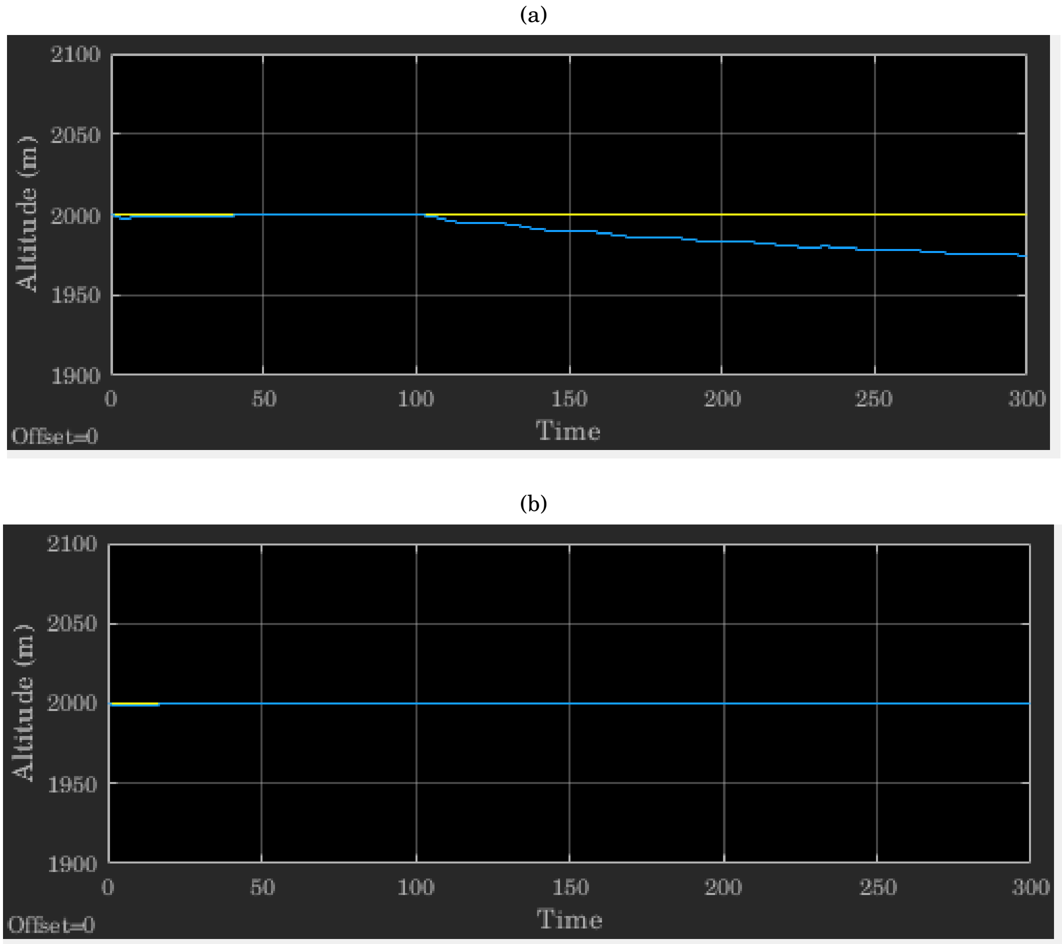


FIGURE 5.1. (a) Case with a thrust of 1300N can not keep levelled flight (b) With 2500N levelled flight can be achieved

In conclusion, to be able to fly a levelled flight with this aircraft model, the propeller must achieve around 1500N thrust, at minimum, at the conditions specified in table 5.1.
Taking into account the power output of electric motors is substantially lower than that of fuel-powered motors, it is consequently not as easy to achieve said thrust values. This is the reason why actual electric-powered aircrafts tend to be light even inside the category of light aircrafts, ranging from about 800 to 1500kg (taking into account the aircrafts analysed in table 3.2). The *SkyHogg* original model flies with a weight of 1299kg, proving it suitable for implementing an electric motor drive.

5.1.2 Working with *JavaProp*

As it was already mentioned, *JavaProp* is a freeware tool available on the Internet to design and analyse propellers. It has some restrictions to its reliability: small number of blades (less than

15) and the propeller loading should not be too high [49].
The application allows to enter some design parameters and test them, modifying the propeller to fulfil off-design conditions. Therefore, an iterative process was followed, based on trial and error, to determine the geometry of the blades which would perform well in the simulation conditions. In table 5.2 some important geometric parameters can be observed, so as to grasp the dimensions of the actual blade.

TABLE 5.2. Geometric parameters of the blades

N° of blades	**Diameter (m)**	**Chord**	
		Tip (mm)	**Root (mm)**
4	1.65	50	126.3

The blades have different standard airfoil geometries along the span, which are listed in table 5.3. These airfoils were selected for being common in propeller design and have been proven to be suitable. The sections of the blade which do not correspond to any of the listed below have interpolated airfoils, with the interpolation being from the beginning airfoil shape to the ending as to create a smooth blade surface and shape.

TABLE 5.3. Airfoils along the span

Airfoil			
r/R = 0	r/R = 0.35	r/R = 0.65	r/R = 1
MH 112 16.2%	MH 114 13%	MH 114 13%	MH 116 9.8%

Asides from detailed geometry values, *JavaProp* also provides coefficients for the estimation of thrust and power. It is important to note the coefficients *JavaProp* uses differ to those which are most common in the literature. The definitions for the coefficients employed are exhibited under these lines and the nomenclature used coincides with the one employed in JavaProp, for the sake of simplicity.

The traditional coefficients, the ones mostly found as thrust and power coefficient (respectively) in aeronautic literature are as follows:

$$T_C = \frac{T}{\frac{\rho}{2} v_\infty^2 S} \qquad (5.1)$$
$$P_C = \frac{P}{\frac{\rho}{2} v_\infty^3 S}$$

On the other hand, the ones named propeller coefficients by *JavaProp* are defined as:

$$C_T = \frac{T}{\rho\, n^2 D^4} \qquad (5.2)$$
$$C_P = \frac{P}{\rho\, n^3 D^5}$$

There is an important parameter used throughout the design, called the advance ratio, which quantifies the distance advanced by the propeller in a single revolution and adimensionalised by dividing by the propeller's diameter [50]. This parameter which provides the conversion between both definitions of coefficients. The definition of this parameter (which is non-dimensional) is:

$$J = \frac{v_\infty}{n\, D} \qquad (5.3)$$

Knowing this, the conversion between coefficients would be:

$$C_T = \frac{\pi}{8}\, T_C\, J^2 \qquad (5.4)$$
$$C_P = \frac{\pi}{8}\, P_C\, J^3$$

For the designed blade, the values for both coefficients as a function of the advance ratio are presented in two graphs in figure 5.2. It is important to bear in mind *JavaProp*'s calculations are only reliable when the propeller loading is not too high; this is when $T_C \lesssim 2$, reason why there is a line showing this limit in 5.2(a). The data represented is obtained directly from *JavaProp*.

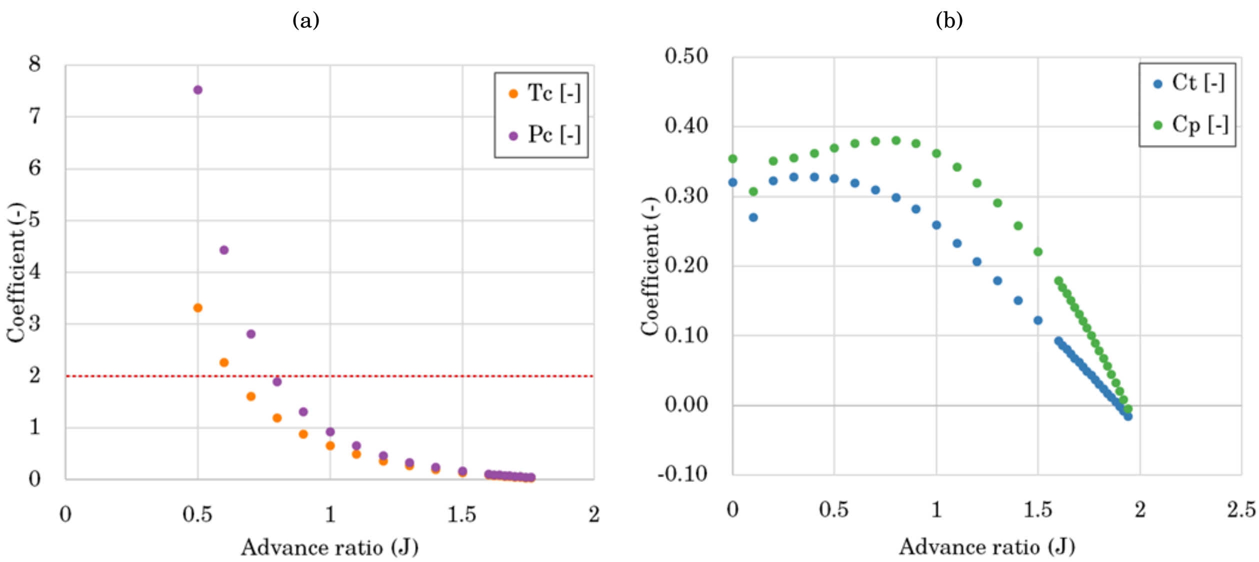


FIGURE 5.2. (a) Traditional thrust and power coefficients used in aeronautics (b) Thrust and power coefficients defined by *JavaProp* as propeller coefficients

To simplify, the coefficients which will be employed throughout the whole project will be the *JavaProp* definition of thrust and power coefficient, that is the coefficients named C_T and C_P, pictured in 5.2(b) and defined in equation 5.2.

This coefficients can be manipulated and used to obtain the thrust and power in different conditions, as they are defined for a innumerable situations by being characterized as a function of the advance ratio. As it will be indicated in detail in the next sections, although the coefficient might be defined for a wide range of advance ratios, not all of them are valid because of the mentioned problems with high loading. After all, this is just a numerical tool to obtain theoretical values for thrust and power. This problematic is taken into account in next section and results are presented and discussed.

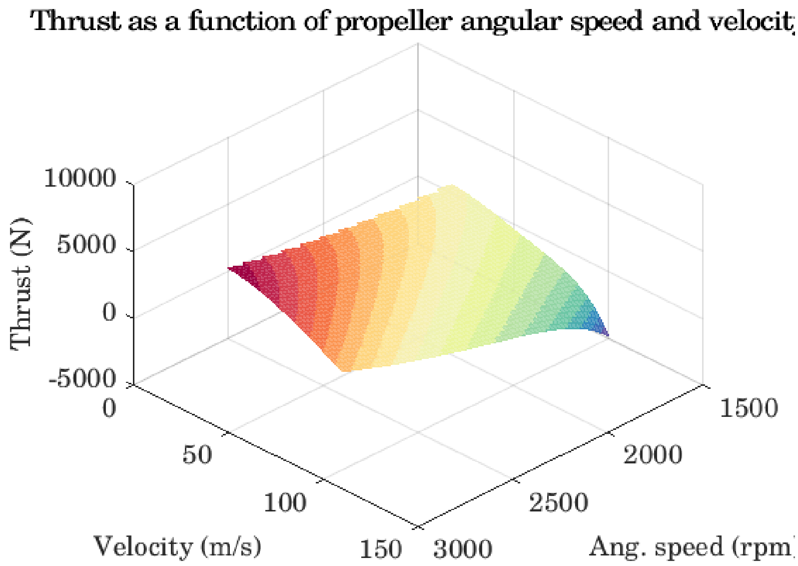
5.1.3 *JavaProp* results

JavaProp provides information in the form of points, due to the fact it works by dividing into small sections the blade to do its calculations. Once the coefficients have been extracted from the *JavaProp* application, it is necessary to work with them in order to visualize the data of interest. To start off, a polynomial adjustment of the points in figure 5.2 is executed. This polynomial is further discussed in section 5.2.

Having the polynomial curves of the coefficients, 3D graphs containing the values of thrust and power in different conditions were done in *Matlab*, taking into account that results for high loading are unreliable and thus were not to be included. These surface plots are the visual representation of the capabilities of the propeller. Anything outside the bounds dictated by the surface is theoretically not possible for the propeller being questioned.

The plots work with a coloured scale, which turns to hotter colours as the values increase, which make it easier to identify the wavy shape the surface is doing. Both graphics, thrust and power, can be seen in figure 5.3. They both refer to the case the aircraft is flying at sea level, that is, with an air density of $\rho = 1.225 \frac{kg}{m^3}$. If any other altitude was to be studied, it would require other plots and would bear slightly different results.

(a)



(b)

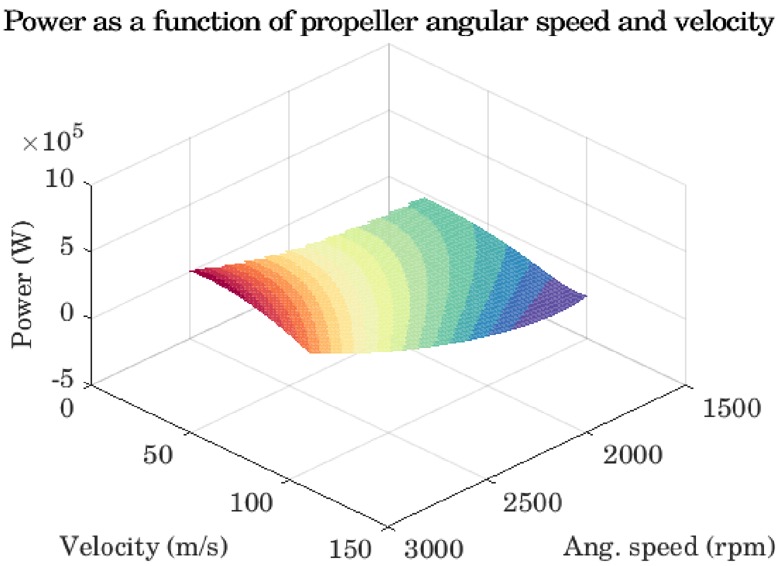


FIGURE 5.3. (a) Thrust at sea level as a function of velocity and propeller's angular speed,leaving out high loading conditions (b) Power at sea level as a function of velocity and propeller's angular speed, leaving out high loading conditions

It can be observed how in the thrust plot in figure 5.3(a) there exists cases at low angular speed and high velocity where the values for thrust are below zero. This describes the phenomenon of thrust reversal, which means the thrust acts against the aircraft's movement forward, decelerating it. It is not important for the analysis and will not be discussed further.

Because the 3-dimensional graphics proved to be confusing when one is unable to manipulate them into showing different perspectives, in figures 5.4 and 5.5 the same information regarding the behaviour of thrust and power for the designed propeller, at different propeller speeds and velocities, can be seen in a much more appealing form.

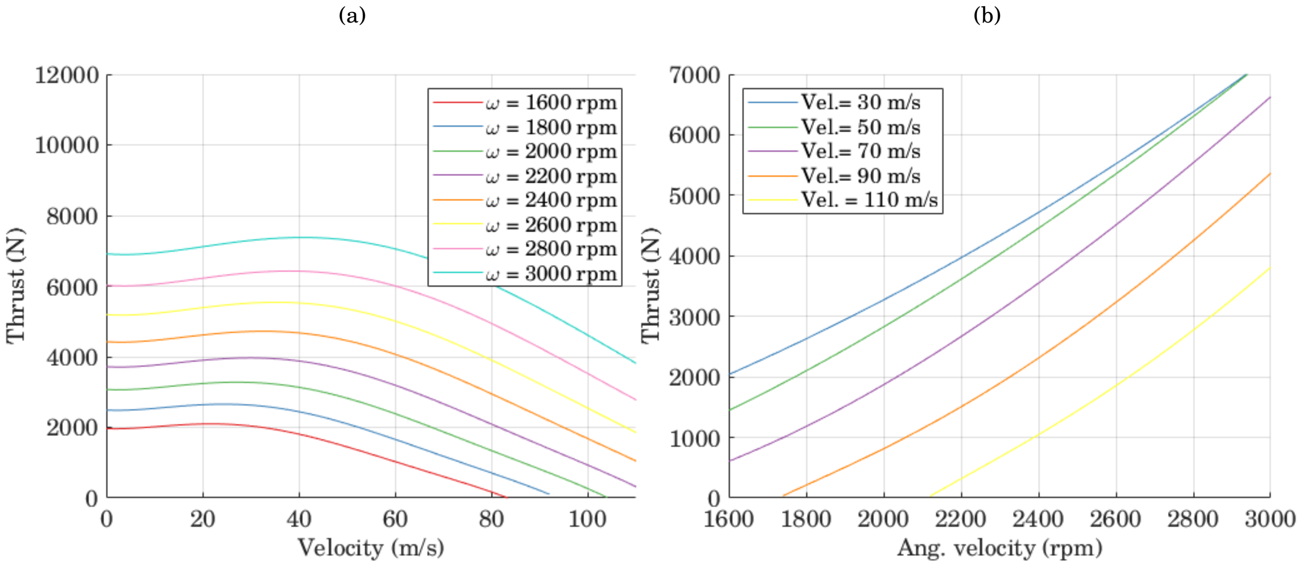


FIGURE 5.4. (a) Thrust at sea level as a function of velocity, for different angular speeds (b) Thrust at sea level as a function of angular speed, for different velocities

As it may seem logical, thrust increases with increasing propeller rotational speed. Also, the amount of thrust decreases with increasing velocity. Another obvious conclusion which can be drawn from the figures is that there are some velocities which cannot be achieved, theoretically, at certain propeller rotational speeds.

The levels of thrust this propeller is theoretically able to achieve will be limited by the power needed to do so, as the amount of mechanical power provided to the propeller by the motor is limited and, due to the efficiency not being optimum, not completely transformed into thrust.

As for power, the power needed for relatively low velocities is virtually the same and higher than the power needed for greater velocities. Similarly to thrust, the power decreases with velocity although not at a such fast rate.

