

# Energy Efficiency Optimization in UAVs: a review

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**Abstract.** In recent years, development of Unmanned Aerial Vehicles (UAV) has become a significant growing segment of the global aviation industry. The present paper provides an overview of the research conducted on the field of UAV energy efficiency optimization.

## Introduction

Efficient energy utilization on an UAV is essential to its functioning, often needed to achieve the operational goals of range, endurance and other specific mission requirements. The considerable amount of data produced by the UAVs requires high data rate connectivity such as that offered by free space optical (FSO) communication. When using FSO links some important issues need be considered in power consumption for pointing, acquisition and tracking (PAT) subsystem of the FSO. Due to the limitations of the space available and the mass budget on the UAV, it is often a delicate balance between the onboard energy available (i.e. fuel) and the achievement of the operational goals [1].

Three methods of achieving energy efficiency onboard the UAV are encountered in the relevant literature, namely:

- o optimization of mission waypoints
- o use of a Hybrid-Electric Propulsion System onboard the UAV.
- o use of effective power management systems.

## Mission Waypoint Optimization

One of the challenges in the control of UAVs is to make them autonomous or semi-autonomous in order to relieve the operator from the constant monitoring. One such application is the area coverage, where the task is to find the minimal route that connects the defined set of waypoints. Both deterministic and non-deterministic methods have been applied for the solution of the trajectory optimization problem: Ant Colony Optimization [2], Mixed Integer Linear Programming [3] [4], Evolutionary Algorithms [5][6], Genetic Algorithms [7]-[9], Stochastic Sampling [10], Particle Swarm [11] as well as Neural Networks [12].

Exploitation of wind energy in order to optimize the flight trajectory is also encountered in the relevant literature. Several studies suggest that the performance of UAVs may be considerably improved by utilizing natural resources, especially wind energy, during flights. The key challenge of exploiting wind energy in practical UAV operations lies in the availability of reliable and timely wind field information in the operational region. In [13], a strategy that combines wind measurement and optimal trajectory planning onboard UAVs is proposed and explored. During a cycle of the flight, a UAV can take measurements of wind velocity components over the flight region, use these measurements to estimate the local wind field through a model-based approach, and then compute a flight trajectory for the next flight cycle with the objective of optimizing fuel.

As the UAV follows the planned trajectory, it continues to measure the wind components and repeats the process of updating the wind model with new estimations and planning optimal trajectories for the next flight cycle. A methodology to generate optimal trajectories that utilize the vertical component of wind to enable flights that would otherwise be impossible given the performance constraints of the UAV, is also presented in [14]. Reference [15] adopts a network modeling approach to formulate the problem of finding minimum energy flight paths. The relevant airspace is divided into small regions using a grid of nodes, inter-connected by arcs. A function, representing energy cost, is defined on every arc in terms of the solution of a constrained nonlinear program for the optimal local airspeed to fly in a given wind field. Then, shortest-path models are implemented on the network to find the optimal paths from an origin to a destination. A Gaussian distribution is used in [16] in order to determine uncertainty in the time-varying wind fields. Next, a Markov Decision Process is used to plan a path based upon the uncertainty of Gaussian distribution. This technique provides not only an effective energy-path planning method which can effectively exploits the wind field, but also a robust flight path.

Apart from vertical wind components, other atmospheric effects as thermal gusts and wind gradients represent significant sources of energy that an aircraft can potentially tap to increase endurance and range. In [17], the feasibility of improving UAV mission effectiveness by extracting energy from the atmosphere is explored. Specifically an aerial surveillance mission in the vicinity of a geographic ridge is considered. Cross winds blowing over the ridge produce regions of lift on the windward side that can be exploited to increase mission duration. In [18], solar and piezoelectric energy harvesting techniques are selected and integrated into UAVs. The analysis showed that the UAV with energy harvesting generated less entropy. Moreover, it was demonstrated that the addition of the solar and piezoelectric devices would supply usable power for charging batteries and sensors and that it would be advantageous to implement them into a small UAV. In [19], a receding horizon controller which computes a sequence of pitch rate commands with the goal of maximizing energy gain over a fixed horizon is derived. An energy based reward function is used to maximize energy gain with only local knowledge of atmospheric wind conditions. The results show that the controller is effective in maximizing energy gained from the surrounding air, resulting in altitude or velocity gain.

