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Experimental study on efficient propulsion system for multicopter UAV design applications

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ABSTRACT

The usage of multicopter unmanned aerial vehicles (UAVs) has increased for various military and civilian purposes. The choice of propulsion system of such a vehicle is crucial to fulfill the intended mission requirements. The present study focuses on evaluating the efficiency of propulsion system by experimenting with different motor, propeller and battery combinations. The connection between the electronic speed controller (ESC) signal, current, power, thrust and torque in relation to propeller size is determined. It is observed that regardless of battery capacity or motor type, the thrust and torque produced for a given motor speed (RPM) for a specified propeller are similar. The higher capacity battery with 6000 mAh, denoted as B2 battery, consumes less current and can attain higher motor speed to produce the required thrust force than a lower capacity battery with 3300 mAh, denoted as B1 battery. The most efficient propeller, 12 inches in diameter (P4 propeller), is observed to achieve efficiency levels of 12.9 % for the B1 battery and 11.4 % for the B2 battery. Similarly, the most efficient motor, 700 KV motor (M1), is determined to exhibit efficiency of 64.29 % when coupled with the B1 battery and 62.01 % when coupled with the B2 battery. It is identified that using the B2 battery results in an increased payload capacity of 5.82 N, compared to 2.02 N with the B1 battery. Furthermore, when considering both scenarios with and without payload, greater endurance is observed when B2 battery is used as opposed to the B1 battery.

1. Introduction

Multicopter unmanned aerial vehicle (UAV) drones are used for a range of military and civilian purposes, including search and rescue missions, disaster management, surveillance, photography, construction management, agriculture, etc. [1–3]. The multicopters proved to be extremely appealing. This is due to its minimal structural complexity and ease of usage, as well as its hovering and vertical take-off and landing capabilities, which allow it to operate in confined spaces [4]. Two of the most common are the quadcopter and hexacopter.

The choice of propulsion system is critical in multicopter design. The propulsion system consists of motors, propellers, and a battery. To give the flying vehicle the desired attitude [5], the rotational speed of the motors must be changed. The required forces and torque are generated by the propellers attached to the motors. These motors are powered by batteries. The brushless direct current (BLDC) motors are commonly used in multicopters. The reasoning behind usage of such motors and their efficiencies were discussed in Lee and Pan [6] and Carev et al. [7]. As a result, the performance of the propulsion system is crucial [8,9] to the drone design and in determining its efficiency [10] since it influences the maneuverability, allowed payload capacity and endurance.

Several studies have been focused on propeller performance in the context of propeller diameter, Reynolds number effects and propeller efficiency. Deters [11] and Deters et al. [12] have tested 27 off-the-shelf propellers and 4 in-house printed propellers to study the effect of Reynolds Number and efficiency, on the other hand 36 inch propellers efficiency details were examined by Durand [13]. Dantsker et al. [14] have reported the data set for 17 propellers with diameters ranging from 12 to 21 inch for motor speed ranging from 1000 to 7000 RPM. Brandt and Selig [15] tested 79 propellers with a single motor in sizes ranging

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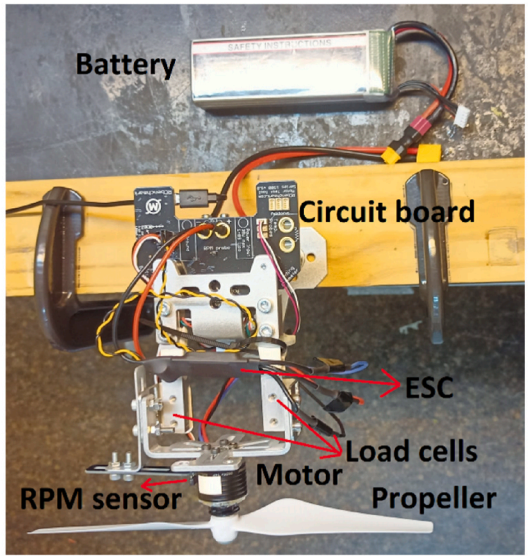
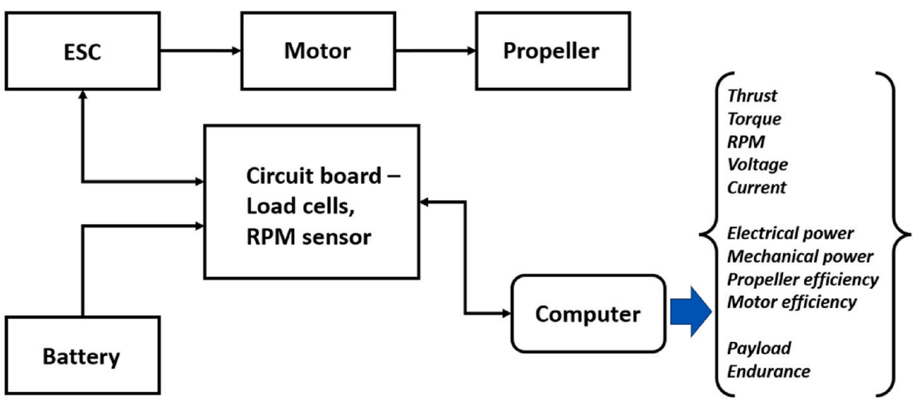


(a)



(b)

Fig. 1. (a) Photograph of test stand and (b) schematic view of experimental system.

Table 1
Test stand specifications.

Parameter	Minimum	Maximum	Resolution
Thrust (N)	−49	49	0.049
Torque (Nm)	−2	2	0.005
Current (A)	0	55	0.1
Voltage (V)	0	50	0.05
RPM	10	30,000	–

from 9 to 11 inches. Thrust and torque were measured at desired rotational speeds (RPMs) over a range of propeller advance ratios to study low Reynolds number effects. Furthermore, the static thrust was determined at propeller speeds ranging from 1500 to 7500 RPM, depending on propeller diameter. With lower RPMs, the results revealed Reynolds number effects on performance degradation. 30 propellers tested data were reported by Merchant [16] and Merchant and Miller [17] while Zhu et al. [18] tested six different types of propellers manufactured by a single company to create a database. Ol et al. [19] reported measurements on propellers with regard to the Reynolds number effects. Considering the importance of propeller efficiency, Gur [20] proposed a semi-empirical method to evaluate the propeller performance by finding the maximal efficiency and maximum thrust of the propeller. Kaya and Kutay [21,22] used the momentum and blade element theories and proposed a second order polynomial curve fitting algorithm to accurately calculate the forces and moments at various rotor speeds. Kaya et al. [23] reported the performance of the propeller by studying various motor-propeller combination to calculate the endurance of the quadrotor.

The researchers have investigated the effective sizing, optimization, and design approaches for multirotor drones. Delbecq et al. [24] describes an approach for optimizing drone designs using scaling laws and similarity models while keeping cost-effectiveness and time-efficiency in consideration. Pollet et al. [25] emphasized on forward flight design optimization, using aerodynamic modeling, optimization techniques, and computational fluid dynamics simulations. Additionally, Biczyski et al. [26] discussed a multirotor sizing methodology that incorporates flight time estimation as a crucial factor. An overview [27,28] of the components used in the quadcopter's design and the testing procedures were reported.

It has been found that research on propeller performance on one hand and design techniques on the other was carried out. It can be anticipated that higher battery capacity would provide longer flight time but the weight of the battery increases. The weight would be an

Table 2
Motor specifications.

Motor	Description	Mass (kg) [Weight (N)] including cables
M1	 BLDC 700 KV Stator Poles: 12 Magnetic Poles: 14	0.128 [1.255]
M2	 BLDC 965 KV Stator Poles: 12 Magnetic Poles: 14	0.079 [0.774]
M3	 BLDC 935 KV Stator Poles: 12 Magnetic Poles: 14	0.053 [0.519]

important factor as the required thrust to weight ratio needs to be maintained in multicopter design. As lower capacity battery has lower weight, it is not necessary that it can accommodate higher payload. The battery would have an influence on ESC signal, thrust, current, and power which can result in payload capacity and endurance. So, the choice of battery depends on the applications of the multicopter where it may require higher payload or endurance. On the other hand, it must be ensured that the propulsion system for any multicopter delivers roughly 50 % greater thrust than its actual weight. If thrust is lesser than that, the vehicle may not be able to take-off or respond to control commands properly. Even in windy conditions, the vehicle must stay stable and fully operational. A multicopter with a high thrust-to-weight ratio will have better maneuverability. In addition, the selection of motors and propellers are crucial to design/fly an efficient multicopter. The objective of the present study is to investigate the efficient propulsion system with three BLDC motors, five propellers ranging in size from 9 inches to 13 inches and two different capacity lithium-polymer (LiPo) batteries for applications to design multicopter UAVs. Based on the efficient motor-propeller combination for different batteries, the payload and endurance are determined. To the best of the authors' knowledge, limited studies have presented an exhaustive evaluation of a propulsion system as part of multicopter design methodology. The database created, and the findings presented in this study can aid researchers and engineers in designing any efficient multicopter.

