Energy Monitoring System for Low-Cost UAVs

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Abstract

In the present, unmanned aerial vehicles, particularly low-cost models, lack intrinsic safety systems despite increasing interest by the civilian public for these platforms, posing a threat to other aircraft, people and property. Integrated in a larger project that addresses safety issues for this type of aircraft, this work aims to contribute to the enhancement of their safety features by proposing an energy monitoring system capable of providing updated estimates of the final state of energy of the onboard sources, enabling the operator to understand if the planned mission can be completed safely, given its energetic requirements and taking into account environmental conditions such as wind and solar radiation. The remaining energy estimate enables better energy awareness during mission planning and the online updates allow to account for unexpected disturbances and obstacle avoidance. The proposed energy monitoring system is qualitatively validated and three methods not previously considered in the literature are proposed to estimate the required energy to complete a given planned mission, and their performance is evaluated using simulation software. It is concluded that the methods discussed are very sensitive to the quality of the data and simulation tools available, and those available would be inadequate for simulating a real scenario. Nonetheless, solid foundations for future work are established.

Keywords: UAV Safety, Mission Feasibility, Mission Energy Requirements, Energy Estimation Models, Energy Sources

1. Introduction

Unmanned aerial vehicles (UAVs) are aircraft that operate without an onboard pilot, either being remotely piloted or flying autonomously. In the present there are a variety of civilian applications for UAVs including, but not limited to, border patrol, local law enforcement, inspection of structures and dangerous locations, wildfire, wildlife and crop monitoring, aerial photography and video capture, communications relay, weather monitoring, supply transportation and recreation [1].

In the aerospace industry, the growth of the UAV sector has been the largest in the current decade and this trend is expected to continue. The spending in this market sector is projected to grow from 6.4 billion dollars annually (in 2014) to 11.5 billion dollars in the following ten years, while the civil market will, by 2024, reach 14% compared to the present 11% [2].

The lack of intrinsic safety systems for these platforms are the greatest concern in the industry regarding this market sector. The United States Government Accountability Office (GAO) identified as the main safety issues for UAVs the difficulty to reliably detect and avoid obstacles and other aircraft, in the same way that a manned aircraft can, the vulnerabilities in the command and control of the UAV, due to jamming or spoofing of the global positions system (GPS) signal or of the overall communications system with the ground station (which requires an uninterrupted channel), the lack of standards for operating UAVs and to guide their technological development, and the lack regulations to promote the integration of these aircraft in a national airspace [3].

Nonetheless, the interest by the general public for low-cost remotely piloted platforms has grown in recent years, but these aircraft are often manipulated by untrained operators and do not possess relevant safety mechanisms. It is expected that, in the near future, as operational regulations become well defined, embedded safety systems will be a requirement for unmanned aircraft [2].

Being safety a major concern in the aerospace industry, LAETA (Associated Laboratory of Energy, Transportation and Aeronautics) is funding the Drones Safe Flight project that aims to tackle this issue in the domain of low-cost UAVs. The main aspects studied in this project are flight energy management, mission planning and obstacle detection and avoidance.

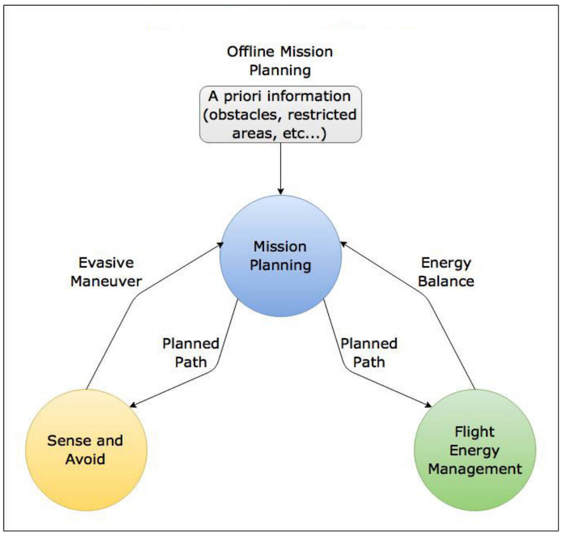

Figure 1: Low-cost UAV safety enhancement

The energy management (or energy monitoring) module is responsible for assessing the energy requirements and expected energy balance for the assigned mission, and for the aircraft's safe return to base, accounting for meteorological conditions experienced such as wind and solar radiation. The mission planning module verifies the need to adjust the mission according to the energetic constraints identified, and plans a different mission if necessary. The obstacle detection and avoidance module should detect threats in real time and issue a warning to the operator or automatically trigger the execution of an evasive manoeuvre. If an energetic deficiency is detected, or an evasive manoeuvre is solicited, the mission should be adjusted, and the change communicated to the energy management module for the reevaluation of the aircraft's energetic requirements. The final goal is to ensure that the aircraft can execute the mission successfully or return to base safely when necessary, through automatic mission planning and management, or by providing directives for the operator to intervene. Figure 1 illustrates the interaction between the three modules.

