DEVELOPMENT OF A BLDC MOTOR BASED STARTER-GENERATOR FOR AN EXPERIMENTAL UAV

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Abstract: Electric power generation for fixed-wing unmanned aerial vehicles (UAVs) is often generated with the aid of brushless DC (BLDC) motors mechanically coupled to the engine. Conventional alternators and generators are usually unsuitable for this purpose due to the weight concerns of the UAV. Moreover, by using a BLDC motor for power generation, the engine of the UAV can be started by rotating the starting ring gears on the flywheel of the engine with the aid of this motor, thereby serving as an autostart mechanism for the engine. This work considers the design of a BLDC motor based starter-generator for an experimental medium-range, medium-endurance UAV at reduced weight while meeting the performance specifications of the UAV in terms of range and endurance. The design comprises of a belt driven A2212 BLDC motor which serves as a starter-generator, a 12v LiPo battery and a microcontroller based battery management system to increase the endurance of the UAV by ensuring that the battery operates only within acceptable conditions. Results from numerous simulations indicate that this design is capable of generating sufficient power at 12volts for the avionics components of the UAV whenever the engine rotated at 4500RPM or above.

Keywords: BLDC, UAV, Fuselage, Flywheel, Power

Introduction

Unmanned aerial vehicles (UAVs) utilize DC electricity to power onboard electronic components and this power is usually obtained from the following sources: batteries (Lee *et al*., 2014); hydrogen fuel cells (Gadalla et al., 2016); alternators/generators (Annen et al., 2003) and solar panels (Shiau & Ma, 2015). While each of these sources have advantages in terms of weight contribution, charging and discharging times, size, energy and power densities, it should also be noted that each of these sources have limitations (Townsend et al., 2020). For example, solar panels are quiet with low operational and maintenance costs but depend on the availability of sunlight and as a result may not supply peak power demands. Conversely, alternators/generators are robust enough to meet power demand but are often bulky and require complex maintenance (Townsend et al., 2020). It is therefore of critical importance to determine the right source or combination of sources necessary to meet the required power demand of the UAV while minimizing the overall weight.

Various power generation schemes have been investigated for use on UAVs: Dudek et al. (2013) analyzed the use of a fuel-cell stack as a main source of power for small unmanned aerial vehicles. The stack was comprehensibly tested and characterized at the laboratory on the basis of thermal efficiency which was used to calculate the expected time of flight without the need to refuel. It was reported that this design was sufficient to meet the power demands of the UAV. Shiau & Ma (2015) developed a solar power management system for an experimental UAV. The system consisted of a solar panel, a maximum power point tracking (MPPT) equipment, and a battery management system for the batteries. In this design, the solar panels were made to conform to the shape of the wings and fuselage of UAV and the battery was charged in constant current and constant voltage mode. Prasad (2018) developed an autonomous onboard power generating system for long range UAVs for the purpose of increased endurance. The study was aimed at the design of a mini power generation system to charge up the battery as well as to power up the avionics system of an experimental multirotor UAV. The reported system consisted of a charge controlling unit for the battery, a BLDC motor for the propellers and a motor generator. It was reported that this design was capable of providing charge to the battery of the UAV whenever the propellers spun.

Previous works have considered generating electric power with all sorts of power generating devices. Additionally, the possibility of starting the engine of the vehicle automatically with a starter-generator has also been explored. While these concepts find great relevance in the operation of conventional aircrafts and a few UAVs, there is need to explore a low cost starter-generator alternative for use in small UAV. This work presents the design of a low cost starter-generator system for a small UAV based on a BLDC motor. This BLDC motor based design offers not just reduced weight but also offers the possibility of inflight engine restarts from a remotely operated ground control station.

he remaining components of the paper are outlined as follows: Section 2 comprehensively discusses the design methodology giving emphasis on the various sub-components of the generator system. Section 3 discusses engine starter sub-components. The result findings are presented in Section 4. A conclusion and recommendation for future works are highlighted in Section 5.