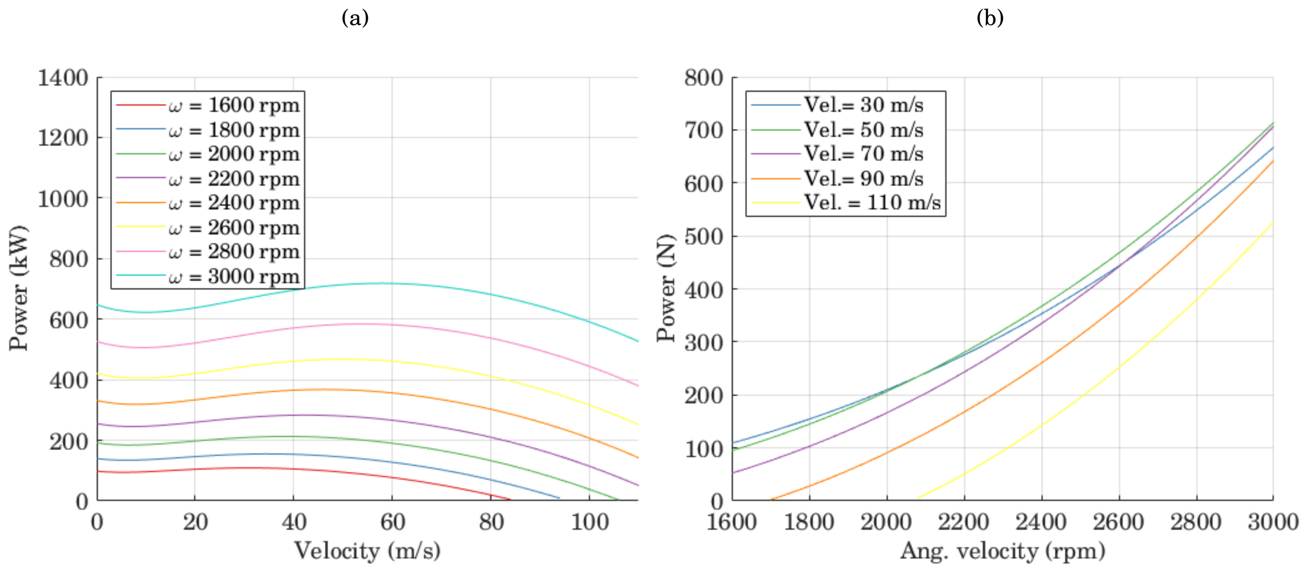


FIGURE 5.5. (a) Power at sea level as a function of velocity, for different angular speeds (b) Power at sea level as a function of angular speed, for different velocities

For both cases, power and thrust, there exists a decrease in the nominal value at small velocities which is more noticeable at high propeller rotation speeds. This is not to be taken into account, given that, as it has already been mentioned, low advance ratios produce unreliable results due to high loading.

It is important to note that, similarly to thrust, even though the propeller is theoretically capable of achieving the power values represented in the figures, there is a limiting factor: the electric motor. In table 3.2 it is possible to see how the technology has only developed to the point of achieving 260 kW of power for electric motors (in 2015). However, figure 5.5 shows the theoretical power needed to achieve certain conditions is way over this value, reason why electric aircrafts are usually limited to low-altitude and relatively low-velocity flights.

Regarding the theoretical efficiency of the propeller, the equation to calculate this is shown in equation 5.5.

$$\eta = \frac{T\,v}{P} = \frac{C_T}{C_P}\left(\frac{v_\infty}{n\,D}\right) = \frac{C_T}{C_P}\,J \tag{5.5}$$

Because of the dependency of both thrust and power on the altitude, velocity and propeller speed, some graphs ar presented to further understand the influence of these parameters on the efficiency.

The efficiency increases with the velocity of the aircraft for any given altitudes, although it decreases with the increase of altitude. For a given propeller speed, there exists a velocity which implies the efficiency plummeting and consequently an increased difficulty to fly. This velocity limit increases with propeller rotation speed and is independent of the flying altitude. All of these conclusions can be obtained from figure 5.6.

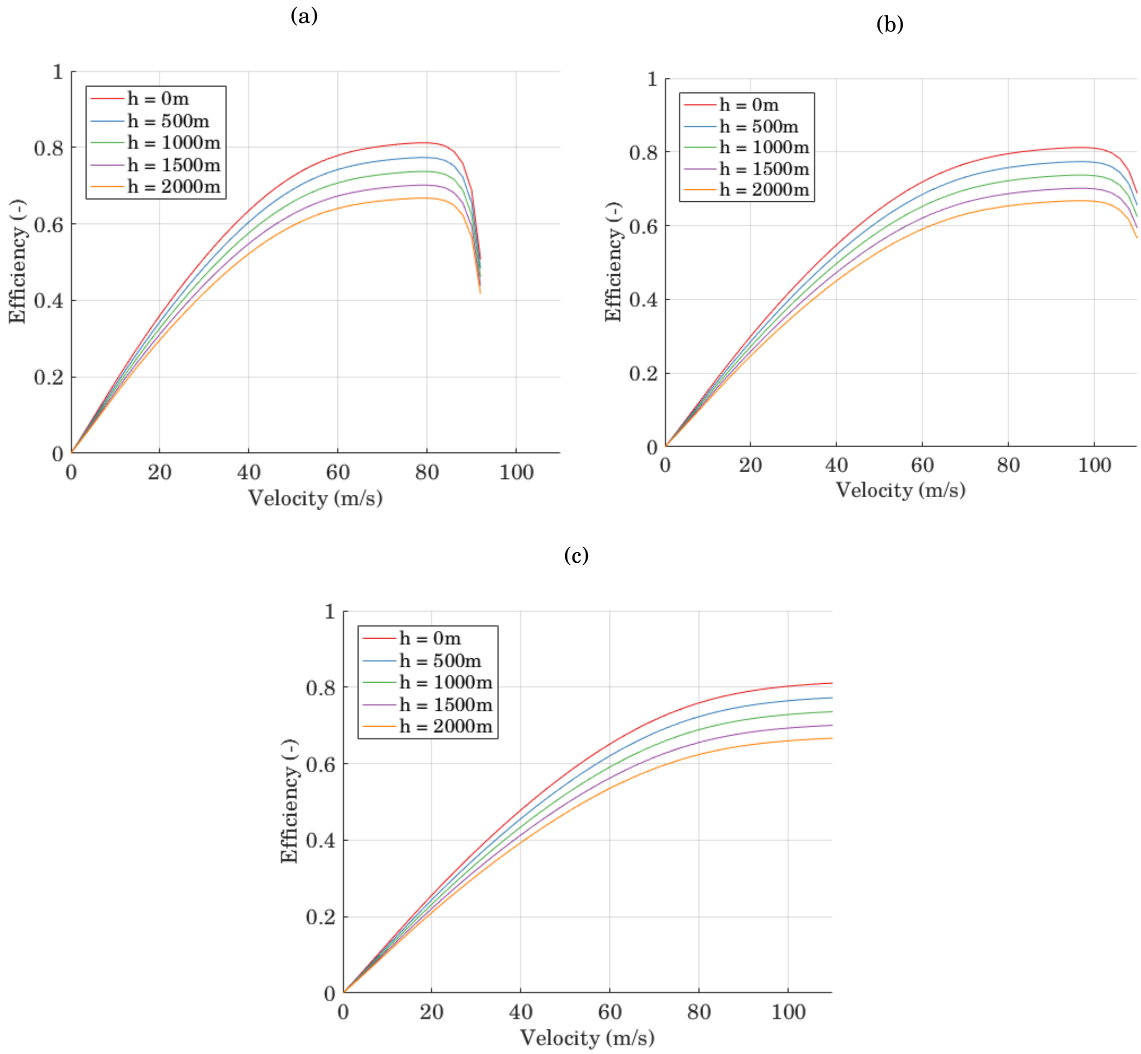


FIGURE 5.6. Efficiency at different altitudes and velocities for a propeller speed of (a) 1800rpm (b) 2200rpm (c) 2600rpm

However, for a given altitude, there exists a limit to the efficiency that can be achieved, regardless of the propeller speed and the velocity. This limit is lower as the altitude increases, meaning the propeller efficiency is greater when it flies at low altitudes. This is a reason why light aircrafts are kept at low altitudes: the increased propeller efficiency allows for an extended range due to a better utilisation of the mechanical power used to rotate the propeller, transforming it

into thrust.
From figure 5.7(a) it can be deduced the maximum efficiency for this custom designed propeller is of $\eta_{max} = 0.82$, which corresponds to the efficiency at sea level.

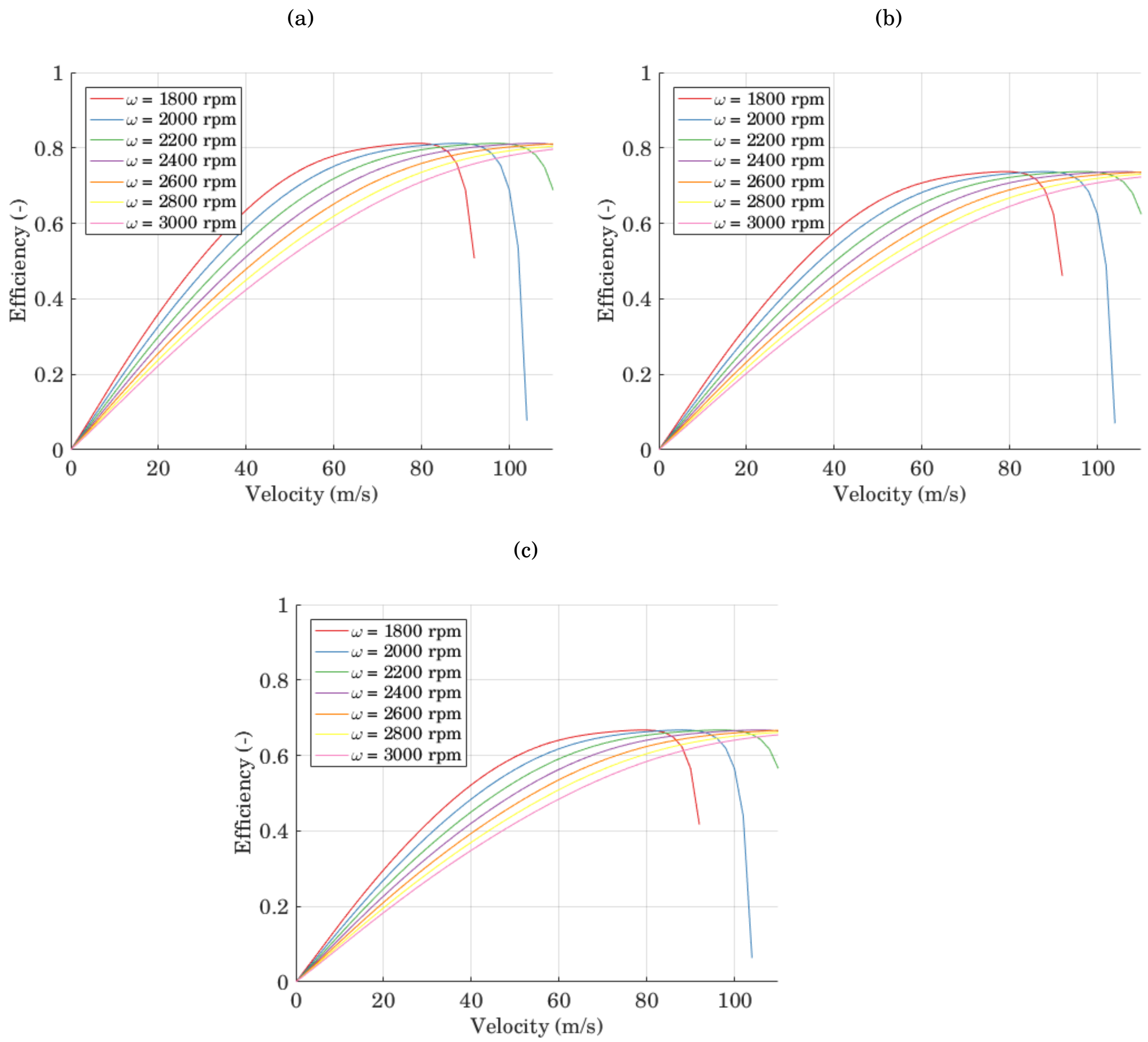


FIGURE 5.7. Efficiency limits for different propeller speeds at (a) sea level (0m) (b) 1000m (c) 2000m

To allow a broader view of these phenomenons, in figure 5.8(a) the maximum efficiency is represented as a function of altitude. It is clear looking at this figure why propellers are the least preferred to fly at high altitudes: up to 50% of all mechanical power is not transformed into thrust at over 5000 m above sea level. Similarly, figure 5.8(b) is a graphic representation of the limit velocity for propeller rotation speeds. As it could be seen in figure 5.6, surpassing these velocities implies a sudden drop in efficiency.

It is to be taken into account that although they might seem to follow a linear trend, these representations are theoretical and do not take into account 3D effects which could severely affect the efficiency, such as reaching supersonic speeds at the blade tip. It is expected the performance of the propeller will change drastically once it approaches the speed of sound.

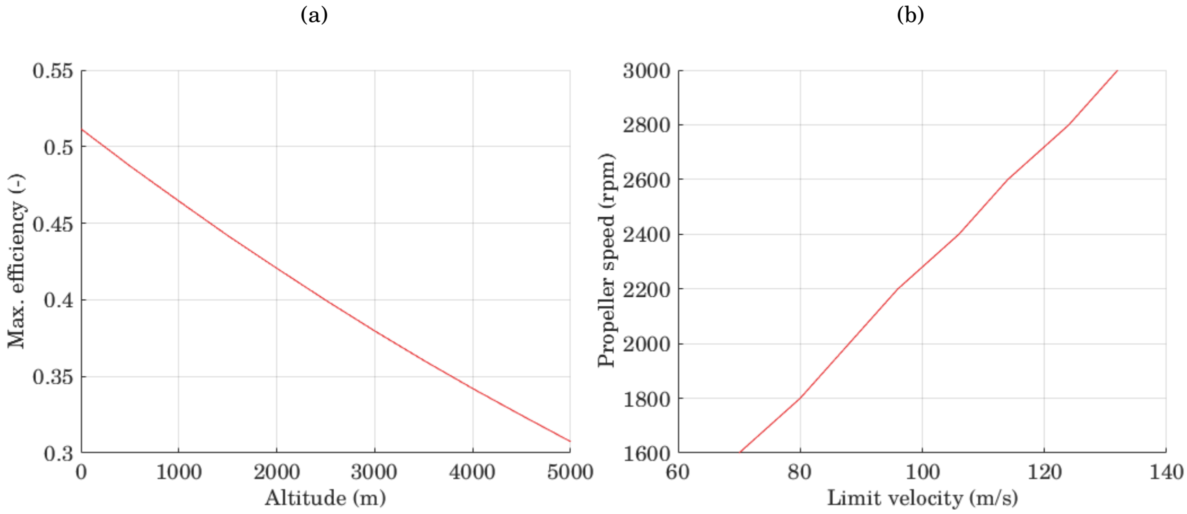


FIGURE 5.8. (a) Maximum achievable efficiency as a function of altitude (0m) (b) Velocity limit for different propeller rotation speeds

5.2 Implementation of the propeller to the model

In the simulation, the propeller will be modelled as a block which will require the input of the values needed to calculate the advance ratio at each instant, that is the velocity and the angular speed, and which will produce as an output the values for the C_T and C_P coefficients for that particular instant. Therefore, the propeller in the simulation is boiled down to merely its thrust and power coefficients.

The inside of the block will work with the aforementioned coefficients, which will be required to be as a function of the advance ratio by adjusting a polynomial line to the points calculated in *JavaProp*. The reason for this is that the application only provides a table of values and while the coefficients could be just retrieved from the table, the polynomial coefficients of high degree have proven to adjust nearly perfectly and work appropriately. Following, the expressions for polynomials of these non-dimensional coefficients can be found.

$$\begin{aligned} \mathit{Thrust}: C_T &= -0.1049J^5 + 0.5509J^4 - 0.9814J^3 + 0.5328J^2 - 0.0425J + 0.3046 \\ \mathit{Power}: C_P &= 0.0854J^6 - 0.5922J^5 + 1.6295J^4 - 2.2583J^3 + 1.3988J^2 - 0.2495J + 0.3457 \end{aligned} \tag{5.6}$$

These expressions are only valid for the propeller designed and are very sensible to any changes, reason why they should be recalculated if any variations to the propeller where to be done. The adjustment of the curves to the points has a coefficient of determination $R^2 > 0.99$ in both cases. The polynomials in question are represented in figure 5.9.

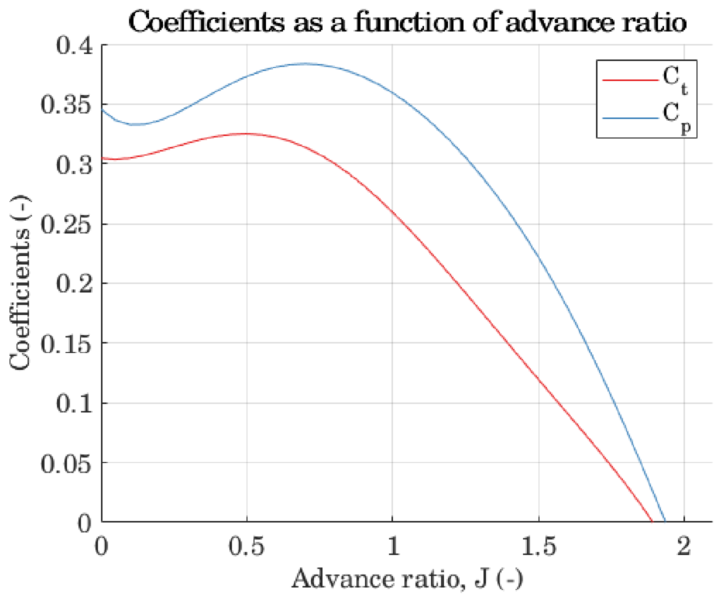


FIGURE 5.9. Polynomial adjustment of the thrust and power coefficients

A more detailed explanation, accompanied with pictures, will be done in the next chapter, which will describe the totality of the propulsion block in which the propeller system is included, in subsection 6.1.1.

CHAPTER 6

PROPULSION BLOCK

This block contains the fundamental modifications applied to the *Sky Hogg* simulation. In section 4.2 the original layout was shown, where it could be appreciated how the model only uses a direct thrust input, ignoring any engine implications. This chapter's aim is to describe the totality of the modifications performed on the subsystem to transform it into an electrically propelled aircraft.
The modification of this propulsion block aims to describe and follow the dictations of the propeller and motor, adjust to their limitations and deviations, in opposition to the original model where a thrust as a function of throttle was employed. However, the simplifications considered in the original model regarding considering thrust forces negligible in Y and Z axes are kept. Likewise, the moments on all three axes are considered null.

6.1 Overview

As described in section 4.2, there are three main parts to the propulsion block: propeller, electric motor and batteries. The general distribution of the modified block is as follows in figure 6.1. The two most important subsystems, propeller and electric motor, are tinted in blue and magenta, respectively, to improve identification and readability. It can be seen how the outputs of the propulsion subsystem are the same as in the original model: the thrust and moment in all three axes.

The inputs to the model are the wind density (obtained from *EnvData*, environment data), the velocity, and the pilot commands (throttle); as opposed to the original model, which only had the latter as an input. The signals entering and exiting blocks carry names which are self-explanatory.