The overall goal of this work is to contribute to the increase in low-cost UAV safety, through the development of a system capable of generating an updated estimate of the state of total energy remaining onboard the aircraft at the end of the mission (the margin remaining in terms of energy), capable of being run on the airborne avionics hardware, enabling better energy awareness when planning a mission or advising a mission adjustment or a return to base if the energy margin drops below a defined safe value. The first estimation is done pre-mission (offline) and later the update of the estimate is periodic as the mission progresses (online), taking into account the conditions experienced (wind, solar radiation, handicapped airframe or trajectory change, either due to a pilot or ground control command or automatic obstacle avoidance manoeuvres), as well as those predicted for the remainder of the mission.

2. Related Works

Predicting the mission energy requirements is essential to evaluate the capacity of an UAV to complete it safely. In [4] and [5] the authors propose a mission energy prediction model for unmanned ground vehicles with online updates given the measurements made. In [6] an energy consumption model for static and dynamic components of an unmanned ground vehicle is derived, which can be used to calculate the online energy consumption of the components or to predict mission energy requirements. In the case of autonomous underwater vehicles [7], a linear regression model is used to estimate the energy consumption of the vehicle, obtaining the linear coefficients through a least squares fitting method applied on recorded data. Reference [8] presents an energy model to estimate the energy required for the mission, based on experimental characterization of the propulsion system, as well as an offline mechanism to estimate if enough energy is available to complete the mission safely, and an online method to determine how much energy is required for a safe return to the launch position, and when this command should be triggered.

In [9] the derived energy balance equations are used to assess the energy margins of the aircraft and analyse the viability of perpetual endurance.

Development of a system with the capacity to generate an updated estimate of the state of the total energy remaining onboard an aircraft at the end of the mission is, to the best knowledge of the author, scarcely discussed in the literature. The closest example found relating to the energetic evaluation of a given mission is presented in reference [8]. In that work the energy assessment is used to perform an offline mission feasibility test, complemented by an online fail-safe feature in which the UAV returns to the launch position in case of insufficient energy to complete the mission. This is very similar to the goal of the energy monitoring system (EMS) required for the Drones Safe Flight project, although in [8] the environmental conditions are not accounted for in these estimates, which should influence the return to launch feature developed, since it is assumed that this command is triggered when the required energy to return to the launch position (without accounting for wind) is equal to the remaining available energy in the batteries, which in reality could potentially lead to insufficient energy to complete the return to launch command.

In [9] the energy margins of a perpetual endurance mission are predicted, although in this work the required energy to complete the mission is assumed constant throughout the whole flight. The estimates are also not updated given the experienced flight conditions, since this work only intended to demonstrate the perpetual endurance capacity of the aircraft considered.

As such, this work contributes to the reinforcement of the literature regarding energy balance and energy awareness estimates for UAVs, introducing methods not previously considered to periodically evaluate the capacity of a given aircraft to complete the assigned mission, in real time, and considering the influence of wind.

3. Energy Estimation Models

Figure 2 provides an overview of how the estimation of the remaining energy at the end of the flight is obtained.

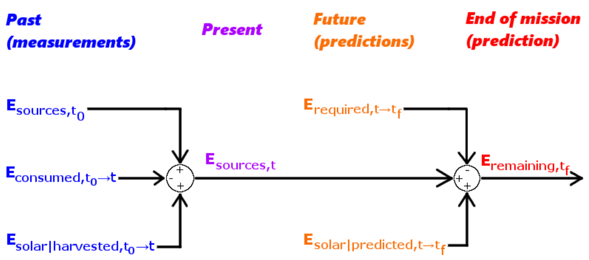

Figure 2: Energy balance at end of mission

In essence, for a given instant during the mission, this is an energy balance problem. The problem of energy balance is divided in two stages: past energy flow and future energy flow.

The past energy flow analysis starts with the initial state of the system, the energy available in all energy sources at the start of the mission $E_{sources,t_0}$, then the energy flowing out of the system (measured consumed energy) is subtracted, $E_{cons,t_0 \to t}$, and the energy harvested (flowing into the system) $E_{solar|harv,t_0 \to t}$ is added. This results in the energy available in the energy sources in the present (at time instant t) $E_{sources,t}$, with the corresponding mathematical description given by

$$\begin{aligned} E_{sources,t}(t) = & E_{sources,t_0} + E_{solar|harv,t_0 \to t}(t) \\ & - E_{cons,t_0 \to t}(t)\,. \end{aligned} \quad (1)$$

