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Development of a Turbo Electric Distribution System for Remotely Piloted Aircraft Systems

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ABSTRACT

Turboelectric distributed propulsion systems are paving the way for more electric aircraft systems (TeDP). This type of system provides a solution for some of the drawbacks of current low-energy-density batteries, which limit the ability of long-endurance electric aircraft. However, turboelectric propulsion requires the use of advanced turboelectric motors, superconductive materials and cryogenic cooling technologies, which are still under development and may be in production in the near future. This paper investigates a turboelectric propulsion system that can be considered an initial step in the production of TeDP in a remotely piloted aircraft system with the use of existing technology. This is achieved by replacing the gear and the starter motor of a turboprop with a high-speed permanent magnet electric machine to generate electrical power and propelling the aircraft through a distributed electric propulsion system. In this theoretical study, an augmentation to Breguet's range and endurance equation is developed. This study confirmed that the new system is 31% lighter than the turboprop engine. Then the effect of the weight savings is used in the distributed electric propulsion (DEP) aerodynamic studies and found that there is a drastic increase in the range for a TeDP developed with the high-speed machine.

Keywords: Turboprop gear system; Distributed propulsion systems; High-speed machines.

INTRODUCTION

The development of efficient propulsion systems for aircraft is vital not only in response to fuel costs and supply, but also to address environmental concerns. There are various forms of internal combustion (IC), electric and hybrid propulsion systems, which are currently being developed to improve overall performance. Pure IC engines convert the chemical energy stored in fuel to mechanical energy via combustion, while the electric engine converts the chemical energy stored in the battery to mechanical energy. The former delivers higher range and endurance, while the latter has higher propulsive efficiency and offers design flexibility. A hybrid system uses the benefit of both to offer an advanced propulsion system (Eqbal *et al.* 2018).

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Among the advanced hybrid propulsion technologies, one of the most promising concepts is the turboelectric distributed propulsion system (TeDP). This system has been at the forefront of new propulsion concepts (Nalianda and Singh 2014) and part of the National Aeronautics and Space Administration (NASA) subsonic fixed wing (SFW) project to reduce the aircraft fuel burn, emission and noise (Kim *et al.* 2018). By definition, TeDP is a series hybrid propulsion system where a gas turbine engine is used to power a directly coupled electric generator to produce electric power. This electrical power is transferred to small electric motors called propulsors (Bowman *et al.* 2018). This type of system is commonly used in ships and trains where a diesel engine is used to power electric motors for locomotive motion (Hayes and Goodarzi 2018). The method of using multiple electric motors to propel the aircraft, rather than a single motor, is known as distributed electric propulsion (DEP) (Nalianda and Singh 2014).

The main advantage of TeDP is that the core gas turbine is isolated from the propulsors. This, in turn, allows the gas turbine and the electric motor to run in its optimum operating condition and is similar to a series hybrid configuration (Eqbal *et al.* 2018). Other advantages of TeDP include reduction in weight of aircraft and wing structure (Ko *et al.* 2003), and reduction in sound levels (Thomas 2003; Hill *et al.* 2004; Diedrich *et al.* 2006). Furthermore, a significant advantage is a reduction in operational costs due to fuel, as the system is theorized to be working at higher efficiencies across various stages throughout the mission. Further improvements to propulsive efficiency have been investigated, such as a distributed propulsion system acting as a boundary layer injection system to add aerodynamic benefits into the overall aircraft design (Teperin *et al.* 2017). Such concepts allow for integration flexibility for use in various aircraft configurations, such as tube and wing (T&W) (Felder *et al.* 2011; Lian and Wu 2018), hybrid wing body (HWB), blended wing body (BWB) and placing the propulsions strategically in the specific sections of the aircraft, that can reduce the drag and increase lift.

Boundary layer injection (BLI) serves as the base for all the advantages exhibited by DEP. The fundamental principle of BLI propulsion is that a propulsor ingests and reaccelerates the airframe boundary layer, which reduces the wake deformation downstream. It then adds kinetic energy for the same net force, which decreases the power to be added to the flow by propulsor (Teperin *et al.* 2017). In other words, the propulsion is directed to fill in the wing wake reducing boundary layer and pressure drag while increasing the propulsive efficiency (Moore and Fredericks 2014; Moore and Ning 2018). Theoretical studies conducted by Smith Junior (1993) have shown that there is an increase in propulsive efficiency of 127%.

Similarly, Ameyugo *et al.* (2006) has shown, in a numerical investigation, the power savings of 12.2% and the propulsive efficiency of the BLI propulsor is 117.3% compared to the free stream propulsor of 80.9%. In a remotely piloted aircraft systems (RPAS), Teperin *et al.* (2017) showed the power saving coefficient of 21% when a propeller is placed behind the fuselage compared to the forward position and drag coefficient is 28.5% less. Similarly, Rao *et al.* (2017) has shown a reduction in shaft power in case of wake injection by 10% and BLI by 18%. Two independent experiments at NASA achieved a propulsive efficiency of 103% (Goldschmied 1986), while others found that 50% power could be saved using BLI and counter-rotating propellers in an experimental aircraft. Additionally, Alba *et al.* (2017) has shown the total drag reduction of over 30% by optimizing the wing chord and twist distribution behind a given propeller.

Distributed electric propulsion also has positive advantages during takeoff when the aircraft requires more power. In a conceptual design, the study found that a wing with propellers across the entire span at the optimal diameter for the load (8 propellers for a 300 km range constraint) can reduce the takeoff distance by over 80% when compared to the optimal 2 propeller case using the same models (Moore and Ning 2018). There is over a 100% increase in the wing lift coefficient, which leads to a 36% reduction in lift-off speed. The concept also is capable of producing 2.9 times more thrust during takeoff with only an 11% increase in total aircraft mass. Moreover, NASA is developing a full electric DEP aircraft named X-57 Maxwell and has shown that the DEP can provide a positive change to the lift during takeoff and landing (Borer *et al.* 2019).