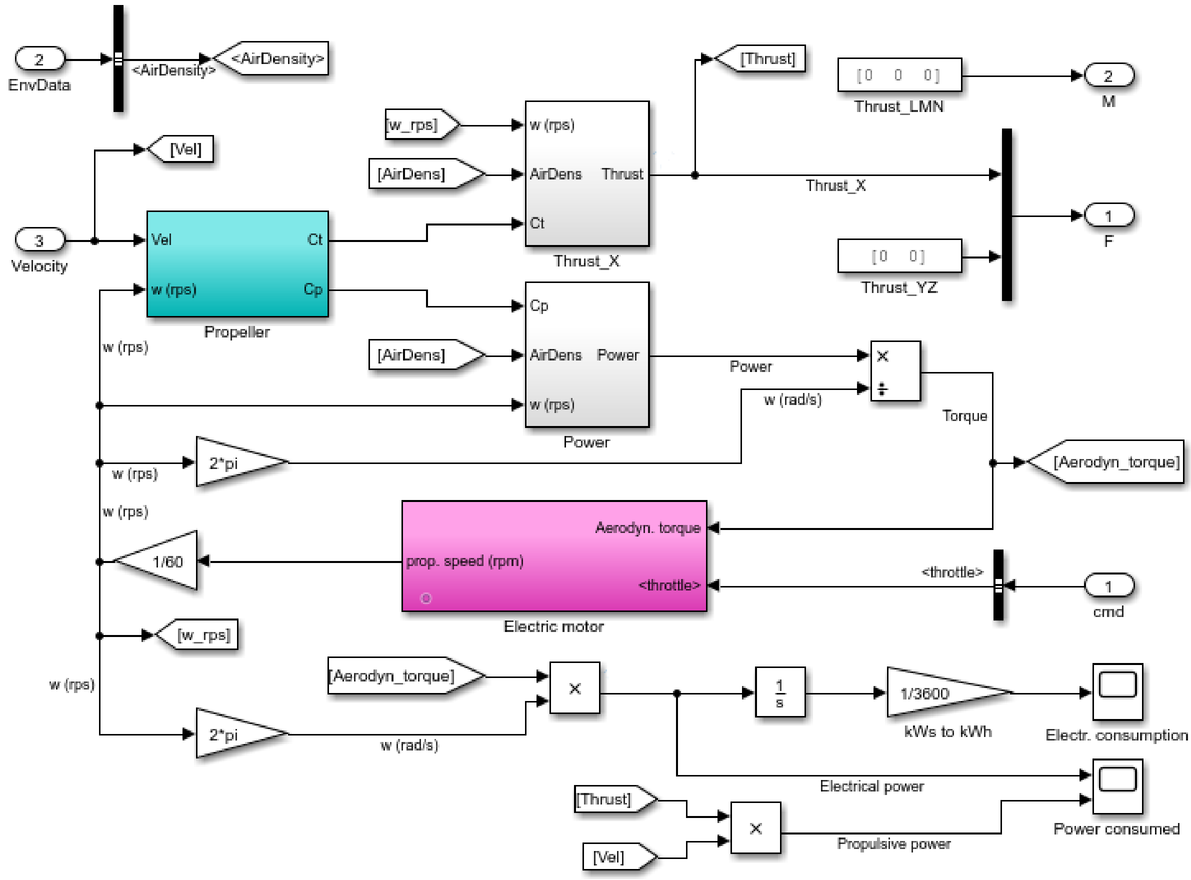


FIGURE 6.1. View of modified propulsion block

The scopes and the values they represent add nothing to the model and are a mere form of monitoring the correct functioning of the subsystem, reason why the parts involving calculations of signals to represent in said scopes will not be discussed in this part.

6.1.1 Propeller block

To implement the propeller to the model, a block with the parameters which has as inputs the propeller blade speed and the aircraft absolute velocity was implemented. This values serve to calculate the advance ratio, which is the parameter which this block actually needs. The value for the diameter was stored as a variable in the model workspace. Also, because the aircraft mostly follows a linear movement along its longitudinal direction, which coincides with the x axis, the velocity taken into account is just that for said axis.
The interior of this block can be seen in figure 6.2.

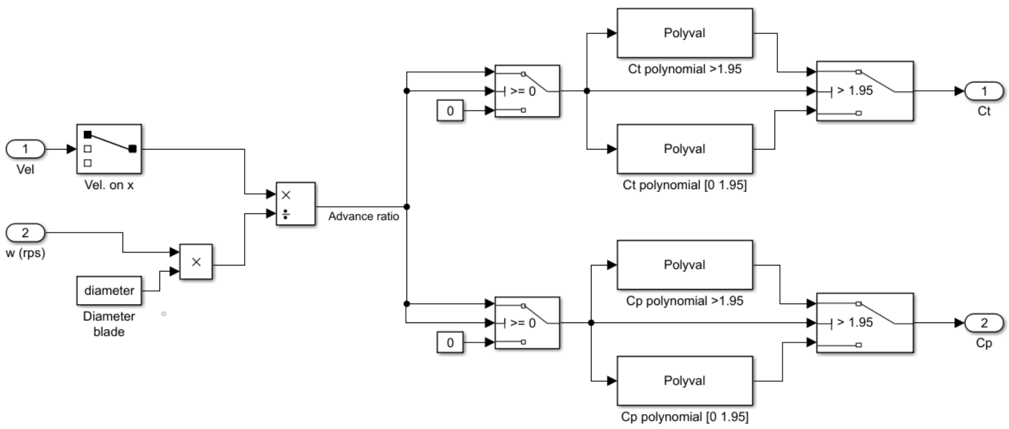


FIGURE 6.2. Propeller subsystem implemented in Simulink

Because the polynomials modelling thrust and power coefficients are only proven to be valid an interval from 0 to 1.95, and due to their high degree (which makes them more prone to abrupt variations), conditions had to be applied which describe the behaviour of said coefficients outside the interval of validity. Advance ratios under zero were considered to be equal to zero and for advance ratios over 1.95 the coefficients were assumed to behave in a linear way following the tendency they had before reaching 1.95 value. This was done to avoid anomalous results during the simulation, but bearing in mind that values of the advance ratio out of the valid interval would imply defective behaviour regardless.

6.1.2 Power and thrust subsystems

The thrust and power subsystem have the function of implementing the thrust and power equations; they are just another form of the equation 5.2. The block's functioning can be summarized into the equation 6.1.

$$\begin{aligned} T &= C_T\,\rho\,n^2 D^4 \\ P &= C_P\,\rho\,n^3 D^5 \end{aligned} \tag{6.1}$$

The block distribution is straightforward. Constants such as the blade diameter are stored in the *Matlab* workspace and retrieved by the model in *Simulink*. It is to be taken into account that the nomenclature of equation 6.1 may not exactly match the one displayed on figure 6.3, but correspond to the same values.

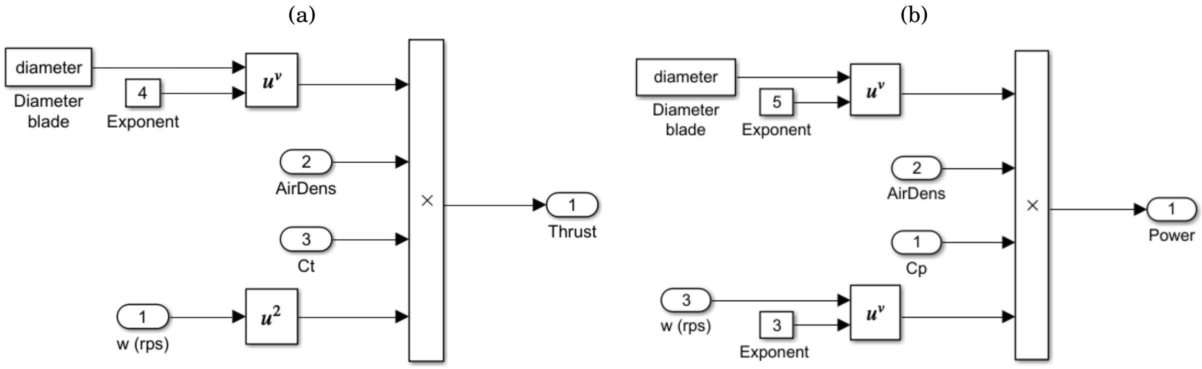


FIGURE 6.3. (a) Thrust subsystem in *Simulink* (b) Power subsystem in *Simulink*

6.2 Electric motor block

This block is of great importance, as it is a central piece to the modification and the very reason it would be considered an electric and thus greener aircraft.
This block will have as input the pilot's commands, which is quite trivial as it needs the amount of throttle commanded, and the current aerodynamic torque so as to adjust the desired torque to the actual one. The obvious output of the electric motor will be the propeller speed, given it controls the torque applied to the shaft, which conclusively affects the propeller's rotational speed.

In this block, the permanent magnet synchronous motor implemented was provided done by the tutor; so it is the design of control which is of interest.

6.2.1 Brushless electric motor control

By analysing the available data on electric aircrafts, which can be seen in table 3.2, it becomes quite clear that brushless electric motors are the most popular election. For this reason, the motor chosen to substitute the piston engine in the *SkyHogg* was a brushless motor.

For the simulation part, the fact that the motor to be simulated is a brushless AC motor is quite convenient to develop its controller because theory shows it is possible to use the same control strategy in a DC motor than in an AC motor if the latter is done similarly enough to the former.

If for an AC machine we define a system of reference, which is aligned with the magnetic field generated by the permanent magnets in the rotor, the equations for the magnetic flux would result as shown in equation 6.2, where there is an additional term for flux, generated by the permanent magnets, which is more specifically the flux linkage due to the permanent magnet (in the equation it is highlighted in red). On the other hand, when considering the equations for the stator, the outcome is similar to the DC case, just with some additional terms which, again, are due to the permanent magnets.

$$\begin{aligned} \lambda_d &= L_d i_d + \lambda_0 \\ \lambda_q &= L_q i_q \end{aligned} \tag{6.2}$$

$$\begin{aligned} v_d &= R_s i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \\ v_d &= R_s i_q + \frac{d\lambda_q}{dt} + \omega_r \lambda_d \end{aligned} \tag{6.3}$$

When plugging in equation 6.2 into equation 6.3 the result is approximately a first order system, which is comparable to that of the DC case. The electromagnetic force induced by the permanent magnet is present in the form of the rotor angular speed times the flux, $\omega_r \lambda_0$. The resulting system can be seen in equation 6.4.

$$\begin{aligned} v_d &= R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \\ v_d &= R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \lambda_0 \end{aligned} \tag{6.4}$$

The system is missing the torque expression, which is stated in equation 6.5. In order to allow the control of the torque with this AC machine, a usual approach is to force one of the currents to be zero, modification which results in a simplification of the torque equation as well as a simplification of the overall system. With this adaptation, the torque comes as a constant times a current, which is desirable in order to develop a controller. Said constant is given the name λ_m, for the sake of simplicity.

$$\begin{aligned} T_m &= \frac{2}{3} p (i_q \lambda_d - i_d \lambda_q) \\ with\, i_q &= 0 \\ T_m &= \frac{2}{3} p \lambda_d i_q = \lambda_m i_q \end{aligned} \tag{6.5}$$

It becomes clear that in order to control the torque, the only necessary thing will be to control the currents. So as to control said currents i_d and i_q, it is necessary to make some assumptions. In first place, it will be assumed ω_r varies at a slow rate, thus making the term $\omega_r \lambda_0$ negligible. Next, a first order linear system will be forced by grouping some terms:

$$\begin{aligned} v_d &= -\omega_r L_q i_q + u_d \\ v_q &= \omega_r L_d i_d + u_q \end{aligned} \tag{6.6}$$

$$u_d = R_s i_d + L_d \frac{di_d}{dt}$$
$$u_q = R_s i_q + L_q \frac{di_q}{dt} \tag{6.7}$$

Finally, equation 6.7 is where the control law will be applied. Translating it to the frequency domain, what is seen in equation 6.8 is obtained.

$$I_d = \frac{1}{R_s + sL_d} U_d(s)$$
$$I_q = \frac{1}{R_s + sL_q} U_q(s) \tag{6.8}$$

Of course, the brushless AC motor simulation has much more to it. The system of reference considered for the control is just a tool, and actually what the motor outputs is triphasic current. Therefore, transforming the currents from a system of reference to another becomes a necessity. The first step is to transform the triphasic system of reference into a biphasic system by performing the appropriate transformations. The transformation is done by just considering that, by definition, (ideal) triphasic currents bear between them a separation of 120°, and the target is for the biphasic currents to be orthogonal.

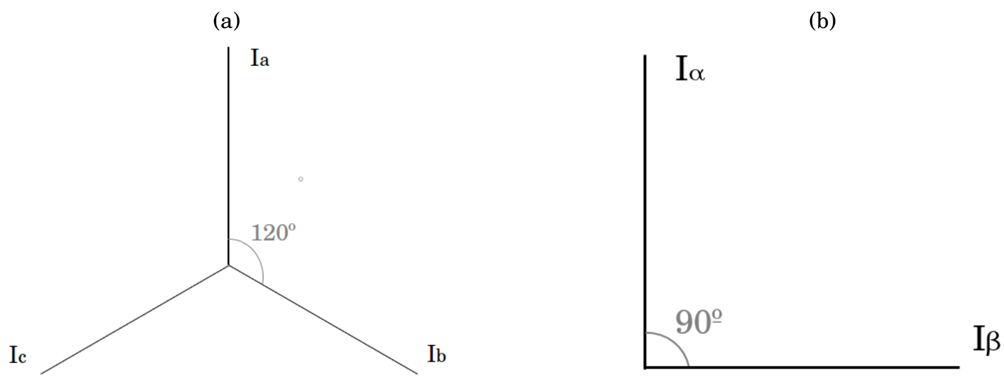


FIGURE 6.4. (a) Triphasic current diagram (b) Biphasic current diagram

The transformation, known as the Clarke transformation, becomes trivial geometry, consisting of a conversion matrix stated in equation 6.9.

$$\begin{pmatrix} 1 & sin(-30) & sin(180+30) \\ 0 & cos(-30) & cos(180+30) \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} = \begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix} \tag{6.9}$$

Nonetheless, this is still not the system of reference that has been used to design the control. The system of reference of I_q and I_d, these two currents are aligned with the magnetic field, which rotates along with the magnets. This is the same as saying a stationary system is transformed into a rotational reference frame. Knowing the angle the magnets bear with the stationary system, the transformation to the desired rotating system of reference just needs a rotation matrix, in equation 6.10. This transformation process is known as the Park transformation.

$$\begin{pmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{pmatrix} \begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix} = \begin{pmatrix} I_d \\ I_q \end{pmatrix} \tag{6.10}$$

On the other hand, of course this transformations need to be undone, but from the voltage part because, following the theory developed above, what comes as input to the brushless motor is triphasic voltage. Regardless, the transformations applied will be the inverse Park and inverse Clarke transformation, respectively.

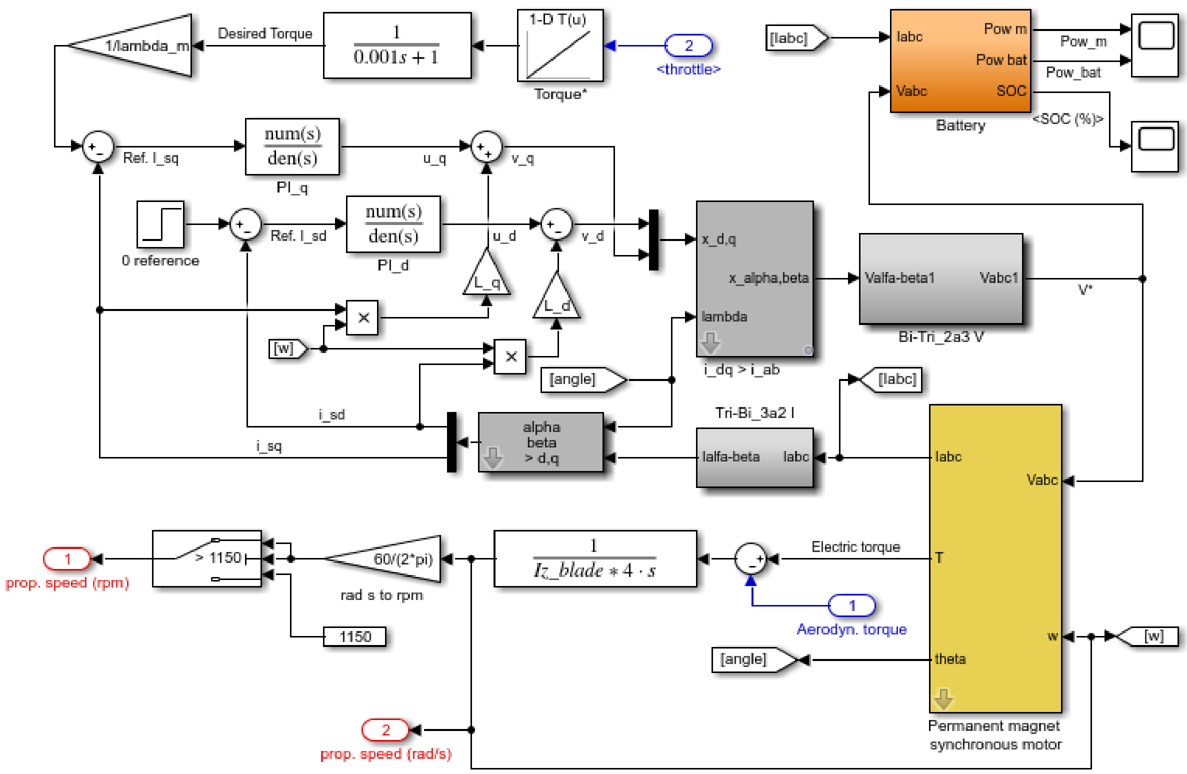


FIGURE 6.5. View of the brushless AC motor in the *Simulink* environment

In figure 6.5 a general view of the electric motor block can be seen. The block involving conversions between systems of reference are shown in grey, whilst the permanent magnet motor is coloured in yellow and the batteries in orange. The inputs are highlighted in blue and the outputs are in red, to enhance visual understanding.

The way this element works in the simulation is quite clear. The electric motor controller takes the throttle command as its input; this command selects the torque to be demanded. The torque actually follows a linear increase, meaning a null throttle will be commanding a torque of zero and the maximum throttle will equal to the greatest torque available. This desired torque is what is 'fed' to the controller, which determines the necessary current, named I_{sq} in the simulation. The outcome of the PI controller, tuned with *Simulink*'s *Control System Tuner*, is the intermediate u_d which when added to the current signal times the inductance and the rotational speed results in the voltage, v_d. Simultaneously, the exact same is happening to the other current signal, labelled I_q, which has a reference current of zero.

The two voltages come together for their change of system of reference,after which they finally go as input to the motor.

Regarding the tuning of the controllers, as mentioned it was performed with *Simulink*'s *Control System Tuner*, but nonetheless required the parameters to be adjusted. For this controllers, a PI law was deemed sufficient, as the interesting part is to control the stationary behaviour.

The PI control was designed compromising the overshoot and the settling time. A low overshoot is desirable so as to avoid power peaks and a rapid settling time is essential. Finally, the parameters which where found to meet the conditions in a balanced way are shown in table 6.1.