Knowing the present state of the system, all that is left to do to obtain the future energy flow is subtract the expected energy to flow out of the system in the future (required energy to complete the mission) $E_{req,t \to t_f}$, and add the expected energy to flow into the system in the future (solar energy expected to be harvested in the remainder of the mission) $E_{solar|pred,t \to t_f}$. This in turn results in the estimated final state of the system, the estimated remaining energy in the sources at the end of the mission E_{rem,t_f}, mathematically described by

$$\begin{aligned} E_{rem,t_f}(t) = & E_{sources,t}(t) + E_{solar|pred,t \to t_f}(t) \\ & - E_{req,t \to t_f}(t)\,. \end{aligned} \quad (2)$$

3.1. Past Energy Flow

Assessing the energy available in the sources of the aircraft at a given time instant ($E_{sources,t}$) requires measurements of current I and voltage U in different positions of the electric circuits onboard, illustrated in figure 3, as well as of volumetric fuel flow rates $\dot{V}_{fuel}$ out of the fuel tank in case the aircraft is powered by fossil fuels, such that the past flow of energy into and out of the system can be evaluated.

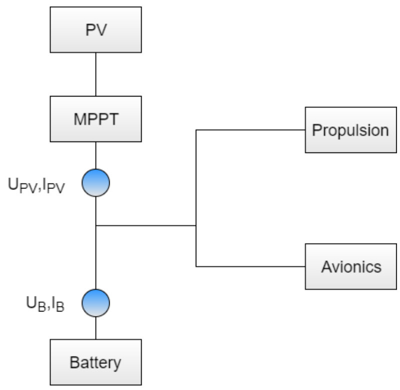

Figure 3: Possible points of voltage and current measurement (in blue) in the electric circuits of the aircraft

3.1.1 Initial Energy Available in the Sources

The energy available in the energy sources at the start of mission is modelled by

$$\begin{aligned} E_{sources,t_0} = & E_{battery,t_0} + E_{fuel,t_0} + E_{p,t_0} \\ & + E_{k,t_0}\,, \end{aligned} \quad (3)$$

where $E_{battery,t_0}$ and E_{fuel,t_0} are the energy available in the battery and in the fossil fuel tank at the start of the mission respectively, and E_{p,t_0} and E_{k,t_0} are the potential and kinetic energies of the aircraft at the start of the mission, respectively. The initial energy stored in the battery is given by

$$E_{battery,t_0} = SoC\,Q_{nom} U_{nom} 3600\,, \quad (4)$$

where SoC is the state of charge of the battery (between 0 and 100%), Q_{nom} is the nominal charge of the battery and U_{nom} is the nominal voltage of the battery. This model assumes that the battery is not affected by Peukert's law [10], and that the SoC is known from the pre-flight charging process.

The initial energy contained in the fuel tank is related to the volume of fuel it contains, expressed in (5).

$$E_{fuel,t_0} = u_{fuel} m_{fuel,t_0} = u_{fuel} \rho_{fuel} V_{fuel,t_0} \,, \quad (5)$$

where u_{fuel} is the specific energy of the fossil fuel, ρ_{fuel} is its density and V_{fuel,t_0} is its volume at the beginning of the mission. This assumes ρ_{fuel} is estimated for a given temperature and V_{fuel,t_0} is measured.

The initial potential energy is

$$E_{p,t_0} = mg(h_{t_0} - h_{t_f}) \,, \quad (6)$$

where h_{t_0} is the altitude of the aircraft at the start of the mission.

Finally, the initial kinetic energy of the aircraft is zero, since its ground speed is also zero.

3.1.2 Consumed Energy

The model for the energy consumed is given by

$$\begin{aligned} E_{cons,t_0 \to t}(t) = & \int_{t_0}^{t} \dot{E}_{battery}(t) dt \\ & + \int_{t_0}^{t} \dot{E}_{solar|harv}(t) dt \\ & + \int_{t_0}^{t} \dot{E}_{fuel}(t) dt \,. \end{aligned} \quad (7)$$

The terms of equation (7) are given by equations (8) through (10).

$$\int_{t_0}^{t} \dot{E}_{battery}(t) dt = \int_{t_0}^{t} U_B I_B dt \,, \quad (8)$$

$$\int_{t_0}^{t} \dot{E}_{fuel}(t) dt = u_{fuel} \rho_{fuel} \int_{t_0}^{t} \dot{V}_{fuel} dt \,, \quad (9)$$

where $\dot{V}_{fuel}$ is the fuel volumetric flow. This assumes that the quantities U_B, I_B, U_{PV}, I_{PV} and $\dot{V}_{fuel}$ are measured. It is important to notice that I_B can be both positive and negative, depending on whether the battery is being discharged or charged, respectively.