Distributed electric propulsion comes with technical challenges, such as finding the right balance between the electric motor and the propeller. The higher the speed of propulsor motor, the lower the overall structural weight. Nevertheless, this can create a high propeller tip speed and approaching Mach 1 creates shockwaves and has a detrimental to not only the propulsive efficiency but also impacts propeller maintenance and lifecycle (Hanson and Fink 1979; Hitchens 2015). The turbo-electric engines in development need high electrical efficiencies, capabilities associated with superconductivity to be viable (Armstrong 2015).

Another issue is that, with the present technology, it is not possible to create a TeDP system that is light enough to be efficient. All these drawbacks open the possibility of a direct-run high speed machine to generate power, where it replaces the large gear systems in a turboprop or a turboshaft engine.

A number of high-speed electrical machine options exist for the use as a turbine coupled power generator for DEP. Over the past two decades, electrical machines have been developed for high-speed operations with military and civil aeroengine integration, high-speed turbochargers, air compressors and microturbines, in addition to high-speed machine tools. The technology can also be scaled down and translated for the use in turbo-electric power generation in RPASs. The candidate electrical machine options are the switched reluctance machine, flux switching machine, induction machine and the permanent magnet machine.

The switched reluctance machine (Fernando and Barnes 2013; Fernando 2014; Yu *et al.* 2018) and the flux switching machine (Nasr *et al.* 2017; Selema *et al.* 2018) have been proposed for more-electric aircraft power generation systems. High speed induction machines (Pyrhonen *et al.* 2009) have been developed for high-speed waste heat recovery systems. In contrast, more researches have been conducted on high-speed permanent magnet machines (Fernando *et al.* 2011; Fernando *et al.* 2016; Fernando *et al.* 2018; Song *et al.* 2019; Varyukhin *et al.* 2019; Wang *et al.* 2019; Xu *et al.* 2019). The permanent magnet machine offers higher power density compared with the other forms of machines due to the high air-gap flux density. As a result, the permanent magnet machine can be considered as the most suitable option for DEP in RPAS. Other machines, such as the switched reluctance machine and the induction machine, offer the advantage of operability in high temperatures, such as in applications where the machine is directly integrated within the turbine spool. However, when the machine can be placed externally and coupled with the turbine spool with sufficient cooling such as in RPAS, the permanent magnet machine option tends to be optimal due to a comparatively lower weight.

High power to weight ratio of high-speed machines (Ma *et al.* 2015; Yoon *et al.* 2016) has developed a recent interest in the turboelectric machine in aircraft and RPAS applications (Gerada *et al.* 2014; Schnell *et al.* 2019). Some research concentrated on high-speed machine designs for aircraft (Lahne and Gerling 2015; Yoon *et al.* 2016; Jikumaru and Kuwata 2018). Few methods on the integration of electric generators on the turbine gear to use it as an auxiliary power plant (Cavagnino *et al.* 2013; Bojoi *et al.* 2016). Other research focuses on a high-speed machine design study to directly integrate on the external rotor of a turbojet to use an auxiliary power (Vavilov *et al.* 2016). Another design used a battery-assisted turboelectric power plant to assist the takeoff phase or to use as a range extender with the series architecture aircraft integration (Becker and Sheffler 2016; Boling *et al.* 2020). None of the studies in the current body of knowledge have shown the impact on range and endurance when a heavy gear system and starter motor of a turboprop engine is replaced with a high-speed machine to produce a primary electrical power source. This study concentrates on developing a high-speed machine as a direct replacement of a gear system and investigates the potential weight savings of an engine configuration of this nature. A modification of the common range and endurance equation is augmented to assist in approximations of the overall effect of the proposed propulsion concept while investigating the distributed propulsion design. The study main objective is to show the impact of using a high-speed machine to pave the way for a TeDP with existing technologies, where it can be used as a replacement to the heavy gear system on a shaft powered gas turbine. Moreover, the research scope is limited to the weight comparison based on a specific model of the micro gas turbine, where comparison and savings will be changed the type of power plant used. The study drawback is that the experiment analysis is not included, which is the scope of future research.

SYSTEM DESIGN

A Pilatus PC-9 model aircraft with a scale ratio of 1:3.8 was selected for the experiment validation of the TeDP system; the details of which are provided in Table 1 and are illustrated in Fig. 1. The advantage of this model is that the suited wing area, structure and modifiable airframe can be used for future research on the multiple DEP electric motor configuration concept. In terms of the gas turbine, a Kingtech K-45P turboprop engine was chosen. Moreover, obtainability of a turbojet model (K-45) and availability of online test data provides a benchmark for performance and weight comparisons.

Table 1. Aircraft data.

Total weight, W_1	18 kg
Wingspan, b	2.65 m
Wing Area, S	1.117 m^2
Area of wing, S	0.80645 m^2
Length of aircraft	2.50698 m
Aspect ratio, AR	6.283
Oswald's efficiency factor, e	0.758
Drag coefficient, C_{Do}	0.0358

Figure 1. Pilatus PC-9 RC scale model (used with permission) (BigPlanes 2020).

The power required and the power available for the aircraft are calculated using Eqs. 1 and 2, respectively, using the equations from Fraas (1943) and Greatrix (2012).

$$P_{req} = \frac{1}{2} \mathrm{p} V^3 \mathrm{S} C_{DO} + \frac{W^2}{\frac{1}{2} pVS}\left(\frac{1}{\pi e AR}\right) \tag{1}$$

$$P_{AV} = n_P P_W \tag{2}$$

where, P_{REQ} = power required, (W); P_{AV} = power available, (W); P_W = power. W,C_D = coefficient of drag. The results from these for the scale PC-9 are plotted in Fig. 2.

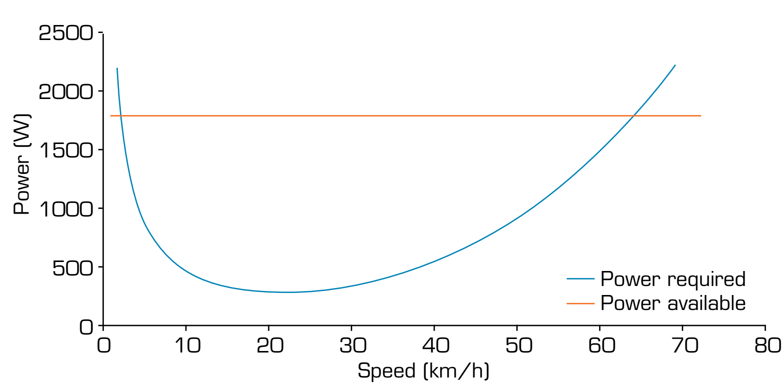

Figure 2. Aircraft data showing the power required and the power available.