2. Experimental system

The dynamometer setup 'Series 1580 Test Stand' [29] is used to evaluate the efficiency of propulsion system for applications in multicopter UAV design. A similar setup was used in Mathur and Atkins [30]. The test setup is mounted on an anti-vibration platform to carry out the necessary experiments (Fig. 1). The specifications of the test stand are mentioned in Table 1.

The testing and data acquisition are carried out using the RCbenchmark software [29]. The Electronic speed controller (ESC) signal is used as an input to control the motor speed (RPM) during the experiments. The tests are carried out by setting the desired RPM to measure the required parameters. The tests are conducted between 1500 RPM and 7500 RPM. The present study investigates 3 motors, 5 propellers and 2 batteries, their specifications are mentioned in Table 2 to Table 4.

All tests are conducted under static conditions with no freestream flow. The experiments conducted within a spacious environment, with more than 2 m of open space on all sides of the experimental setup, ensuring that there were no boundary wall effects. For every combination of motor, propeller, and battery, a dataset consisting of 1500 data points was collected at a 40Hz frequency. The analysis reported in the subsequent sections are based on the mean average of these datasets. Statistical data analysis has been carried out using an in-house developed MATLAB code.

Before initiating the experiments, system noise data has been recorded and subsequently subtracted from the actual data. The standard deviation of this noise data is measured to be approximately, 10^{-3}.

Table 3
Propeller specifications.

Propeller	Size (inch)	Pitch (inch)	Material	Mass (kg)	Weight (N)	Photograph
P1	9	4.5	Plastic	0.012	0.117	
P2	10	4.5	Carbon nylon	0.013	0.127	
P3	11	8	Plastic	0.022	0.215	
P4	12	4	Carbon fibre + Epoxy	0.013	0.127	
P5	13	4.4	Carbon fibre + Epoxy	0.014	0.137	

Table 4
Battery specifications.

Battery	No. Cells (s)	Capacity (mAh)	Discharge rate (C Rating)	Mass (kg)	Weight (N)	Cut off voltage (V)	Nominal voltage (V)	Maximum Voltage (V)	Maximum continuous ampere draw (A)
B1	3	3300	60	0.267	2.618	9	11.1	12.6	198
B2	4	6000	50	0.558	5.472	12	14.8	16.8	300

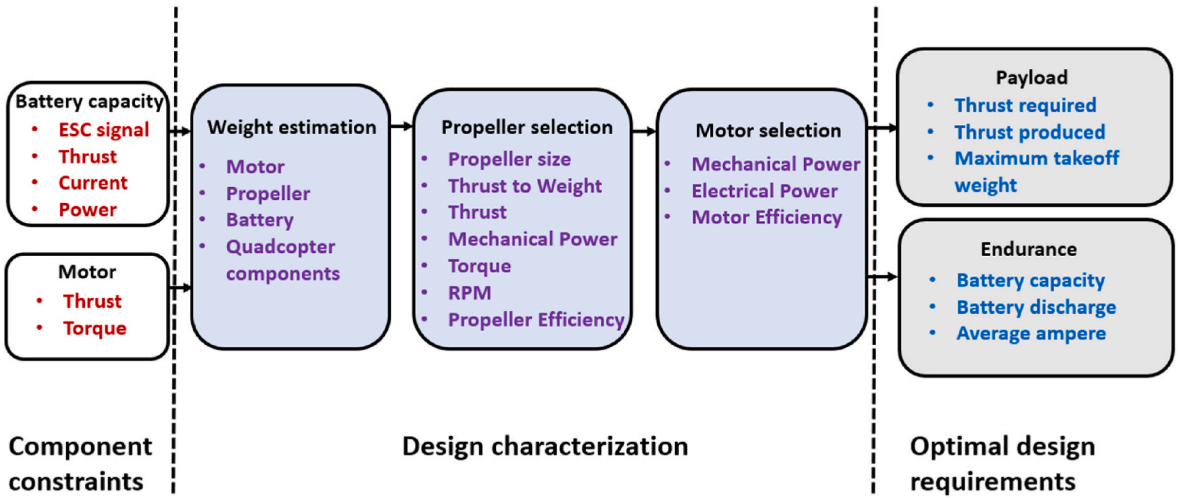


Fig. 2. Design methodology flow chart.

Upon subtracting the noise from the actual data, it has been observed that removing the noise data is not imperative for the current set of experiments. Additionally, it is found that once the dataset exceeded 1200 data points, the difference remained in the order of 10^{-3}. Consequently, the current experiments used 1500 data points for averaging. Furthermore, the initial runs of each experiment have been conducted multiple times, revealing minor differences. To ensure consistency, all experiment cases are subsequently repeated three times. In each repetition, the error is found to be around 10^{-3}.

3. Results and discussion

Fig. 2 shows the design methodology flow chart, which includes three phases such as components constraints, design characterization and optimal design requirements. It represents the battery capacity constraints on various parameters such as ESC signal, thrust force, current, and power, followed by the constraints of different motors on thrust and torque produced by different propellers, and then weight estimation of the quadcopter, estimating the payload and endurance by selecting the most efficient motor and propeller combination.

3.1. Component constraints

3.1.1. Battery capacity constraint

(i) ESC signal variation due to battery capacity change

Fig. 3 shows the battery capacity constraints on ESC signal with respect to motor speed (RPM). The ESC signal pulse width of BLDC motor would range from 1000us to 2000μs [3,31]. Since the motors being used would operate in this range, it can be anticipated that a smaller ESC signal required to operate at a desired RPM would be preferable because it can lead to reach higher RPMs. In Fig. 3, the solid line and square symbol indicates the lower capacity battery (B1) and the dash line and circle symbol indicates the higher capacity battery (B2). Battery details are mentioned in Table 4. Identical colour denotes the identical propeller, for example black colour for propeller P1. Propeller details are mentioned in Table 3. M1, M2 and M3 denote Motor 1, Motor 2 and Motor 3, respectively (see Table 2).

It has been found that B2 requires less ESC signal to reach the appropriate RPM for a specific motor-propeller combination. It can be anticipated that, using B2, there is a possibility to reach higher RPMs compared to B1. In Table 5, the highest RPMs for B1 and B2 are mentioned. This demonstrates that B2 has reached a higher RPM than B1 as anticipated.

It should be noted that certain cases have not attained the intended maximum RPM of 7500, which could be because the ESC has just reached its maximum (Table 5) or because the thrust has reached its maximum (section 3.1.1 (ii)). This proves that using B2 allows for greater RPM, but its weight is more than twice of B1 (see Table 4). Since the thrust to weight ratio, along with the current and power consumption, is a crucial consideration, it is not appropriate to make a choice between B1 and B2 at this stage.

Additionally, it has been noticed that, in all cases, except for P3, where the ESC signal increases with increase in propeller size, the relationship between ESC signal and propeller size is directly proportional. To draw attention, P3 is exempt for M3, as illustrated in Fig. 3c. Therefore, it should be noted that P3 behaves distinct than other propellers. Propeller pitch/diameter could be the reason for this anomaly. There exists scope for exploring in this regard. In consideration of the limited investigation, it can be said that the ESC signal is directly proportional to propeller size.

Fig. 4 shows the effect of battery capacity on thrust production. For both batteries in all cases, the thrust produced by the motor-propeller increases as RPM increases. For a given RPM, it has been found that the thrust produced for B1 is consistently similar to B2 in all cases. This reveals that the produced amount of thrust force is not significantly affected by employing different battery capacities.

Table 6 provides information on each case's maximum thrust. In some cases, the maximum thrust produced by B1 and B2 differs. For example, in the case of M1P1, the maximum thrust force produced by B1 is less than that of B2 since B1's maximum RPM is less than that of B2's.