Material and Methods

This proposed design consists of a BLDC motor which serves two purposes. It generates electricity for the vehicle by converting the mechanical energy from the engine's rotation into alternating current (AC) in accordance with Faraday's law of induction. The BLDC motor also facilitates the start of the engine by rotating the engine's shaft whenever a control signal is sent. To ensure that the battery is operated only at acceptable conditions, a battery management system (BMS) is integrated into the design. The BMS comprises of a microcontroller based circuit responsible for charging the battery at rated current and voltage as well as determining the State-of-Charge (SOC), Temperature and State-of-Health (SOH) of the battery. The proposed starter-generator topology is given in Figure 1.

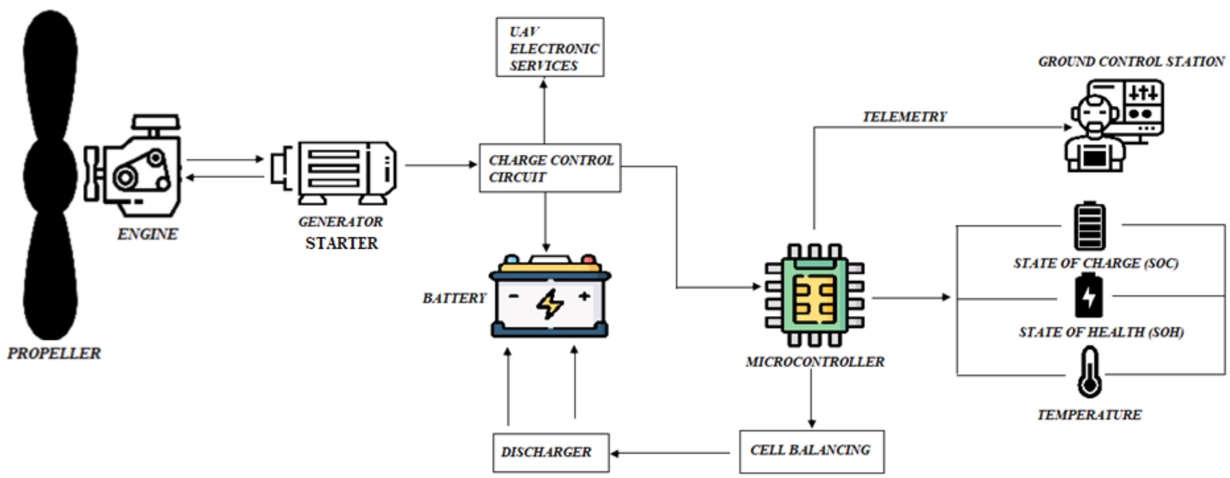


Figure 1: BLDC Motor Starter-Generator Topology

Battery selection

This step involves selecting the type of battery to be used. Common choices include lithium ion (Li-ion), Lithium polymer (LiPo),
Lead acid etc. While choosing a suitable battery type, it is important to pay attention to a number of factors. These factors are outlined below:

- Ambient temperature threshold
- Maintenance and Ventilation requisites
- Anticipated cell life
- Dimensions (size, weight)

The battery capacity needed to meet the total load over a given time can be computed using the following equation according to (Heising, 2007).

$$C_{minimum} = \frac{E_{bck}(B_{af} \times B_{tf} \times B_{cf})}{V_{dc} \times B_{dod} \times B_{ef}} \quad (1)$$

Where:
E_{bck}: Total designed energy over back up time
B_{af}: Battery aging factor: This describes the reduction in battery performance due to age
B_{tf}: Temperature correction factor
B_{cf}: Capacity rating factor: This accounts for voltage reduction during discharge
V_{dc}: Battery voltage
B_{dod}: Maximum depth of Discharge
B_{ef}: System efficiency: This accounts for the battery losses