3.1.3 Energy Harvested

Given the nomenclature of figure 3, the solar energy harvested from the beginning of the mission until time instant t, is described by

$$\int_{t_0}^{t} \dot{E}_{solar|harv}(t) dt = \int_{t_0}^{t} U_{PV} I_{PV} dt \,, \quad (10)$$

3.2. Future Energy Flow

To estimate the energy remaining in the sources at the end of the mission $E_{remaining,t_f}$ (the final state of the system), it is necessary to estimate, at a given time instant, how much energy is still required to finish the mission and how much solar energy is expected to be harvested until the end of the mission, as previously shown in equation (2).

3.2.1 Energy Required

The required energy to complete the mission is obtained by estimating the future consumption of the propulsion system $E_{prop,t \to t_f}$, the future consumption of all the avionics equipment $E_{av,t \to t_f}$ and also taking into account the change in mechanical energy (ΔE_p and ΔE_k) between the instant of calculation t and the end of the mission, leading to

$$\begin{aligned} E_{req,t \to t_f}(t) = & \Delta E_p(t) + \Delta E_k(t) \\ & + E_{av,t \to t_f}(t) \\ & + E_{prop,t \to t_f}(t) \,. \end{aligned} \quad (11)$$

The change in gravitational potential and kinetic energy, from time instant t until the end of the mission, can be obtained from equations (12) and (13) respectively, from the definitions of potential and kinetic energy.

$$\Delta E_p = E_{p,t_f} - E_{p,t}(t) \,, \quad (12)$$

$$\Delta E_k = E_{k,t_f} - E_{k,t}(t) \,. \quad (13)$$

Assuming that the power required to operate each avionics component is constant throughout the mission, equation (14) can be used to calculate the required energy to power the avionics systems, in which $P_{instruments}$ is an array whose elements are the (constant) power required to operate each instrument onboard the aircraft.

$$E_{av,t \to t_f}(t) = \sum_i \int_{t}^{t_f} P_{instruments,i} dt \quad (14)$$

To estimate the required propulsion energy to finish the mission successfully three different approaches were considered.

First Approach:

The propulsion power required to maintain flight in an equilibrium condition (cruise or hover) is initially established.

Integrating the propulsion power required to fly in the equilibrium condition ($P_{prop,eq}$) over the expected remaining mission duration nets the propulsion energy required for flight in this equilibrium state ($E_{prop,eq,t \to t_f}$), as described by

$$E_{prop,eq,t \to t_f}(t) = \int_{t}^{t_f} P_{prop,eq} dt \,. \quad (15)$$

A correction (or safety) factor C_f is then multiplied by this propulsion energy required projection, in order to pull the estimate closer to the real value, as expressed in

$$E_{prop,t\to t_f}(t) = C_f E_{prop,eq,t\to t_f}(t)\,. \qquad (16)$$

The correction factor has to be determined experimentally or through flight simulations, and will be unique for each aircraft.

Second Approach:

Based on the force diagram of figure 4 (for a generic aircraft), the required thrust is obtained.

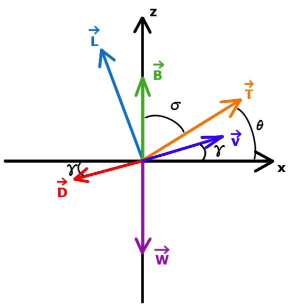

Figure 4: Force diagram for a generic aircraft

The balance of forces is therefore given by

$$\begin{cases} L - Wcos(\gamma) + Bcos(\gamma) + Tsin(\alpha) = 0 \\ Tcos(\alpha) - D - Wsin(\gamma) + Bsin(\gamma) = ma \end{cases} \qquad (17)$$

where B represents the buoyancy force.

The drag polar curve ($C_D = f(C_L)$) and the relationship between lift coefficient and the angle of attack ($C_L = f(\alpha)$) of the aircraft are used in addition to equation (17) to solve the balance of forces, assuming the desired acceleration for each mission segment, the weight and buoyancy (in case the aircraft in study is a dirigible balloon) of the aircraft are known.

Air density ρ is modelled according to the Earth's atmosphere standard model of reference [11].

The climb angle γ is calculated according to the waypoints defined during mission planning

The aircraft types considered all use propellers to generate thrust, which is related to the power that has to be transfered to the air by the propellers for a given manoeuvre. Using momentum theory [12] it is possible to estimate the mechanical power that the propeller of an helicopter during hover is required to transfer to the air ($P_{propeller,i}$) through

$$P_{propeller,i} = \rho \omega_i^3 \pi r_p^5 C_{p,i}\,, \qquad (18)$$

where r_p is radius of the propellers used, ω_i is their angular velocity and $C_{p,i}$ its their power coefficient, which can be obtained from experimental characterization of the propeller or from appropriate tables as a function of thrust required and airspeed. Tables like this can be obtained from manufacturer data, for example at `www.apcprop.com/v/PERFILES_WEB/listDatafiles.asp`.

This expression can then be used as an approximation for the required power that has to be transferred to the air by each of the propellers of an aircraft.