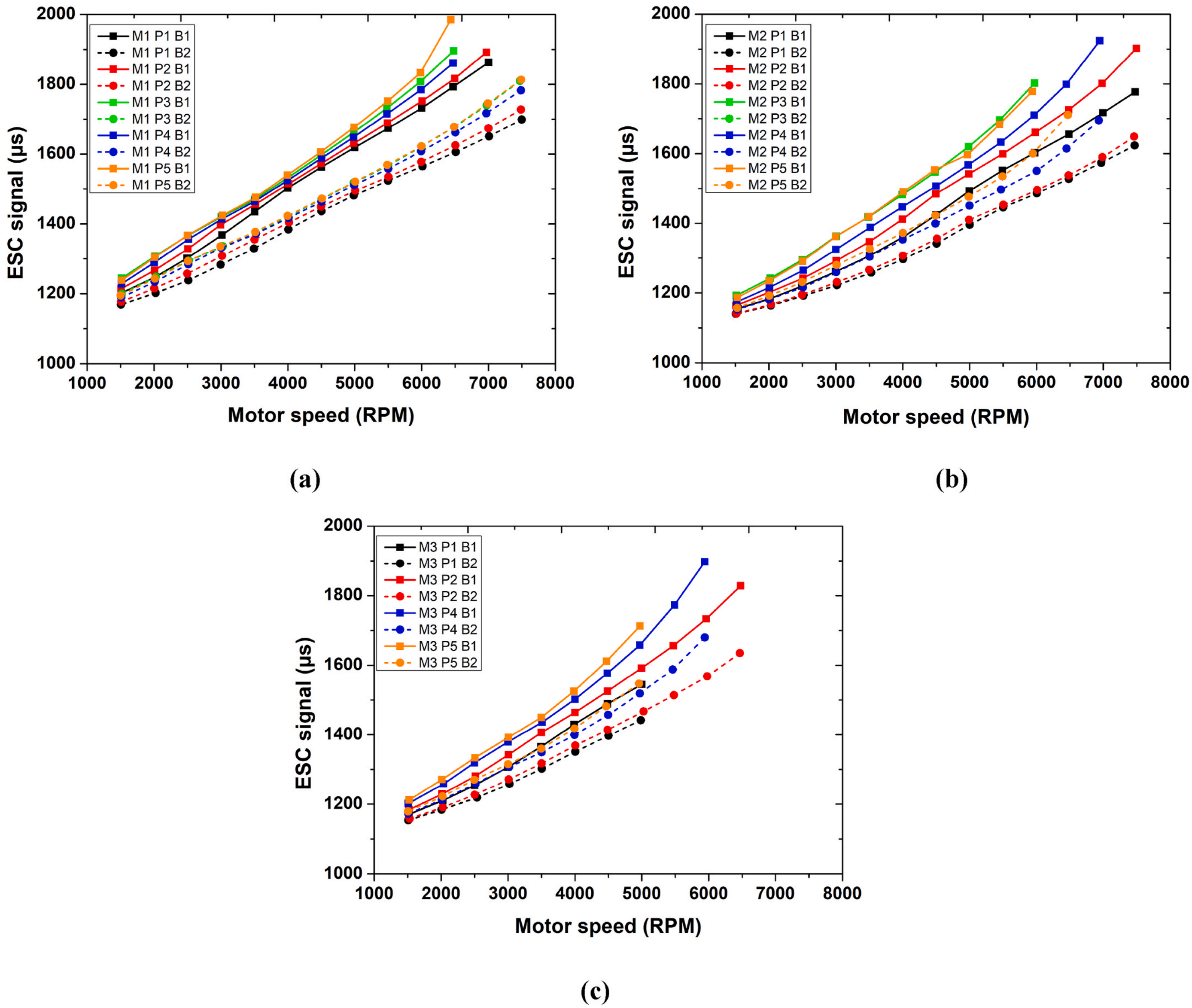


Fig. 3. Battery capacity effect on ESC signal for motors (a) M1, (b) M2 and (c) M3.

Table 5
Maximum motor speed and ESC signal achieved.
(ii) Thrust variation due to battery capacity change

	Motor speed (RPM)						ESC signal (µs)					
	M1		M2		M3		M1		M2		M3	
	B1	B2	B1	B2	B1	B2	B1	B2	B1	B2	B1	B2
P1	7000	7500	7500	7500	5000	5000	1863	1699	1777	1624	1545	1442
P2	7000	7500	7500	7500	6500	6500	1892	1728	1902	1649	1828	1635
P3	6500	7500	6000	6500	–	–	1896	1810	1802	1685	–	–
P4	6500	7500	7000	7000	6000	6000	1861	1783	1924	1695	1897	1680
P5	6500	7500	6000	6500	5000	5000	1985	1813	1778	1711	1713	1547

This is due to the ESC signal requirements, which was previously mentioned, depends on battery capacity.

This established that, regardless of battery capacity, motor-propellers produce identical amounts of thrust, therefore the choice of battery depends on how the designer/user wants it to operate. The choice of battery for a mission that requires higher RPM would be B2, while one that requires less weight would be B1.

On the other side, as propeller size increases correspondingly increases the thrust produced at a given RPM. It has been noted that P3 produces thrust that is comparable to P4 for both M1 and M2 (Fig. 4a and b). It indicates that P3 is more effective at producing thrust force, even though its performance is dependent on the current, power and ESC signal it consumes. The ESC signal for P3 is comparable to that for P5, and it does not reach higher RPMs, such as 7500 for battery B1 with

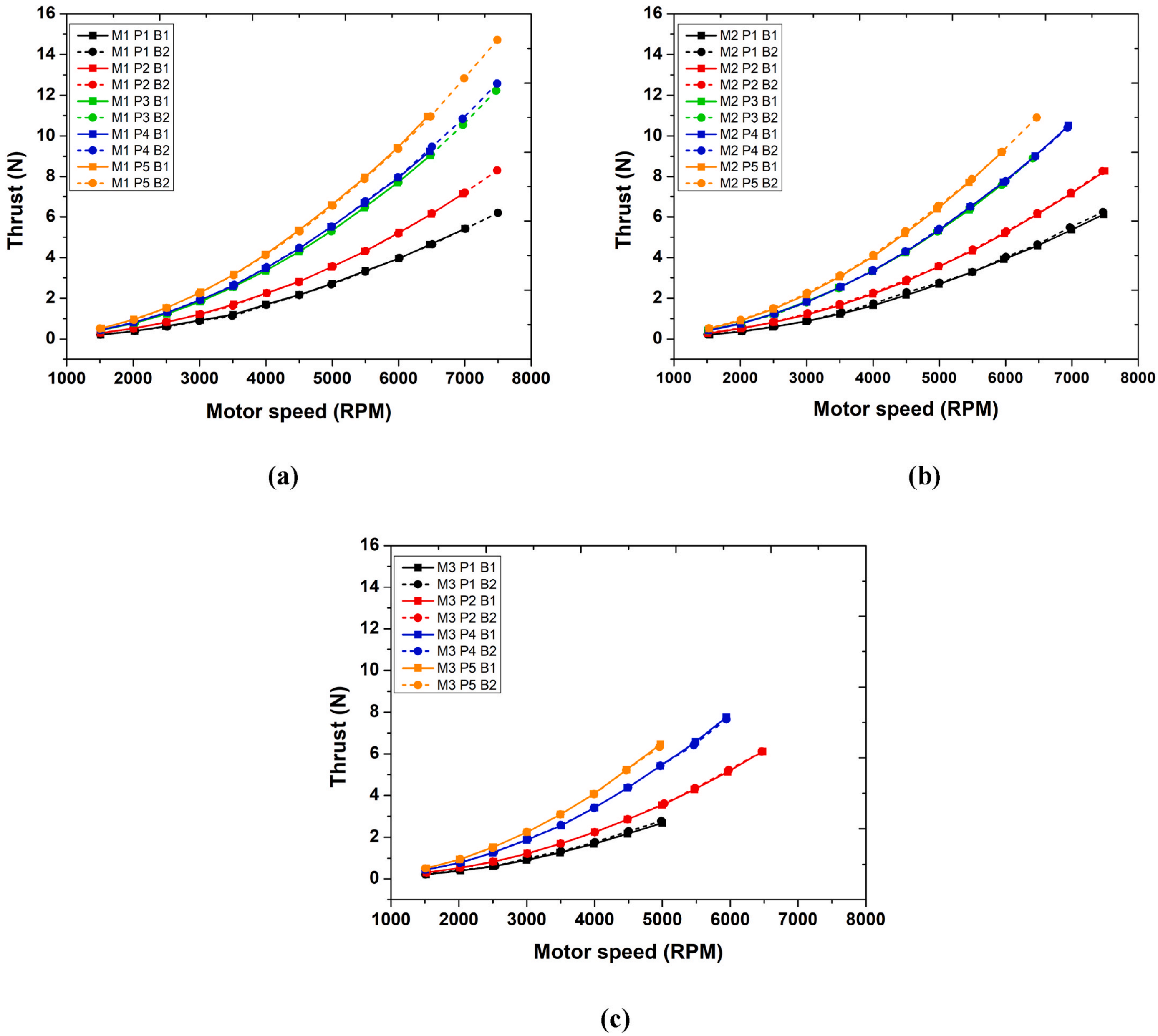


Fig. 4. Battery capacity effect on thrust for motors (a) M1, (b) M2 and (c) M3.

Table 6
Maximum thrust (N).

(iii) Current variation due to battery capacity change

–	M1		M2		M3	
	B1	B2	B1	B2	B1	B2
P1	5.414	6.194	6.122	6.733	2.675	2.972
P2	7.133	8.306	8.269	8.269	6.115	6.119
P3	9.036	12.225	7.673	8.899	–	–
P4	9.251	12.577	10.503	10.406	7.761	7.653
P5	10.953	14.712	9.177	10.905	6.465	6.337

M1 and very low RPMs for both batteries (B1 and B2) with M2. This proves that P3 is inadequate. The subsequent sections discuss the impact on current and power consumption.

