

Design Considerations for Long Endurance Unmanned Aerial Vehicles

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1. Abstract

The arena of Unmanned Aerial Vehicles (UAVs) has for many years been dominated by the defence industries. The reason for this can be attributed to the complexity and cost of designing, constructing and operating of these vehicles. An additional contributing factor is the legislative issues around operating an unmanned aircraft in civilian airspace. However in recent years advances in micro-electronics especially Micro Electronic Mechanical Systems (MEMS) and advanced composite manufacturing techniques have placed the design and construction of UAVs in the domain of the commercial civilian users. A number of commercial UAV applications have emerged where the legislative requirements for operating of a UAV in segregated airspace can be met. UAVs are extremely well suited for the dull, dirty and dangerous tasks encountered in performing surveying and surveillance applications. For these tasks the primary design considerations in the design of the UAV would be the propulsion system, the guidance and control system and the payload system.

2. Introduction

The European Unmanned Vehicle Association identifies five main categories of UAVs (Sarris, 2001):

- **Close range** – fly in a range of less than 25 km. Usually extremely light;
- **Short range** – operate within a range of 25-100km.
- **Medium range** – Able to fly within a range of 100-200km. Need more advanced aerodynamic design and control systems due to their higher operational performance.
- **Long range** – Fly within a range of 200-500km. Require more advanced technology to carry out complex missions. Need satellite link in order to overcome the communication problem between the ground control systems and aircraft created by the curvature of the earth.
- **Endurance** – Operate in a range more than 500km, or can stay in the air for more than 20 hrs. This is considered the most sophisticated of the UAV family due to their high capabilities.

This chapter presents design considerations for UAVs which can be categorized as endurance UAVs. The design considerations discussed include the primary UAV systems namely, propulsion system, navigation and control system and sensor payload system.

Renewable energy sources is an attractive alternative to the conventional fossil fuel based propulsion systems. The renewable energy sources evaluated for long endurance UAV applications include solar energy, hydrogen fuel cells and energy storage sources such as batteries and super capacitors. The advantages and disadvantages of each source are presented. Results from an algorithm developed for the selection of the optimal energy source based upon the application requirements and constraints are presented. Implementation issues around a solar powered UAV for long endurance applications are discussed. The results of the feasibility study of using solar power for long endurance UAVs are presented.

Advances in the development of MEMS based inertial sensors have enabled the development of low cost inertial navigation systems for use in UAV applications. An overview of the field on inertial navigation is presented along the advances in inertial sensors. Some considerations that impact the selection of the inertial sensors and the final design of the navigation system are presented. A number of options for the improvement of the navigational performance of the low-cost inertial sensors by combining the sensor data with the measurements from other sensors such as GPS, cameras and altimeters are discussed.

Another aspect of UAV design is the control system. Autonomous control is of paramount importance for the safe and successful operation of unmanned aircraft that is operated out of visual range. The development of UAV autopilots is presented by looking at the classical and the modern approaches to control system development.

UAVs are extremely well suited for applications where the payload consists of optical image sensors such as cameras. Cameras offer powerful lightweight sensors suited for a variety of tasks. In keeping with commercial trends (in contrast to the military environment) some of the functionality associated with the operation of long range UAVs can be "outsourced" by using existing infrastructure. This effectively increases the risk of an unsuccessful UAV mission (in a commercial sense), but lowers the cost of development and operations.

Image processing solutions invariably implies large processing power, which leads to high power requirements. By using the pervasiveness and low cost of the mobile communications technology and industry, some of the processing can be "outsourced" to a powerful ground processing station. This opens up a Pandora's box of opportunities, i.e. real-time scene identification, automated mission control, visual cues, speed and orientation estimations, super resolution of low resolution sensory information, etc. Recent trends see high speed, parallel processing Graphics Processing Units (GPU) integrated into low powered mobile phones. This can provide high speed processing power on-board the UAV for complex image processing applications. A balance need to be maintained between local, on-board processing requirements (e.g. for reliable navigational purposes) and higher level functionality (associated with the mission).

The next section presents the design considerations for long endurance UAV applications with regard to renewable energy propulsion sources, navigation and control aspects and payload applications.

3. Electrical Power Sources for Long Endurance UAV Applications

Unmanned Aerial Vehicles are ideally suited for long endurance applications, but to be able to make full use of this feature, effective power sources need to be developed to ensure the long endurance functionality of the propulsion system and onboard equipment. For a UAV the flight endurance is in direct relationship to the total weight of the craft. In order to maximise flight endurance the need for high density energy sources are created. The

objective of this section is to present design considerations for high energy density, cost effective, non-carbon emitting and renewable energy sources. The following energy sources and combinations thereof are considered:

- Lithium Polymer (Li-Po) Batteries;
- Super Capacitors (SC);
- Photo Voltaic (PV) Cells; and
- Hydrogen Fuel (FC) Cells.

Lithium Polymer batteries and super capacitors are in essence only energy storage mediums. However in the context of UAV power sources these energy stores can be considered as energy sources for supplying power to the UAV and associated onboard equipment.

3.1 Solar Energy

Solar energy refers to the solar power collected from solar irradiance by photovoltaic cells. The power output of photovoltaic cells depends primarily on the absolute value and spectral distribution of irradiance in the plane of the photovoltaic cell and the resulting operational temperature (Luque & Hegedus, 2003). Much research has been conducted with regards to the factors influencing solar power generation which is beyond the scope for this chapter. The total amount of energy produced by the photovoltaic cells is a function of the geographical position (latitude, longitude, and altitude), time of the year, atmospheric absorption and efficiency of the photovoltaic cells. The Linke turbidity factor (Muneer et al., 2004) is used to characterize the clearness of the sky. The lower this factor, the clearer the sky, the larger the beam irradiation and the lower the relative fraction of the diffuse irradiation. For higher altitudes, the absorption is lower because of less radiation scattering by the atmosphere which lowers the Linke turbidity factor. Typical values for the Linke turbidity factor are listed in Table 1.