TABLE 6.1. Specifications of the PI controllers

Controller input	**Response time (μs)**	**Settling time (ms)**	**Overshoot (%)**
I_{sq}	740	3.7	11.5
I_{sd}	730	201	7.86

The controllers finally took the forms shown in equation 6.11.

$$
\begin{aligned}
G_{I_{sq}} &= \frac{0.19154s + 143.50856}{s} \\
G_{I_{sd}} &= \frac{0.01498s + 4.58156}{s}
\end{aligned} \tag{6.11}
$$

The permanent magnet motor also has two other outputs: theta and the electric torque. Theta is used in the aforementioned process, where its mission is to help in the conversion between different systems of reference. On the other hand, the electric torque is compared to the aerodynamic torque, from which the speed of revolution is obtained by means of using the same equality as in equation 6.5 minus the losses by shaft friction, which are considered negligible. This rotational speed is sent as a block output, so it can be used in the propeller block.

There exists an element which has a function which should be cleared up. Just before the output of the propeller speed, there is a selector block. This block's function is to choose to output the calculated propeller speed if it is bigger of equal to the constant connected underneath, which stands for a propeller speed in revolutions per minute. This constant is the minimum propeller speed to avoid the propeller's high loading at the starting flight conditions. It does not actually represent a physical component and is just a quick fix for the fact that the missions which the simulation is going to be flying will not start from the ground and thus should not start with a propeller speed of zero.

One last thing to take into account is that what has been exposed up to now would fit any brushless AC motor, but what makes it the particular motor in the simulation is the definitions of its parameters. They are shown in table 6.2 and were scaled from a 60kW industrial motor in [51].

TABLE 6.2. Parameters of the simulated permanent magnet motor

Resistance, R_s (Ω)	**Inductance, L_d L_q (H)**	**PM magnetic flux, λ_m (Wb)**	**Nominal power (kW)**	**Max. Angular speed, ω_{max} (rad/s)**
0.0112	7.32×10^{-5}	1.732	180	251

6.3 Batteries

This component is too of great importance, given as it has already been mentioned that it limits the autonomy of the aircraft and thus conditions its usefulness for different missions. A parameter which will need to be calculated regarding the batteries is the total energy they are able to provide. In order to calculate this, an energy density for batteries must be chosen and then the available battery weight.
The energy storage technology up to 2009 had developed Lithium-Ion batteries of up to 265Wh/kg [52], and there exists evidence the number might be up by now. Anyway, to be conservative, the energy density chosen for the batteries to be simulated is of 250Wh/kg.

In order to compute the battery available weight, there were a number of things which had to be assumed about the *SkyHogg*. Given there exists little information on the model and knowing it is a model theoretically developed during the nineties, an aircraft of similar characteristics was found to serve as an approximation for the *SkyHogg*'s unknown data. The aircraft found as of likewise features was the *Lancair IV*, developed during the same decade and of a very similar shape and size.

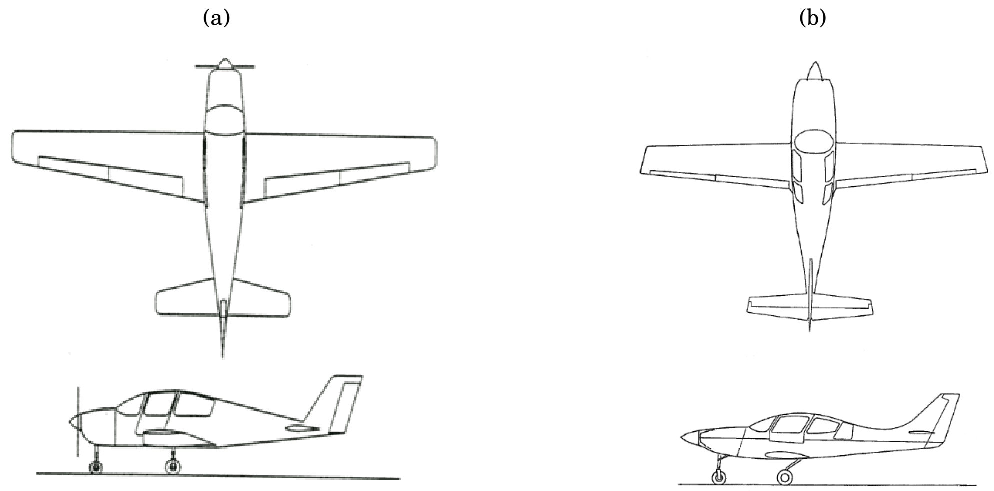


FIGURE 6.6. Comparison between similar aircrafts (a) The *SkyHogg* plans (b) Plans of the *Lancair IV* [53]

The weight values are those of interest. They are presented in table 6.3. It is assumed the weight of the propeller and propeller bearing will be very similar and thus is not taken into account when calculating.

TABLE 6.3. Weight values of the *Lancair IV-P* and the electric motor

Empty weight (kg)	**Gross weight (kg)**	**Engine weight (Continental IO-550) (kg)**	**Dry weight (without engine) (kg)**	**Electric motor weight (kg)**
998	1610	195.5	802.5	20

Finally, considering the *SkyHogg*'s modified weight will be the *Lancair IV*'s dry weight plus the electric motor, this leaves the altered aircraft with an empty weight of **822.5kg**, which has a large margin to consider for batteries before it reaches the gross weight.

The unaltered simulation of the *SkyHogg* flies with a weight of 1299kg, and considering two people of 80kg are on the aircraft, a margin of 316.5kg is left for batteries, considering the weight stays unmodified. To round it up, it will be considered a grand total of 300kg of batteries are implemented in the *SkyHogg*.

The table below summarizes the batteries' situation.

TABLE 6.4. Battery characteristics for the *SkyHogg*

Battery energy density (Wh/kg)	**Batteries weight (kg)**	**Batteries energy (Wh)**
250	300	75000

In the simulation, the power consumed by the motor needs to be calculated so the battery can provide it. In triphasic circuits, the power being consumed is calculated as seen in equation 6.12. Of course, internally, the battery presents some losses, which are in fact very low and for the simulation were considered to be of 2%. This losses means the power being drained from the battery is actually slightly higher than what it provides the motor.

$$P = i_a V_a + i_b V_b + i_c V_c \tag{6.12}$$

To compute the state of charge of the battery, there exist uncountable different models and approaches. To simplify the simulation, a predefined battery block which includes a state of charge output was used. The input to that block is the battery current, which is computed as shown in equation 6.13.

$$i_{bat} = \frac{P_{bat}}{V_{bat}} \tag{6.13}$$

The discharge law followed is as seen in equation 6.14, where Q stands for the maximum theoretical capacity in Ah.

$$SOC = 100\left(1 - \frac{1}{Q}\int_0^t i(t)dt\right) \tag{6.14}$$

The parameters which the battery mask uses are the nominal voltage and rated capacity, which ultimately describe its energy. The nominal voltage was set to be 500V after looking in the literature for batteries implemented in electric vehicles of similar characteristics [54]. To have a more realistic initial state of charge, it was set to 90%, to take into account the take-off and climb consumption.

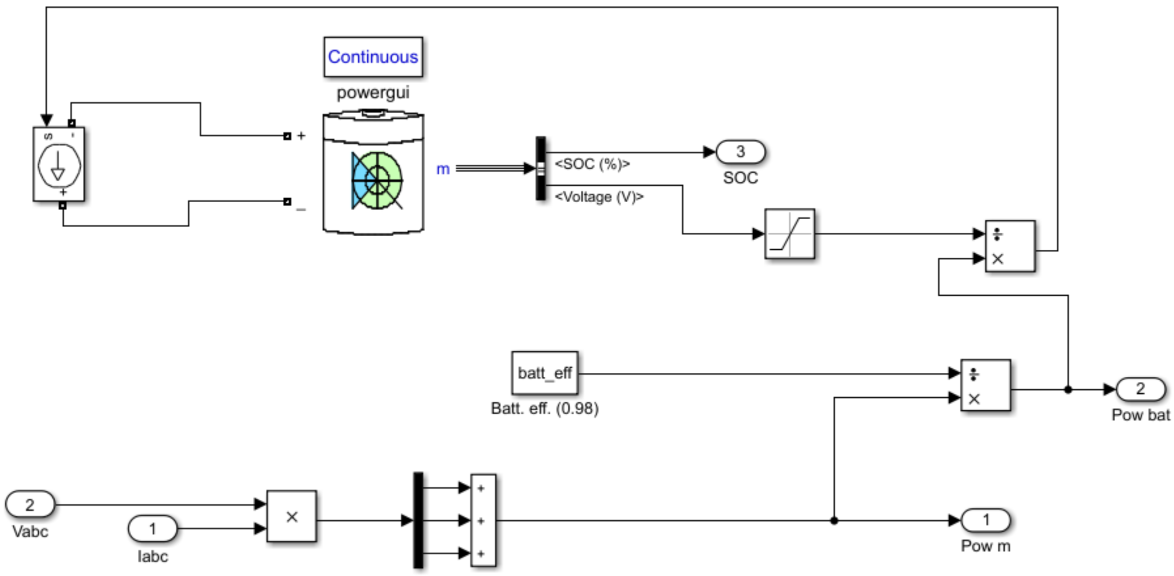


FIGURE 6.7. View of the inside of the battery block

Chapter 7

Performance and results

This chapter's aim is to present the results for tests carried out with the simulation, which was explained in the above sections. The *SkyHogg* electric modifications must be tested in a simulation environment to analyse the feasibility of performing the actual modification. Basing the viability of the modification upon the fact the aircraft will be used mainly for low altitude, short flights near the airport, such as for pilot training, missions are designed and tested based on the premise the flights will be carried out by inexperienced pilots and will only involve simple manoeuvres.

7.1 Performance during normal use

This first section will test the capability of the modified aircraft to fly casual situations, the type a light aircraft would fly in normal conditions, as in pilot training lessons.

7.1.1 Levelled flight at constant throttle

This section aims to describe the aircraft's performance in the simplest type of flight: a levelled, simple flight. This will draw a picture of the capabilities of the aircraft and will pave the way to simulating more complicated missions.

For this particular section, the mission will be kept very simple, and it is described in table 7.1. The aim is to look at aircraft parameters, such as power consumed, efficiencies of the motor and charge of the batteries and extrapolate for longer levelled flights, which also most certainly happen in real life.

TABLE 7.1. Description of mission for the levelled flight case

Simulation time (s)	**Altitude (m)**	**Flight TAS (m/s)**
100	1700	65

The representation of the vertical profile of this mission can be seen in figure 7.1. The actual altitude does not exactly correspond with the commanded altitude because the elevator is controlled by the autopilot, which is defined by two discrete zeta controllers which may allow for some error. Still, the error is quite small when put into perspective, of about 5 meters. This error would also be expected to happen in a real life case given the imperfect nature of autopilots and sensors which could also be to blame for the deviation.

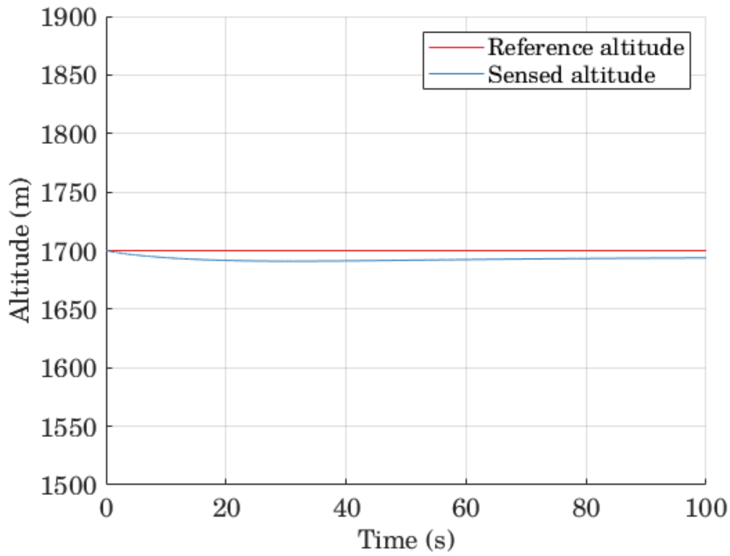


FIGURE 7.1. Vertical profile of a levelled flight at 1700 meters

In this first mission, it might come as quite obvious the power consumption will be kept approximately constant too, as there is no manoeuvring that could affect it, such as accelerating or descending. This will allow for a first calculation of the power losses in the motor and the efficiency of the propeller.The fact this type of flight does not affect the power consumption will also allow to observe the discharge of the battery for this particular case, which should be approximately linear.

The top values for power in each case can be obtained easily by manipulating the figures. Although they might seem exactly constant in figure 7.2, because they are really big values they are not exactly constant and do vary in some hundreds of Watts, but because the conditions of the simulation are kept the same, so should the efficiencies, reason why the values were taken on some random time. From here it is trivial to obtain the efficiencies; the motor efficiency is of $\eta_{motor} = 0.985$ and the efficiency of the propeller for this particular case is $\eta_{prop} = 0.779$. The motor proves to have a really good efficiency, with <2% of losses.

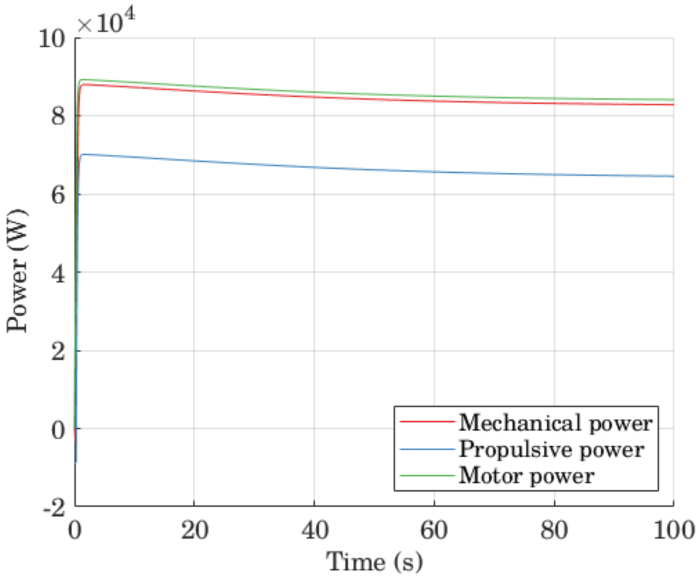


FIGURE 7.2. Power plots in a levelled flight

The power losses in the motor can be calculated by employing the formula shown in equation 7.1. It uses the root mean square value of the current, which is computed from the peak value of the intensity.

$$P_{loss} = 3 R_s \, i_{RMS}^2 = 3 R_s \left(\frac{I_{max}}{\sqrt{3}} \right)^2 \tag{7.1}$$

It now seems convenient to analyse the triphasic voltage and current behaviour in the motor during this levelled flight. As may be expected, there exists at the very start a transition part, when both the current and voltage start from zero. Again, this is because of the special case of starting the flight from a dynamic situation in which it is already at an altitude and requires a starting velocity different to zero. Nevertheless, both parameters reach their final forms in a reduced amount of time, both reaching the correct peak value for the voltage case or reaching the right frequency, which applies for both.

Because of the high frequency, in order to be able to observe the behaviour of both parameters, only the first second of the simulation was plotted in figure 7.3, to improve readability. The behaviour observed during the second half of the plot is equal to the behaviour obtained during the rest of the simulated seconds.

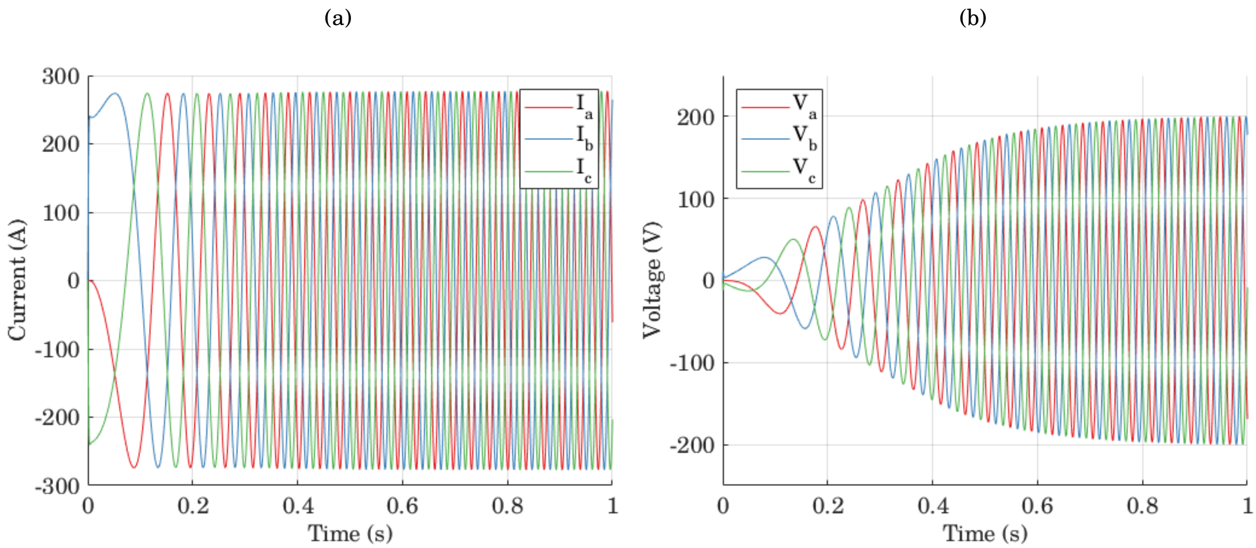


FIGURE 7.3. (a) Triphasic current levels for the first second of levelled flight (b) Triphasic voltage levels for the first second of levelled flight

Now it is easy to check the peak value for the current is $I_{max} = 274.5$A, and reading the resistance value from table 6.2 the power losses in the motor are easy to compute.

$$P_{loss} = 3 R_s \, i_{RMS}^2 = 843.93\text{W} \tag{7.2}$$

The losses calculated in equation 7.2 might seem big but they are definitely not when compared to the power of the motor, which reaches a value of 82.79kW, meaning the calculated losses are equal to about 1.015% of the motor power, which coincides with the motor efficiency calculated before.

Now, observing the state of charge of the batteries, although bearing in mind the batteries start the simulation with a charge of 90% to take into account the energy consumption whilst taking off and climbing, it is easily appreciated how the discharge appears to be perfectly linear, at a rate of 1.1% of discharge every 100 seconds. This may be seen in figure 7.4.

The equation the battery block follows to calculate the state of charge is shown in 6.14.

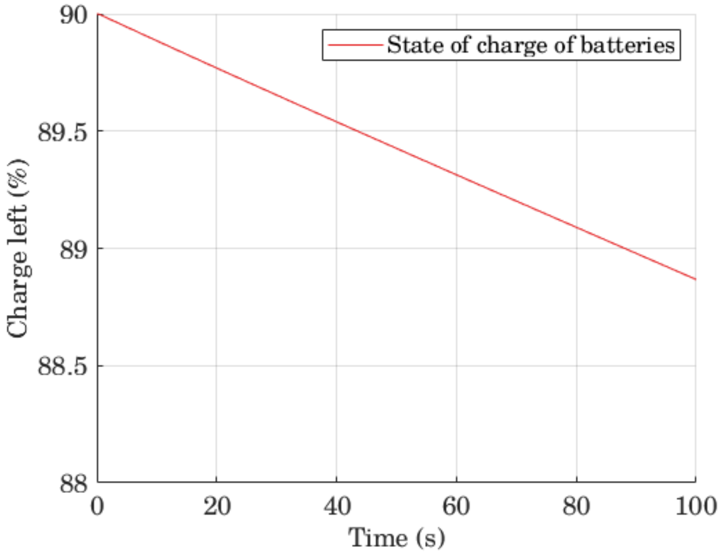


FIGURE 7.4. State of charge variation a levelled flight

This 100 seconds simulation is too short to observe any non-linear behaviour in the discharge, but considering the discharge was to be linear all the way and knowing it is recommended to not fly with the battery charge under 20% it can be stated the aircraft could fly in these conditions for around 106 minutes, which is just a little under two hours. Of course, this is not taking into account the landing consumption.