For both batteries (B1 and B2) in all cases, the current drawn by the motor-propeller increases as RPM increases as shown in Fig. 5. Similar observations were reported in Ref. [32]. It has been observed that B1 consumes more current than B2 does for a given RPM. This establishes that using a battery with a lower capacity requires more current to run at the specified RPM. In this perspective, it can be said that choosing B2 over B1 is preferable. Since it is commonly known that the multicopter's battery powers all its sensors, it would be preferable if the battery used less current. It should be noted that, as was described in the previous

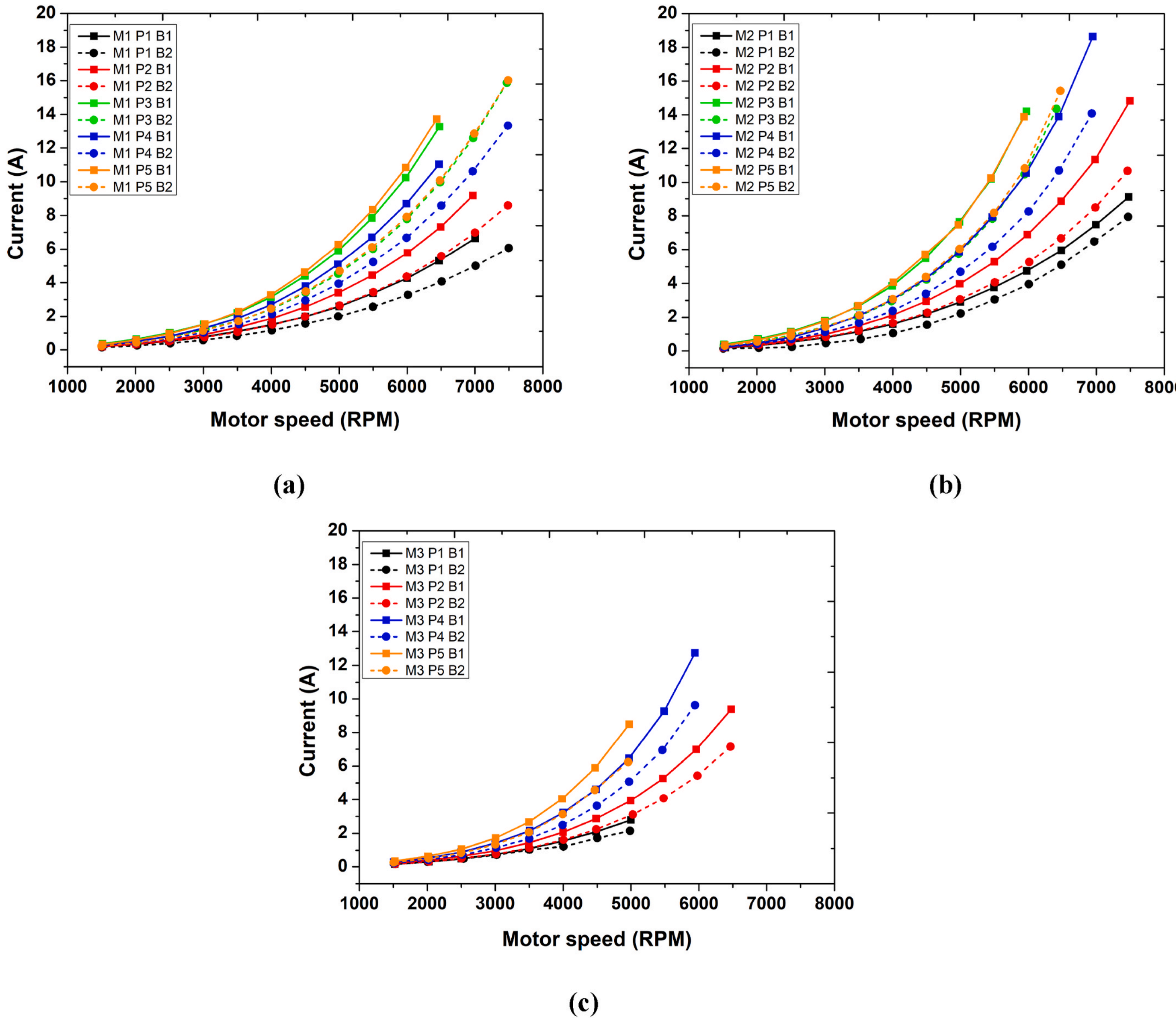


Fig. 5. Battery capacity effect on current for motors (a) M1, (b) M2 and (c) M3.

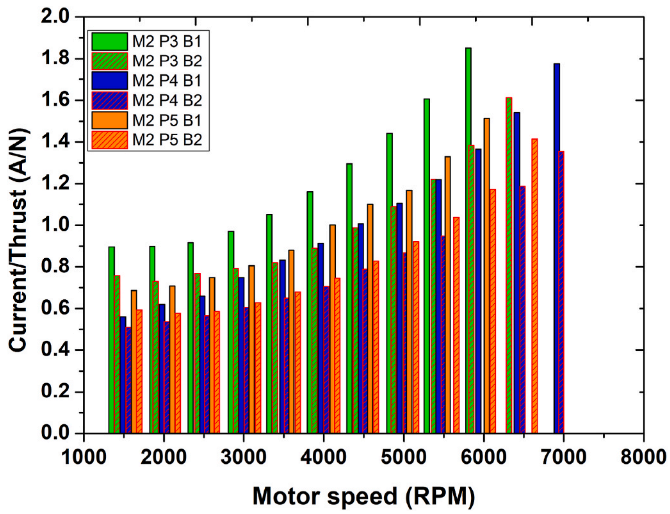


Fig. 6. Battery capacity effect on current to thrust ratio for motor M2.

(iv) Power variation due to battery capacity change

sections (i) and (ii), using B2 allows for higher RPMs and identical thrust as B1. This proves that using B2 can consume lesser current and can reach higher RPM to produce required thrust. Therefore, B2 is preferred over B1. Point to be noted that B2 is heavier in weight compared to B1.

On the other side, with P3 as an exception, the current drawn for a particular battery B1 or B2 is proportional to propeller size. The current drawn increases with increase in propeller size for all three motors. In addition, P3 uses more current, similar to P5 (larger propeller). This proves that P3 is inadequate. But as mentioned in the previous section, the amount of thrust produced is greater for P3. This proves its benefit. However, P3's thrust is comparable to P4's. As a result, P3 draws as much current as P5, and produces as much thrust as P4. This demonstrates poor performance because the current to thrust ratio is undoubtedly higher as shown in Fig. 6 for M2 as an example.

For both batteries (B1 and B2) in all cases, the power drawn by the motor-propeller increases as RPM increases as shown in Fig. 7. Power is defined as Electrical Power in equation (1).

$$\text{Electrical Power (W)} = \text{Voltage (V) x Current (A)} \quad (1)$$

It has been observed that B2 consumes slightly more power than B1 does for a given RPM. This signifies that using a battery with a lower capacity requires less power to run at the specified RPM. In other words, since current multiplied by voltage is power, by comparison of the data from the previous section (iii) indicates that B2 provides more voltage at a given RPM than B1. This means that a higher capacity battery (B2) provides more voltage and may deplete faster, but B2 has higher bandwidth so it may not deplete faster. Therefore, the choice between B1 and B2 cannot be made on this basis. Endurance calculation as reported in the subsequent sections would reveal this aspect.

3.1.2. *Motor constraints on thrust and torque*

As mentioned previously, using different battery capacities has no influence on thrust production for a given RPM. This section examines how motors affect thrust force and torque with respect to RPM. Fig. 8 illustrates the five propellers (i.e., P1 to P5) for three motors and two batteries. Only one case figure regarding torque has been shown (Fig. 9) for the sake of brevity. It has been observed that the thrust and torque produced by each propeller for all motors are identical. This means that regardless of the motor used, the thrust and torque generated at a specific rotation speed will remain the same.

3.2. *Design characterization*

To determine and validate the outcomes from section 3.1, the design process with weight estimation followed by the selection of propeller and motor is carried out. To recall, it has been found that the thrust and torque produced for a given RPM for a specified propeller are similar regardless of battery capacity or motor type. The higher capacity battery (B2) consumes less current and can attain higher RPMs to produce the required thrust force than a lower capacity battery (B1).

3.2.1. *Weight estimation*

Multicopter design is an iterative process. It has to begin with some assumptions. Currently, it is assumed to have 450 mm frame and the sensors such as Flight controller, GPS module, Telemetry module and ESC are known. Fig. 10 shows the in-house built quadcopter with all the parts assembled. The details of quadcopter components are mentioned in Table 7. The motors, propellers and batteries are the variables considered in the study.

The total weight of the quadcopter is defined as maximum takeoff weight (MTOW). W_K is the weight of the quadcopter without weight of propulsion system (W_M, W_P, W_B), which is equal to 8.335 N (known). Since various motors, propellers and batteries are considered, the MTOW would be estimated accordingly. The tradeoff study is performed for three different motor types namely M1, M2 and M3, five different propeller types namely P1, P2, P3, P4 and P5 and two different battery types namely B1 and B2 (see Tables 8 and 9 for details).

$$MTOW = W_K + W_M + W_P + W_B \quad (2)$$

$$W_K = W_{frame} + W_{sensors} + W_{other} = 8.335N \quad (3)$$

where, W_M is total weight of four motors used in the quadrotor, W_P is total weight of four propellers used in the quadrotor, W_B is weight of the battery used in the quadrotor, W_{frame} is weight of the frame used in the quadrotor, $W_{sensors}$ is weight of the sensors used in the quadrotor and W_{other} is weight of the other components used in the quadrotor.