From Table 2 (Kingtech 2020), the maximum power output of the turboprop is 5.2 kW; however, the power is set at 2 kW in this work. This is done to keep the aircraft within the performance parameters. Similarly, the calculations are made assuming the propulsive efficiency to be at 90%. The extra power from the turboprop exhaust is not measured, which accounts for an extra 10% power from the turboprop (El-Sayed 2017). Figure 2 shows the power available for the aircraft to be 1800 W when the propulsive efficiency set at 90%.

Table 2. Turboprop data.

Type	Free turbine
BSFC	0.0054
Max Power	5.2 kW
Max RPM	170,000
Length	335 mm

SYSTEM PERFORMANCE

Using the technique given by Anderson Jr. (2016), a modified range and endurance equations are derived, shown in Eqs. 3 and 4, respectively, which provides a simple comparison of different hybrid configurations;

$$R = \frac{1}{g}\frac{3.6n_p}{BSFC}\frac{C_L}{C_D}\frac{n_E}{an_E+(1-a)}\ln\left(\frac{W_F+W_A+W_P}{W_A+W_P}\right),, \tag{3}$$

$$E = \frac{1}{g}\frac{n_p}{BSFC}\frac{C_L^{3/2}}{C_D}\frac{n_E}{an_E+(1-a)}(2\rho S)^{\frac{1}{2}}(W_1^{-1/2} - W_o^{-1/2}), \tag{4}$$

where,

$$W_o = W_F + W_A + W_P \tag{5}$$

$$'W_1 = W_A + W_P \tag{6}$$

In both equations, the efficiency gain of the system to "break-even" is given by Eq. 7:

$$e = \frac{n_E}{an_E+(1-a)} \tag{7}$$

In Eq. 7, n_E is the electric efficiency, while *a* is the hybridization factor. The hybridization factor is the ratio of power provided by the IC engine to the ratio of electric power (Eqbal *et al.* 2018). For a turboprop engine, the hybridization factor is one. Substituting in Eq. 7, the efficiency gain equates to one and gives the values of the direct mechanical power. Conversely, for the pure turbo-electric engine, as the hybridization factor trends to zero, the total mechanical energy trends to electric energy.

The range and endurance of the RPAS are calculated using Eqs. 3 and 4, and the data from Table 3. The weight of aircraft and engine data is taken from the manufactures specifications, while the fuel weight is 2 kg, making the total takeoff weight 18 kg.

Figure 3 displays the range to hybridization factor of the aircraft. Range and endurance are a direct function of electrical and propulsive efficiency. The maximum range of the pure turboprop aircraft is 71.60 km, while the turbo-electric is 68.02 km, which is 95% of the former. However, the propulsive efficiency of a pure electric aircraft and the aerodynamic advantages of a DEP (Ameyugo *et al.* 2006; Felder *et al.* 2011) are higher than a turboprop engine, which in turn should give a higher range and endurance.

Table 3. Aircraft electric and weight distribution.

Electric efficiency	95%
Propulsive efficiency	90%
Aircraft weight	14.2 kg
Propulsion system weight	1.8 kg
Fuel weight	2 kg
Total weight	18 kg
Cl/Cd at 60 km/h	9.93

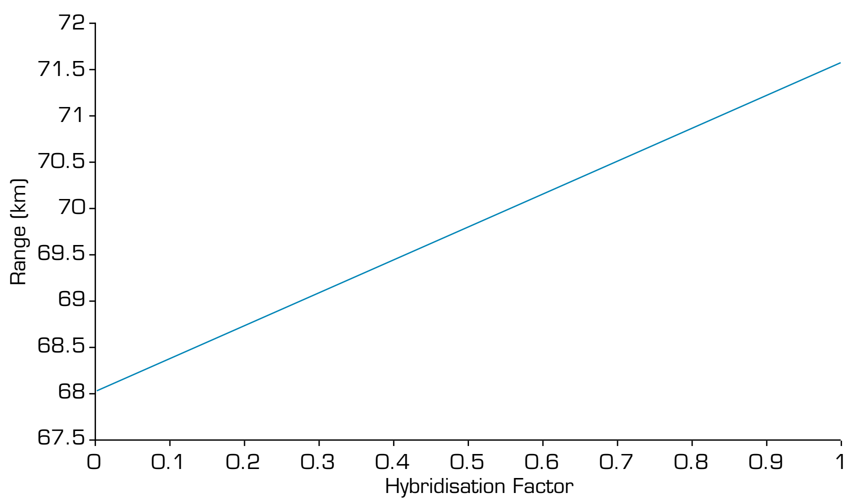

Figure 3. Range as a function hybridization factor when the velocity of aircraft is set at 60 km/hr.

ELECTRIC MACHINE DESIGN

The maximum power required for the aircraft was found to be 2 kW (Fig. 2). At this power output, the turboprop core operates at approximately 120 k RPM. To achieve the speed, availability of cooling and potential to reduce weight, the permanent magnet (PM) generator option is chosen and analyzed using Ansys Maxwell (Fig. 4).

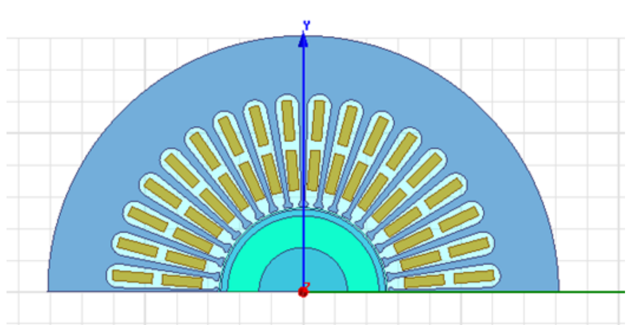

Figure 4. High speed machine in Ansys Maxwell.