T_{LK}	Sky Condition
1	Pure sky
2	Very clear sky
3	Clear sky
5	Summer with water vapour
7	Polluted urban industrial

Table 1. Typical values for the Linke turbidity factor

The amount of solar energy available per day for propulsion of a solar powered UAV is not only dependant on the clearness of the atmosphere but also highly dependant on the time of the year. UAVs operating during the summer months, when the available energy is at its highest, has approximately 2.2 times the energy available relative to operation during winter months when the available energy is at its lowest. Even when a worst case summer day (with Linke turbidity equal to 5) is compared with a clear winter's day (with Linke turbidity equal to 2), the ratio of available solar energy in summer is still on the order of 1.5 to the available solar energy in winter. This difference in available solar energy is mainly contributed by the distance between the earth and the sun increasing in winter and the smaller sun angle and the shortening in day light hours as a result of the inclination of the

earth axis. When designing solar powered UAVs, consideration has to be given to the expected operating time of the year. Designing for minimum available solar energy conditions may result in an over design by a factor of 2 under maximum available solar energy conditions. An over design factor of 2 has significant negative impact on the UAV airframe design in terms of size and cost. A positive impact may be that the excess solar energy available may be used to overcome the increased aerodynamic drag when the UAV is flying at faster speeds. This may result in UAVs which can be operated at higher flying speeds during the summer months, when the available solar energy is at a maximum. Figure 1 shows the theoretically available energy which can be collected in the southern hemisphere at a latitude of 25 degrees by a photovoltaic array of 1 m² with an efficiency of 16% as a function of the time of the year. Another issue to consider is matching the output of the photovoltaic cells to the input of the energy storage medium, which can make a great difference in the efficiency of power utilization, thus some form of maximum power point tracker will be required (Luque & Hegedus, 2003).

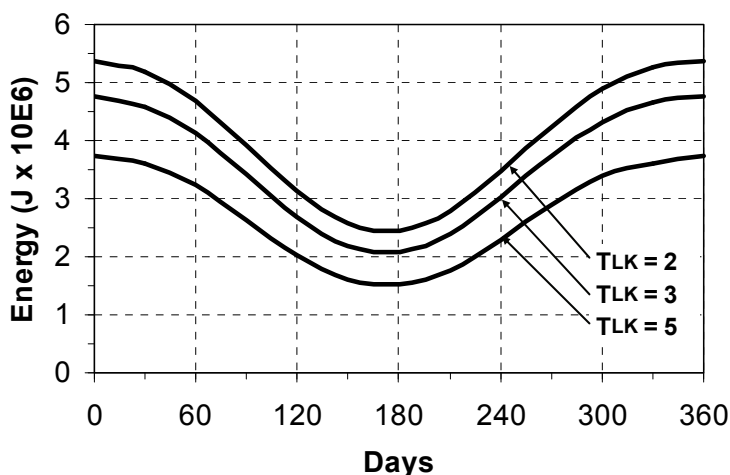


Figure 1. Available solar energy per day which can be collected by a 1 m² photovoltaic array with a 16% efficiency for various values of Linke turbidity factor where day 1 corresponds to the summer solstice in the southern hemisphere

3.1.1 Solar Energy Advantages

Advantages of using photovoltaic cells as energy sources can be summarized as follows:

- Very little maintenance required;
- Photovoltaic cells are non-polluting; and
- Essentially no operating cost. The greatest cost of photovoltaic cells is the initial acquisition costs.

3.1.2 Solar Energy Disadvantages

Disadvantages of photovoltaic cells are the high initial procurement cost and the fact that it can only generate electrical power during daylight hours which necessitates the use of energy

storage mediums. Secondly photovoltaic cell efficiency is rather low in the range of 14% to 18% for commercially available terrestrial grade cells. Space grade cells have efficiencies as high as 24% (Luque & Hegedus, 2003). The dependence on the atmospheric conditions makes solar energy a lot less predictable and seasonal variations will affect the design.

3.2 Lithium Polymer Cells

Lithium polymer cells are constructed using a flexible, foil-type case containing an organic solvent. In lithium-ion cells a rigid case presses the electrodes and the separator onto each other whereas in polymer cells external pressure is not required because the electrode sheets and the separator sheets are laminated onto each other. Lithium polymer batteries, the next generation power source (van Schalkwijk et al., 2002) since no metal battery cell casing is needed, the weight of the battery is reduced and it can be formed to shape. The denser packaging without inter cell spacing and the lack of metal casing increases the energy density of Li-Po batteries to over 20% higher than that of a classical Li-ion batteries. Lithium polymer cells are considered fully charged when the cell terminal voltage reaches 4.2 V and are fully discharged when the cell terminal voltages decreases to a voltage of 3.0 V. (van Schalkwijk et al., 2002). A variety of Li-Po batteries are commercially available consisting of different series and parallel configuration of cells making up the required battery voltage and current characteristics.

3.2.1 Lithium Polymer Cell Advantages

In UAV applications the obvious benefit of using Li-Po batteries is the higher energy density offered. Advantages of Li-Po batteries can be summarized as follows:

- High energy density;
- Low self-discharge properties;
- The flexible casing of the polymer batteries allow for design freedom in terms of profile thicknesses; and
- Low maintenance.