When a multicopter is hovering, the basic rule states that the thrust is equal to its weight. This implies that the thrust to weight (T/W) ratio is 1. However, the multicopter must take off and maneuver, which demands greater acceleration and thrust. As a general rule, the propellers should create twice the thrust required to hover. That means the thrust to weight ratio should be 2, which would provide better operation control. The thrust required (TR) for both scenarios is shown in Table 10 and Table 11.

As a design methodology of multicopter, the selection of propulsion system process begins with Table 10. It shows the minimum thrust required by the multicopter to hover with T/W equal to 1. Table 11 demonstrates the same with T/W equal to 2. It is to be noted that, if the designer is interested to have T/W as 1, can see Tables 10 and 12 which indicates the motor, propeller and battery which are capable. Fig. 4 can be referred to understand the thrust force produced by each case. The present study is interested in T/W as 2, and the most efficient propulsion system is evaluated accordingly. The evaluation process begins with the selection of an efficient propeller, discussed in the subsequent section.

3.2.2. *Propeller selection*

With the given quadcopter frame size of 450 mm, the maximum propeller diameter/size that are suitable can be calculated using cosine rule as shown below.

In Fig. 11, A, B, C and D are the motors, AE, BE, CE and DE are the four arms of the frame.

AE and BE = 225 mm and β = 90°.

From Cosine rule,

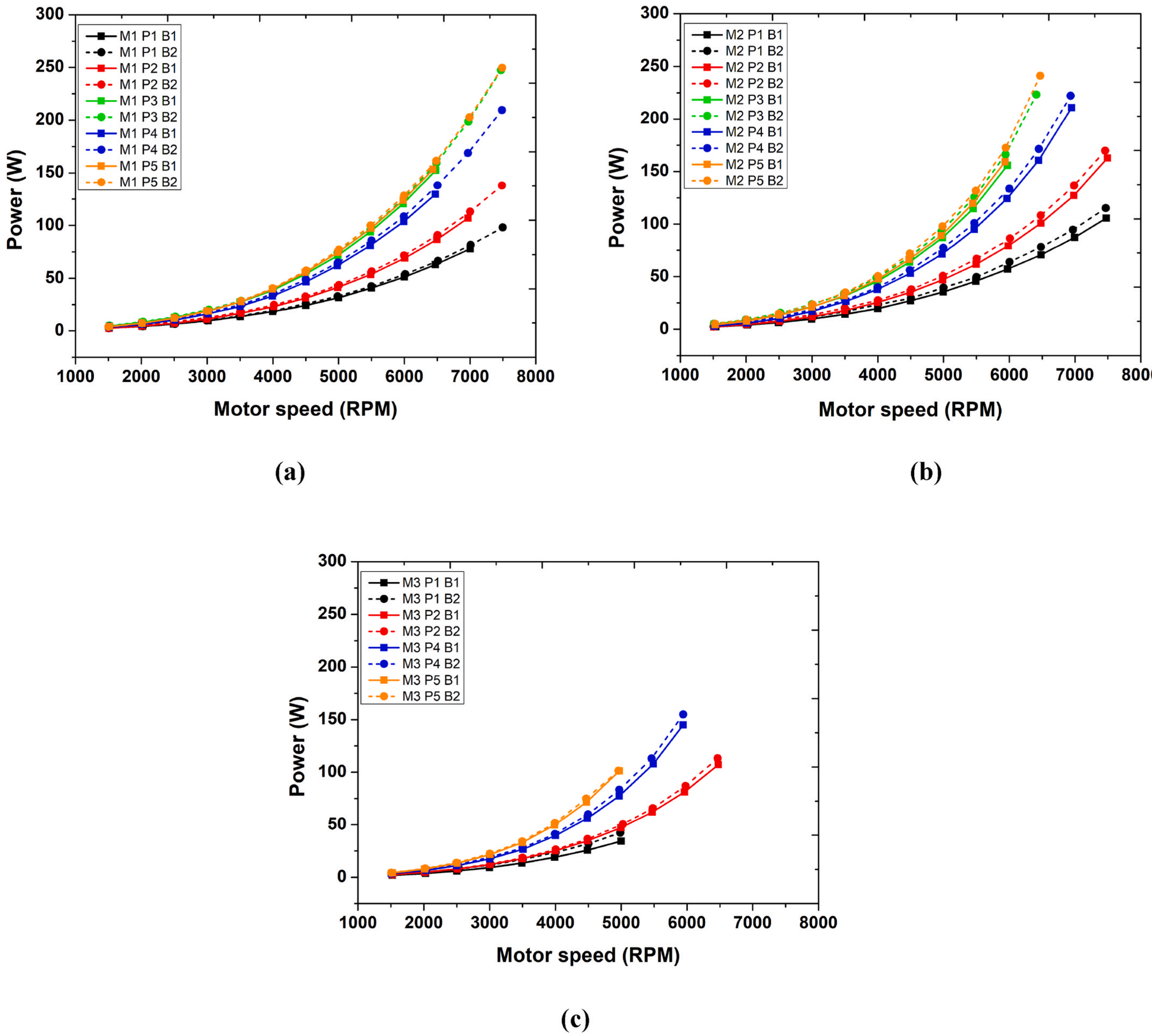


Fig. 7. Battery capacity effect on power for motors (a) M1, (b) M2 and (c) M3.

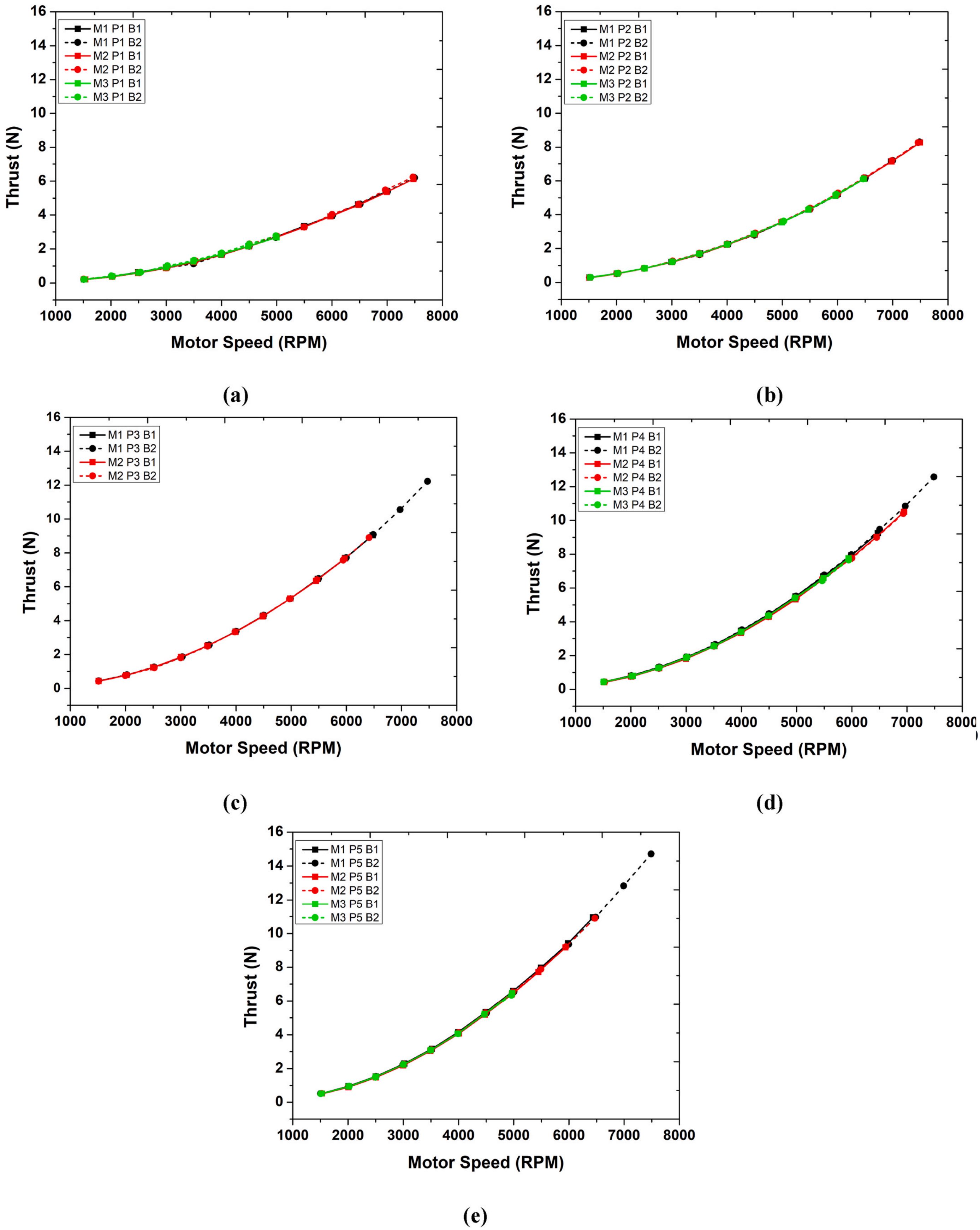


Fig. 8. Motors effect on thrust for propellers (a) P1, (b) P2, (c) P3, (d) P4 and (e) P5.