The total propeller power required $P_{propeller}$ is then obtained by summing the power required from each of the individual propellers, as expressed in

$$P_{propeller} = \sum_{i=1}^{n_{props}} P_{propeller,i}\,. \qquad (19)$$

Finally dividing the total propeller power required by the efficiency of the propulsion system η_{prop} results in the electric propulsion power required to be extracted from the sources in the future, as given by

$$\dot{E}_{prop} = P_{prop} = \frac{P_{propeller}}{\eta_{prop}}\,. \qquad (20)$$

The propulsion required energy is therefore obtained by integrating the propulsion required power that has to be extracted from the energy sources in the future, thus

$$E_{prop,t\to t_f}(t) = \int_t^{t_f} P_{prop}\, dt\,. \qquad (21)$$

Third Approach:

One more possibility to determine the required propulsion and avionics power required is to experimentally characterize the energy requirements of an aircraft as a function of airspeed, exemplified in figure 5 for an aircraft (LEEUAV - Long Endurance Electric UAV, a small fixed wing solar powered aircraft designed by several institutions belonging to the research line of LAETA) while in cruise condition. If it is possible to provide an estimate for the required airspeed at different flight stages, the required propulsion energy to finish the mission can then be obtained by integrating the corresponding value of required electric power P_{el} from the curve over the expected remaining duration of the mission, as described by

$$E_{av,t\to t_f}(t) + E_{prop,t\to t_f}(t) = \int_t^{t_f} P_{el}\, dt\,. \qquad (22)$$

Notice that since this particular experimental characterization is only valid for cruise, this approach results in an underestimation of the power requirements for take-off and climb. If a more detailed experimental characterization of the power requirements for different flight stages was available, a better quality estimate could be obtained.

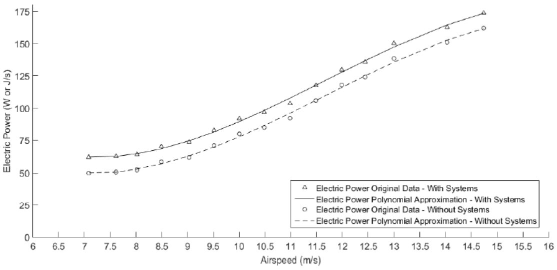

Figure 5: Power required as a function of airspeed for the LEEUAV during cruise (with photovoltaic panels installed) [13]

3.2.2 Energy Harvested

Assuming level flight (which constitutes the largest percentage of mission time), the approach of reference [14] can be used to estimate the solar irradiance in a given location, at a given time. It should be noted that this model is used for aircraft operating at high altitudes, and the effects of temperature, humidity and albedo are not accounted for.

The equations of the aforementioned model are summarized below in equations (23) through (27).

$$J = J_{0n} \tau sin(\zeta)\,,\; J_{0n} = J_{SC}\left(\frac{r_{ES,0}}{r_{ES}}\right)^2\,, \qquad (23)$$

$$r_{ES} = r_{ES,0}\left(\frac{1-\epsilon^2}{1+\epsilon\, cos(\nu)}\right)\,, \qquad (24)$$

$$\begin{aligned}\zeta =& \frac{\pi}{2} - arccos(sin(\lambda)sin(\delta) \\ &+ cos(\lambda)cos(\delta)cos(\mu(H)))\,,\end{aligned} \qquad (25)$$

$$\delta = \frac{23.45\pi}{180} sin\left(360\frac{284+d_n}{365}\right)\,, \qquad (26)$$

$$\mu(H) = \pi - \pi\frac{H}{12}\,,\; \nu = 2\pi\frac{d_n - 4}{365}\,, \qquad (27)$$

where J is the solar radiation (or solar power per unit area), J_{0n} is the intensity of the extraterrestrial normal solar radiation, τ is the transmittance factor, ζ is the zenith angle, J_{SC} is the extraterrestrial normal solar radiation constant, $r_{ES,0}$ and r_{ES} are the mean and real distances between the Earth and the Sun respectively, ϵ is the eccentricity of Earth's orbit, ν is the true anomaly, d_n is the day of the year, counting from the first of January (day 1), λ is the latitude of the location, δ is the solar declination angle, μ is the hour angle and H is the hour of the day. The values of the constants are defined in table 1.

It is important to note that this model may output negative values for the solar irradiance (before and after sunset), and in this case its value will be simply set to zero.

Table 1: Definition of constants for the solar irradiation model

Constant	Value
τ	0.85
J_{SC}	1367 W/m^2
ϵ	0.0167
$r_{ES,0}$	149597870.7 km

The expected energy to be harvested from a given time instant t until the end of the mission is finally obtained by integrating the power output of the solar panel over time, as described by

$$E_{solar|pred} = \int_t^{t_f} J\, S_{PV}\, \eta_{PV}\, dt\,. \qquad (28)$$

where S_{PV} is the solar panel area and η_{PV} is its efficiency.