For the purpose of providing power for a medium range (>1000km), medium endurance (>15hrs) UAV, a Lithium Polymer battery was chosen for energy storage due to its high power to weight ratio (Okafor et al., 2021). A capacity of 15000mah was also determined to be sufficient based on equation (1)

State of Charge (SOC) Determination

Determining the state of charge of the battery is an important part in the design process. This is performed to enable the pilot of UAV in the GCS ascertain the operational state of the battery which is crucial to the overall UAV endurance. There are several methods of determining a battery's SOC. These methods include, open circuit voltage method, impedance spectroscopy, internal resistance, Kalman filtering, coulomb counting and others (Piller et al., 2001). The coulomb counting method is the most common technique for calculating the SOC. Since the charge and discharge are directly related to the supplied or withdrawn current, this method is performed by determining the amount of current that flows in and out of the battery. Equation 2 gives a direct indication of the SOC of a battery (Okafor et al., 2021).

$$SOC = SOC_{old} + \frac{1}{C_N}\int_{t_0}^{t}(I_{batt} - I_{loss})\, d\tau \quad (2)$$

Where

C_N is the rated capacity

I_{batt} is the battery current

I_{loss} is the current consumed by the loss reactions?

Charging circuit

Battery charging is an important aspect of this work. For improved endurance, there is need to ensure that the battery can provide its rated current and voltage at all times. Lithium Polymer (LiPo) batteries due to their chemical combination need a specialized constant-current constant-voltage charging scheme. This is a charging scheme which comprises of constant current charging in which the charging current is kept constant until a certain voltage is attained. Next, constant voltage charging is then implemented to ensure that the charging voltage is kept constant until the battery is fully charged. For the purpose of charging a 12 Volts lithium based battery, the constant-current constant-voltage charging scheme was implemented. The charging schematic represented in Proteus is given in Figure 2. It comprises of h-bridge circuitry designed with 6 P-channel MOSFETS. This circuit is responsible for rectifying the 3-phase AC generated by the BLDC motor into DC electricity. Furthermore, this design incorporates a microcontroller which coordinates the workings of the entire circuit. The microcontroller determines the speed of rotation of the engine with the aid of a hall-effect speed sensor. This is necessary in-order to facilitate a transition from starting to generation mode after start-up when the engine reaches a self-sustaining speed. Once in generation mode, the microcontroller obtains the charging current, voltage as well as temperature. This is done to estimate the State-of-Charge of the battery as well as prevent overcharge.