So, in conclusion, the modified aircraft performs okay in a levelled flight at the stated conditions. This is the minimum it should do in order to be considered a viable modification. The next step involves analysing its performance during an actual mission.

7.1.2 Climbing and descending flight

For this part, the analysis is going to consist on climbs and descents of the aircraft. The climb profile will be a succession of three steps at different climb rates and a descent immediately after the last step, which is intended to bear some similarity with a pilot training lesson based on climbing and descending practice. The total simulation time is of a 8 minutes and 20 seconds, so it would just account for a fraction of the lesson, assuming they usually are of an hour of duration. For the record, the actual time spent simulating this mission was of 35 and a half minutes.

For this simulation the throttle will accompany the altitude variation commands and the velocity will change freely depending on the conditions, given there will exist deceleration and acceleration due to the changes in thrust because of the throttle variations.

In table 7.2, a summary of the mission as it was intended and its output can be observed.

TABLE 7.2. Description of mission for climbing/descending flight

Simulated time (s)	**Starting altitude (m)**	**Ending altitude (m)**		**Maximum altitude (m)**		**Flight TAS (m/s)**	
		Command	**Sensed**	**Command**	**Sensed**	**Min**	**Max**
500	1700	1780	1775	1840	1836	54	65

To make it clearer, in figure 7.5 its profile as a function of time is represented. The aircraft followed in an accurate way the commanded altitudes, allowing for a deviation of no more than 5 meters.

The altitude commands were designed as a succession of steps with a rate limiter along with a variation of throttle whenever the aircraft was about to increase or descend. the throttle varied accordingly, as shown in subfigure 7.6(a).

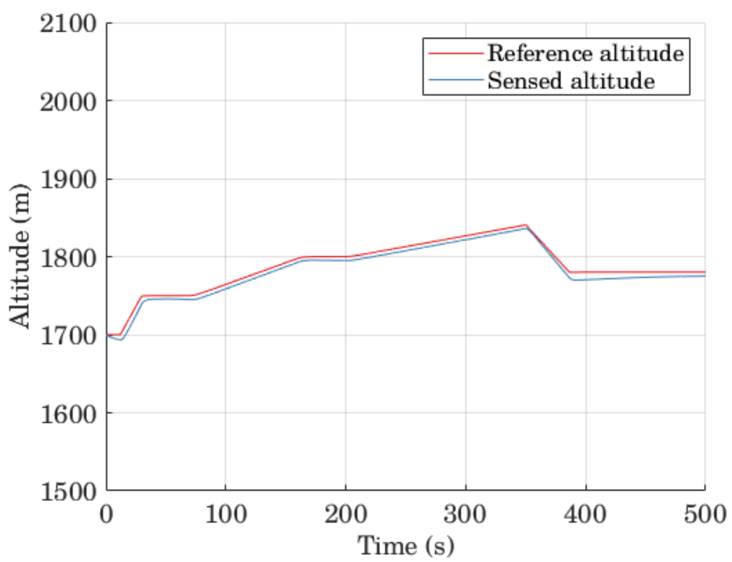


FIGURE 7.5. Vertical profile of the climbs and descents in a flight

To make the simulation as accurate as possible, the throttle was varied in a linear but smooth way coinciding when the elevator was turned to climb or descent, imitating what a pilot would do with the throttle lever in the cockpit. Towards the end, the throttle is kept descending at a really slow rate, as if the pilot's intention was to slow down the aircraft.

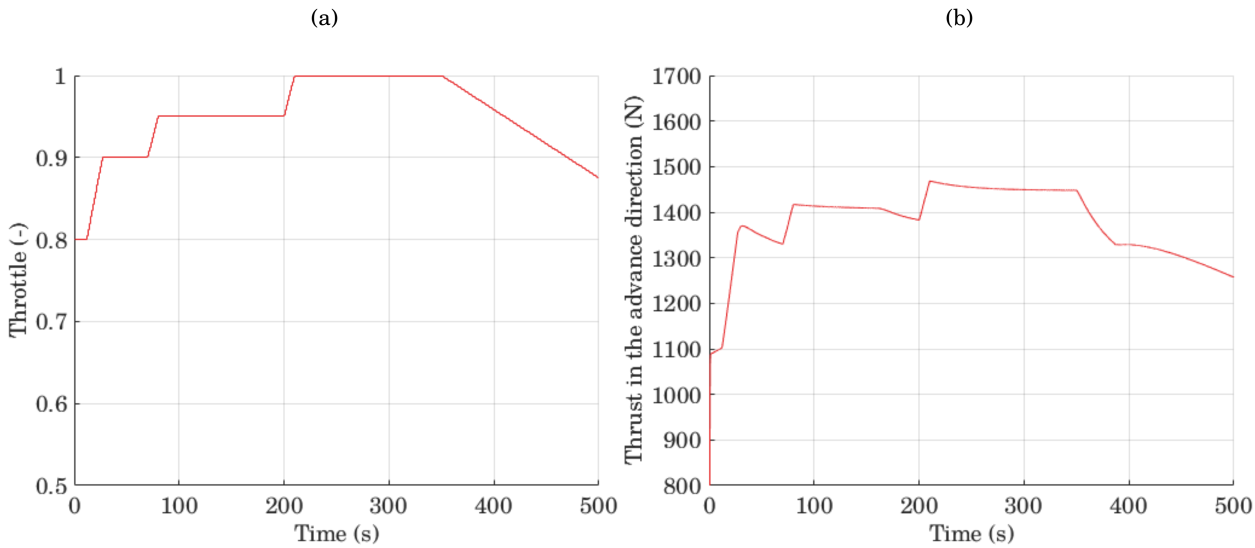


FIGURE 7.6. (a) Throttle variations, ranging from 0.8 to full throttle (b) Thrust variations along the flight

Towards the end, although throttle keeps being steadily decreased, the aircraft is kept levelled. To observe the effect it has, it is of great interest to observe the velocity variations along the simulation.
As expected, there exists a nearly direct relation between the throttle variations and the thrust, as the throttle lever is expected to, ultimately, conduct thrust, although what it directly controls is torque.

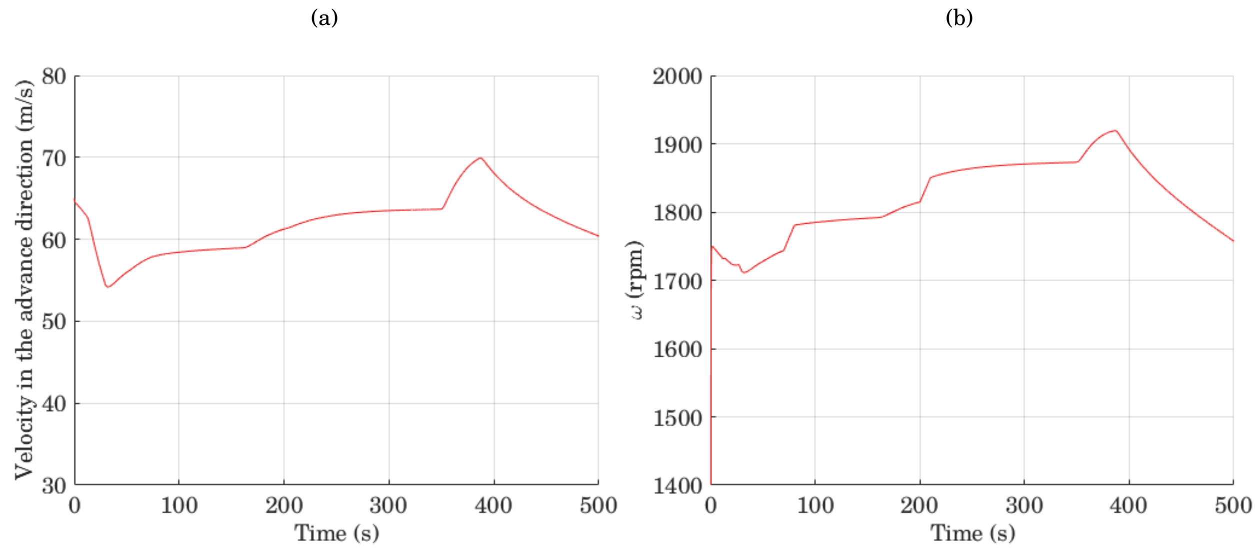


FIGURE 7.7. (a) Velocity in the advance direction variations along the simulation (b) Propeller revolution speed during the simulated flight

Velocity and propeller speed can be observed in figure 7.7, where their direct relation is undeniable. They both show peaks at the point when the altitude was commanded to go up and when the opposite was mandated. This is because whenever the aircraft was to climb the velocity in the advance direction was reduced, considering thrust would be used to push the aircraft upwards against gravity. The same occurred in the downwards direction but yielded the opposite effect: the thrust would be used to help push downwards the aircraft, thus accelerating it. At the point where the *SkyHogg* is flying a levelled flight while the throttle is still being diminished, the velocity steadily decreases, thus meaning a slow down of the advance rate.

With respect to the power consumption, it does approximately follow the throttle variances, which was expected, given its definition involves a direct relation with current and current is controlled to satisfy the torque demands, commanded by throttle.

The power does not reach or even get near the maximum power the motor is able to attain, which is 180kW. As it can be observed in figure 7.8, the maximum motor power consumption comes when the throttle is at its maximum, reaching a value of approximately 11.9kW of motor power. This is an indicator the aircraft is capable of performing at higher speeds and at different altitudes with an electric aircraft of these characteristics if the amount of charge left available does not become an obstacle.

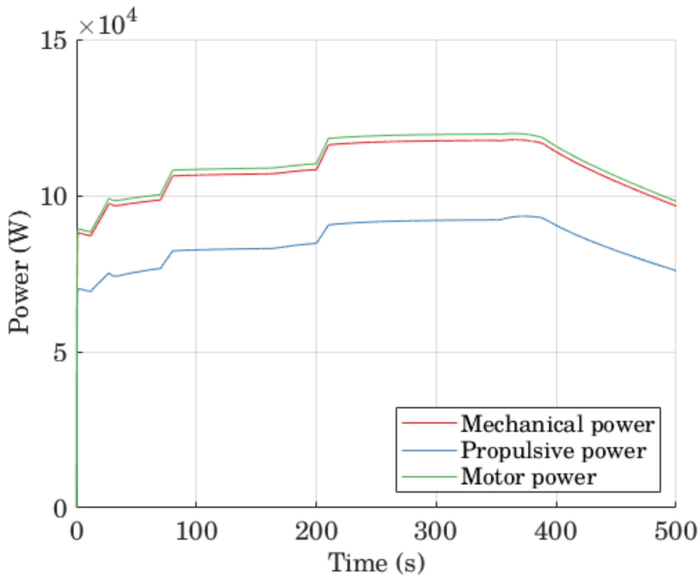


FIGURE 7.8. Power used in different components during the climbs and descents in a flight

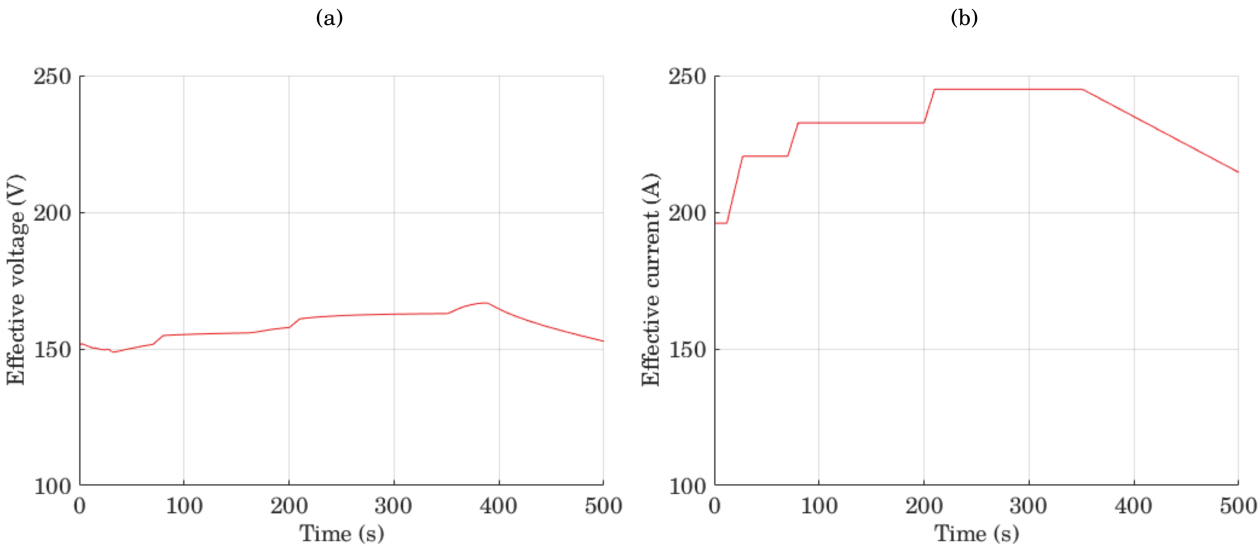


FIGURE 7.9. (a) Effective current for the flight involving climbs and descents (b) Effective voltage for the flight involving climbs and descents

Finally, another important parameter to take into account would be the state of charge of the batteries after this flight involving changes in throttle. In figure 7.10, the battery state of charge is observed to be approximately linear, although not totally.

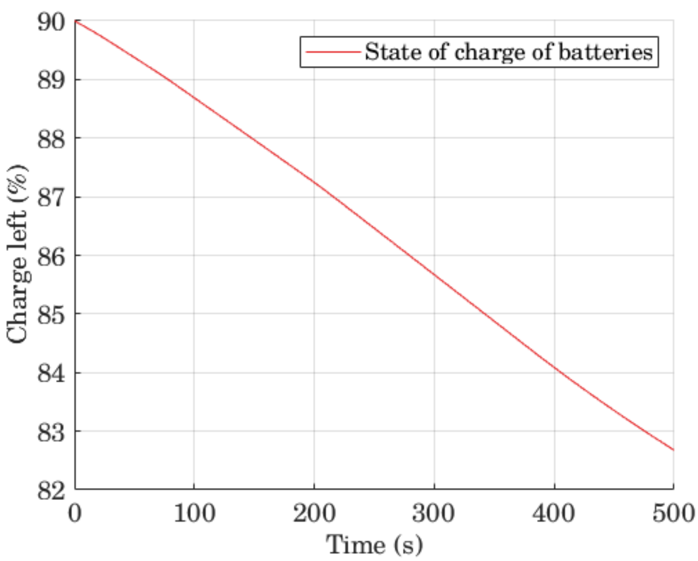


FIGURE 7.10. Battery drainage during the climbs and descents

Also, comparing to the levelled flight simulation when 100 seconds consumed 1.1% of the battery, the fact there is an increase in throttle and velocity is to blame for a quicker decrease of the state of charge, of 1.3% discharge in 100 seconds. Put into other words, this second flight consumed 18.2% more battery in the same amount of time, when compared to the levelled flight.

The state of charge at the end of the simulation was of 82.7%, which, by estimating every lapse of 500 seconds would consume the same, would allow for approximately 80 total minutes of flight (taking into account one must not fly with battery levels under 20%), still over the hourly class expected in flight lessons.

All in all, the conclusion which can be extracted is everything functions as expected and although autonomy limitations are quite obvious when compared to piston powered engines, the high-energy batteries which have been implemented allow for an acceptable amount of flight-time, considering the mission.

7.2 Performance in event of motor failure

This section shall study the plausibility of regaining control of the aircraft in a case in which the power stopped for 20 seconds. It is a fairly large amount of time for a motor error and will allow to conclude if the aircraft is powerful enough to recover of such event.

The way to simulate this was by assuming the throttle suddenly became zero (although the throttle lever might not have been touched) after which the pilot takes 20 seconds to resolve the failure, during which the aircraft experiments a free fall. When this time has passed, the pilot regains control of the throttle lever and finally initiates a slow rate climb to a safe altitude.

In first place, table 7.3 shows the main points of this mission.

TABLE 7.3. Main points of the motor failure mission

Simulated time (s)	**Starting altitude (m)**	**Ending altitude (m)**		**Minimum altitude (m)**	**Flight TAS (m/s)**	
		Command	**Sensed**		**Start**	**Max**
180	1700	1400	1389	900	65	115.5

The information on the table will be more clearly observed in successive images. To start off, a figure of altitude against time is presented, in order to bear in mind the magnitude of the fall.

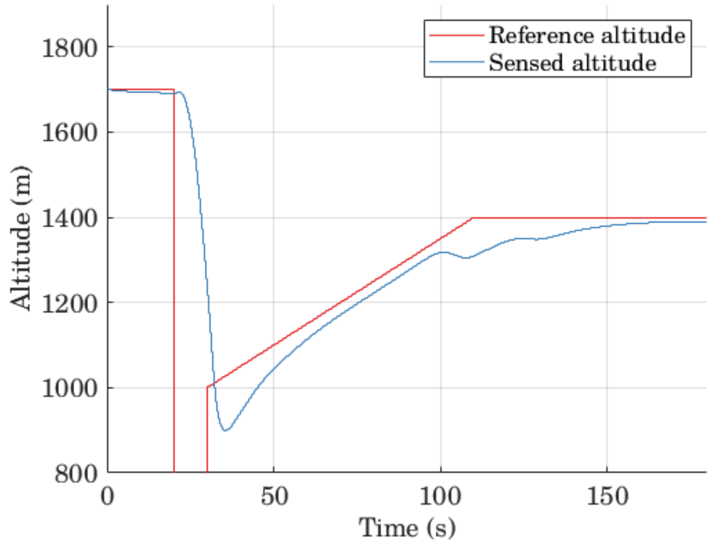


FIGURE 7.11. Altitude against time in the case of a simulated motor failure

For simulation purposes, the desired altitude was set to zero during the motor power out in order to let the aircraft fall freely. It can be seen how it takes quite long for the aircraft to recover even after the order of regaining altitude has been commanded. Also, the fact that it lost altitude again at 100 seconds of time, just to regain it some seconds later and finally put up with the altitude command.

In total, it took the aircraft two minutes from the time it stopped falling to the moment it reached the altitude which was commanded after the fall.

