White Paper

How to select the ideal propulsion system for an Unmanned Aerial Vehicle

Abstract

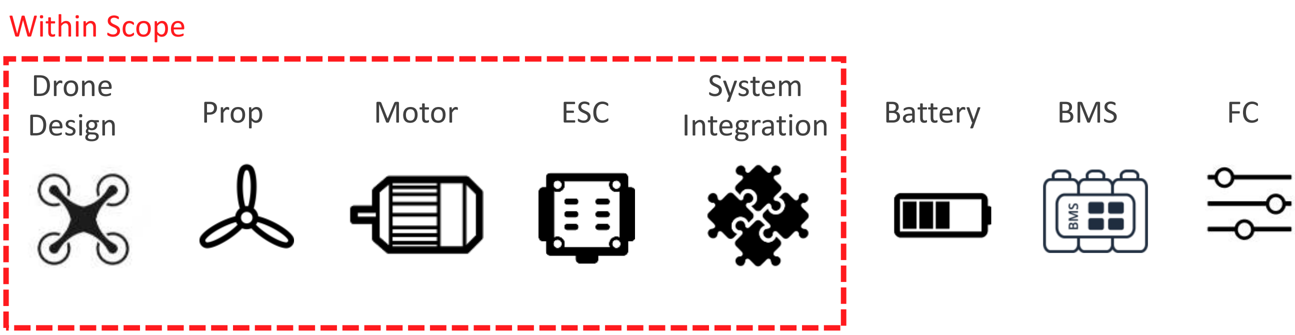
This white paper describes the key steps in selecting an optimal propulsion system for a UAV. These steps comprise building the design framework, selecting propellers, choosing the best motor and ESC configuration as well as integrating all components. The reader of this paper can expect to receive insights into UAV propulsion system design, get valuable design tips, learn how to enhance endurance and gain an overview of the key success factors in propulsion design.

1. Introduction

This white paper is focused on unmanned (or uncrewed) aerial vehicles ("UAVs"), which in our definition includes airborne drone systems and excludes any ground or seaborne drone systems. Further, we primarily focus on battery-powered UAVs, while certain sections of this paper may also be relevant for UAVs with combustion engines or fuel cells. Based on our experience, there is limited literature describing the key steps in designing the propulsion system of a UAV. Thus, we present here a concise overview of the steps in designing the propulsion system, share valuable tips and insights, explain how endurance can be maximized as well as discuss other key success factors in designing the system.

Before we dive into the details, we would like to define the key components of the propulsion system. The below chart illustrates the parts, which are covered in this paper. Other parts such as the battery, the battery management system ("BMS") or flight control ("FC") are excluded. In addition, it should be noted that this paper covers UAV design only on a high level and focuses primarily on the components of the propulsion system.