There are many types of electric machines used in power generation, which spreads from types of current, alternating current (AC) and direct current (DC), brushed and brushless, outrunner and inrunner (Krishnan 2001; Rahman *et al.* 2004; Bilgin *et al.* 2019). The machine used for the application is a brushless synchronous AC inrunner motor. Alternating current machines are lighter and more efficient than the DC machines (Fernando *et al.* 2016; Fernando *et al.* 2018). Brushless machines have higher efficiency and less maintenance than there brushed counterparts, as there are no electrical contact points. Similarly, a permanent magnetic motor is used due to the high power to weight ratio in high-speed applications. Since the outrunner creates mechanical alignment issues at high speed, an inrunner generator is designed reducing the influence of the centrifugal forces at high RPMs. The high-speed machine brushless inrunner generator requires the magnets to be aligned together under strict tolerances. A sleeved method is used for the magnetic retention, made from Inconel steel due to the capability of the tensile strength (Fernando and Gerada 2014). A high-speed ceramic bearing is used in real-life application to further increase efficiency gains, while coping better with heat dissipation in the high revolutions per minute (RPM) state. Since the high-speed machine is a high ampere AC and the electric propulsor motors are DC, a passive diode bridge rectifier is used to convert the AC to DC (Fernando *et al.* 2011) and a buck converter is used to change the step down the amperage. Three inrunner permanent magnet (PM) machines named machine 1, machine 2 and machine 3 (Fig. 5) have been designed and analyzed using Ansys Maxwell. The machine construction specifications, dimensions, losses and weight comparison are shown in Tables 4, 5 and 6, respectively.

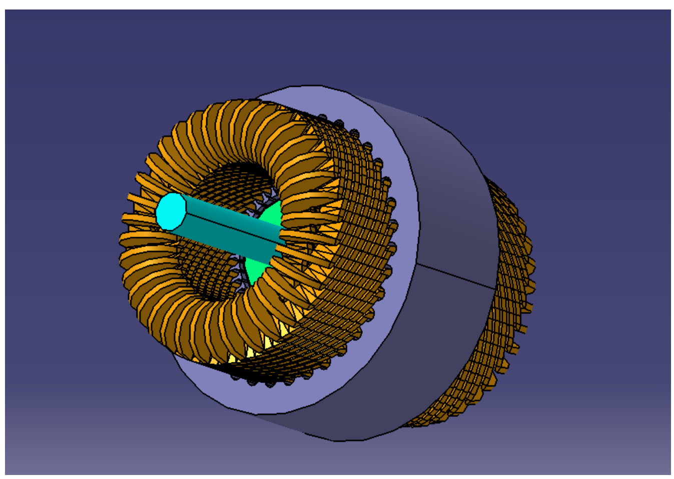

Figure 5. Design of the High RPM machine.

Table 4. Machine construction specifications.

Machine type	Surface permanent magnet machine
Magnet retention	INCONEL alloy 718 sleeve
Nominal frequency	1.66 kHz
Core material	JFE Supercore 10JNHF600
Number of poles	2
Number of stator slots	36
Winding type	Distributed winding
Rectification	Passive diode bridge rectifier

Table 5. Machine dimension.

Machine	1	2	3
Rotor outer diameter (mm)	30	20	10
Shaft diameter (mm)	8	6	4
Stator outer diameter (mm)	90	60	30
Stator inner diameter (mm)	32	21.5	10.4
Magnet thickness (mm)	10	7	5.8
Sleeve thickness (mm)	1	0.25	0.1
Airgap width (mm)	1	0.75	0.2

Table 6. Machine performance at full load (2 kW/120 k RPM).

Machine	1	2	3
Core losses [W]	14.40	25.91	51.17
Eddy current losses [W]	0.65	161.42	114.14
Copper losses [W]	15.01	11.95	20.69
Total losses [W]	30.07	38.53	72.52
Efficiency [%]*	99.40	99.23	98.57

*The bearing loss for the given shaft diameter is not included.

Considering the overall aircraft weight, the PM machines add a significant weight component; however, it is conceived to be far less than a gearbox generator system in which it is replacing. The different portions of the PM machine include the magnet retention sleeve, PM, winding copper and the steel core; itemized in Table 7. The electromagnetic efficiency is in the range of 98 to 99%; however, this does not include the bearing losses (Nelias *et al.* 1994; Pouly *et al.* 2010; Chaudhari *et al.* 2015). The bearing losses may involve another 3% at that speed and it can, therefore, be assumed to achieve 95% efficiency. The electromagnetic losses are mainly dissipated as heat in the machine contributed from ohmic losses in the winding, eddy current losses and core losses in the electromagnetic core. Air cooling can be used for the thermal management of the PM machines, as the heat generated is within 100 to 200 W range. For large high-speed machines, such as those used in turbine integrated power generation systems, an integrated active cooling system needs to be used for both the gas turbines and the electric devices and the additional weight needs to be accounted for. However, in the case of RPASs, the electrical generator is comparatively low power and can be easily air-cooled due to the external placement. Therefore, passive cooling can be used with the advantage of lower weight implications.

Table 7. Weight distribution.

Machine	1	2	3
Stator weight [kg]	0.21	0.25	0.40
Magnet weight [kg]	0.03	0.04	0.07
Copper weight [kg]	0.15	0.12	0.19
Sleeve weight [kg]	0.006	0.002	0.004
Shaft weight [kg]	0.005	0.0051	0.016
Total weight [kg]	0.41	0.43	0.70
Stator weight [kg]	0.21	0.25	0.40

Comparison of the three different versions of machines shows that the higher the diameter, the more the weight of the machine can be reduced. However, placement of the generator is directly in the path of the inlet airflow and the space envelope is constrained by the outer diameter of the machine. Considering the three different versions, the reduction of diameter from 30 to 20 mm increases the machine weight by approximately 18%, while further lowering the diameter to 10 mm increases the weight by 87%. Therefore, a diameter of 20 mm is selected considering the acceptable trade-off of weight while allowing sufficient space for inlet airflow to the engine.