3.2.2 Lithium Polymer Cell Disadvantages

Lithium polymer cells have special recharging procedures necessitating the use of specifically designed chargers. Charging Lithium cells is the most hazardous aspect of the batteries. Cell count and terminal voltage are of utmost importance when charging Li-Po batteries. It is important not to exceed both the high voltage limit of 4.2 V and the low voltage limit of 3.0 V. Exceeding these limits can permanently harm the battery and may result in a fire hazard. When series cells configurations are employed to obtain the required battery terminal voltage cell balancing circuits are required to ensure an even voltage distribution over the cell stack. Failure to balance the series cell stack may cause overcharging of individual cells with the associated fire hazards. Lithium polymer batteries are also subject to ageing effects, due to this the expected lifetime of such batteries is limited. Disadvantages of Lithium polymer batteries can be summarized as follows:

- Special charging circuits required to maintain cell voltage within safe limits;
- Subject to aging;
- Subject to cell balancing for series stack configurations;
- High procurement cost; and
- Requires special disposal processes.

3.3 Hydrogen Fuel Cells

Polymer electrolyte membrane fuel cells (PEMFC) are constructed using a solid polymer as electrolyte, absorbent electrodes combined with a platinum catalyst. Hydrogen gas is recombined with oxygen gas producing electricity with water vapour as emission. Onboard storage of the hydrogen would be required for UAV applications. Alternatively, hydrogen may be manufactured onboard the UAV from electrolysis of water using solar energy. A closed loop system could be operated whereby the water from of the PEMFC can be electrolyzed into oxygen and hydrogen for later re-use. Oxygen is generally obtained from the surrounding air. Operating temperatures are relatively low around 80 °C, enabling quick starting and reduced wear. Platinum catalysts are required for operation and to reduce corrosion. Polymer electrolyte membrane fuel cells are able to deliver high energy densities at low weight and volume, in comparison to other fuel cells (Barbir, 2005).

3.3.1 Fuel Cell Advantages

The advantages of using PEMFCs can be summarized as follows:

- Relative high efficiency;
- High energy density;
- Low noise;
- Non carbon producing only water emission; and
- Low maintenance.

3.3.2 Fuel Cell Disadvantages

The biggest disadvantages of using PEMFCs are the initial procurement cost and the safety issues regarding the storage of the onboard hydrogen gas. PEMFCs also suffer from a limited lifetime.

3.4 Super-Capacitors

Super capacitors, (SC) or Ultra-capacitors are also known as Electric Double Layer Capacitors (EDLC). Super capacitors have a double layer construction consisting of two carbon electrodes immersed in an organic electrolyte. During charging, ions in the electrolyte move towards electrodes of opposite polarity; this is caused by an electric field between the electrodes resulting from the applied voltage. Consequently, two separate charged layers are produced. Even though the capacitors have a similar construction to batteries, their functioning depends on electrostatic action. No chemical action is required; the effect of this is an easily reversible cycle with a lifetime of several hundreds of thousands of cycles (Conway, 1999).

3.4.1 Super-Capacitors Advantages

The advantages of Super capacitor energy sources can be summarized as follows:

- High cell voltages are possible, but there is a trade-off with storage capacity;
- High power density;
- No special charging or voltage detection circuits required;
- Very fast charge and discharge capability; and
- Life cycle of more than 500,000 cycles or 10-12 year life time.

3.4.2 Super-Capacitors Disadvantages

Disadvantages of Super capacitors can be summarized as follows:

- Low energy density;
- Low power to weight ratio when compared to current battery technology;
- Moderate initial procurement cost; and
- High self discharge rate.

3.5 Electrical Power Source Comparison

When considering an electrical energy source for powering of an UAV the before mentioned advantages and disadvantages must be compared. The key performance parameters for energy sources in UAV applications were identified as:

- Energy density (Wh/kg);
- Energy unit cost (Wh/\$); and
- Lifespan (years).

Figure 2 shows a comparison of the key performance parameters for the energy sources considered.

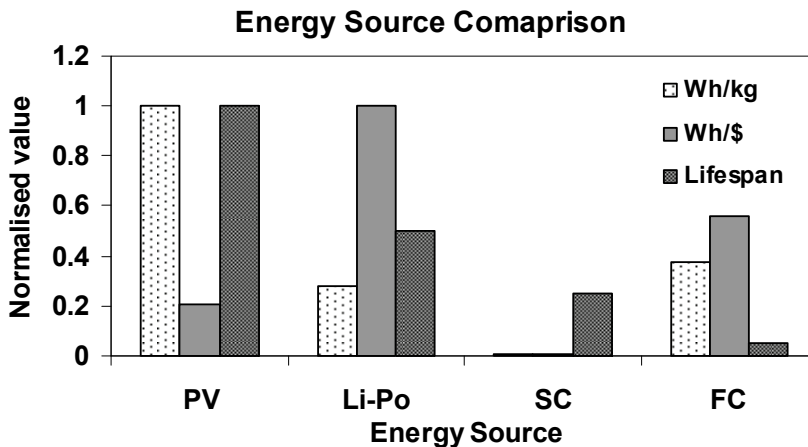


Figure 2. Normalised comparison of the key performance parameters for the energy sources considered

An algorithm was designed which is capable of determining the most applicable selection of the energy source, from the sources considered for a given UAV application. The UAV application is quantified by the user input of the following parameters:

- The electrical power required by the application;
- The maximum allowed weight of the power source;
- The required time duration for the supply of electrical power. This can also be considered as the flight duration; and
- The maximum cost limit for the power supply.

The results from the selection algorithm are presented in Table 2.