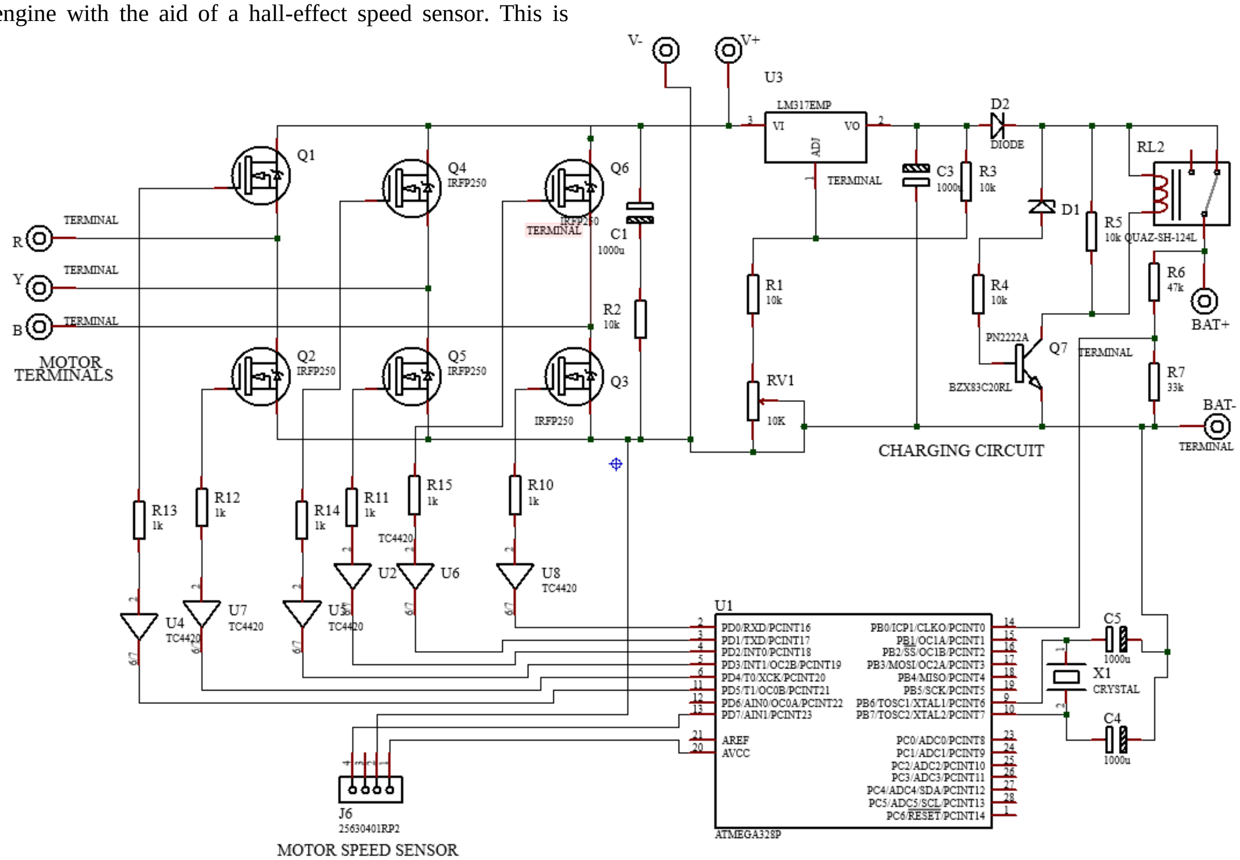


Figure 2. Overall Circuit Schematic

Output voltage

Most battery manufacturers recommend sizing a battery charger at about 25% of the battery capacity (Shinkafi et al., 2021). Thus, a 15Ah, 12-volt battery would require a 3.75A 12-volt charger (or less). Larger chargers may be used to decrease charge time but may decrease battery life. Chargers of lower capacity may also be used for long term floating and maintenance. For the purpose of charging a 12-volt battery, the voltage profile given in Figure 6 was developed after successful rectification by the H-bridge circuit.

Auto start system

The auto start system comprises of the h-bride circuit which also serves as a three phase rectification circuit for the system. The h-bridge circuit functions as a motor driver circuit interfacing the microcontroller with the motor. It should be noted that for the purpose of interfacing motors with controllers, the primary requirement for the operation of the controller is a low voltage and low current. However, the motor requires a high voltage and current for its operation. Hence, the h-bridge essentially acts as current amplifier and a bridge between the microcontroller and motor. The auto start mechanism of the vehicle is triggered by the microcontroller through the h-bridge circuit. Consequently, speed monitoring of the engine is carried out with the aid of a Hall Effect speed sensor to ensure that the H-bridge circuit transitions to a rectification once the engine reaches a self-sustaining speed. The MATLAB schematic of the auto-start system is give in Figure 3.