PROPULSION SYSTEM WEIGHT

Figure 6(a) shows the cutaway comparison of a Kingtech k45TP similar to a standard free turbine turboprop engine used in manned aircraft. The total weight is 1800 g, which includes the combustion core (480 g) and the starter motor (220 g). The starter motor is powered by a battery to rotate the compressor to a pre-set RPM and power the ignition in the combustion chamber. After ignition, the clutch mechanism disengages the starter motor and it remains as unuseful weight thereafter. Another factor to consider is the weight contribution of the free gas turbine section, which weighs 1100 g, where the reduction gear has the highest weight share in a turboprop engine (El-Sayed 2017; Kroes and Wild 2018).

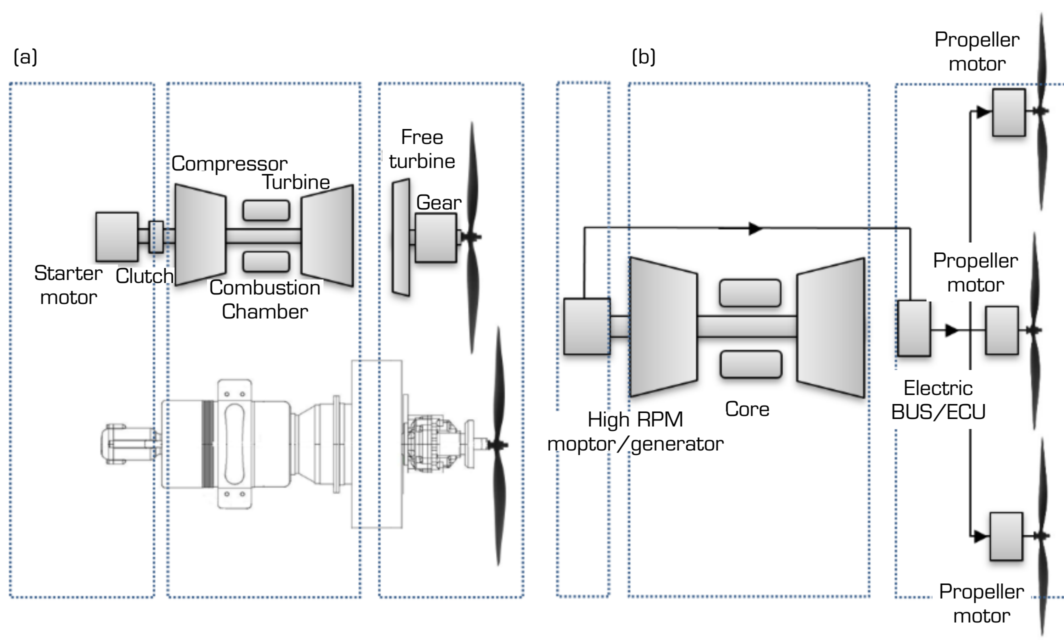

Figure 6. Comparison of parts weights.

Figure 6b shows the new design replacing the starter motor and the free turbine section with a high RPM generator, shedding a total weight of 1320 g. Since the high RPM machine is used as both a motor and a generator, it can be used as a starting device for the turbine. The existing starter motor originally on the engine is no longer required. The new addition also includes nonconductive shaft coupling part to significantly reduce heat transfer from the gas turbine shaft to the electric machine shaft. In summary, the modified design (Fig. 6b) only utilizes the turbine core from the original turboprop engine.

Machine 2 is selected for the new design, which gives a proper balance between the others.

From the Kingtech K45G data, the total weight of the gas turbine is 700 g and the starter motor is 220 g. Since there is no need for the starter motor, this weight is subtracted, giving a total weight of the core to be 480 g. After adding the weight of the high-speed machine (436g) (Table 7), the total weight of the turbine core is 916 g (this does not include the weight of the bearing and casing, which can be negligible and is equivalent to the extra anchoring mechanism and the parts removed from the turboprop).

Then, the propeller system was designed and the off-the-shelf motors were observed to provide propulsive power. After that, the weight distribution for 1, 2, 6 and 8 propulsor configurations are calculated and plotted in Fig. 7 for the 2-kW shaft power.

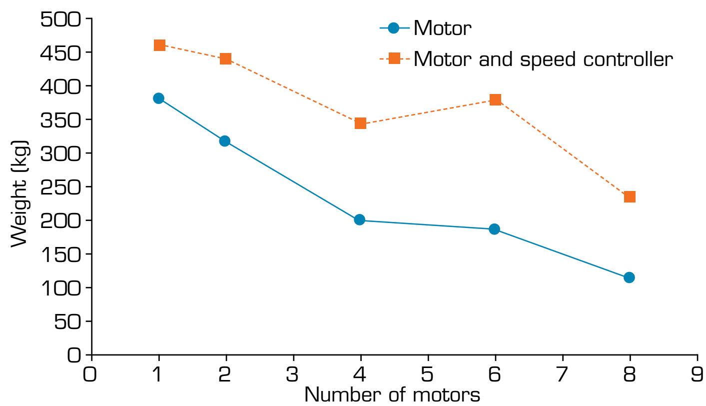

Figure 7. Weight of the motors vs. the number of motors.

Figure 7 shows that the weight of the propulsion system reduces with the number of propulsors, like previous study by Ameyugo *et al.* (2006). However, the weight of the motor depends on the nominal speed, application, brand and design type. The objective of this study does not focus on optimum propulsor motor/propeller selection and, however, is part of ongoing work. Also, explicitly designing the electric motor for this purpose will reduce the actual weight of the electric system and electronic speed control (ESC), as the off-the-shelf motors are designed for a drone or a single-engine aircraft, thus making the weight approximations conservative in nature. Similarly, the purpose-specific design avoids some of the electric conversion circuits used, which also contributes to further weight savings.

The eight motor configuration resulted in the lightest design and was used thereafter for a propulsor configuration. After the integration of the motors, the DEP propulsion system weight is approximately 1250 g. The total weight includes the turbine weight (480 g), high speed machine (436.0 g) and 234.4 g for the ESCs and electric motors and the remaining weight of the electric bus, which is to convert the AC motor to DC power. The AC-DC power conversion circuits includes diodes, capacitors and electric wires. After the addition, the new design is 30.6% lighter than the pure turboprop.