## Hybrid-Electric Propulsion System

Efficient energy utilisation on an UAV is essential to its functioning, often required to achieve the operational goals of range, endurance and other specific mission requirements. Due to the limitations of the space available and the mass budget on the UAV, there is often a need to compromise between the onboard energy available (i.e. fuel) and achieving the operational goals. One technology with potential in this area is the use of Hybrid-Electric Propulsion System (HEPS) [20]. Hybrid technology combines the advantages of two or more power sources to create a more efficient propulsion system for a vehicle. While many variants of hybrid systems are available today, most derive from three basic categories: series, parallel and power-split. While most systems utilize an internal combustion engine as the primary power source, others use fuel cells or turbine engines. Each system has unique advantages and disadvantages adaptable to the specific needs of a vehicle [21].

**Series Configuration.** In a series hybrid configuration (Fig. 1(a)), the primary propulsion source is an electric motor (EM). Typically, an internal combustion engine (ICE) drives a generator, which then provides power to the motor and an energy storage system. As the combustion engine is not mechanically linked to the driveshaft, it is able to operate at its optimum torque and speed range independent of power demand. Excess energy from the generator may be stored in a battery, capacitor or flywheel for high demand operation [21]. Large vehicles, like buses and locomotives, are the most common use for this type of configuration [22].

**Parallel Configuration.** Parallel hybrid-electric propulsion systems (Fig. 1(b)) are beneficial for small UAV. The benefits include increased time on station and range as compared to electric-

powered UAV and reduced acoustic and thermal signatures not available with gasoline-powered unmanned aerial vehicles [23]. Moreover, the parallel HEPS configuration enables the powering of the UAV using the ICE alone, the EM alone, or a combination of both power plants depending on the operating conditions. This results in the advantage of redundancy, which is important in both civilian and military applications [24].

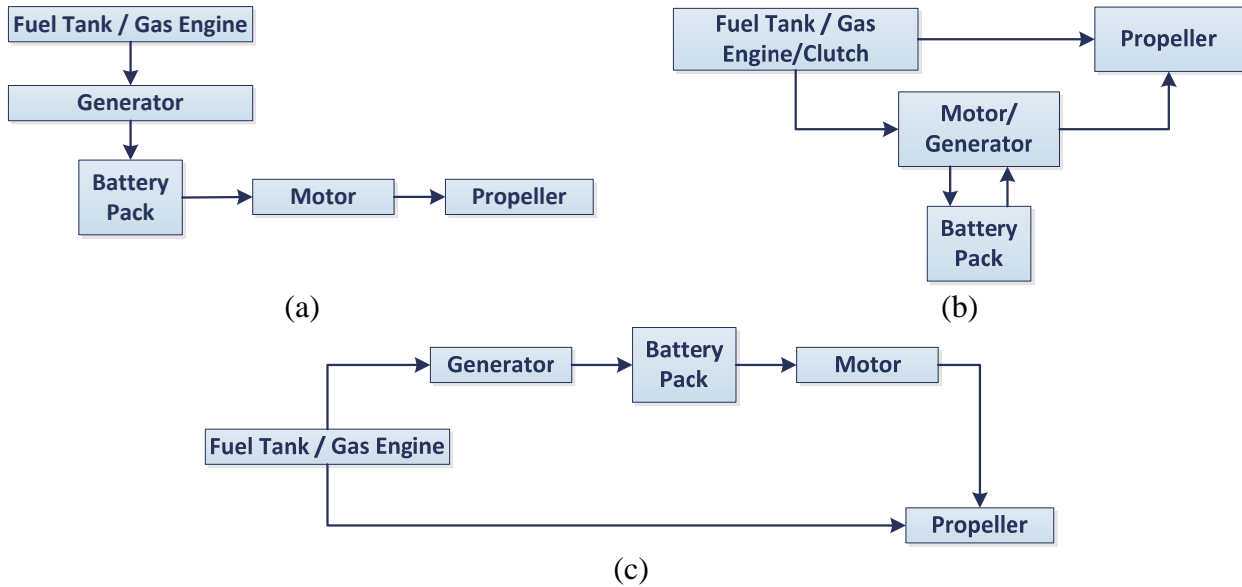


Fig. 1 HEPS configuration: (a) Series, [23] (b) Parallel [23], (c) Power-split.

**Power-Split (Series-Parallel) Configuration.** The power-split (or series-parallel) configuration (Fig. 1(c)) lacks a driveline clutch, but uses a system of planetary (epicyclic) gears to transfer power from the combustion engine and the electric motor to the wheels. The engine delivers torque to the wheels for propulsion after splitting a portion to a generator for conversion to electricity. The electric power recombines with engine mechanical power at the planetary gear. Since the combustion engine power and speed are decoupled from the overall propulsive demand, the engine is able to run at or near optimal conditions [21].