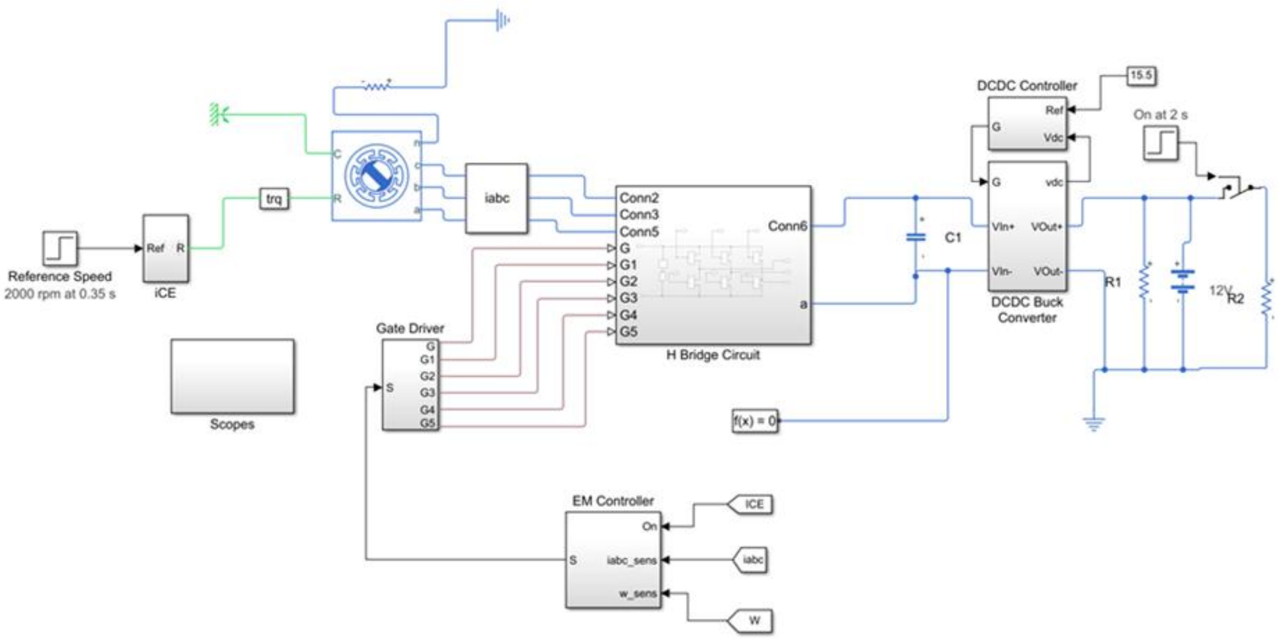
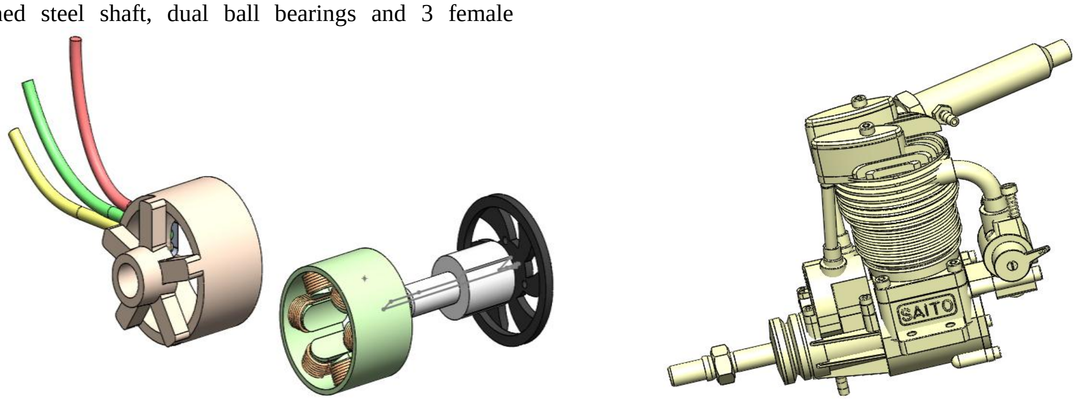