Flight Duration (h)	Power Source Weight (kg)	Required Power (W)	Solution 1	Solution 2
2	5	40	PV	Li-Po
10	4	20	Li-Po	FC
12	10	150	FC	PV-Li-Po
21	10	200	PV-Li-Po	None
24	20	200	FC	PV-Li-Po

Table 2. Applicable energy source for various UAV application requirements

From Table 2 follows for longer flight durations and high power ratings the preferred solution is hydrogen fuel cells or a photovoltaic-lithium polymer battery hybrid power supply. For lower power supply weight budgets and relatively short flight time durations the demands are met by using photovoltaic cells or lithium polymer battery supplies. Hybrid solutions are preferred above the fuel cell solution at lower weight requirements due to the photovoltaic cells advantage in power density, but the initial costs exceed that of fuel cells. However considering the life expectancy of the hybrid solutions this option becomes more attractive. A fuel cell solution is and all round good option and the relative simplicity of such a system makes this option very attractive.

From the results presented in Table 2 one of the ideal power solutions for long endurance UAV flights is the hybrid solution between the photovoltaic cells and Li-Po batteries. Considerations for implementation of hybrid photovoltaic cells and Li-Po batteries are presented in the next section.

3.6 Considerations for the Implementation of a Hybrid PV-LiPo UAV Power Source

Charging of a Li-Po battery requires the application of a 4.2 V voltage source across each cell in the battery with the current limited to the C rating of the battery. This is referred to as constant voltage, constant current charging. In Li-Po batteries the individual cells are connected in a series configuration in order to achieve the desired battery terminal voltage. The series connecting of cells requires that the cells are all identical in capacity and state of charge. This may not always be true. High discharge rates can cause cell imbalances as does cell aging. Series connection of Li-Po cells in batteries may lead to cell drifting, which poses serious dangers when charging. The proposed solution is therefore to connect all the Li-Po cells in parallel forcing the cells to the same state of charge. There are additional benefits of having the cells in parallel such as:

- Each cell ages the same amount if equal current sharing is implemented significantly reducing the charging safety hazards;
- Increased redundancy when cell stacks are set up so that the remaining sources pick up the slack of a faulty cell; and
- All cells in the stack are forced to same state of charge.

There are however a number of disadvantages to parallel connection of cells in battery stacks which may include the following:

- Cell isolation circuitry may be required to prevent a faulty short circuited cell to discharge the remaining cells; and

- Lower battery terminal voltage which would necessitate the use of boost converters to obtain the required operational voltage.

Charging a Li-Po cell at 1C for 1 hour will ensure that at least 70 % of the rated power will be charged. Considering the graph shown in figure 3, it is observed that the power input into the cell starts to fall off once the voltage of the cell reaches 4.1 V. By paralleling Li-Po cells in an overly large battery stack a battery is created which is able to store all the available energy generated by the photovoltaic cells. Thus it would be best to use a battery stack, consisting of a number of cells connected in parallel, with output voltage regulation using a self adjustable booster circuit. The power rating of the battery should be such that 70 % of the battery power capacity coincides with the maximum total power obtainable from the PV cells for the flight duration. This arrangement not only simplifies the circuit design by eliminating the need for specialised current limiting charging circuits but also ensures that all the available power generated by the photovoltaic cells can be stored without the need for complex switching circuits to switch the excess energy to the remaining batteries.

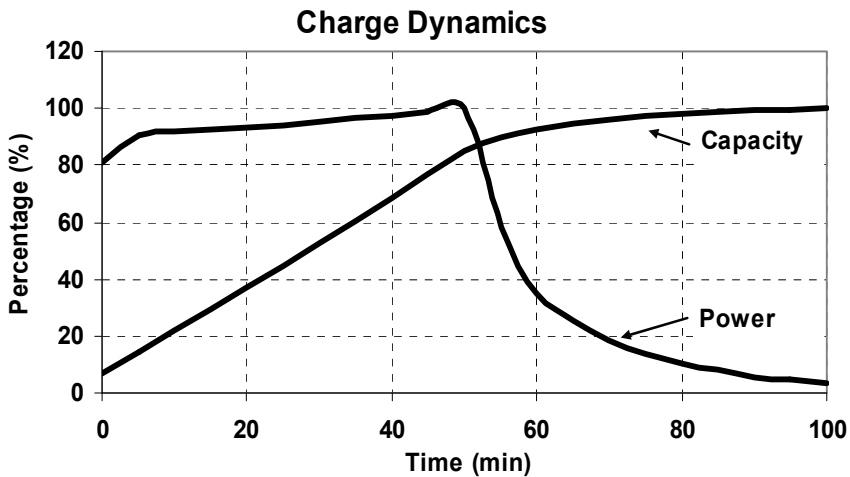


Figure 3. Power input into the battery per unit of time as function of time. The capacity of the battery is indicated as a percentage

In order to evaluate the feasibility of the proposed electrical power source a simulation was performed of the typical power flow during a long duration UAV flight

3.7 Long Endurance Solar Powered UAV Flight Simulation

For the evaluation of long endurance low altitude solar flight a simulation model was realized. The simulation model includes a radiation model which is parameterized by the geographical position and the time of the year (Bird & Halstrom, 1981). A facility is provided whereby the flight start time can be entered as an offset to the simulation time. The model of the solar panel takes into account the solar array size and efficiency. The power generated by the solar array is then made available to the battery model. A UAV aircraft model was implemented which computes the required power for level flight.

Electrical power required by the avionics is added to the power required for level flight to obtain the total power requirements for the UAV flight. Figure 4 shows the power progression graph for the power flow of the UAV during a long duration UAV flight of 48 hours. The flight was started at 18:00 in the evening on summer solstice with a fully charged battery.