4. Simulations and Results

In this section the simulations performed on the EMS and the main results obtained are discussed.

The online simulations were performed by using a Simulink® model of a multirotor available on the internet, which had some flaws in the control system designed, for example, while moving in a straight line, the motors angular velocity would be the same as that of the hover condition, independently of the reference ground speed. The angular velocity of the motors only changed to perform attitude corrections. Nonetheless this model was used in the online simulations due to a lack of alternatives.

The offline simulations were performed using MATLAB® scripts and available data regarding the LEEUAV aircraft.

4.1. Online Simulation Results

The online simulations are intended to preview the behaviour of the EMS through the course of an entire mission, with continuous updates. The first method to calculate the required energy to complete the mission, discussed in section 3.2.1, was used in this case. However, it was not possible to perform the simulations including the influence of wind on the dynamics of the aircraft due to the limitations of the control system designed for the multirotor.

The correction factor C_f was first calibrated by performing a series of simulations with different missions under different conditions. Due to the issues with the control system, discussed previously, it was found that the correction factor has no relationship with the mission duration, which is not realistic. Despite this fact, the maximum value found for the $C_f = 1.0487$ is used in order to perform the following analysis and evaluate the performance of the EMS given this choice.

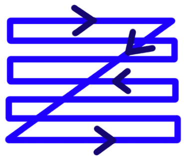

Figure 6: Mission path for online simulations

The mission path chosen for the online simulations is shown in figure 6, with the initial and final points on the ground, and the path being followed at an altitude of 10m. The results of this simulation, therefore the values of each parameter of the past and future energy balances, are shown in figure 7.

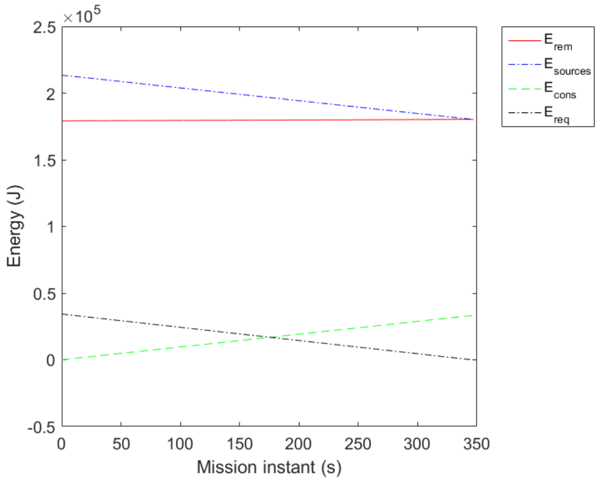

Figure 7: Estimate for the energy remaining at the end of the mission and its components

Since the aircraft used in the online simulations is a multirotor, it does not possess PV panels, meaning that $E_{solar|pred,t \to t_f}(t) = 0$ and $E_{solar|harv,t_0 \to t}(t) = 0$.

The qualitative analysis of figure 7 is promising. As the mission progresses the consumed energy increases as expected, starting at 0J and ending with its maximum value; similarly, the estimate for the required energy to complete the mission decreases over time, having its maximum value at $t = 0s$, and reaching 0J at the end of the mission. Notice that the estimate for the required energy at $t = t_0$ is almost equal to the value of the consumed energy at $t = t_f$, which indicates that the estimate for the required energy is very satisfactory.

The energy available in the energy sources (battery and mechanical energy in this case) decreases over time as expected. From its initial value it decreases around 35kJ until the end of the mission, around the same amount of total consumed energy, which makes sense.

The estimate for the energy remaining in the energy sources at the end of the mission should, ideally, be a straight line (constant value over time), meaning that at any instant, during the course of the mission, it is possible to predict the final state of the energy sources. This parameter is the most important in the context of the energy monitoring system. Its analysis is what allows the operator or the mission planning module to understand whether or not there will be enough energy available to finish the planned mission. If the value of E_{rem,t_f} drops below zero at any moment, it means the UAV will not have enough energy to finish the planned mission successfully, and the mission should be changed accordingly. However, for a real scenario, a safety threshold must be defined in order to avoid accidents, and if E_{rem,t_f} drops below this value, the mission should be immediately replanned.

In the case of this particular mission, since the energy remaining estimate is approximately at around 84% of the total energy of the battery during the whole duration of the mission, it means that this mission is feasible. From the results shown in figure 7, it appears that the energy remaining estimate is approximately constant, however in fact there is a slight increase over time of around 1100J. Do note that this simulation does not include the effect of wind on the aircraft's dynamics.

The reason for this increase is due to the fact that the required energy is an overestimate (due to the C_f chosen) of the amount of energy that will actually be consumed in the remainder of the mission, leading to a rate of consumption that is in reality lower than that which was estimated.