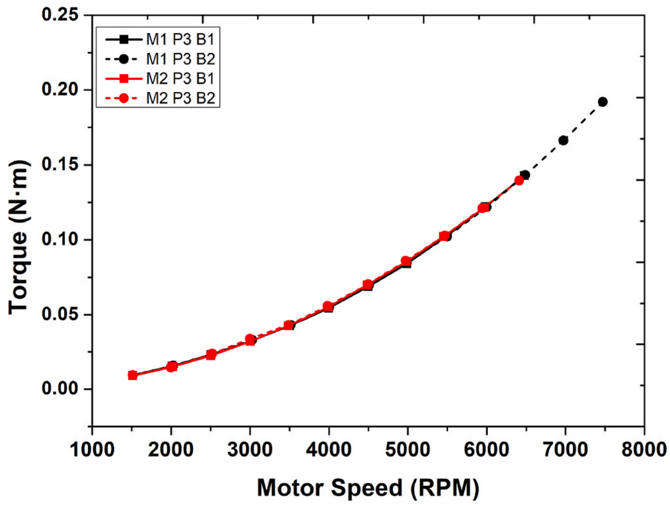


Fig. 9. Motors effect on torque for propeller P3

Fig. 10. Photograph of the fully assembled quadcopter [33].

Table 7
Quadcopter components.

Part	Part	Description
Frame	Frame	F450
Sensors	Flight controller	CUAV V5+
	GPS module	Neo 3
	Telemetry module	FSIA6B
	ESC	40A
Other	Other components	Power distribution board and wiring/cables

$$AB^2 = AE^2 + BE^2 - 2\cos\beta \times AE \times BE \tag{4}$$

Therefore, AB = 318.198 mm = 12.52 inch. = BD = CD = AC = L.

It is found that a maximum of 12.52 inch propeller can be used. This defines that considering the 13 inch propeller i.e., P5 is ruled out from the subsequent evaluation process. This is illustrated in Fig. 11, which show that for propellers P1 to P4, 2R is lesser than L, while it is not for propeller P5. It must be noted that, for 450 mm frame, commonly 10 or 11 inch propellers are being used as the propeller efficiency may have an effect if the propellers are placed too close together. However, the effect of propeller spacing is beyond the scope of the present work. The 450 mm frame is chosen as an example to provide a descriptive approach on selection of propeller for the convenience of readers/designer.

Fig. 12 shows the T/W trends with respect to RPM. In these figures, it has been encircled the propellers that can produce the desired T/W ratio of 2. Table 12 shows that the motor-propeller-battery combination that can be considered for further evaluation of propeller selection. From Table 12 it has been observed that, for T/W = 1, M3P1 cannot generate thrust required for both batteries (B1 or B2), while all other cases can generate thrust required. To use P1 with M3 the total weight of the vehicle must be reduced, the only headway is to use the small capacity battery. This would certainly have lesser endurance. The present study is intended to have T/W as 2, certainly, the minimum thrust requirement is higher, thereby some of the motor-propellers with battery combinations are ruled out for further evaluation.

The propeller efficiency is calculated using the below equation,

$$\text{Propeller Efficiency}(\%) = \frac{Thust}{Mechanical\ Power} \times 100 \tag{5}$$

where,

$$\text{Mechanical Power}(W) = \frac{2\pi\tau RPM}{60}; \tag{6}$$

τ is Torque given in Nm

As shown in Fig. 13, at T/W = 2, the most efficient propeller is found to be P4 for both batteries (B1 and B2). The most efficient propeller for B1 in descending order with respect to the motors is M3, M2 and M1. Similarly, for B2, the order is M2 and M1. The details are mentioned in Table 13. Therefore, the propellers except P4 are ruled out for next level evaluation, as they have a lower efficiency.

3.2.3. Motor selection

From section 3.2.2, it has been found that P4 is the most efficient propeller. The next step is to find the efficient motor for P4 at T/W = 2. The motor efficiency is calculated using below equation,

$$\text{Motor Efficiency}(\%) = \frac{Mechanical\ Power}{Electrical\ Power} \times 100 \tag{7}$$

Table 8
Components weight.

<table>
<tr><th colspan="10">Motor</th></tr>
<tr><th colspan="4">4 × M1</th><th colspan="2">4 × M2</th><th colspan="4">4 × M3</th></tr>
<tr><th colspan="2">Mass (kg)</th><th colspan="2">Weight (N)</th><th>Mass (kg)</th><th>Weight (N)</th><th colspan="2">Mass (kg)</th><th colspan="2">Weight (N)</th></tr>
<tr><td colspan="2">0.512</td><td colspan="2">5.021</td><td>0.316</td><td>3.098</td><td colspan="2">0.212</td><td colspan="2">2.079</td></tr>
<tr><th colspan="10">Propeller</th></tr>
<tr><th colspan="2">4 × P1</th><th colspan="2">4 × P2</th><th colspan="2">4 × P3</th><th colspan="2">4 × P4</th><th colspan="2">4 × P5</th></tr>
<tr><th>Mass (kg)</th><th>Weight (N)</th><th>Mass (kg)</th><th>Weight (N)</th><th>Mass (kg)</th><th>Weight (N)</th><th>Mass (kg)</th><th>Weight (N)</th><th>Mass (kg)</th><th>Weight (N)</th></tr>
<tr><td>0.048</td><td>0.470</td><td>0.052</td><td>0.509</td><td>0.088</td><td>0.862</td><td>0.052</td><td>0.509</td><td>0.056</td><td>0.549</td></tr>
<tr><th colspan="6">Battery</th><th colspan="4" rowspan="2">Quadcopter without propulsion system</th></tr>
<tr><th colspan="3">B1</th><th colspan="3">B2</th></tr>
<tr><th>Mass (kg)</th><th colspan="2">Weight (N)</th><th>Mass (kg)</th><th colspan="2">Weight (N)</th><th colspan="2">Mass (kg)</th><th colspan="2">Weight - W_K (N)</th></tr>
<tr><td>0.267</td><td colspan="2">2.618</td><td>0.558</td><td colspan="2">5.472</td><td colspan="2">0.850</td><td colspan="2">8.335</td></tr>
</table>

Table 9
MTOW with battery B1 and B2.

	B1						B2					
	M1		M2		M3		M1		M2		M3	
	Mass (kg)	Weight (N)	Mass (kg)	Weight (N)	Mass (kg)	Weight (N)	Mass (kg)	Weight (N)	Mass (kg)	Weight (N)	Mass (kg)	Weight (N)
P1	1.677	16.445	1.481	14.523	1.377	13.503	1.968	19.299	1.772	17.377	1.668	16.357
P2	1.681	16.484	1.485	14.562	1.381	13.542	1.972	19.338	1.776	17.416	1.672	16.396
P3	1.717	16.838	1.521	14.915	1.417	13.896	2.008	19.691	1.812	17.769	1.708	16.749
P4	1.681	16.484	1.485	14.562	1.381	13.542	1.972	19.338	1.776	17.416	1.672	16.396
P5	1.685	16.524	1.489	14.602	1.385	13.582	1.976	19.377	1.78	17.455	1.676	16.435

Table 10
MTOW and thrust required for T/W = 1.

	MTOW (N)	TR by each propeller (N)		MTOW (N)	TR by each propeller (N)
M1P1B1	16.445	4.111	**M1P1B2**	19.299	4.824
M1P2B1	16.484	4.121	**M1P2B2**	19.338	4.834
M1P3B1	16.838	4.209	**M1P3B2**	19.691	4.922
M1P4B1	16.484	4.121	**M1P4B2**	19.338	4.834
M1P5B1	16.524	4.131	**M1P5B2**	19.377	4.844
M2P1B1	14.523	3.63	**M2P1B2**	17.377	4.344
M2P2B1	14.562	3.64	**M2P2B2**	17.416	4.354
M2P3B1	14.915	3.728	**M2P3B2**	17.769	4.442
M2P4B1	14.562	3.64	**M2P4B2**	17.416	4.354
M2P5B1	14.602	3.65	**M2P5B2**	17.455	4.363
M3P1B1	13.503	3.375	**M3P1B2**	16.357	4.089
M3P2B1	13.542	3.385	**M3P2B2**	16.396	4.099
M3P3B1	13.896	3.474	**M3P3B2**	16.749	4.187
M3P4B1	13.542	3.385	**M3P4B2**	16.396	4.099
M3P5B1	13.582	3.395	**M3P5B2**	16.435	4.108

where, formulation for Mechanical Power is shown in equation (6) and Electrical Power in equation (1).