Figure 3: MATLAB representation of Auto-Start Circuit

Result and Discussion

The proposed starter-generator system comprises primarily of a Saito FG 21 engine and an A2212 BLDC Motor. The A2212 brushless DC motor is a 52.7g, 150 Watt motor with a maximum efficiency of 80%. It features a 3.2mm hardened steel shaft, dual ball bearings and 3 female conductors for speed control. This motor was chosen as the primary source of electrical power generator due to mass consideration, efficiency and durability. A CAD model of the A2212 motor and the Saito FG 21 engine is given in Figure 4 (a) and Figure 4 (b)



(a) A2212 BLDC Motor

(b) Saito FG-21 4 Stroke Engine

Figure 4. Components of the Starter-Generator System

Experimental findings reveal that this proposed system is capable of generating sufficient power at 12 volts whenever the shaft of the engine rotates at a speed equal or greater than 4500 RPM. The profile of the engine while transitioning from idle to generating mode is shown in Figure 5. Consequently, the voltage generated by the BLDC motor after rectification is shown in Figure 6.

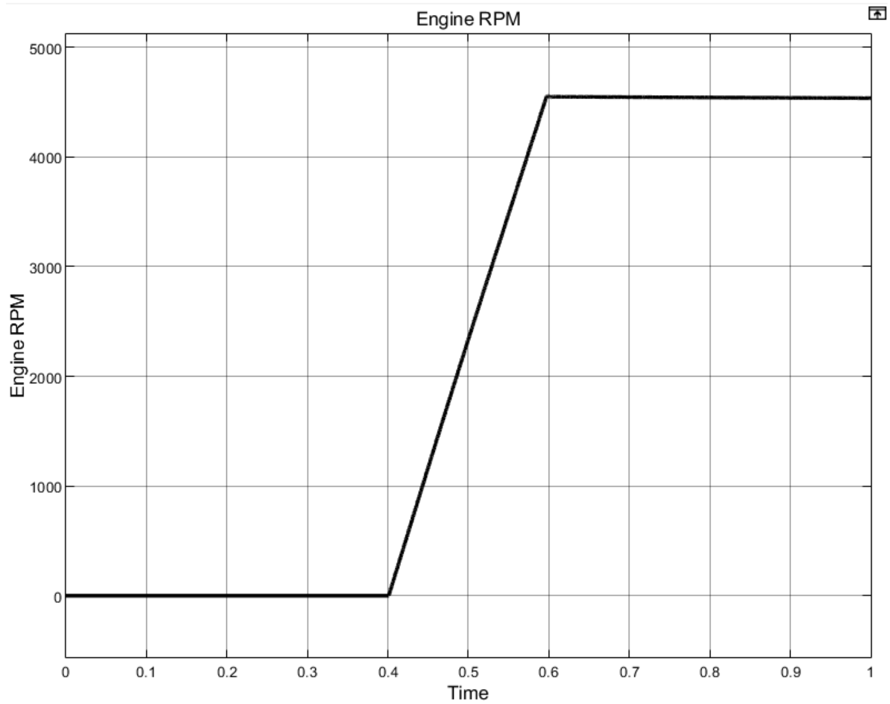


Figure 5: Engine RPM while in generator mode

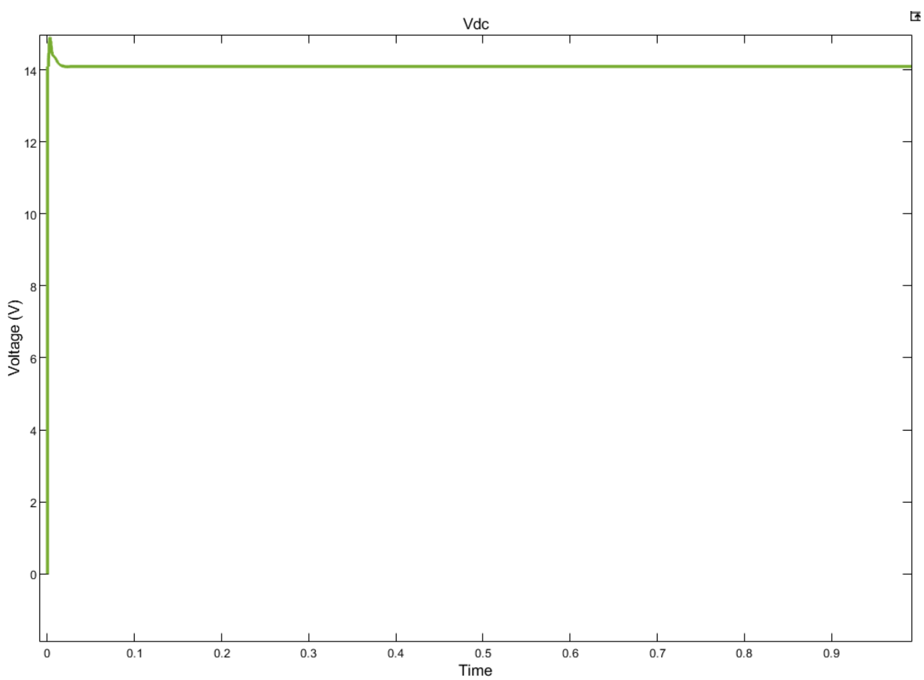


Figure 6: Voltage Output after Rectification

The overall assembly of the UAV power generation and auto start systems is shown in Figure 7. This comprises a BLDC motor mechanically connected to the UAV engine with a belt. This is done to ensure that the rotation of the engine's shaft rotates the rotor of the motor thereby producing an EMF across the stator coils proportional to the speed of rotation of the engine in accordance with Faraday's law. Additionally, a mass breakdown of the starter-generator system is given in Table 1 by detailing the estimated mass of each component.