Better insight into the power balance requirements can be obtained by plotting the energy flow graph of the UAV as in figure 5. It can be seen that the energy collected by the solar array always exceeds the energy used by the UAV.

The contribution of the fully charged battery can be seen as the flight starts at 18:00 in the evening. The initial battery charge is nearly depleted at 06:30 in the following morning from where charging resumes to full capacity at 17:00 in the afternoon. As the available light diminishes towards the evening the battery starts to discharge to supplement the dwindling available solar energy. At about 06:00 in the morning of the second day the battery is again nearly discharged when the following charge cycle begins.

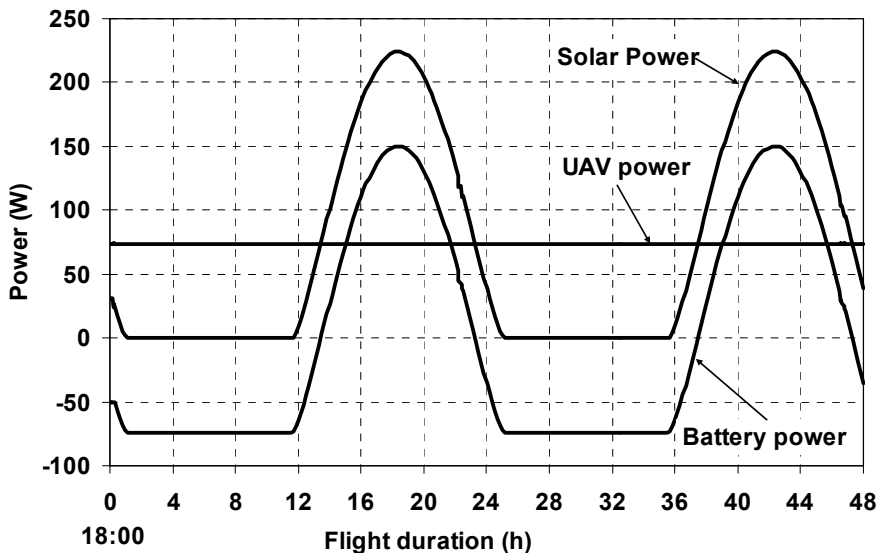


Figure 4. Power flow for a long endurance solar powered UAV requiring 74 W for maintaining level flight. A solar array of 1.2 m² with efficiency of 16 % is collecting the solar energy. Negative power means power being supplied by the battery

From the work presented it can be concluded that the primary consideration in the design of a PV-LiPo hybrid power supply for low altitude long endurance UAV is the available solar energy which can be collected by the photovoltaic array mounted on the wing surface of the UAV. The available solar energy is very strongly dependant on the time of year and the clearness of the atmosphere. During operation of long endurance flights the UAV must be trimmed for optimal speed ensuring maximum endurance. The capacity of the energy store can be determined by the power and energy requirements of the UAV. By taking these considerations into account it would be possible to a PV-LiPo hybrid power supply to power a low altitude long endurance UAV capable of demonstrating sustained flight.

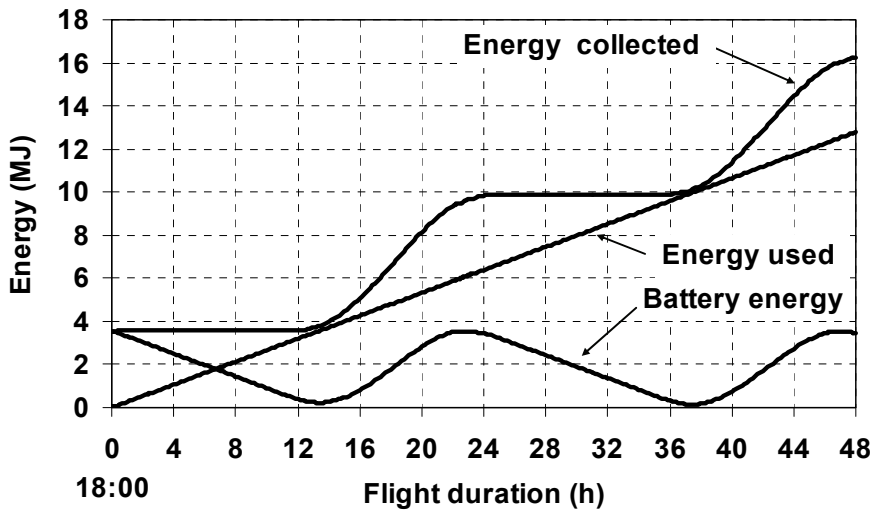


Figure 5. Energy flow for a long endurance solar powered UAV for a flight duration of 48 hours

4. Navigation and Control

Consider the following example of a situation that frequently arises. Let's say company ABC Imaging have expert knowledge in the development of some high-powered thermal imaging sensor and they consider it a profitable business opportunity to integrate the thermal imaging payload with a UAV and sell the complete product with the sensor as an integrated payload. How should they go about the integration of their payload with the UAV as their expertise is in the field of thermal imaging sensors and not autonomous aircraft? It is suggested that this company follow one of the following three options:

1. Recruit a whole team of engineers with UAV knowledge and build their own system, including the airframe and all the subsystems, from scratch - usually resulting in excessive cost and delays in getting the integrated product into the market;
2. Acquire some of the key components such as the airframe, the control system, communication links, etc. as building blocks and integrate these with their imager to obtain the UAV system. This could mean that some of the minor components needed for the cooperation and management of the various subsystems be developed; or
3. Obtain an off-the-shelf fully functional UAV as an aerial platform and integrate their imager as payload with this platform.