Fig. 14a shows that for B1, the most efficient motor has been found to be M1 with 64.285 % while M2 and M3 have 51.802 % and 46.228 %, respectively. Fig. 14b shows that for B2, the most efficient motor has been found to be M1 with 62.010 % while it is 47.127 % for M2. The details of the same are mentioned in Table 14. Therefore, it can be concluded that for both batteries, the most efficient motor is M1.

3.3. Optimal design requirements

3.3.1. Payload

From sections 3.2.2 and 3.2.3, it has been found irrespective of battery capacity, motor M1 and propeller P4 has been found to be most efficient. With M1 and P4 combination for two batteries (B1 and B2), the maximum payload the quadcopter can carry has been estimated in the present section.

To calculate the payload, the maximum thrust produced (TP) and minimum thrust required (TR) by each motor-propeller unit have been considered. Fig. 15 and Table 15 shows the respective parameters for M1P4B1 and M1P4B2. For both cases (B1 and B2), RPM for TR is lesser than TP. This indicates that additional weight can be added to the MTOW, which can be called payload. It is to be noted that Fig. 15 show the TP and TR for one motor. These values are multiple by 4 as quadcopter is considered in the present study (Table 15).

Calculation of payload by maintaining the Thrust to Weight ratio as two for battery B1 is mentioned below.

$$T / W = 2 \tag{8}$$

The maximum thrust produced (TP) for M1P4B1 is 37.004 N, using equation (8), thrust produced can be written as $TP = 37.004/W_{11} = 2$; so, the maximum weight of the quadcopter with M1P4B1 is $W_{11} = 18.502$ N. We know from Table 11, MTOW for M1P4B1 is 16.484 N, this is denoted as W_{12}.

Table 11
MTOW and thrust required for T/W = 2.

	MTOW (N)	TR by each propeller (N)		MTOW (N)	TR by each propeller (N)
M1P1B1	16.445	8.222	**M1P1B2**	19.299	9.648
M1P2B1	16.484	8.242	**M1P2B2**	19.338	9.668
M1P3B1	16.838	8.418	**M1P3B2**	19.691	9.844
M1P4B1	16.484	8.242	**M1P4B2**	19.338	9.668
M1P5B1	16.524	8.262	**M1P5B2**	19.377	9.688
M2P1B1	14.523	7.26	**M2P1B2**	17.377	8.688
M2P2B1	14.562	7.28	**M2P2B2**	17.416	8.708
M2P3B1	14.915	7.456	**M2P3B2**	17.769	8.884
M2P4B1	14.562	7.28	**M2P4B2**	17.416	8.708
M2P5B1	14.602	7.3	**M2P5B2**	17.455	8.726
M3P1B1	13.503	6.75	**M3P1B2**	16.357	8.178
M3P2B1	13.542	6.77	**M3P2B2**	16.396	8.198
M3P3B1	13.896	6.948	**M3P3B2**	16.749	8.374
M3P4B1	13.542	6.77	**M3P4B2**	16.396	8.198
M3P5B1	13.582	6.79	**M3P5B2**	16.435	8.216

Table 12
Selection of Motor – Propeller – Battery combination.

	T/W = 1	T/W = 2		T/W = 1	T/W = 2
M1P1B1	YES	NO	M1P1B2	YES	NO
M1P2B1	YES	NO	M1P2B2	YES	NO
M1P3B1	YES	YES	M1P3B2	YES	YES
M1P4B1	YES	YES	M1P4B2	YES	YES
M1P5B1	Eliminated	Eliminated	M1P5B2	Eliminated	Eliminated
M2P1B1	YES	NO	M2P1B2	YES	NO
M2P2B1	YES	YES	M2P2B2	YES	NO
M2P3B1	YES	YES	M2P3B2	YES	YES
M2P4B1	YES	YES	M2P4B2	YES	YES
M2P5B1	Eliminated	Eliminated	M2P5B2	Eliminated	Eliminated
M3P1B1	NO	NO	M3P1B2	NO	NO
M3P2B1	YES	NO	M3P2B2	YES	NO
M3P3B1	NA	NA	M3P3B2	NA	NA
M3P4B1	YES	YES	M3P4B2	YES	NO
M3P5B1	Eliminated	Eliminated	M3P5B2	Eliminated	Eliminated

Yes – indicates the combination can generate the minimum thrust required.
No – indicates the combination cannot generate the minimum thrust required.
Eliminated – indicates that the propeller size does not fit for the current quadcopter frame.
NA – indicates that propeller does not fit with motor or no data is available.

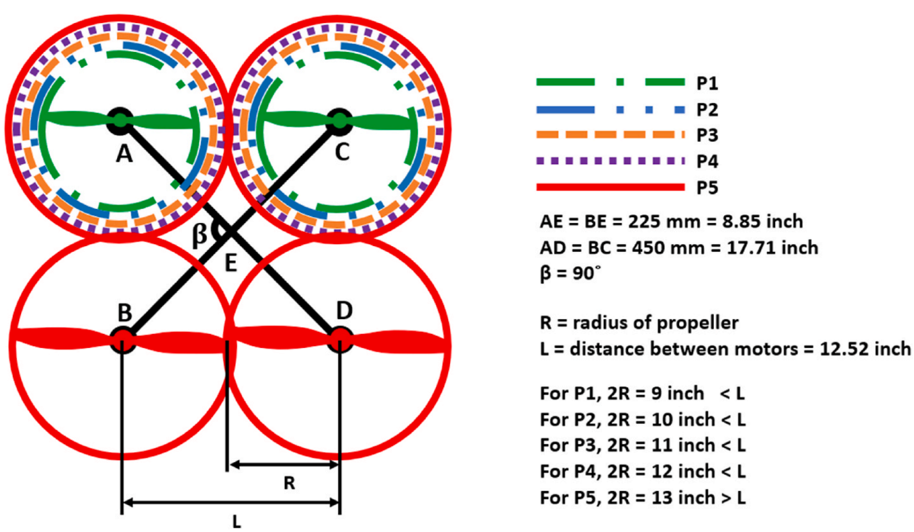


Fig. 11. Schamatic representation of quadcopter frame for propeller selection based on size.

Therefore, the maximum payload the quadcopter carries with M1P4B1 combination is, $W_{Payload\_M1P4B1} = W_{11} - W_{12} = 2.018$ N.

The revised maximum takeoff weight of the quadcopter for M1P4B1 is $MTOW_{Revised_{M1P4B1}} = W_{12} + W_{Payload\_M1P4B1} = 18.502$ N.

(B) Payload calculation for battery B2

The maximum thrust produced (TP) for M1P4B2 = 50.308 N, so, the maximum weight of the quadcopter with M1P4B2 is $W_{21} = 25.154$ and $W_{22} = 19.338$ (see Table 11 for MTOW of M1P4B2).

Therefore, the maximum payload the quadcopter carries with M1P4B2 combination is $W_{Payload\_M1P4B2} = W_{21} - W_{22} = 25.154 - 19.338 = 5.816$ N.

The revised maximum takeoff weight of the quadcopter for M1P4B2 is $MTOW_{Revised_{M1P4B2}} = W_{22} + W_{Payload\_M1P4B2} = 25.154$ N.

It has to be noted that the maximum payload can be increased to 20.52 N and 30.97 N for M1P4B1 and M1P4B2, respectively, if T/W is maintained as 1.

Table 16 and Fig. 16 show the maximum payload and MTOW details. It has been found that M1P4B2 can carry higher payload.