Figure 1: UAV Propulsion System Design



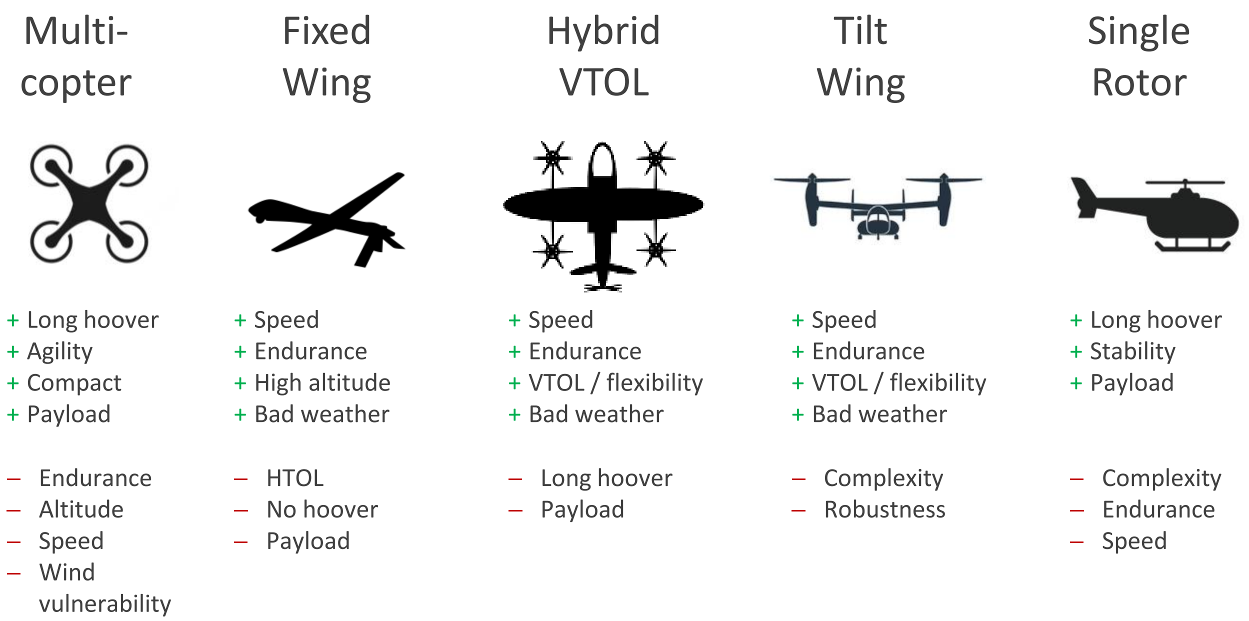
2. UAV Design

Before selecting any component, the engineer needs to define the key characteristics of the drone design. This starts with defining the target payload as well as the load profile or mission profile that the UAV should perform. The load profile comprises e.g. required flight times for lift, hover and cruise, required speed in different scenarios and target endurance. In addition, information on altitude and ambient conditions should be gathered.

A more iterative step is defining the maximum takeoff weight (“MTOW”) of the UAV. We recommend choosing an initial target MTOW and then keep refining it throughout the design process.

The next step is choosing a suitable drone design. There are many different designs, which all have their pros and cons. Ultimately, the design is dependent on the load or mission profile of the UAV as well as end-user preferences. The below figure shows different UAV designs with their pros and cons.

Figure 2: UAV Designs



Another step in the UAV design is the selection of the energy source. Based on the load profile and required endurance, a battery powered system, a combustion engine powered system, a combination of both or even a fuel cell powered system can be selected.

Another very important point to consider is system reliability and safety. Especially for larger systems safety and certification becomes increasingly important (worth a separate white paper). For applications in harsh environmental conditions the robustness of the UAV design and the propulsion system is a factor which should be considered. Many UAV designers also consider redundancy in the propulsion system (e.g. through using more motors or redundant motor winding/ESCs) as becoming increasingly important.

The last step of the UAV design is the selection of the operating voltage of the system. Again, this step can be considered iterative and dependent on different factors. However, it is important to define a target voltage range, ahead of the motor/ESC selection.

The key factors to consider are:

- Size/weight of drone, incl. required continuous power, cable length and cross-check that current does not get excessive leading to heavier cabling
- Safety (requirements for high voltage) and isolation
- Battery type (high power density for high performance vs. high energy density for endurance)
- Availability of electronic components (DC/DC, ESC, BMS, charger)

3. Prop Selection

The next logical step in UAV propulsion design, is the selection of the size and type of propellers. The chosen UAV design typically defines the number of propellers. However, in certain scenarios UAV engineers may decide to go for coaxial design (e.g. for redundancy purposes). Choosing the right prop type is highly dependent on UAV design and user preferences, e.g. rigid, folding, variable pitch, two- or three-blade design.

The first step in propeller design requires the estimation of required thrust based on MTOW as well as adding to this a safety factor to determine peak thrust. For larger drones, a safety factor of 1.3-1.6x is often sufficient, for smaller drones a factor of 2-3x is often chosen. Based on this data, the required thrust range per propeller can be calculated and a propeller size with sufficient thrust and best efficiency can be selected.

The overall aim of prop selection is choosing the best fitting propeller, i.e. the one with the highest gram-per-watt over the entire load profile, while limiting the size as much as possible. For a multicopter drone with relatively long hover times or a VTOL lift prop, a lower pitch is recommended. This provides for higher efficiency and better static thrust. For horizontal/forward flight a relatively high pitch is required. This keeps the rpm low and reduces drag.

In addition, the size of the propeller should be considered. Often, the UAV design limits the maximum possible propeller size. However, if the engineer has certain headroom, it is important to weigh the pros and cons of smaller vs. larger propellers (see below figure).

Figure 3: Pros & Cons of Prop Sizes

Large Prop	Small Prop
+ More Efficient	+ More dynamic
+ Less noisy	+ Lower weight
- Less dynamic	+ Lower torque demand
- Higher weight	+ Lower cost
- Higher cost	- Less efficient
- Higher torque demand	- More noise

Once the propeller is chosen, it is important to identify the performance requirements for the motor using propeller measurement data.

4. Motor Selection

The first step of the motor design goes back to the selected propeller. The engineer needs to gather the required rpm and torque for the key load points from the propeller datasheet. This data shall be added to the load profile, which can then be used to select a suitable motor.