It should be clear that each one of the options have its advantages and disadvantages. Option 1 is a high risk alternative that should probably be taken if the company is eager to establish a long-term presence in the UAV field and expand their technical capability beyond their current field of expertise. Options 2 and 3 usually results in lower risk and lower product-into-market delays, with Option 3 probably resulting in the shortest development time with the least amount of flexibility.

The perspective that will be presented in this section does not necessarily present one of the options as superior to any of the others. The choice of the developmental strategy is a business decision that needs to be evaluated on the merit of the position of the business. It is, however, suggested that small companies with focused payload expertise should generally follow Option 3, somewhat larger companies or ones that have a broader base of technical knowledge could opt for Option 2 with the large companies with an established engineering presence usually deciding on Option 1 or a combination of Option 1 and 2.

The objective of this section is therefore to provide an overview of the autopilot development process and address key technologies that are represented in this process. It will be assumed that the reader does not necessarily have a background in navigation and control. A conceptual overview of some of the key technologies will therefore be presented as part of the content of this section. As the focus of this chapter is on the design considerations of a UAV and not necessarily on the research aspect of control and navigation, predominantly mature, proven techniques of control and navigation are presented. Emphasis will therefore be placed on the design constraints without going into too much of the supporting theory.

As the focus of this chapter is on long endurance UAVs, which is generally considered to be fixed-wing aircraft, the rest of this section will discuss building blocks that can be used in the development of such systems. Apart from complete UAVs and commercially available autopilots, most of the other building blocks are generic enough to be used on different UAV configurations such as airships or rotorcraft.

(Valavanis, 2007) presents a good overview of the development of autonomous helicopter and quadrotor UAV systems. Also included in this book are a variety of subjects on the supporting operations and subsystems needed to develop a successful UAV system. This reference is considered as a good reference for both the inexperienced as well as the established UAV systems engineer who need to gain insight into all the components and subsystems that are needed in modern UAVs.

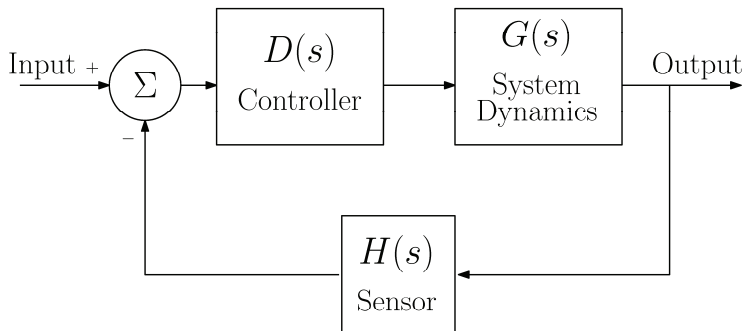


Figure 6. Generic control system block diagram

4.1 Navigation Systems

This section will consider the navigation and control (N&C) system components and subsystems by first looking at the algorithmic aspects involved in the development of the N&C system and then looking at the hardware on which the algorithms can be implemented and that is required to perform the various tasks. The actuator, although being

modelled as part of the controller, will be considered as being part of the airframe and will therefore not be discussed any further. An overview of a generic control system is presented in figure 6. From this block diagram it can be seen that the core building blocks of any control system are the

- Dynamics model of the system – known as the plant;
- The sensor that measures the variables of interest; and
- The actual control algorithm as implemented on the control processor. The actuator is not indicated on the diagram, but is considered to be part of the controller.

4.1.1 Navigation

The sensor system of an aircraft is generally called the navigation system. This system constitutes one of the most critical components on any aircraft and it is of even greater importance on a UAV where there is no pilot onboard that can use his own senses to act as a backup “navigation system”. Due to the criticality of the navigation system, it usually consists of a combination of sensors that are complementary in nature. From an intuitive perspective it should be apparent that the variables of interest for autonomous UAV control are the aircraft

- Altitude;
- Position;
- Velocity;
- Acceleration; and
- Orientation (attitude).

The selection of sensors is therefore supplementary in nature to ensure that a trustworthy set of the most critical parameters are available at all times. Apart from the availability of the critical system parameters, it is also necessary to perform some calculations on these parameters and combine the various measurements to provide the optimal set of system variables at all times.

The next two subsection present a discussion of the fundamental algorithms involved with navigation and then discuss the process of combining the measurements from various sensors into an optimal measurement.

4.1.1.1 Navigation Algorithm

The core element of aircraft navigation systems is the inertial navigation system (INS). The INS consists of a sensor block called the Inertial Measurement Unit (IMU) and the navigation processor used to implement the navigational equations. (Titterton and Weston, 2004) present a comprehensive discussion on the various inertial sensors as well as the navigational equations necessary for successful INS development.

The IMU consists of a triad of 3 orthogonal gyroscopes and a triad of 3 orthogonal accelerometers. Most modern navigation systems make use of strapdown navigation where the IMU is fixed to the body of the aircraft. The gyroscopes therefore measure the angular rotational rate of the aircraft body in the body (x,y,z) coordinate system (also known as the body frame) relative to inertial space. The accelerometers measure the aircraft acceleration in the body frame in terms of the body x,y and z components.

The advantage of classical inertial navigation is a self-contained system that does not require any external measurements to operate and the navigation sensors are therefore not susceptible to external sources of interference.