**HEPS control and power management.** Various HEPS control systems are encountered in the relevant literature, based on Neural Networks [25][26] or Fuzzy Logic [27]. HEPS optimization is also performed in [28][29].

The use of alternative power sources such as solar or fuel cells is also investigated in [27][30]. In terms of HEPS power management, two types of power control logics are investigated: passive and active [30]. The passive power management simulation shows that the behaviour of each power source and its integrated system is adequate for the overall flight envelope. In addition, the active power management simulation demonstrates that active power management yields more efficient power distribution and better system safety than passive power management does.

**HEPS sizing.** The design of a UAV including HEPS should not be based on the simple conversion of a conventional UAV by removing the original power train and installing the appropriate components for the hybrid-electric power train. A conceptual design approach should be adopted, involving compromises such as a reduced payload mass is necessary to allow for the larger mass of the hybrid-electric propulsion system. Conceptual design is implemented in [23], where the focus is the initial sizing of the wing and the hybrid-electric propulsion system components for a conventional high-wing UAV. The sizing problem is treated as a constrained optimization formulation and is solved with a MATLAB optimization routine that uses a sequential quadratic programming method. HEPS optimization for UAVs is also implemented in [31], where the propeller model and the model for the electric system, together with various optimization

schemes and sensitivity analysis are used to design optimal propulsion systems for a mini UAV for various goals and under various constraints.

### **Effective power management systems**

In [32], a system that improves the UAV flight reliability and energy efficiency, by setting-up capabilities to restart the engine at flight, is presented. The management system hardware structure consists of an electric starter/generator, electrochemical battery and supercapacitor storages, electronics power converters and specialized controller. The system design has high reliability as well as specific-weight energy and power characteristics, which are major for the UAV overall flight time. In [33], a fuel cell system for application as a power source in UAVs is developed. The fuel cell system consists of a fuel cell stack, hydrogen generator, and hybrid power management system. A hybrid power management system using an auxiliary battery is developed and evaluated for efficient energy management. Hybrid power from both the fuel cell and battery powers takeoff and turning flight operations, while the fuel cell supplies steady power during the cruising flight. The capabilities of the fuel-cell UAVs for long endurance flights are validated by successful flight tests. According to [34], the polymer exchange membrane (PEM) fuel cell and Li-Ion battery hybrid power plant shows a great potential to replace the IC engines from UAVs due to high energy and power densities of the power sources. In this reference, an energy management system that receives the feedbacks from the battery, the load power and the fuel cell system control parameters is developed. Moreover, in this power and energy management system, the fuel cell system is operated at optimum power region and the battery supplies the transient power to the propulsion system.

**Solar power management systems.** A substantial body of work is available on the analysis and design of solar powered aircrafts [35]. The feasibility of solar-powered flight is reviewed in [36][37], and the history of solar-powered flight is discussed in [38]-[40]. Solar-powered UAV possesses broad research value for technology development and commercial applications. A solar-powered UAV could in principle stay overhead indefinitely as long as it had a proper energy-storage system to keep it flying at night. The design of the power management system for such aircraft is challenging due to possible rapid attitude changes during maneuvers. Reference [41] presents the design of a solar power management system for an experimental UAV. The system provides the power required for the on-board electronic systems on the UAV. The power management system mainly consists of the maximum power point tracking, the battery management, and the power conversion stages. In [35], the energy-optimal path planning and perpetual endurance for UAVs equipped with solar cells on the wings, which collect energy used to drive a propeller, is considered. Perpetual endurance is the ability to collect more energy than is lost during a day. The problem is then formulated as an optimal control problem, with the bank angle and speed as inputs. The work presented in [42] proposes a hybrid photovoltaic (PV) panel/rechargeable fuel cell/rechargeable battery energy storage system to provide enough energy for the UAV long endurance flight. PV panel can provide clean energy for the UAV during daytime. Its energy source is solar so there is no fuel weight issue. Rechargeable fuel cell is responsible for the night flight when there is no irradiance and thus no power can be extracted from the PV panel. In addition, the extra energy from the PV panel during the strong irradiation time can be stored. Rechargeable battery provides the difference between the burst load power and the output power of the PV panel and/or fuel cell, and it can also be recharged by the PV panel.

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