From the addition of the new design, the updated range is calculated, keeping the electric and propulsive efficiency the same. Adding this value in Eq. 3, the new range of the aircraft is 66.6 and 70.3 km for 90 and 95% electric efficiencies, respectively, when comparing to the range of the pure turboprop of 71.6 km.

Figure 8 shows the range of the new propulsion system compared to the turboprop with different efficiency parameters. As shown in previous study by Jansen *et al.* (2015), electrical efficiency has a vital role in the range. However, integration of the increased propulsive efficiency from a DEP can easily overcome all the range shortcomings, including structural weight gains of a DEP to increase the range further. From the base values given in Table 8, some model configurations are calculated with same range and tabulated in Table 9.

Distributed electric propulsion provides a wide range of improvements for an aircraft through increased propulsive efficiency, an increase in aerodynamic efficiency, an increase in lift and reduction in drag, a decrease in power plant weight and a decrease in aircraft structural weight (Goldschmied 1986; Ko *et al.* 2003; Ameyugo *et al.* 2006; Diedrich *et al.* 2006; Felder *et al.* 2011; Nalianda and Singh 2014; Becker and Sheffler 2016; Alba *et al.* 2017; Kim *et al.* 2018; Lian and Wu 2018; Moore and Ning 2018; Schnell *et al.* 2019). Even though the new turboelectric power plant is lighter than the existing pure turboprop, it may not result in improved range as it is necessary to consider the problem as a multidimensional one due to the various parameters in the range equation. A study has been performed (Table 9) using Eq. 3, keeping the current turboprop as a base aircraft reference to find the percentage of change in each parametric change of the new turboelectric engine given the same range as a pure turboprop. The changes in various parameters give insight into what is required to achieve equivalent base aircraft range. Arbitrary changes to propulsive efficiency, propulsion weight and other parameters give insight into the effects of the change to other parameters. Graphical representation could not be adequately achieved as it is a complicated multidimensional problem.

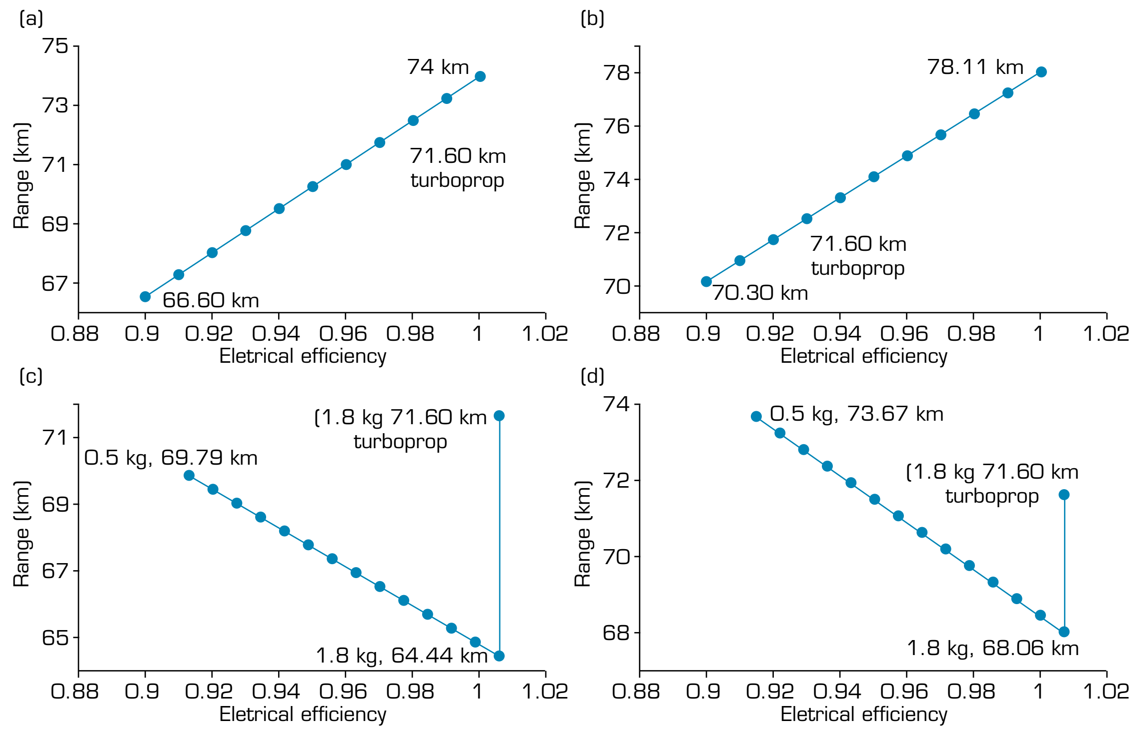

Figure 8. Range and efficiency estimation: a) range vs. electric efficiency for 90% propulsive efficiency; (b) range vs propulsive efficiency for 95% electrical efficiency; c) range vs. propulsion weight for 90% electrical efficiency and 90% propulsive efficiency. d) range vs. propulsion weight for electrical efficiency and 90% propulsive efficiency.

Table 8. New aircraft design specifications.

Aircraft	Base
Electric efficiency	90%
Propulsive efficiency	90%
Weight of the propulsion	1.25 kg
Weigh of aircraft	14.2 kg
Weight of fuel	2 kg
Cl/CD	9.93
SFC	0.0054

Table 9 gives different combinations to compare and trade off weight changes and efficiency changes to the range of the pure turboprop configuration. Column 1 shows a required increase of 7.0% in propulsive efficiency to give the comparable range to the pure turboprop. Similarly, column 13 shows a small increase in electrical efficiency and propulsive efficiency of 1.8% and a weight reduction of 0.13%. With a combination of lift to drag ratio and fuel consumption, the aircraft range can approach that of the pure turboprop. From the literature (Ko *et al.* 2003), the multiple advantages of DEP are clearly understood. Even though the standard electric efficiency is between

90 to 92%, the propulsive efficiency of pure electrical and DEP has an advantage (Kim *et al.* 2018). Ameyugo *et al.* (2006) have shown that the DEP can reduce the weight of the aircraft wing. Similarly, the powerplant weight can be further reduced by increasing the speed of generator (Li *et al.* 2016; Ismagilov *et al.* 2018), which in turn reduces the size of the gas turbine, as well as the weight of the high-speed generator. Furthermore, construction techniques, such as the use of advanced composite materials, making hollow shafts and switching to high energy density material electric wires and shifting to composite ceramic bearings can reduce the weight further. Another option to give the same range is a reduction of specific fuel consumption (SFC), as the research from Vijlee *et al.* (2007) has already shown that the direct coupling of a high-speed machine can reduce fuel consumption. Taking all these into consideration, it shows the new system can have an increased range over the existing turboprop engine. The addition of the battery storage can increase the range further.