The navigational equations that are applied to the IMU output to obtain the complete set of navigation parameters is presented in block diagram form in Figure 7. It consists of the double integration of the measured acceleration to obtain the aircraft velocity and then the position. In a strapdown navigation implementation the acceleration is measured in the aircraft body axis and the position of the system is required in a local level coordinate system called the navigation frame. To determine the aircraft acceleration in the navigation frame, it is necessary to determine the orientation of the aircraft body frame relative to this navigation frame and use this description of the relative orientation between the two axis systems to convert the acceleration measurement from the body frame to the navigation frame. This is where the gyroscopes come into play. As presented in figure 7, the gyro cluster measurement of the aircraft angular rate relative to the inertial frame is integrated to determine the system's orientation (known as the attitude). The attitude can be presented in terms of Euler angles (roll, pitch and yaw), in terms of a direction cosine matrix or in terms of a quaternion representation (Titterton & Weston, 2004; Stevens & Lewis, 2003; Farrell, 2008; Rogers 2007; Groves, 2008; Farrell & Bath, 1999). The attitude representation is used to convert the accelerations to the navigational frame. Some additional corrections for the effect of the Earth's rotational rate on the gyros, changes in gravity as a function of position and altitude and the Coriolis effect resulting from the relative rotation between the two frames is also needed as presented in Figure 7.

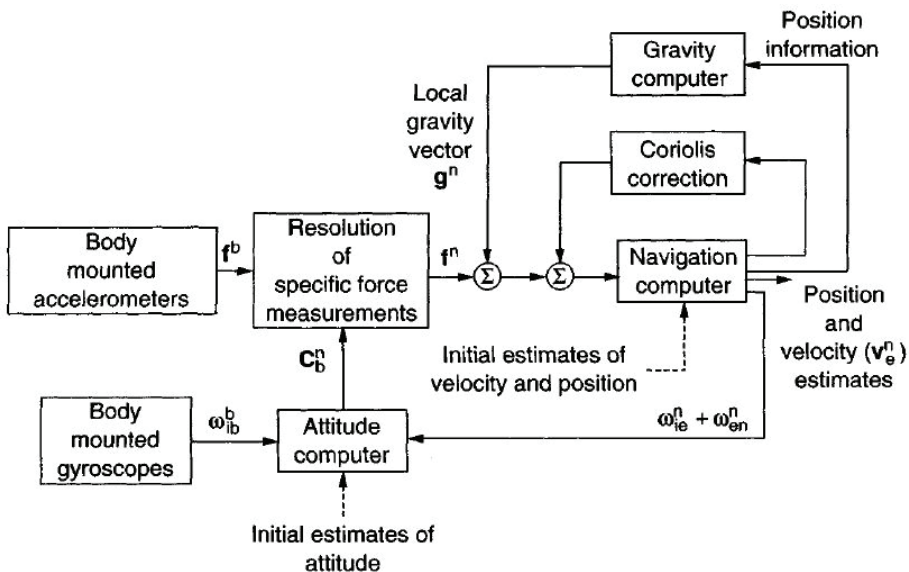


Figure 7. Inertial navigation system algorithm block diagram. Taken from Titterton & Weston (2004)

The navigation equations presented in Figure 7 is collectively known as the INS. The output of INS consists of the complete system position, velocity, acceleration, orientation and angular rates of rotation. These parameters are used by the control system as the measurements of the system motion on which the control action will be performed.

In some situations the complete navigational solution is not required and only the aircraft orientation and heading is required by the control system. A standalone GPS unit is then used for position information. Such a unit is called an attitude and heading reference unit (AHRS). The AHRS consist of a simplification of the INS equations presented in Figure 7 by not performing the computations to determine the aircraft position and velocity.

Pure inertial navigation solutions have the advantage of being immune to interference as it does not depend on data received from external sensors. To be usable in an independent configuration, it is necessary to use reasonably high quality sensors. The reason being both gyros and accelerometers are subject to significant sensor measurement noise and the noise directly impacts the navigation solution. Any errors in the accelerometers are integrated twice and any gyro errors are effectively integrated three times during the calculation of the aircraft position. The result is that even a small error in any of the sensors cause the navigational solution to rapidly deteriorate.

IMUs used to perform pure inertial navigation portray very low levels of sensors noise. These very high quality inertial sensors (known as inertial grade IMUs) are very expensive, typically costing in the range of millions of US-dollars and can generally be used to navigate autonomously for periods of time ranging from a couple of hours up to a number of days and even longer depending of the quality of the sensor. Lower quality inertial sensors used to navigate autonomously for about an hour are called sub-inertial grade sensors while the lowest quality sensors are called tactical grade sensors. Sub-inertial grade sensors are generally about an order cheaper than the inertial grade sensors, but are still about an order more expensive than the tactical grade sensors. The problem with tactical grade sensors are, although relatively cheap, they cannot be used as the primary sensors for navigation for any period longer than a couple of minutes before the accumulation of errors start to dominate the navigational solution.

4.1.1.2 Hybrid navigation

The accumulation of errors in pure inertial navigation system and the high cost associated with inertial grade sensors have resulted in the practise of aiding the navigational solution with other sensors. Probably the most widely used navigational aide is the Global Positioning System (GPS), which provides high accuracy position and velocity measurements with bounded errors which can be used to improve the pure inertial navigational solution when combined with the output of an INS (Steven & Lewis, 2003; Farrell, 2008; Rogers, 2007; Groves, 2008; Farrell & Bath, 1999). GPS and INS measurements are combined in an optimal way using an estimation algorithm known as the Kalman filter.