4.2. Offline Simulation Results

Since it was not possible to perform flight tests to collect data, and no guidance and control Simulink models of the aircraft were available, only offline simulations were performed for the case of the LEEUAV, given the available data from previous works (polar curve, relationship between lift coefficient and angle of attack, and the plot of figure 5), to assess the performance of the EMS in this case. The offline simulations aim to predict if the planned mission is feasible (before take-off). In this case, the second and third methods discussed in section 3.2.1 are used to estimate the required energy to complete the mission.

Additionally, the simulations were performed for a simple climb, cruise and descent mission profile, in which it was assumed that the aircraft turns off the engines and glides to the landing point during descent. The mission profile and the corresponding ground speed profile are shown in figures 8 and 9 respectively.

An initial simulation without wind was performed to compare the predicted propulsion power

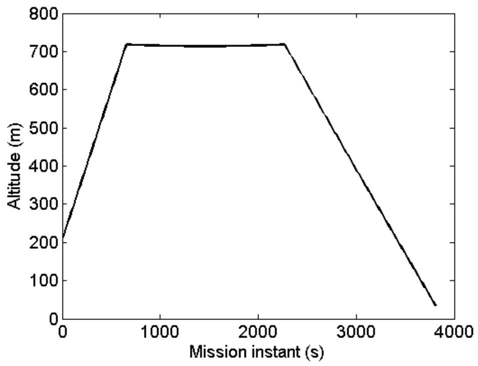

Figure 8: Mission profile chosen

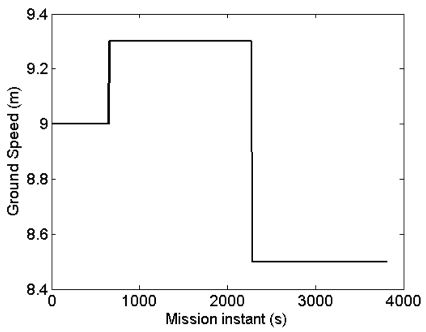

Figure 9: Ground speed profile for the chosen mission

requirements for different flight stages using each method used to estimate the required energy to complete the mission, and the results are shown in table 2.

Method 3 is very accurate at predicting the power required to fly during cruise, due to the fact that it derives from an experimental characterization. This means that method 2 overestimates the power requirements for cruise by approximately 106%, which is not good. Method 3 on the other hand, severely underestimates the power requirements for climb, since the experimental characterization on which method 3 is based on was performed only for the cruise condition, and no data was available for climb. The required power for the descent stage is zero since it is assumed the aircraft glides while descending.

Table 2: Comparison between the predicted propulsion power required to fly each stage by each method

	Predicted power required (W)	
Flight Stage	**Method 2**	**Method 3**
Climb	~578.3	247.1
Cruise	132.8	64.4
Descent	0	0

Table 3: Wind temporal profile considered in the simulations

Mission instant (s)	**Wind speed (m/s)**
0	1.2
600	0.8
1200	1.9
1800	1.5
2400	0.3
3000	0.7
3600	0.6
4200	1.0

Table 4: Results of the offline simulations

Energy (kJ)	**Day:172 Hour:9h**	**Day:172 Hour: 15:45h**	**Day:355 Hour:9h**
$E_{sources,t_0}$	408.911		
E_{req} M2	836.575		
E_{req} M3	382.642		
$E_{solar\|pred}$	627.213	428.649	263.041
E_{rem} M2	199.549	0.985	-164.623
E_{rem} M3	653.482	454.917	289.310

Although the errors found are not satisfactory, this does not necessarily mean that the proposed methods should be discarded. These results allow, however, to conclude that these methods are sensitive to the quality of the data available to perform the estimates, and in order to improve them, and further investigate their validity, better data has to be obtained.

For the following simulations, an arbitrary temporal wind profile was chosen and is shown in table 3, in which the mission instants indicate when the respective wind speed changes to that value.

The influence of performing the mission in different days of the year (day 172 - Summer Solstice, and day 355 - Winter Solstice) and different starting hours was also investigated. The results obtained are shown in table 4, in which M2 and M3 represent method 2 and method 3 respectively.

Two main conclusions can be drawn from this table. First it is possible to observe that during the Summer Solstice more solar energy is expected to be harvested compared to the Winter Solstice when the mission begins at the same hour, which makes sense. Also, on the same day more energy is expected to be collected if the mission starts in the morning than if it starts later in the afternoon, which is also a result to be expected.