Table 9. Percentage change to achieve the same range as base aircraft.

Aircraft	1	2	3	4	5	6	7	8	9	10	11	12	13
Electric efficiency	-	7.0	3.6	-	-	2.0	2.0	-	-	-	-	1.8	1.8
Propulsive efficiency	7.0	-	3.6	3.7	2.7	2.7	2.0	-	-	-	-	0.01	1.8
Weight of the propulsion	-	-	-	-0.29	-0.21	-	-0.15	-	-	-	-0.27	-	-0.13
Weigh of aircraft	-	-	-	-	-2.4	-1.8	-1.8	-	-	-	-	-	-
Weight of fuel	-	-	-	3.5	2.6	1.8	1.8	-	-	-	-	-	-
CI/CD	-		-	-	-	-	-	-	7.0	3.5	3.5	1.8	1.8
SFC	-		-	-	-	-	-	-7.4	-	-3.7	-3.7	-1.8	-1.8

Considering the effects of DEP from various studies, the predicated range can be estimated (Table 10). It shows that the combined effects of fuel consumption, aircraft weight savings, propulsive efficiency and the drag reduction can give up to a 98.85% increase in range for the proposed design.

Table 10. New increased range after the effects of other studies combined.

Advantage	Range (km)	Change (%)
2.7% less fuel consumption[1]	72.25	2.77
4.4% lighter aircraft[1]	73.08	3.98
Propulsive efficiency of 117.3%[2]	88.66	10.49
Drag Reduction of 28.5%[3]	98.37	39.92
Combination total	136.98	98.85

[1]Ko *et al.* (2003). [2]Ameyugo *et al.* (2006). [3]Teperin *et al.* (2017).

GAS TURBINE CONFIGURATION VARIATIONS

As the King Tech K45P is a free-turbine engine, the free turbine section and the starter motor section were replaced with a high-speed machine. However, there are multiple gas turbine configurations that can be used for the new system. From literature, there are mostly three types of gas turbines, such as one, two and three spool configurations (Kroes and Wild 2018), which depend on the number of internal coupling shaft, linking the compressor and turbine stages together. One spool means one shaft system (compressor turbine pair), two means two shaft systems (typically on a concentric shaft). For the gas turbine, the best options are either a single spool or two-spool free turbine, as given in Fig. 9.

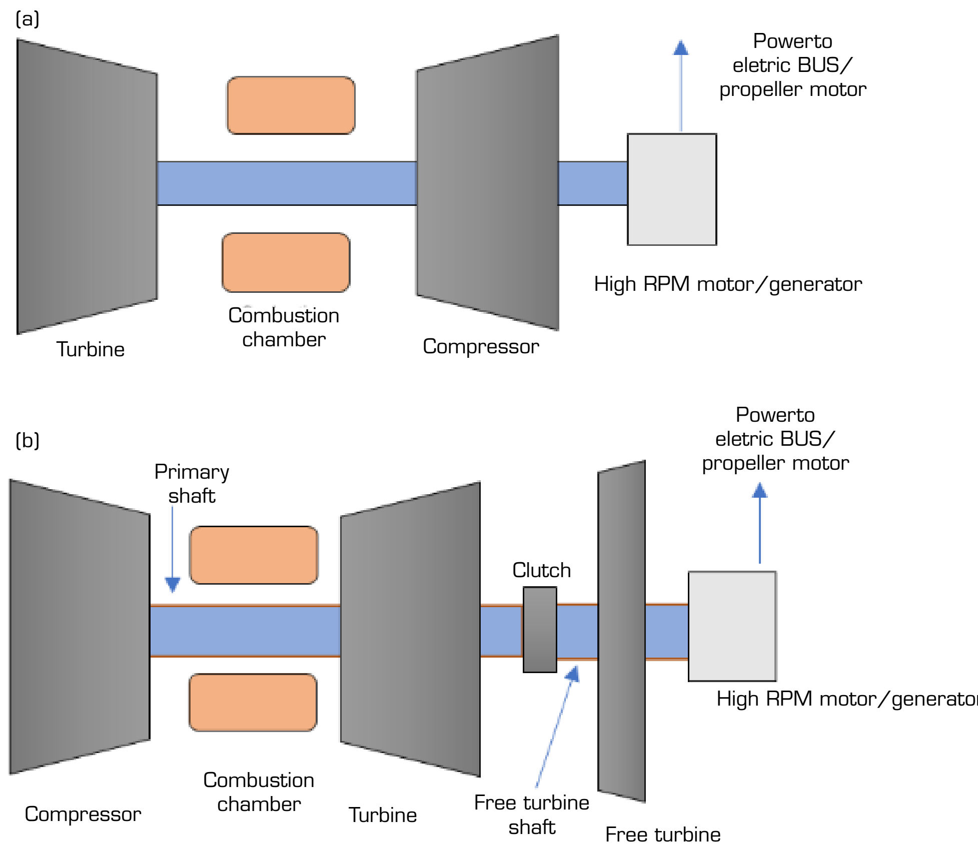

Figure 9. Comparison of single spool and double spool configuration.