Various configurations for the combination of the data exist, but the actual functionality of the Kalman filter does not differ much. The Kalman filter is a statistical estimator using the noise properties of the various sensors to determine the weighting factors when combining the measurements. References on the applications of Kalman filters to inertial navigation are found in (Steven & Lewis, 2003; Farrell 2008; Rogers, 2007; Groves, 2008; Farrell & Bath, 1999; Maybeck, 1994). A more detailed discussion on Kalman filtering and optimal estimation is presented in (Maybeck, 1994; Simon, 2006; Zarchan & Musoff, 2005; Lewis et al, 2008). A typical use of the Kalman filter in navigation aiding is the complementary filtering scheme (Bar-Shalom & Li; 2001) as presented in Figure 8.

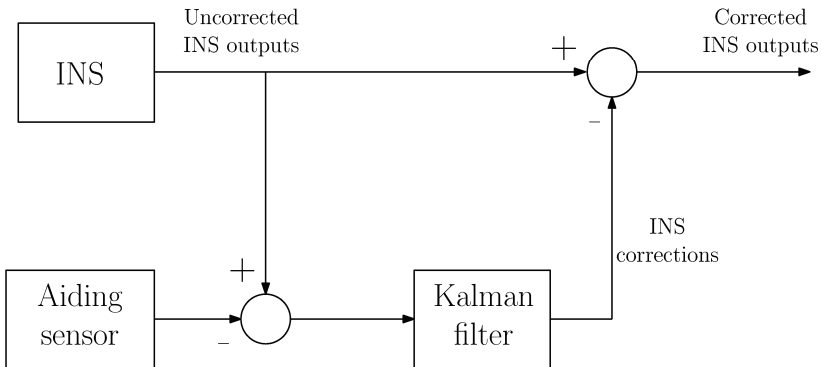


Figure 8. Complementary filtering as used for INS aiding

One of the disadvantages of GPS that became clear in recent years during the Afghanistan and Iraq wars is it can be jammed, either from specifically designed jamming equipment or by accident by transmitters operating in the GPS frequency band. This has motivated significant research into the use of alternative sensors for navigation aiding. The use of optical sensors as vision-based navigation aids is receiving much attention due to the sensor being independent of external transmitters like GPS. The advent of high-powered image processing hardware is contributing to the increased momentum of this method of aiding. Imaging sensors are used as aiding sensors in the following configurations:

- Optical altimeter, where two or more cameras are used to develop an altimeter through stereo vision;
- Feature detection in Simultaneous Localization and Mapping (SLAM), where the image is processed to determine the location of features in the scenes and these features are either correlated with known locations of features or used to develop a map used to update the navigational information;
- Range sensor through stereo vision, where the sensor is not purely used as an altimeter, but where distance to identified features in the image is determined from the combination of multiple images; and
- Angular rate sensor, where the system's angular rate can be determined using optical flow techniques.

Apart from GPS and optical sensors, other sensors frequently used in navigational aiding on UAVs are:

- Magnetometer, utilising the Earth's magnetic field to determine orientation and sometimes position information;
- Barometric sensors, using air pressure to determine the aircraft altitude;
- Laser altimeters, providing very high accuracy altitude measurements; and
- Radar, a ground-based sensor predominantly under military control but sometimes available for civilian use.

4.1.2 Calibration and alignment

Two critical tasks associated with inertial navigation that can severely influence the navigation accuracy are the calibration and alignment of the INS. Calibration is the process whereby the errors associated with the IMU are determined and stored in software for use in an online compensation routine. IMU calibration is an extremely specialized area that requires expensive test equipment. This is an area that should be ventured into with great care and it is therefore suggested that pre-calibrated inertial sensors be used whenever possible. By following this approach the inner technical workings of the IMU is hidden from the application engineer who simply want to use the sensor as a black-box measurement device.

Alignment is the process whereby the initial position and orientation of the IMU is determined to act as initial conditions for the INS integration equations. Traditionally, strapdown inertial systems depended on gyrocompass alignment (also known as static alignment or ground alignment) of the system as described by (Britting, 1971). In this method the accelerometers are used to determine the initial estimate of tilt (roll and pitch) angles of the aircraft through a process known as analytical alignment. Once the tilt angles are known, the rotational speed of the Earth is measured by the gyros to determine the heading of the IMU. The initial alignment results are refined using a Kalman filter while the heading converges to the actual value. The whole process usually takes about 10 to 15 minutes. Position is either determined by positioning the aircraft at a known position on the runway, or from a high accuracy GPS position measurement. Disadvantages of this approach to alignment is that the gyros need to be quite accurate (at least in the high end of the sub-inertial grade sensors) to detect the rotational rate of the Earth performing the heading alignment. In fact, the need for accurate heading alignment is the biggest driving factor when specifying accuracy of the gyros in the IMU. If alternative alignment techniques are used, gyro requirements can be significantly reduced, thereby reducing the total IMU cost. (Farrell, 2008) presents some alternatives for alignment with the use of a magnetometer to determine the heading angle being the most widely used method for low-grade IMUs which is not sensitive enough to detect that Earth's rate of rotation.

4.1.3 Design Considerations: Long Endurance Navigation

From the discussion on navigation presented in the previous sections, the following design considerations can be highlighted for long endurance missions:

- Proper calibration of the navigation sensors and high accuracy alignment before the start of the mission are of utmost importance to ensure good navigation data for long endurance missions.
- Low grade inertial sensors cannot be used to perform autonomous navigation without being aided by an additional sensor. GPS is the logical choice for aiding the low grade IMUs by means of Kalman filter mechanization.
- A high accuracy reliable GPS receiver is essential if lower accuracy inertial sensors are used.
- Although not discussed here, the navigation computations and the method and sequence in which these computations are performed on the navigation computer is very important as any delays in data resulting in skewing or stale data could be catastrophic to the system performance.

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