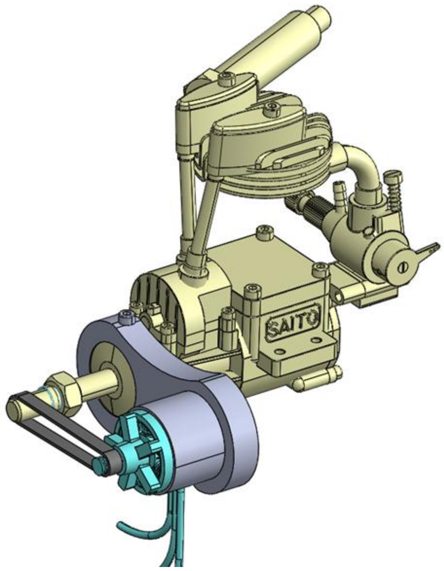


Figure 7: CAD Assembly of Starter-Generator System

Table 1: Mass breakdown of major components of starter-generator system

	Component	Mass
1	150W A2212 BLDC motor	~150g
2	ATmega 328 Microcontroller	~2g
3	Belt coupling with frame	~15g
4	16MHz Crystal Oscillator	~2g
5	Hall Motor Speed Sensor Module	~5g
6	ACS712ELECTR-20A Current Sensor	~5g
7	MOSFETS and TC4420 Gate Driver	~10g
8	LM35 Temperature Sensor	~3g
9	Operational Amplifier	~3g
10	LM2596 Switching Regulator	~5g
11	Miscellaneous (cables, resistors, inductors, capacitors, MOSFETS, gate drivers)	~50g
	TOTAL	**~250g**

Conclusion

The design of a power generator and auto start system for an experimental medium-range, medium endurance UAV is carried out in this work. This design entails the modelling and simulation of these proposed systems in the MATLAB/Simulink environment. Experimental findings indicate that sufficient power at 12volts can be generated by the selected BLDC motor whenever the engine operates above 4500 RPM. In comparison with the onboard generator system of the Penguin B UAV which has a mass of approximately 500g (*UAV Factory*, n.d.), this proposed starter-generator system offers not just reduced weight but also offers acceptable performance. Future research can be undertaken towards harnessing the full potentials of lithium-ion based batteries for the purpose of increasing UAV endurance while decreasing charging time.

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