Secondly, the remaining energy term provides insight into under which conditions it is possible to complete the mission safely. With the previously mentioned temporal wind distribution, and using method 2 to calculate the required energy to complete the mission, it is predicted that the mission can be completed safely in the Summer Solstice if it starts at 9h, and the battery would still have around 49.9% of its total energy at the end. If the mission starts at 15:45h however, the battery is predicted to finish the mission with less than 1% of its total energy, which is a value low enough to raise safety concerns, and the mission should be replanned. During the Winter Solstice, the value of remaining energy is negative, meaning that the battery does not have enough energy to complete this mission, since not enough solar energy would be collected to compensate the amount consumed. If method 3 is used instead to calculate the required propulsion power, then the conclusion would be that this mission could be completed safely in any of the conditions considered. In reality, this probably would not be true since given the available data, the power requirements for climb would be underestimated by method 3. With better data available, this method would be more useful and provide more accurate remaining energy estimates.

It was also found that calculating the propulsion power required is much faster with method 3, since in this case the required electric power is directly related to airspeed, while in the case of method 2 it is necessary to search the propeller performance tables for the right parameters given the required trust and airspeed. In longer missions method 3 would also dramatically outperform method 2 in terms of computation speed.

5. Conclusions

In this work, an EMS for the Drones Safe Flight project was proposed, which evaluates the past and future energy balance of the onboard energy sources of the aircraft. Three different estimation methods for the required energy to complete the mission are presented.

The performance of each method and of the overall EMS was discussed and qualitatively validated. The first method was based on the idea of having a base energy estimate corrected by an empirical factor. The calibration of this empirical factor was performed by using a Simulink® model of a multirotor available on the internet. Although some flaws were found in this model it was nonetheless used for the simulations due to a lack of alternatives available. The maximum correction factor found, after simulating a specific mission under slightly different forecasted conditions, should be used to avoid safety issues by overestimating the mission energy requirements, leading to earlier mission replanning, and predicting deficiencies in energy resources ahead of time. Additionally, a safety factor should also be multiplied to the predicted energy requirements for the mission, to account for unforeseen disturbances, the impossibility to predict the real wind conditions and unexpected obstacle avoidance manoeuvres.

Simulations with the second method used propeller manufacturer data, and was concluded that it was not accurate enough for real applications, overestimating the power requirements for cruise by as much as 106%, and therefore an experimental characterization of the particular propellers used on the aircraft is required to obtain higher quality estimates. The polar curve and the curve describing the relationship between lift coefficient and angle of attack used were obtained through software tools, potentially being a source of error. Additionally, the expression used to obtain the propeller mechanical power is based on an equation valid for helicopters in hover, adding extra error.

The third method is highly accurate in predicting the energy requirements for the cruise stage, but since only data for cruise was available the power requirements for the climb stage are underestimated.

These three proposed methods are highly sensitive to the quality of the data and tools available. The biggest challenge found in this work was obtaining appropriate data and simulation tools to validate the proposed methods. The 3 proposed methods are simply workarounds the problem of not having a control and guidance model of the LEEUAV available, leading to underwhelming results. With this in mind the results obtained, although qualitatively satisfactory, should be considered with some criticism.

Clearly there is much room for improvement in future work, although this work attempts to assert the importance of the remaining energy estimation for the safety of low-cost UAVs. This parameter is useful when trying to predict mission feasibility, enabling better energy awareness during mission planning, and contributing to an online assessment of energy resources and mission energy requirements to enhance safety and prevent accidents. However it does not take into account situations where, for example, a very demanding climb condition would exhaust the battery's energy, even though if the flight continued the total energy balance could be positive since in cruise excess solar energy could be collected to recharge the battery. A failsafe to account for situations like these would have to be implemented, for example by breaking down the energy balance problem into subproblems for each mission segment, and if in any segment the remaining energy at the end of the segment was predicted to be negative then the mission would not be feasible.

5.1. Future Work

In future work, the first step should be to focus on the crucial step of estimating the required energy to complete the mission and obtaining high quality data for that effect.

Developing an accurate Simulink® model of the aircraft in study should be a priority, including guidance and control systems with good performance and the influence of wind on its dynamics. This would allow a better calibration of the correction factor. A more realistic battery model than the one suggested in this work, and modelling the power consumption of the onboard avionics equipment could also benefit the simulation model.

Secondly, experimental characterization of the particular propellers used on the aircraft should be obtained, as well as an experimental polar curve and lift coefficient as a function of angle of attack curve from wind tunnel tests, in order to obtain better estimates with the second method.

Performing flight tests and recording electrical power required as a function of airspeed for each flight stage, would benefit the estimates when using the third proposed method.

Flight tests to compare the performance of each alternative presented to calculate the required energy to complete the mission should follow. These would also allow to verify the performance of the EMS, as well as potentially improving the calibration of the correction factor obtained through simulations even further with more data available.

Further in the future, the EMS, the mission planning module and the obstacle detection and avoidance modules should be integrated together and the full system's performance assessed on ground and flight tests, as this is the main goal of the Drones Safe Flight project.

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