Figure 9a defines the single turbine configuration where a high-speed generator replaces the starter motor. In this configuration, there is a single shaft for compressor, turbine and the electric machine. This configuration may require a redesign of the turbine to extract more power, similar to a turboshaft, or it can keep it as it is to be a partial turboelectric configuration. This configuration is often recommended for an electric generation as the power output is constant (Breeze 2016), which is similar to the case where the turbine is established to run at the optimum speed regardless of the cruising condition. Another advantage is the possibility of avoiding the clutch mechanism, a section in a gas turbine that is vulnerable to failure and also increases relative system weight. In a conventional gas turbine, the starter motor rotates the spool to a fixed speed until the combustion chamber is ignited. After that, the clutch mechanism disengages the gas starter motor. However, in this design, the high-speed machine is used as the starter motor and, after the ignition of the engine, it uses the power from the turbine to generate electricity and does not require a clutch mechanism and starter motor. Another advantage is that it is lighter than the free turbine shown in Fig. 9b, as there is no need for an extra turbine, shaft and bearings for the second spool (Breeze 2016).

The free turbine arrangement, Fig. 9b, is where the free turbine shaft is situated inside the spool shaft while running completely independently. There are many advantages of this system; since the gas turbine spool and power turbine spool are independent, they both can work at the optimum rotational condition (Jansohn 2013). Also, for constant flow and constant generator speed, the turbine can provide relatively constant power and compressor flow, regardless of the operating condition. In conclusion, in this system, the high-speed machine is used to rotate both spools in a fixed speed until the gas turbine is ignited. Thereafter, the gas turbine clutch disengages and compressor-turbine spool and the free turbine spool work as separate systems. This dual spool configuration is more complicated and heavier than the single spool system, but has a higher propulsive efficiency. In this configuration, there are multiple design possibilities, such as placing the clutch between the gas turbine and exhaust flow, but the clutch should either be redesigned to cope with high temperature or the shell of the gas turbine should be redesigned to shield the exhaust heat from the clutch.

The main advantage with different configurations of gas turbines are all the designs are readily used in aircraft or on the ground for electric power plants and can easily be adapted.

MECHANICAL AND HEAT CONSIDERATIONS

One of the significant concerns while using a high-speed motor is heat generation, which is vital in the case of a large scale (potentially manned) aircraft where latent heat can be a design problem. For this 2-kW system heat generation is minimal. Table 6 showed that the heat generated from the electric machine is under 50 W, allowing air cooling methods to create the required heat dissipation. This avoids the need for complex heat sink systems for the electric machine, as well as the circuitry. However, in the case of large aircrafts, a system like jacket cooling (Canders *et al.* 2019) and regenerative cooling (Pizzarelli 2017) may be required. Nevertheless, in larger aircrafts, electrical efficiency is a significant concern, as discussed by Kim *et al.* (2018).

The primary concern is placing the electrical systems, including the generator, in unheated flow for maximum heat transfer and cooling. This, of course, could be challenging, as the generator must be at close proximity to the turbine to access the appropriate shaft. Heat transfer through the turbine shaft to the generator may also provide means to overheat the generator. Pre-existing insulation materials can overcome this, such as paints in coupling and different shaft materials directly reduce heat transfer. Vented flow using channels could be effective in heat dissipation at the cost of drag.

The high-speed machine is favorable from a mechanical perspective. For a gas turbine, there is frequent maintenance of the required gear system where the majority of maintenance and repair effort is relatively larger when compared to other subsystems (Samaranayake 2006; Ward *et al.* 2010; Mrzljak *et al.* 2019). Modern electric machines require less maintenance due to the reduction of moving parts and mechanical contact points (Ploetner *et al.* 2013; Sarlioglu and Morris 2015) with the high-speed machines a well-developed concept and readily available in the market (Moghaddam 2014; Zhang *et al.* 2016). The main consideration of the system is the required cooling. If sufficient cooling is not maintained in operation, the machine efficiency is reduced (Yang *et al.* 2016; Canders *et al.* 2019). The integration loss is another matter of concern. If the machine is not integrated appropriately, there will be mechanical coupling loss, which ends in a total power loss.

CONCLUSION

Replacing the gearing of the gas turbine with a high-speed machine and distributing the power through a DEP results in a propulsion system that is 30.6% lighter than the existing gas turbine, which is less than reported in the existing studies, where the hybrid system is larger than the existing pure engine. After considering the advantages of DEP on propulsive efficiency, fuel saving, aircraft weight and drag reductions of the new design could give an increased range of 98.5%. The weight can be reduced further by increasing the speed to provide more rotational energy for electrical generation. The primary concern of the new system is the electric efficiency, where there is a trade-off between minimization of resistance and addition weight due to wires and associated electronics. Apart from the advantages of electrical distribution, existing studies show advantages of increased propulsive efficiency, reduced aircraft weight and fuel-savings by using a directly coupled high speed engine. These can increase the range and endurance of the RPAS. The derived equations give a simplified formula that can be used to calculate the range and endurance, which is an excellent tool to optimize the new design. Since the equation gives the break-even through the hybridization factor, it can be called a universal equation that can be used in parallel, series and series-parallel hybrid configuration.

Modification of the new equation to include a battery system could be beneficial. Maximum electric power is required for takeoff and the propulsion system here is designed to cope with this requirement. This excess energy produced during cruise could be stored in a battery system and can be used as a range extender. Optimizing the propulsion system for the cruise and using the extra battery power for takeoff can be another option.

One of the critical problems is that the off-the-shelf outrunner motors were used as the propulsors, which involved intricate electric designs to convert from AC to DC and conversion of electric powers from the high-speed machine to small motors. These add extra weight and it was not possible to find an adequate range of motors which are suitable for the DEP. Designing a propulsor motor and the speed controllers that are specific to this high-speed design can overcome all these power conversions and mass issues. An optimized system that balances the electric and propulsor system is of future interest.

All the design considerations open up a new area of investigation, but the principal objective of this study is to show the advantage of the high-speed machine and its advantage on the propulsion weight savings.

AUTHORS' CONTRIBUTION

Conceptualization: Eqbal M and Wild G; **Methodology:** M Eqbal, N Fernando, M Marino and G Wild; **Investigation:** M Eqbal, N Fernando, M Marino and G Wild; **Writing – Original Draft:** M Eqbal; **Writing – Review and Editing:** Fernando N, M Marino and G Wild; **Funding Acquisition:** Wild G and Marino M; **Resources:** Eqbal M, Fernando N, M Marino and G Wild; **Supervision:** N Fernando, M Marino and G Wild.

DATA AVAILABILITY STATEMENT

All dataset were generated or analyzed in the current study.

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