The overall aim of propulsion design is to choose components which are as small, as light and as efficient as possible, but still able to handle the most critical load points with a sufficient safety buffer. Critical load points can be climb, long hover times or an emergency situation.

Consequently, the engineer needs to find a motor which is powerful enough to handle the most critical load points but also runs at high efficiency over the majority of the load profile to minimize weight and maximize endurance. While this sounds straight forward, it is often very difficult in reality and requires trade-offs, especially when off-the-shelf motors are selected. Often the best approach is to have a motor manufacturer tailor the motor according to the individual mission requirements. A well-designed motor can be 15-30% more efficient over the entire load profile at same weight and be powerful enough prevent failure in emergency situations.

Another very difficult decision in UAV propulsion design is the trade-off of weight and endurance vs. robustness and reliability. Generally, robust systems such as fully closed BLDC inrunner motors, with IP54 or greater, are heavier and thus negatively affect endurance. However, in harsh environments such as desert, close to sea water or in snow they excel and provide for safe operation as well as reduced total cost of ownership. At the same time, heavier systems provide for more thermal mass, which allows for longer peak power and reduces the risk of overheating. Nowadays, motor manufactures also provide closed motors in weight optimized design, so that the weight advantage of open motors is only marginal. The key message is that engineers need to consider both the power-to-weight but also the power-to-robustness ratio of the propulsion unit.

A further important factor to consider is the thermal design of the propulsion system. In almost all UAV designs, the propulsion system is air cooled. In order to ensure a safe operation of the motor, even under the most unfavorable ambient conditions and at the most challenging load points, the thermal design shall be tailored to the individual UAV design. Possibilities to improve the thermal design include air ducts, active or passive/integrated fans, naca duct, etc.

Lastly, regulation and certification are becoming increasingly important. As UAVs are getting larger and missions are performed over (or close to) populated areas, the requirements for certification are getting more important. Engineers should consider choosing suppliers, which can support the certification process or even provide certified systems.

As highlighted above, there are many factors to consider in choosing the correct motor. Often off-the-shelf solutions are not suitable and UAV engineers are well advised to consider motors which are tailored to the requirements of the individual mission profile. It is also best to get propulsion expert advice on the integration of motor with propeller and run simulations.

5. ESC Selection

In order to choose the best electronic speed controller ("ESC") a few key points shall be considered. The first step in ESC selection is making a decision on the target voltage range of the system. As highlighted above, the target voltage is often chosen at project outset, but it is recommended to reconsider the voltage selection as part of the motor design process. UAV engineers should also check with the motor manufacturer for the ideal voltage range and get input from the battery system supplier. It is important to note that there are pros and cons on choosing high vs. lower voltage. Higher voltages often cause safety concerns and requires more costly components. On the positive side higher voltage often saves weight as currents is lower and less heavy cables can be selected.

The second step is selecting an ESC which is compatible with the chosen motor. Some ESCs require sensor guided motors, others can only handle limited number of poles, etc. It is advisable to always have the ESC manufacturer confirm that the chosen system is compatible.

As for motors, it is also important in the ESC selection process to consider weight vs robustness, check for thermal characteristics, think about redundancy, consider system integration as well as cooling conditions. In addition, it is worthwhile considering additional functionality such as monitoring/heath-check capabilities, prop locking control, datalogging, etc.

Lastly it is often important to speak to the manufacturer of the ESC if the firmware can be adapted and if certain interface adjustments are possible.

6. System Integration and Choosing the Right Accessories

The last step in propulsion design is the integration of all components. As highlighted above, it is recommended to check with the suppliers of each component for compatibility or buy an integrated system solution. It is also recommended to run simulations of the most critical load points of motor/prop/ESC configuration and check that the results are matching requirements. In addition, thermal characteristics should be simulated as well. Once this is all completed, we recommend ordering test equipment and get real life measurement results.

Often a neglected part of propulsion design is choosing the right accessories. Engineers pay a lot of attention to motor design and ESC, but do not optimize the weight on cabling, prop connectors and accessories, such as cable connectors. The overall weight of these components can be significantly reduced through design optimization of the overall drive system (e.g. reduced cable length and diameter) as well as through using light weight components.

7. Bringing it all Together

The aim of this white paper was to highlight the key steps in designing an optimal propulsion system for a UAV. We highlighted the major steps: UAV design, prop selection, motor selection, ESC selection and system integration. It can be concluded that the process of designing a UAV propulsion system is very complex and many (sometimes competing) factors need to be considered. It is highly advisable to work with suppliers that provide engineering support and can help with system integration. Further, it can be concluded that UAV missions are versatile and often standard components are not suitable. Choosing tailored propulsion components can lead to significant efficiency improvements.

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