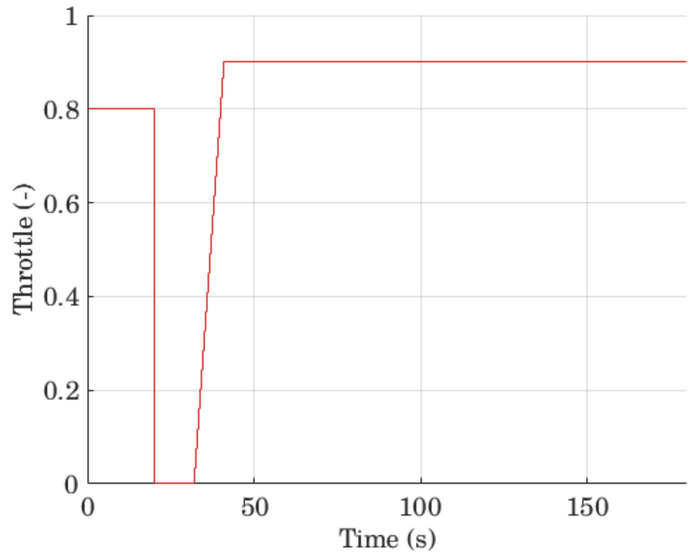


FIGURE 7.12. Throttle commands time in the case of a simulated motor failure

The control on the throttle was simulated by commanding a sudden fall in throttle during a seemingly fine flight. After the 20 seconds passed, the throttle was rapidly commanded to rise to 90%.

In the event of the fall, it is curious to look at the behaviour of velocity and propeller rotating speed.

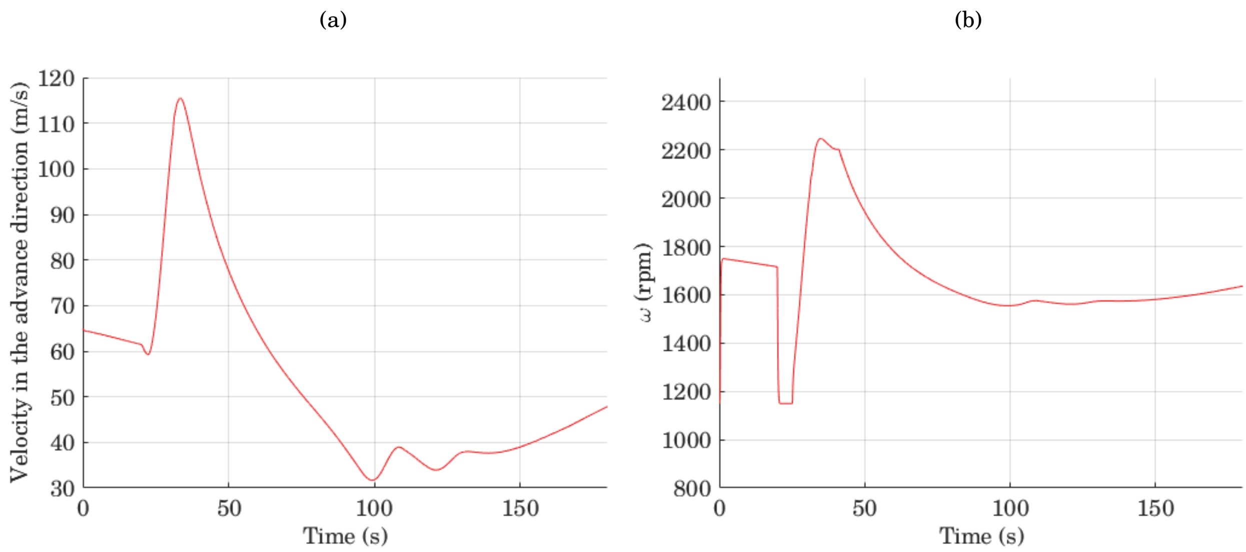


FIGURE 7.13. (a) Velocity in the advance direction variations along the simulation (b) Propeller revolution speed during the event

In figure 7.13(a) just after the motor fails and the aircraft starts free falling, the velocity suffers an incredible growth due to the nose pointing downwards. Just as the throttle is set again to a high value and the altitude is commanded to go upwards, the velocity starts plummeting and does so to the point of reaching nearly 30 m/s, when it oscillates due to the aircraft struggling to keep a velocity which will allow it to reach the commanded altitude.

On the other hand, once throttle is cut, the angular velocity of the propeller falls suddenly, but immediately after, the velocity the aircraft bears in the fall makes it go up again, reaching a peak at the same time as velocity and falling to approximately a constant afterwards. It is important to bear in mind the propeller speed does not actually stop at 1150 rpm, as it keeps falling. The reason this is shown is because of the modification added which is explained in subsection 6.2.1.

It is interesting to observe the effect the fall has on the power consumption of the aircraft. The powers are shown in figure 7.14.

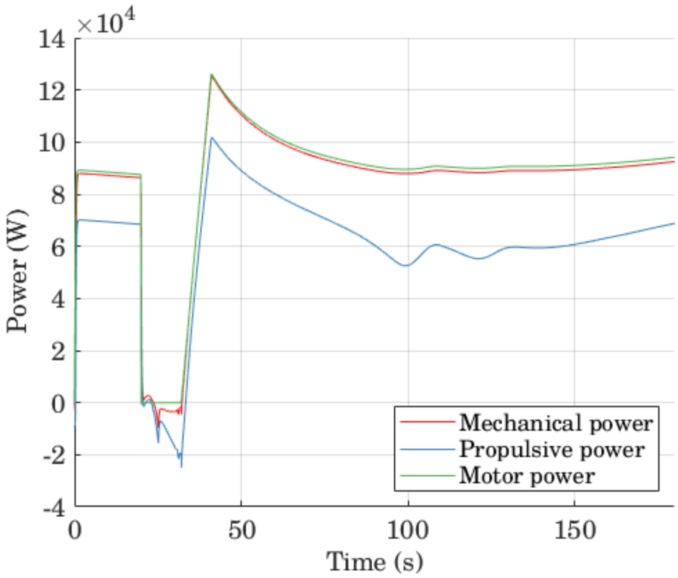


FIGURE 7.14. Power consumption in the case of a simulated motor failure

The obvious that can be extracted from the figure is that the electric motor was off during those 20 seconds, which is what the simulation is all about. It immediately recovers power in the instant when the throttle lever is again being pulled by the pilot.

Other than that, the power consumption has its peak in the moment when the aircraft is falling at a higher speed and the throttle lever is at the maximum it will be. It is curious to note the fact the mechanical and propulsive power reach negative values. This is actually something that can be expected by reviewing the charts of power against velocity and propeller speed in subsection 5.1.3: it happens the value is off the charts and thus, theoretically, it can imply negative power, which is the same as saying the propeller is actually momentously acting as a generator. This is a topic of interest to study in further projects, as it could be a way of recharging batteries during the flight, if the proper technology was developed.
Besides that, the power consumptions seem viable, as even during the peak it does not reach near the maximum motor power. This leads to think the aircraft could still recover from falls which could acquire more velocity successfully.

In respect to thrust, shown in figure 7.15, the profile it shows does not coincide with throttle as closely as it did in the other cases, mainly due to the oscillations it suffers at around 100 seconds, coinciding with the ones the velocity showed. To explain this phenomenon the advance ratio must be calculated, taking into account the velocity at that point is of $v_\infty = 31$m/s and the propeller speed is $n = 1590$rpm $= 26.5$rps. Having this in mind, the advance ratio for this instant is calculated in equation 7.3.

$$J = \frac{v_\infty}{nD} = \frac{31}{26.5\,1.65} = 0.71 \tag{7.3}$$

As already discussed in subsection 5.1.3, if the loading of the blade is high, the results of thrust and power might not be reliable. High loading is for a traditional thrust coefficient of $T_C \gtrsim 2$. For the case being, the high blade loading happens at an advance ratio of under 0.65 (from figure 5.2) but given the situation falls very near, it could be possible the results are unreliable due to this fact and further testing should be done on the matter, involving real life tests.

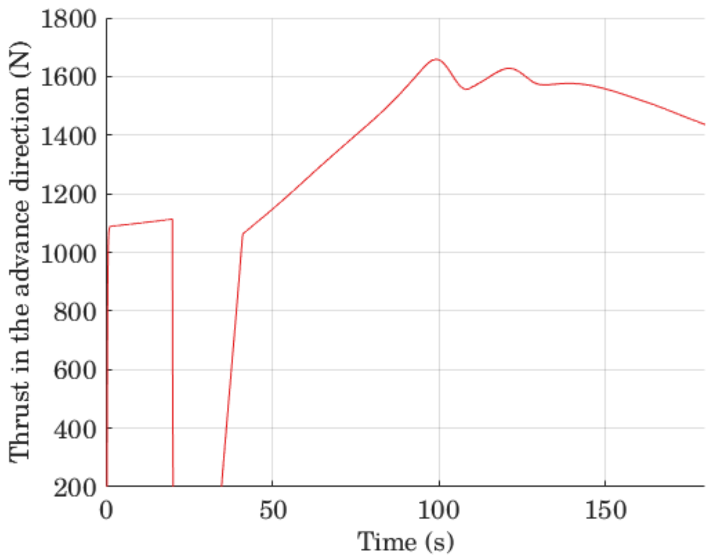


FIGURE 7.15. Thrust as a function of time in a case of motor failure

As for the battery consumption, it was not specially significant, otherwise than the 20 seconds it did not consume anything because, of course, the motor was off.

The consumption seems to keep the same levels as the cases analysed before for levelled and climbing and descending flight, with no noticeable variations in the discharge rate, which is still linear.

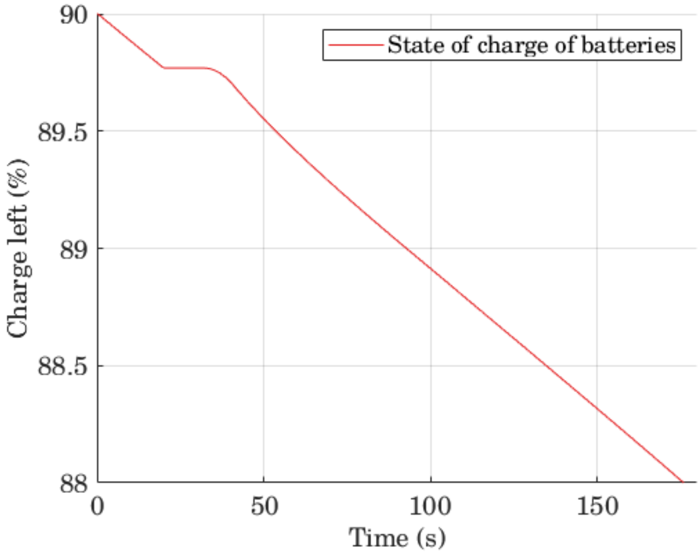


FIGURE 7.16. State of charge variance in a flight with a motor failure

In conclusion, the simulation proves the aircraft is safe in the case of a motor failure and it could recover if it was to happen. This is sometimes required by companies to be certified.

Chapter 8

Conclusions

This chapter summarizes all the final thoughts on this project; all the conclusions extracted from the different simulations in different situations as well as any amplification that could be interesting for future projects to be based on this same topic.

8.1 Conclusions of the project

The project's conclusions after what was analysed in chapter 7, are that, in effect, the modification of an aircraft of the same or similar characteristics to the *SkyHogg* is not only possible but even desirable in certain situations. However, the desirability of these modifications is conditioned by the mission the aircraft will have.

At the present moment, electric motors have only reached a portion of the power piston engines are actually capable of achieving. This limits the climbing speeds and velocities which the aircrafts are capable of. Furthermore, the most limiting part of the modification corresponds to batteries. While light aircrafts comparable to the *SkyHogg* but powered by piston engines are capable of flying for around 5 hours non-stop with a single fuel replenish, the modified electric aircraft could only safely fly for little over an hour at a time, and that would greatly depend on the flight plan. Related to this, another disadvantage the modification bears is, because the discharge is dependent on the mission and the battery energy is not too elevated, it is limiting to some missions where constant climbs or variations in velocity are required. Whilst this is also true for piston engines in the way they consume the fuel, the fact the energy available for electrical flights is lesser makes it a bigger burden.

On the other hand, the fact the modification is viable and may be useful for determinate usages is attractive, keeping in mind fuel prices are continuing to grow and air pollution will force politicians to pass laws on flight time, which will leave electric aircrafts mostly unaffected. It also brings other advantages such as lower noise, allowing for flights near places where noise is limited for aviation.

8.2 Further studies

Much remains to be investigated and tried on the topic of the current project. For the time being, the control applied to the motor could be tested on an actual brushless motor, in order to validate it. Furthermore, experimenting on a test bench with said motor could be an interesting way of validating the actual thrust and torque outputs, checking if it follows that commanded by the throttle lever.

Another interesting project would be studying the possibility of recharging batteries while on flight, which happens at really high speeds and high propeller velocities.

Moreover, this simulations could be tested at a smaller scale before thinking about implementing them to an actual aircraft, such as trying the control out on a RC aircraft and monitoring the battery discharge. The final step would be to actually implement the simulated propeller plant to an actual piston engine light aircraft and perform tests with it.

Appendix A

In this appendix any information which is regarded useful but not included in the rest of the report is contained.

TABLE A.1. Original *SkyHogg* model parameters and variables

Name of variable	**Description**	**Value**
alpha0	Initial angle of attack	0.0170924 rad
bref	Reference span	12.5425 m
cbar	Reference length	1.7526 m
cg_0	Centre of gravity	$\begin{pmatrix} 2.158 & 0 & 0 \end{pmatrix}$ m
inertia	Aircraft inertia matrix	$\begin{pmatrix} 5787.969 & 0 & 117.64 \\ 0 & 6928.93 & 0 \\ -117.64 & 0 & 11578.329 \end{pmatrix}$ kg m^2
mass	Mass when operating (unmodified)	1299 kg
Sref	Wing surface	20.9775 m^2
theta0	Initial inclination angle	0.0170924 rad
wn_act	Angular velocity of actuators	44 rad/s
z_act	Actuator damping ratio	0.7

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Escuela Técnica Superior de Ingeniería del Diseño

Control of an electric Propulsion System for a Light Aircraft

Final Year Project

By

EVA MANEUS SALVADOR

Tutor: RAMON MANUEL BLASCO-GIMENEZ

PLANS

Escola Tècnica Superior d'Enginyeria del Disseny
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Final year Project for the BACHELOR DEGREE IN AEROSPACE ENGINEERING

JUNE 2018

Table of Contents

CHAPTER 1

INTRODUCTION

This document includes the produced plans for the final degree project described in the 'REPORT'. The plans include the design of the propeller and the wiring of the motor and the batteries. They include any necessary information for the completion in pages after the plan.

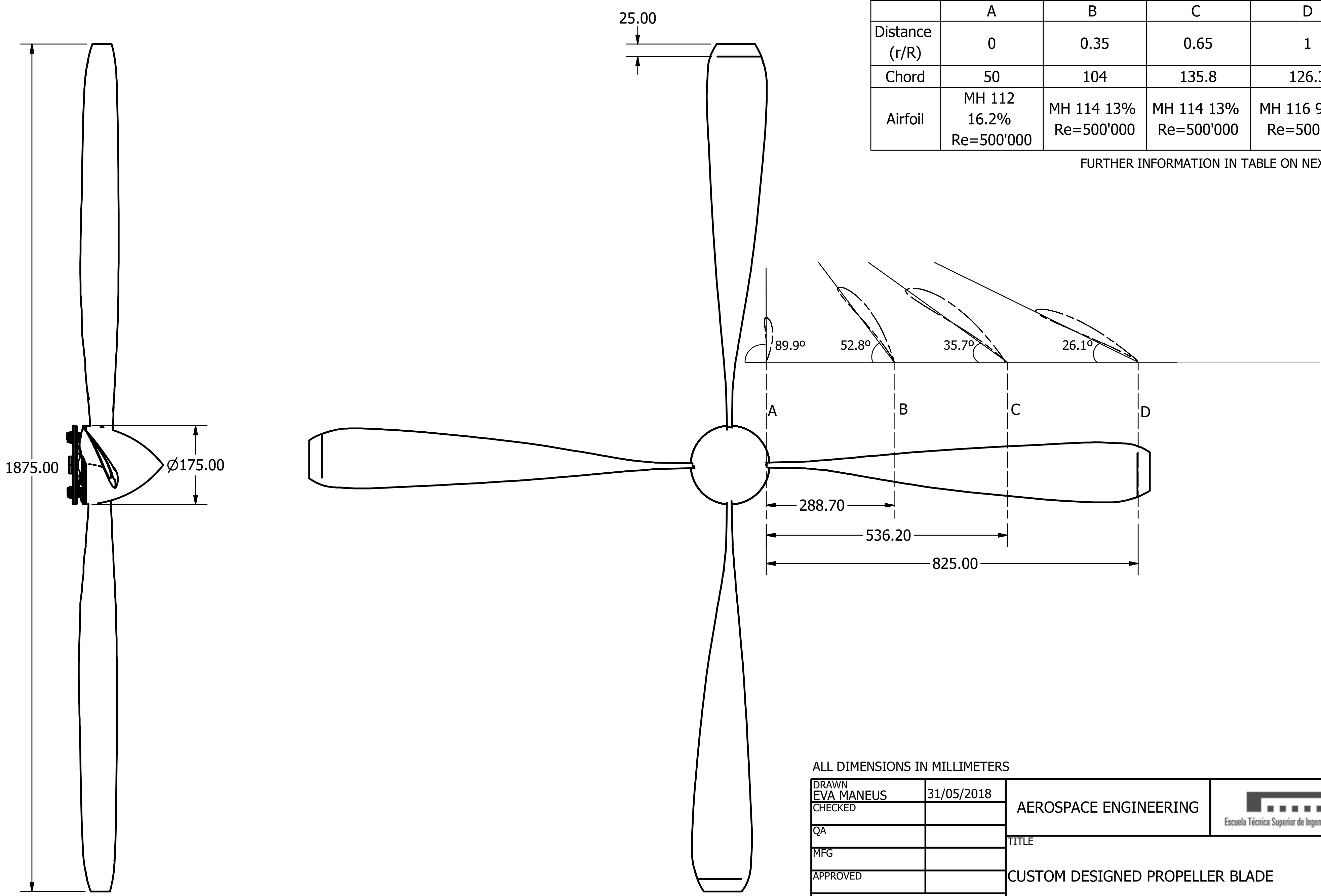
Chapter 2

Propeller plans

Following, the plan in a DIN A3 page is presented. The plan consists of the drawing in the DIN A3 page as well as the table with detailed specifications on next page. Any necessary clarifications and explanations are performed on subsequent paragraphs.

Propeller sections				
	A	B	C	D
Distance (r/R)	0	0.35	0.65	1
Chord	50	104	135.8	126.3
Airfoil	MH 112 16.2% Re=500'000	MH 114 13% Re=500'000	MH 114 13% Re=500'000	MH 116 9.8% Re=500'000

FURTHER INFORMATION IN TABLE ON NEXT PAGE



ALL DIMENSIONS IN MILLIMETERS

DRAWN EVA MANEUS	31/05/2018	AEROSPACE ENGINEERING	Escuela Técnica Superior de Ingeniería del Diseño
CHECKED			
QA		TITLE	
MFG		CUSTOM DESIGNED PROPELLER BLADE	
APPROVED			
UNIVERSITAT POLITÈCNICA DE VALÈNCIA		SIZE A3	DWG NO / REV
		SCALE 1 / 200	SHEET 1 OF 1

2.1 Blade geometry

Table 2.1: Table with detailed blade geometry

r/R [-]	c/R [-]	β [°]	H/D [-]	r [mm]	c [mm]	H [mm]	Airfoil [-]
0	0.0606	89.9	0	0	50	0	MH 112 16.2%, Re=500'000
0.05	0.0663	87.6	3.8	41.2	54.7	6208.1	interpolated
0.1	0.0745	80.5	1.9	82.5	61.4	3083.3	interpolated
0.15	0.0844	73.7	1.6	123.7	69.6	2665.4	interpolated
0.2	0.0952	67.6	1.5	165	78.6	2512.5	interpolated
0.25	0.1061	62	1.5	206.2	87.6	2440.8	interpolated
0.3	0.1165	57.1	1.5	247.5	96.1	2404.5	interpolated
0.35	0.126	52.8	1.4	288.7	104	2386.9	MH 114 13%, Re=500'000
0.4	0.1346	48.9	1.4	330	111.1	2380.2	interpolated
0.45	0.1422	45.6	1.4	371.2	117.3	2380.6	interpolated
0.5	0.149	42.6	1.4	412.5	122.9	2385.8	interpolated
0.55	0.1549	40	1.5	453.8	127.8	2394.4	interpolated
0.6	0.1601	37.7	1.5	495	132.1	2405.4	interpolated
0.65	0.1646	35.7	1.5	536.2	135.8	2418.4	MH 114 13%, Re=500'000
0.7	0.1697	33.8	1.5	577.5	140	2432.8	interpolated
0.75	0.1746	32.2	1.5	618.7	144.1	2448.4	interpolated
0.8	0.1786	30.7	1.5	660	147.3	2464.9	interpolated
0.85	0.1811	29.4	1.5	701.2	149.4	2482.1	interpolated
0.9	0.1813	28.2	1.5	742.5	149.6	2500	interpolated
0.95	0.1774	27.1	1.5	783.8	146.3	2518.4	interpolated
1	0.1531	26.1	1.5	825	126.3	2537.2	MH 116 9.8%, Re=500'000
Tip	-	25.1	-	850	95	-	MH 116 9.8%, Re=500'000

2.2 Clarifications

The tip is an addition to the calculations of the blades just so the blade has a rounded ending that does not affect negatively to the aerodynamics.

The blades are required to have a smooth surface without any imperfections.

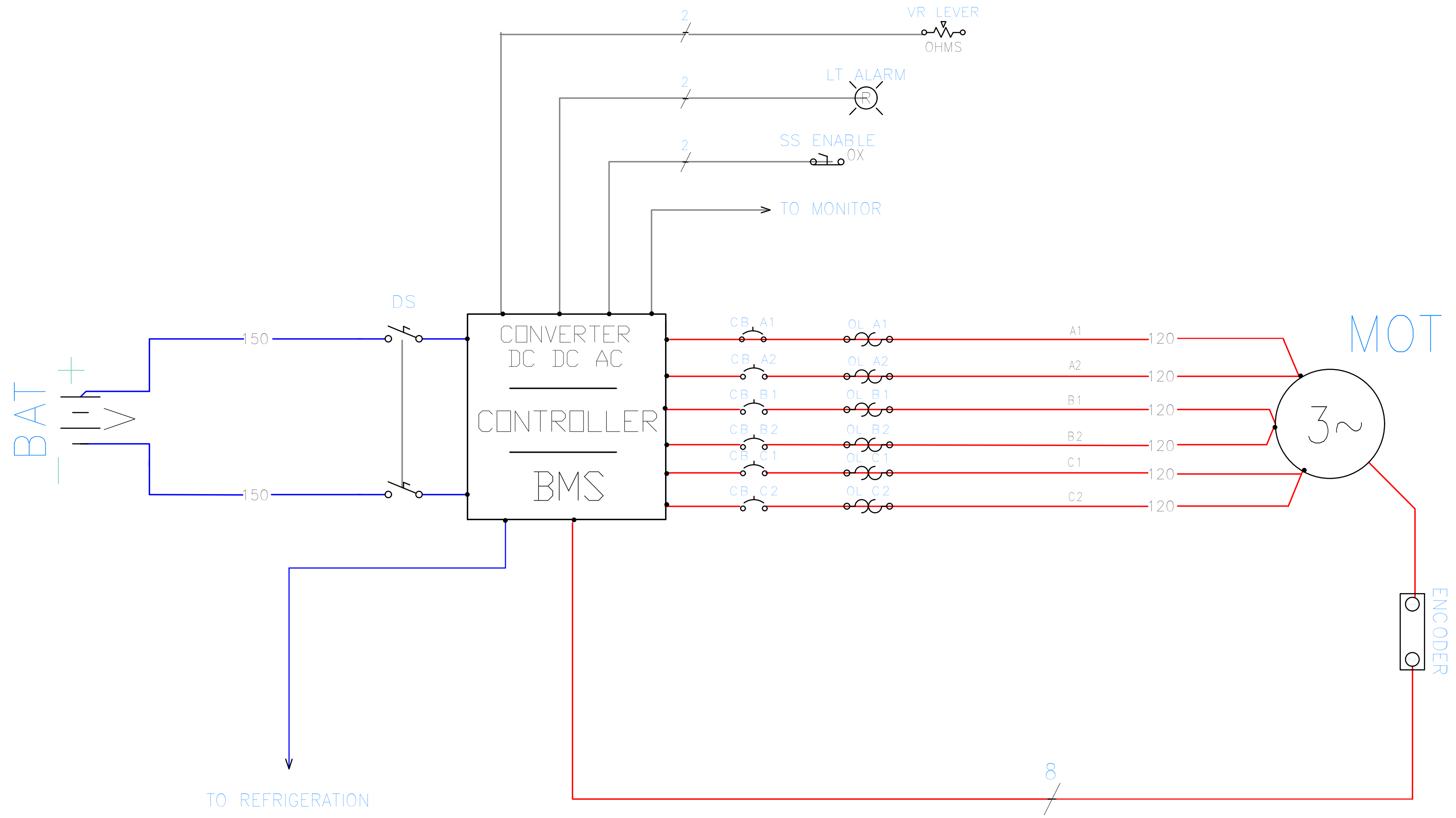
The hub pictured in the plan is a standard. Any spinner with the required dimensions can be implemented as long as the blades can be attached in a safe manner and as long as the aircraft to which it must be incorporated admits the spinner.

In order to attach the blade to the spinner, it is necessary to add a prolongation of the root to fit inside the hub.

CHAPTER 3

MOTOR WIRING PLANS

In the next pages, the plans and explanations for the installation of the motor control and the batteries are presented, as well as the alternative battery system to power the electronics on-board. The calculations for the cable sections involved in the propulsion were performed and the results are included in a table, along with clarifications on the conditions assumed.



DRAWN MANEUS, EVA	26/06/2018		Escuela Técnica Superior de Ingeniería del Diseño
CHECKED		TITLE	
QA		PERMANENT MAGNET SYNCHRONOUS MOTOR CONTROL AND CONNECTIONS	
MFG			
APPROVED			
UNIVERSITAT POLITÈCNICA DE VALÈNCIA		SIZE A3	DWG NO / REV
		SCALE NO SCALE	SHEET 1 OF 1

3.1 Wire sections

Table 3.1: Cable properties

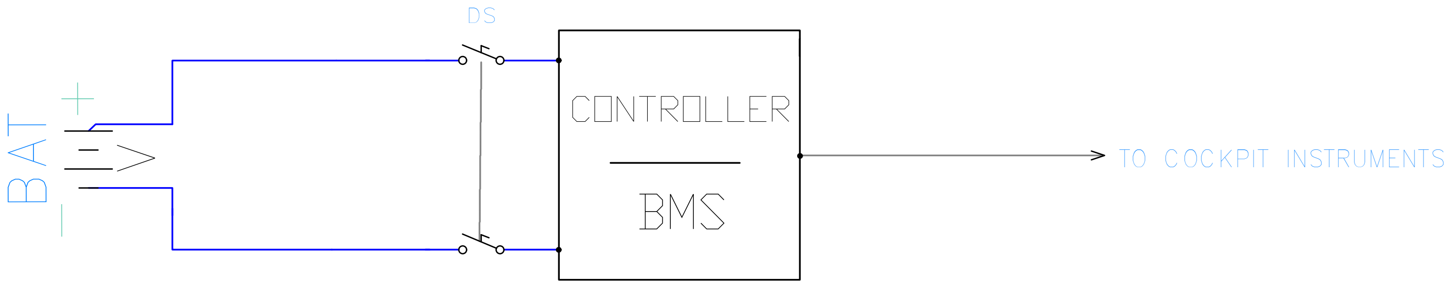
Usage	**Current type**	**Cable type**	**Maximum Calculated current (A)**	**Section (mm^2)**	**Maximum Tolerated current (A)**
To battery	DC	Cu, PVC insulation, unipolar cable	281.4	150	315
To motor	AC	Cu, PVC insulation, 3x unipolar cables	244.7	120	275

3.2 Clarifications

The calculations were done assuming the ambient temperature around the wires when operative will be of 40°C.

The method of installation was assumed to be installed directly upon the walls surrounding the motor.

Section maximum tolerated current obtained from 'Reglamento electrotécnico para baja tensión', from the *Real Decreto Octubre/2004*



DRAWN MAÑEUS, EVA	25/06/2018		Escuela Técnica Superior de Ingeniería del Diseño	
CHECKED		TITLE		
QA		ALTERNATIVE POWER UNIT		
MFG				
APPROVED				
UNIVERSITAT POLITÈCNICA DE VALÈNCIA		SIZE A3	DWG NO	REV
		SCALE NO SCALE	SHEET 1 OF 1	

Escuela Técnica Superior de Ingeniería del Diseño

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SCHEDULE OF CONDITIONS

Escola Tècnica Superior d'Enginyeria del Disseny
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Final year Project for the BACHELOR DEGREE IN AEROSPACE ENGINEERING

JUNE 2018

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Chapter 1

Description of the different works

This schedule of conditions describes the different technical, legal and economic aspects present in this final year project. In this first chapter the different work units will be stated, with the description in detail being in the next chapters of this document.

1.1 Work units

The work units can be separated into two differentiated groups, with these groups being listed following:

- Analysis of requirements and components
- Simulation and testing

1.1.1 Analysis of requirements and components

This functional group includes the parts to the project which involve research and design of the components that will ultimately compose the propulsion system in the modified electrical aircraft.

This group can be broken down into several work units:

- Custom propeller design
- Adequate motor calculation and election
- Suitable batteries

1.1.2 Simulation and testing

This functional group connects the components find in the previous group between them to finally implement the necessary controls to assemble a simulation which can fully function and be ran to test the whole process is indeed working well.

The different work units to this group are:

- Controller design
- Mission testing

CHAPTER 2

General conditions

2.1 General provisions

This section has the purpose of regulating the execution of the different project units, stating the responsibilities of each of the parties involved as well as the relationship between the different parties. Moreover, the distinct legal aspects of the project, as well as its execution conditions will be described, including but not limited to the properties of the materials to be employed, the techniques to use, quality controls and laws and regulations that apply to the project.

2.1.1 Documentation on the works contract

The works contract will include the following documents:

- Conditions set on the contracting document
- Schedule of technical conditions
- The present schedule of general conditions
- Remaining project documentation (report, plans and other documents)

Note the instructions of the project managers will be incorporated to the project as an interpretation of it. In every document of the above listed the written specifications have to be held in higher regard than the graphic ones and the dimensioning on the plans shall be put before the direct scale measurements.

2.2 Optional general conditions

This section describes the relation between the contractor part and the project manager for the execution of the project units.

2.2.1 Functions to develop by the contractor

It is of the contractor's responsibility:

- Organize the different parts to the project, develop any necessary construction plans and authorise the auxiliary and temporary installations for the works.
- Follow and make follow the actual regulations on safety and hygiene in the workplace.
- Serve as the manager to every party involved in the project and likewise coordinate any intervention of subcontractors.
- Revise and certify the validity of any material used, refusing to use any which are not subject to the current regulation or the present schedule of conditions.
- Carry the order book and of the project. Make a register of notes done upon it to be applied on the project.
- Provide the project management with any necessary materials to ease their task.
- Prepare the partial work certifications and the settlement proposal.
- Along with the certificate promotes, prepare the provisional and final reception certificates.
- Subscribe to accident and third-party damage insurances.
- Know the law and verify the project documents. The constructor shall indicate the project documentation is sufficient for the complete understanding of the project or demand clarification if otherwise.
- Elaborate the safety and hygiene plan for its approval by the project management.
- Provide offices for plan consulting and for project management tasks. The offices will hold the work permit, the complete project of execution, the order book the safety and hygiene plan, the incident book and the insurance documentation.
- The constructor shall communicate the person designated as a deputy, which should assume the constructor's functions.
- The works manager, or some attendants, shall be present throughout the working time and keep company of the engineer or the quantity surveyor and provide precise data for dimension checking

- The contract shall do all that is needed to achieve the good construction and aspect of the works, even when these are not specifically required, whenever the engineer says so, always inside the budget limits.

- Any variation that will result in an increment of more than 20 percent on the price of a work unit or more than 10 percent of the whole budget shall require the redoing of the project.

- Clarifications, interpretations or modifications of any precept of the schedule of conditions or any indication on the plans shall be communicated in writing to the constructor, whom shall return the original papers with a sign on the side of every instruction, order or notice received.

- The constructor can require from the engineer or the quantity surveyor or technical engineer whichever instructions or clarifications shall be necessary for the correct execution of the project. At the same time, solutions for any unaccounted problems throughout the project shall be provided.

- The contractor complaints against orders or instructions of the project management will be presented by the engineer, if they are of economic nature, and always following the corresponding schedule of conditions. Complaints against orders or instructions of technical nature shall not be taken into account, but the contractor is allowed to expose in a reasonable manner, although the engineer can limit the answer to an acknowledgement.

- The contractor shall not disallow the engineer, quality surveyor or technical engineer or designated attendants, neither ask for the designation of other professionals for the acknowledgements or measurements.

- In the case of unruliness, incompetence or gross negligence that might severely affect the project execution, the engineer can require the contractor to disallow the workers whom caused it.

- The contractor can outsource work units attaining the conditions numbered in the schedule of conditions without it affecting his or her responsibilities as the general contractor of the project.

- The contractor shall not initiate a work unit without the director's authorisation.

- The contractor is required to follow the indications in the orders book.

2.2.2 Functions to develop by the engineering manager

The engineering manager is the leading manager of the project execution; ruling the starting, the pace and the quality of the works. Will assure the complying with the aforementioned and the safety conditions of the project workers.

The functions reserved for the engineering manager are:

- Compose the supplements or rectifications to the project when necessary.
- Assist the works any time their nature and complexity require so in order to solve the contingencies produced and hand out necessary instructions.
- Coordinate the intervention on the project of other technicians.
- Approve partial work certificates, expedite and subscribe along with the quality supervisor or technical engineer the final certificate of the project.
- Pass partial project certificates, the final settlement and counsel the promoter on the reception ceremony.
- Check on provisional installations, support facilities and safety and hygiene systems in the workplace.
- Arrange and manage the execution following the project, technical standards and ruling for a good construction.
- Perform or have disposition of the tests and trials of materials, installations and other units of work following the control plan as well as any necessary monitoring to assure the quality matches the project expectations and the applicable technical standards.
- Inform the constructor of the test results and give necessary instructions.
- Plan the quality control and economic control of the works.

2.2.3 Order book

It is mandatory for there to be at the working site a book of orders and incidences, reviewed by the corresponding professional collegiates, which shall include the order and modifications applied.

2.3 General terms of execution

2.3.1 Pace of work

The installer or contractor will initiate the works in within the period stated in the schedule of particular conditions, pacing the works so they are finished within the established partial periods in order to complete the work in the time limit stated in the contract. The contractor will communicate the engineer by writing the initiation of the works, at least, three days in advance.

2.3.2 Order of the works

The determination of the order of the works is for the contractor to decide, excepting cases in which due to technical circumstances it is deemed convenient to be varied by the project management.

2.3.3 Extension of the project by unforeseen causes

When the works are to be extended, either by unforesen causes or events of force majeure, works will not be interrupted, being continued according to instructions handed by the engineer whilst the project is being posed or being processed. The constructor shall carry out any necessary works of urgent nature, in anticipation, which will be consigned in an additional budget or paid directly.

2.3.4 Prorogue due to events of force majeure

If due to events of force majeure or independently from the constructor's will to commence the works could not be initiated, or were suspended, o were not finished within the established period, a prorogue will be granted to fulfil the contract if the engineer authorises to do so.

2.3.5 General conditions of execution of the works

The works shall be executed strictly following the project guidelines, the modifications to it that might have been approved and the orders and instructions that are handed in writing under the engineer, the quality surveyor or the technical engineer's responsibility.

2.3.6 Defective works

The constructor shall employ material which comply with the general and particular technical conditions stated in the schedule of conditions and perform the works following what is specified in said document. Until the definitive reception, the constructor is responsible of execution and of any defects that might appear from a bad execution. Whenever the engineer, the quality surveyor or the technical engineer note defects in the works, or materials or machinery which do not fulfil the required condition, before reception of the work defective parts shall be replaced.

2.3.7 Hidden defects

If the quality surveyor has justified reasons to believe hidden defects exist in the construction, before the definitive reception the quality surveyor shall require tests and trials deemed appropriate to be performed on the works considered defective. The tests shall be pais by the constructor, if it exists, and the proprietor, in absence of the former.

2.3.8 Origin of materials and machinery

The constructor shall provide necessary material and machinery of every type on the points deemed convenient except in cases in which the schedule of conditions states a determinate provenance. The constructor shall inform the quality surveyor of the suitability and provenance of the materials and machinery. If the engineer requires so, the constructor will exhibit samples of the materials.

2.3.9 Defective materials

The engineer, at the request of the quality surveyor, will order the constructor to replace the defective materials and machinery with others which meet the quality conditions in the present schedule. If the constructor would not comply, the proprietor would do so, charging the expenses on the contractor.

2.3.10 Tests and trials

The expenses derived from test and trials are to be paid by the contractor, with the possibility of those which do not bear enough guarantees to be repeated. The tests for each installation are specified in the chapter for said installation.

2.3.11 Works without prescriptions

In those works in which no prescriptions exist in the present schedule of conditions nor in the remaining documentation, the constructor shall follow the instructions dictated by the project management.

2.3.12 Reception

2.3.12.1 Provisional reception

Three days prior to the completion of the works, the engineer will communicate the proprietor the proximity of the finalisation date in order to agree upon a date for the provisional reception. This shall be done with the participation of the proprietor, the quality surveyor, the constructor and the engineer. A detailed examination of the works shall be performed, and a certificate will be handed out to each participant, being signed by all of them. From this date, the guarantee period starts if the works are accepted. Following, the technicians from the project management will provide with the finalisation of works certificate. If there existed defects, instructions would be handed to righten said defects, setting a time period in which to do so and after which a new examination will be carried out.

2.3.12.2 Final documentation of the works

The engineer manager will provide he proprietor with the final documentation which shall include the specifications and contents arranged by the current legislation.

2.3.12.3 Definitive measurements and provisional validation

Once the works are received, the quality surveyor shall perform the definitive measurements in the presence of the constructor. The necessary certificates shall be handed out in triplicate, which once the engineer has approved of it and signed will serve for the payment of the proprietor of the remaining balance minus the deposit quantity.

2.3.12.4 Definitive reception

The works will be verified after the guarantee period, which will be stated in the schedule of particular conditions and will not be under nine months. The way to proceed will be the same as for the provisional case. After the guarantee period, the constructor is no longer expected to repair any damages due to the normal conservation of the works.

2.3.12.5 Extension of the guarantee

If the works do not meet the required conditions the definitive reception shall be postponed and the engineer shall indicate the constructor the terms in which the necessary works shall be performed. If these time periods were not followed, the constructor shall lose the amount of deposit.

2.3.12.6 Reception of works with a terminated contract

In the event of contract termination, the contractor shall take away the tools, support facilities, etc. Within the term set in the schedule of conditions the workplace shall be left in the adequate conditions so as the work can be resumed by another company. The finished works shall be received provisionally and definitively once the guarantee period is over.

2.4 General economic conditions

2.4.1 General principle

This section the economic regulations are described and regulated between the proprietor and the contractor, as well as the control functions of the project management. Every person intervening

in the work process are in their right of promptly receiving the quantities according to their actuations as stated in the contract. The proprietor, the contractor and the technicians are allowed to demand from one another the adequate guarantees to comply with their contractual obligations regarding payments.
The contractor shall provide the following deposits:

- Cash deposit or bank guarantee of an amount of 10 percent of the total price of the contract, except if other is stated in the contract.

- Withholding of 5% in the partial certificates or payments being done.

Any penalizations for delays will be covered by the deposit and the repairs will be covered by the contractor company.
If the contractor refused to complete the necessary work to finish off the project in the conditions stated in the contract, the engineer in representation of the proprietor will order its finalisation to another company, paying with the deposit amount, without the actions the proprietor will take if the deposit does not cover the totality of the works being limiting. The deposit shall be returned to the contractor within a time period no greater than thirty days after the work finalisation certificate is signed. The proprietor has the right to demand the contractor proves settlement of payments and the payment of balance caused by the works.

2.4.2 Prices

2.4.2.1 Structure of the pricing

The calculation of prices comes as a result of adding up the direct and indirect costs, the generated expenses and the industrial profit.
The direct costs are:

- Labour, with bonuses, charges and social insurances which directly intervene.

- Materials at the prices paid for the project, necessary for the intervention.

- Equipment and safety and hygiene technical systems ofor prevention and protection of accidents.

- Personnel expenses, fuel and energy derived from machinery functioning and installations used in the execution of the works.

- Deprecation costs and conservation costs of machinery, installations, systems and equipment.

Indirect costs are:

- Costs of installation of offices in the working site, communications, setting warehouses, workshops, administrative staff affiliated. They are represented as a percentage of direct and indirect costs.

The industrial benefit:

- The contractor profit is established as a 6 percent of the sum of the aforementioned costs.

Price of physical construction:

- The result of the addition of the aforementioned excepting the industrial profit.

The contractor company price:

- Addition of direct and indirect costs and the industrial profit. VAT expenses are applied to this amount but it does not form part of it.

2.4.2.2 Contradictory pricing

This phenomenon occurs when the proprietor, via the engineer, introduces units or variations in quality in some of the planned unit or when it becomes necessary to tackle unforeseen events. The contractor is required to accept the changes. The pricing will be arranged between the contractor and the engineer prior to commencing the works.

If the contractor does not claim the prices before signing the contract, it is not allowed to claim a rise in the prices shown in the budget on which serves as a base for the execution afterwards.

2.4.2.3 Revision of contracted pricing

The revision of prices if the increment of the amounts in the units left to complete are not greater than 3 percent of the total contract budget is not admissible. If the variation is an increase, a review will be conducted following the steps stated in the schedule of particular conditions. The contractor receives a difference which resulting from a variation of the CPI over 3 percent. A review formula system contemplated in the State Laws of Contract shall be applied.

2.4.3 Valuation of the works

2.4.3.1 Forms of payment

Excepting cases where the opposite is indicated in the schedule of particular conditions, the payments for the work will be done in one of the following ways:

- A fixed rate, incremented an amount for every work unit, with the invariable amount set beforehand, varying only the units done and applying to the total work units the fixed amount.
- Floating rates per work unit, depending on the work conditions and materials employed in the work, dictated by the engineering manager.
- With lists of day wages and receipt of materials used in the way determined by the schedule of economic conditions.
- By the work hour, following the conditions stated in the contract.

2.4.3.2 Certificates

On each date specified in the contract or in the schedule of particular conditions, tje contractor will compose a valued relationship of the works executed during the time periods according to the measures carried by the quality surveyor.

The executed works will be valued applying to the measurement results the prices stated in the budget for each of the said works, considering also what is stated in the general schedule of economic conditions respecting improvements or substitutions of materials.

The contractor may be present when performing the necessary measurements for the elaboration of the relationship, similarly, the quality surveyor or the technical engineer will send the contractor the results of the measurements so as they can be examined and returned signed or file claims if deemed opportune. The engineer will accept or reject the claims, letting the contractor know the decision. The contractor is then allowed to claim the proprietor on the engineer's settlement.

Parting from the valued relationship, the engineer will complete the certification of the executed work. This certification will be sent to the proprietor in a time period under a month after the date referenced in the certificate and will have a status of document which is subject to variations resulting from the final settlement, without this certificate meaning the approval or reception of the works mentioned in them.

2.4.3.3 Improvements of the works

In the case the contractor, even with the authorisation of the engineering manager, employs materials of higher quality, of higher price or works of bigger dimension, the difference in price will only be paid if the works were completed following the planning.

2.4.3.4 Payments

The payments will be done by the proprietor in the terms previously established and the amounts will correspond those of the work certificates accepted by the engineering manager.

2.4.3.5 Works carried out during the guarantee period

The payment of this works will be done in the following manner:

- If the works are stated in the project and were not completed in the stated time period they will be valued with the prices which appear in the budget and paid following what is established in the project.

- If the works' finality is a repairing the damages derived from usage, they will be paid the price of the day previously agreed upon.

- If the purpose of the works is repairing flaws or defects caused by the installation or quality of the materials, the contractor will be paid no amount.

2.4.4 Penalizations

There exist three types of penalizations, due to a delay in the execution, due to a non-compliance of the contract and due to a delay in the payments.

- Due to a delay in the completion. The compensation due to unjustified delay in the completion of the works will be a 10 per thousand of the total amount of the contracted works for every calendar day delayed after the termination date agreed upon. This quantity will be deducted and withheld from the deposit. The days lost due to forces majeures such as strikes, natural disasters or administrative causes.

- Penalisation due to non-compliance with the contract. It will be established in the contract how the non-compliance or the bad execution of the works is penalised. If the proprietor will not pay the stated amount within the next month of the period agreed upon, the contractor will have the right to receive a four and a half percent annually as interest charges. If the delay is extended to two months after the finalisation of said period, the contractor is in the right of terminating the contract, and settling the executed works.

2.5 General legal conditions

Both parts agree upon letting conflict managers solve any matters.

2.5.1 The contractor

The contractor is responsible upon the works being executed under the conditions established in the contract and in the project documents, excluding the report. Therefore, it is mandatory to undo and redo anything that has been badly done during the works, including cases in which the units have been already paid. Similarly, it is mandatory to follow what is stated in the Contract of Employment law and written under the section of accidents at work, family allowances and social insurance.

The contractor is held accountable for the accidents that might occur due to inexperience or neglect on the work site and its surrounding. The contractor will be the only accountable and must take charge of compensations given insurance expenses and safety measures are included in the price. It is under the contractors responsibility to pay for taxes and excise duties which must be paid during the time the works are being carried out.

The contractor has the right to produce copies of the plans, budgets, schedule of conditions and other project documents.

The following will cause the termination of the contract:

1. Death or incapacitation of the contractor.
2. Bankruptcy of the contractor.
3. Alterations made to the contract by:
    - Modifications to the project which are deemed as fundamental changes by the engineering manager, and whenever a modification accounts for more than a 40% of the value of any of the modified project units.
    - Modifications made to the work units whenever they account for more than 40% of the modified units.
4. The suspension of the works once started and the delay of more than three months from the date of the contract award in the start of the works.
5. Not commencing the works within the time period stated in the contract conditions or the project.
6. The non-compliance of the conditions of the contract when the causes are negligence or are damaging of the works.
7. The unjustified abandonment of the works

2.5.2 The contract

The contract is established between the proprietor or developer and the contractor. Various contract modalities exist:

- Fixed price: An amount for the works is agreed upon and shall not be modified though the volume of the works varies. It is employed in smaller works.
- Contract per work units

2.5.3 Arbitration

Given the case of litigation or disagreement between the proprietor and the contractor, in first place the project management will be contacted. If this would not put an end to the dispute, each part will appoint a surveyor which will act on the behalf of the parts. Ultimately, the dispute shall be solved in court.

Chapter 3

Particular conditions

This chapter's purpose is describing the technical conditions to which the project shall be subject to. This means stating the quality controls, the characteristics of the material and the tests and trials which will be performed. In order to facilitate the reading of this part, it has been broken into groups and units which are in a chronological order. To be able to start a group, it is indispensable all the work units of the group before it have been completed. The division of the work unit and the groups are stated under these lines:

- Analysis of requirements and components
  - Custom propeller design
  - Adequate motor calculation and election
  - Suitable batteries election
- Simulation and testing
  - Controller design
  - Mission testing

3.1 Group 1: Analysis of requirements and components

This group will require researching and calculating the appropriate components for the substitution of the propulsion plant in a light aircraft for an electric propulsion system.

3.1.1 Custom propeller design

Based on tests performed upon a simulation of the unmodified aircraft in *Simulink*, the thrust requirements are found and used in order to design a propeller in *JavaProp*. This process requires iteration and analysis of the data obtained before reaching the final design. The final design must reach the same orders of magnitude the unmodified aircraft reaches. Data of thrust and power coefficients must be obtained from *JavaProp* for its use later on in the simulation. Once the design is complete, it is transferred to a plan using *Autocad* and *Inventor*.

3.1.2 Adequate motor calculation and election

The state of the technology regarding electric motors must be studied in order to choose one which will be suitable: lightweight, powerful and able to be controlled by current. The parameters of the chosen motor shall be extracted for their use in the simulations.

3.1.3 Suitable batteries election

For this unit the state of the batteries technology must also be revised looking for modern improvements. The available battery weight must be calculated taking into account the dry weight of the aircraft after having the engine retired and selecting an appropriate battery weight bearing in mind the mission of the aircraft. Approximate calculations of the autonomy must be done taking into account the discharge of the type of battery. The actual batteries must be chosen attending:

- Their energy density
- The volume they occupy
- The easiness with which they will fit the aircraft's available space

3.2 Group 2: Simulation and testing

This second group assumes all of the work unit before it have been completed and are well done. It will consist on testing the performance of the results obtained in the other group so as to declare the components are valid and fulfil the expectations. Were the results of the test to come out negative and the group 1 should be modified and tested again. The outcome of the tests and simulations could be negative, with this meaning it is not actually possible to perform the desired modifications upon the aircraft being considered and meeting all the requirements at the same time. This case would require the expectations to be relaxed or the project to be restarted.

3.2.1 Controller design

The controller design first requires all the simulation of the propulsion plant to be set up correctly in *Simulink*, including all the parameters obtained from the different parts (propeller, motor and batteries). Once this is completed and functioning, the control law must be designed so as to control the torque of the motor with the throttle lever. PI controllers have to be designed to control the currents. The requirements for these PI controllers are:

- Low settling time
- Little overshoot
- Compromise of the two above

Once the PI designers are completed according to the requirements, the simulation must be tested and proven to work well.

3.2.2 Mission testing

Some missions will be designed to test the validity of the designed electrical propulsion plant. This missions will test the following:

- The normal functioning of the simulation, of the control law and the controller, and the suitability of the installation.
- The possibility of recovering after a problem in the electrical motor involving a free fall, needed for the certification of the modified aircraft.
- Estimating the autonomy during its normal use and deciding whether it is sufficient.

If any of the tests above would not fulfil the expectations set for the particular modification, a process of redoing parts of the previous work units shall be started. Again, if several iterations were performed and the desired results are not achieved, it could be a matter of relaxing constraints or admitting the inconvenience of the modification for that particular aircraft for the particular requirements.

Escuela Técnica Superior de Ingeniería del Diseño

Control of an electric Propulsion System for a Light Aircraft

Final Year Project

By

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BUDGET

Escola Tècnica Superior d'Enginyeria del Disseny
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Final year Project for the BACHELOR DEGREE IN AEROSPACE ENGINEERING

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Table of Contents

Chapter 1

Introduction

This document's purpose is to provide all necessary information regarding the funding of the program developed in the 'REPORT' of this final year project. This part will include the costs of analysis and design of the mentioned project, divided into 5 differentiated project units. These project units, put into two major functional groups are:

- Analysis of requirements and components
  - Custom propeller design
  - Adequate motor calculation and election
  - Suitable batteries
- Simulation and testing
  - Controller design
  - Mission testing

The estimated costs will be calculated for each of these project units and the overall costs for each group will be stated. The calculations will include the estimated costs of labour hours as well as materials and software.

CHAPTER 2

BREAK-DOWN OF COSTS

In this chapter a detailed explanation of the different costs is listed. The listing is in function of the project units described in chapter 1. The costs listed are approximated, due to the estimation of the work hours, which do not necessarily match perfectly with reality.

2.1 Cost of labour hours

This section exposes the costs of the workforce hired to develop this project. It is estimated a single employee working on the project full-time will suffice.

Employee	Work hours per day	Working days	Salary (€/h)	Total (€)
Engineer	8	30	11.25	2700

2.2 Cost of materials employed

In this section, the pricing of indispensable material is stated, including any software licenses needed to complete the project.

Material	**Pricing (€)**
PC	1100
Matlab annual license	2000
+*Simulink*	1000
+Aerospace Toolbox	1000
JavaProp	0
AutoCAD annual license	2075.15

2.3 Cost per project part

This section consists of calculating the time employed in each of the project units' smaller tasks, with these tasks set in a chronological way, and calculating the estimated cost of each of these project units.

2.3.1 Estimation of work hours

2.3.1.1 Analysis of requirements and components

PROPELLER DESIGN	
Task	**Invested hours**
Revision of propellers in similar aircrafts	3
Initial *Javaprop* design	1
Properties calculations and analysis	3
Iterative redesign until reaching optimal	8
Drawing plans	6
TOTAL	21

ADEQUATE MOTOR CALCULATIONS AND ELECTION	
Task	**Invested hours**
Calculating original model performance	2
Scaling motor model	1
Preliminary *Simulink* implementation	2
Drawing wiring plans	6
Calculating wire sections	1
TOTAL	**12**

FINDING SUITABLE BATTERIES	
Task	**Invested hours**
Calculating original model autonomy	2
Preliminary *Simulink* implementation	1
Research about SOC calculation methods	2
Investigating *Simulink* battery block	2
Calculating battery block parameters	1
TOTAL	**9**

2.3.1.2 Simulation and testing

CONTROLLER DESIGN	
Task	**Invested hours**
Investigating AC controller functioning	2
Building controller in *Simulink*	2
Adjusting and testing the controller	3
TOTAL	**7**

MISSION TESTING	
Task	**Invested hours**
Researching and deciding possible missions	2
Setting up scopes and data compilers for each mission	3
Simulating time	8
Post-production of data	8
TOTAL	**21**

2.3.2 Amounts

2.3.2.1 Analysis of requirements and components

Propeller design			
	Quantity	**Price per unit (€)**	**Amount (€)**
Engineering hours	15	11.25	168.75
PC	1	1100	1100
JavaProp	1	0	0
AutoCAD	1	2075.15	2075.15
TOTAL			**3411.40**

Adequate motor calculations and election			
	Quantity	**Price per unit (€)**	**Amount (€)**
Engineering hours	12	11.25	135
Matlab annual license	1	2000	2000
Simulink annual license	1	1000	1000
TOTAL			**3135.00**

Finding suitable batteries			
	Quantity	**Price per unit (€)**	**Amount (€)**
Engineering hours	10	11.25	112.50
TOTAL			**112.50**

2.3.2.2 Simulation and testing

Controller design			
	Quantity	**Price per unit (€)**	**Amount (€)**
Engineering hours	7	11.25	78.75
TOTAL			**56.25**

MISSION TESTING			
	Quantity	**Price per unit (€)**	**Amount (€)**
Engineering hours	21	11.25	213.75
TOTAL			**213.75**

CHAPTER 3

PARTIAL BUDGET

In order to know the total cost for the project, the different project units must be multiplies times the number of times that particular project unit is going to be repeated along the duration of the whole project. This will provide, essentially, the cost per group.

3.1 Analysis of requirements and components

	Quantity	**Cost (€)**	**Total amount (€)**
Project unit 1	1	3411.4	3411.40
Project unit 2	1	31351	31351
Project unit 3	1	112.5	112.50
TOTAL			**3135.00**

3.2 Simulation and testing

	Quantity	**Cost (€)**	**Total amount (€)**
Project unit 4	1	78.75	78.75
Project unit 5	1	213.75	213.75
TOTAL			**292.50**

CHAPTER 4

COSTS OF MATERIAL EXECUTION, PROJECT ADMINISTRATION AND INVESTMENT BUDGETS

The previous parts to this document only included the costs of realisation of the project, but did not take into account costs derived from project administration nor those derived from taxes. This chapter exposes said calculated costs, as well as the material execution budget computed in previous chapters.

Concept	Amount (€)
Functional group 1	6658.90
Functional group 2	292.50
TOTAL	**6951.40**
General expenses (15%)	1042.71
Industrial profit (6%)	417.08
TOTAL	**8411.19**
VAT (21%)	1766.35
TOTAL	**10177.54**

The total material execution budget amount, expressed in EUROS is of: SIX THOUSAND NINE HUNDRED AND FIFTY-ONE WITH FORTY CENTS.
The total investment budget amount, expressed in EUROS is of: EIGHT THOUSAND FOUR HUNDRED AND ELEVEN WITH NINETEEN CENTS.
The total tender budget, expressed in EUROS is of: TEN THOUSAND ONE HUNDRED AND SEVENTY-SEVEN WITH FIFTY-FOUR CENTS.