3.3.2. Endurance

The endurance, E of the multicopter is calculated using equation (9) [28].

$$E = \{(Battery\ capacity \times Battery\ discharge) \div AAD\} \times 60 \quad (9)$$

where,

Battery capacity: Capacity of battery, expressed in ampere hours (Ah). For B1 – 3300mAh or 3.3Ah and B2 – 6000mAh or 6 Ah (see Table 4)

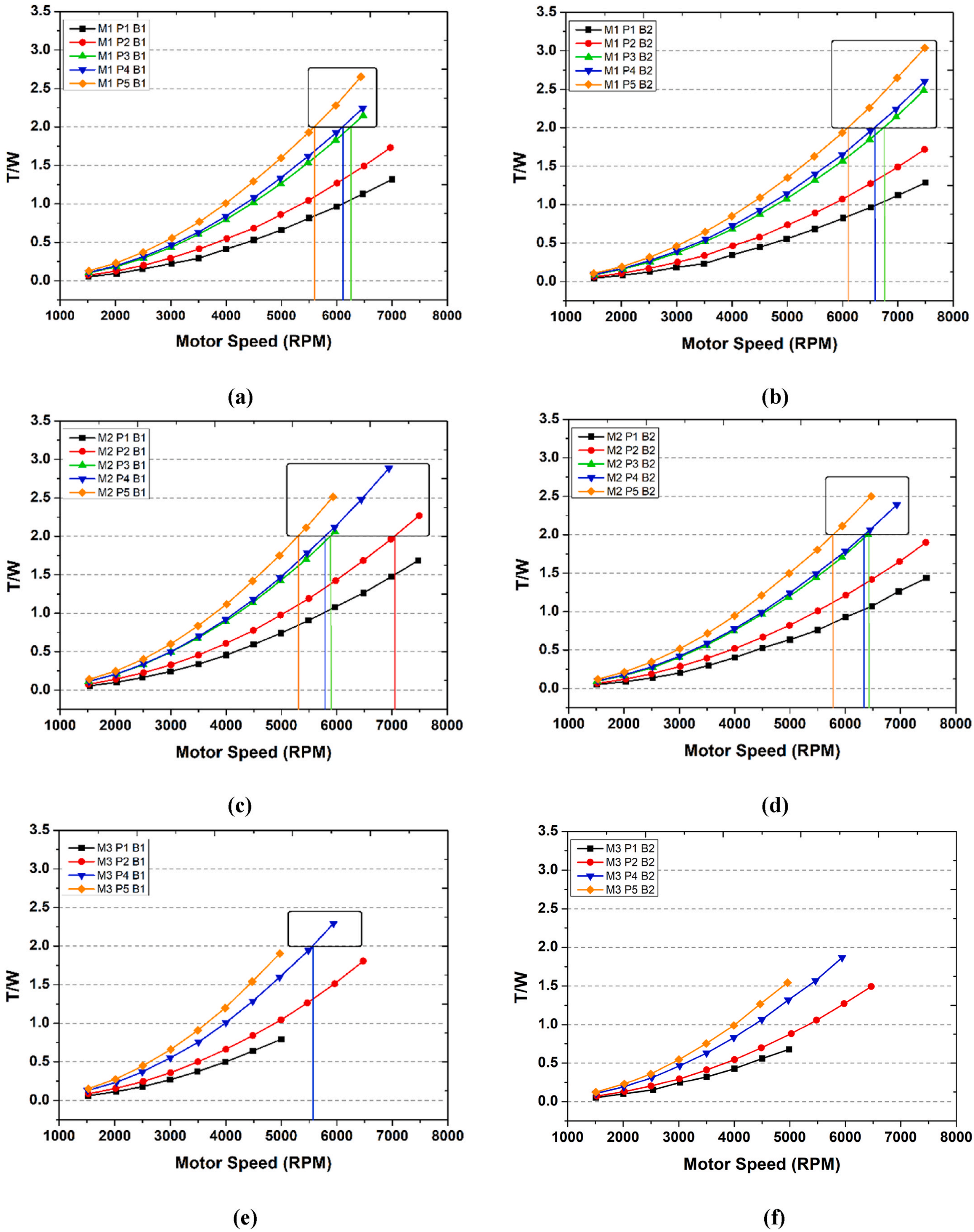


Fig. 12. Thrust to weight ratio for (a–b) M1 with B1 and B2, (c–d) M2 with B1 and B2, and (e–f) M3 with B1 and B2.

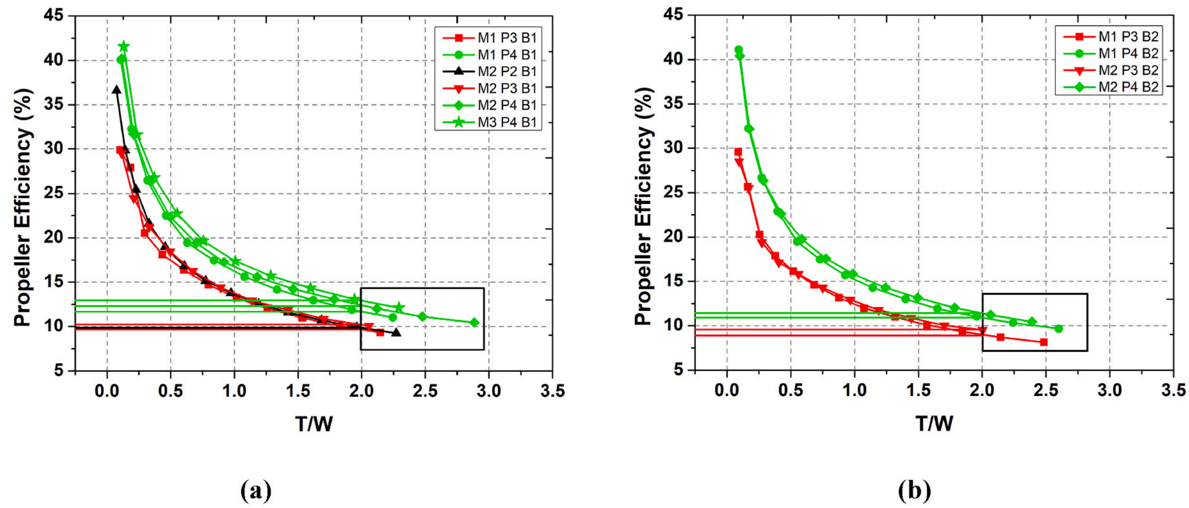


Fig. 13. Propeller Efficiency in percentage for the selected motor-propeller-battery combination.

Table 13
Propeller Efficiency in percentage for battery B1 and B2 with motor-propeller combination.

B1			B2		
Case	Propeller Efficiency (%)	Propeller Efficiency achieved lower than maximum (%)	Case	Propeller Efficiency (%)	Propeller Efficiency achieved lower than maximum (%)
M1 P3 B1	9.6	25.581	**M1 P3 B2**	8.9	21.92982
M1 P4 B1	11.7	9.302	**M1 P4 B2**	10.8	5.263158
M2 P2 B1	9.8	24.031	**M2 P3 B2**	9.5	16.66667
M2 P3 B1	10.1	21.705	**M2 P4 B2**	11.4	0
M2 P4 B1	12.4	3.875	–	–	–
M3 P4 B1	12.9	0	–	–	–

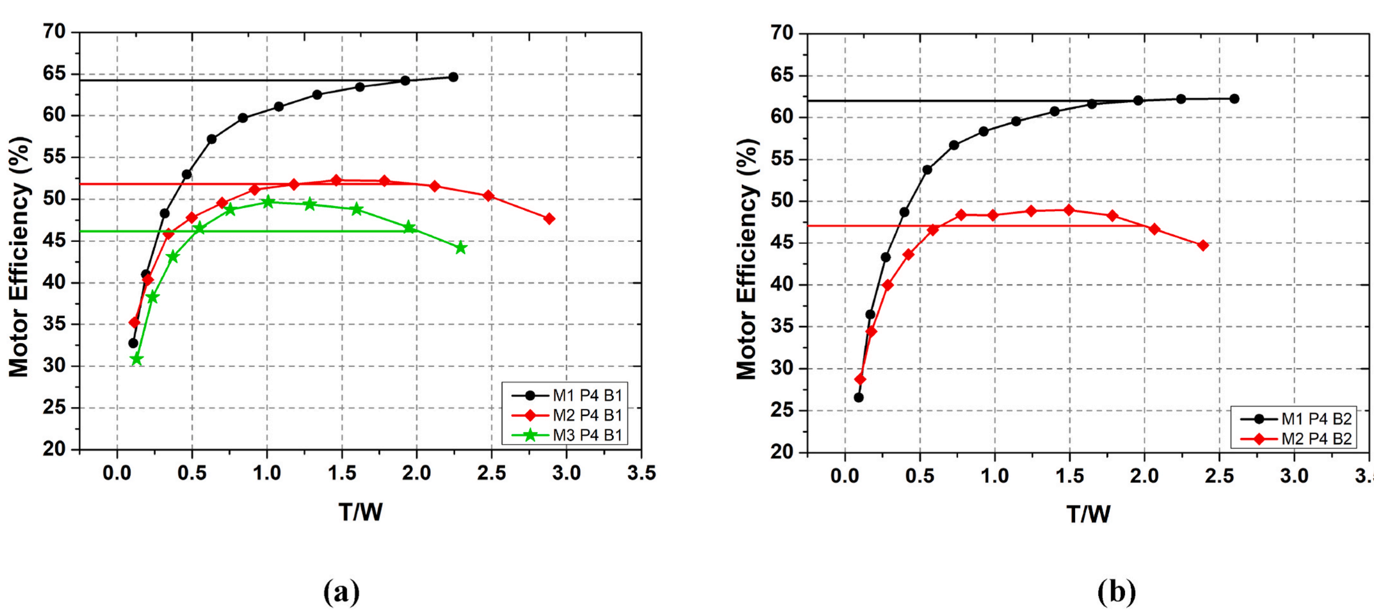


Fig. 14. Motor Efficiency in percentage for most efficient propeller P4 for battery (a) B1 and (b) B2.

Table 14
Motor Efficiency in percentage for battery B1 and B2 with propeller P4

P4B1		P4B2	
Motor	Motor Efficiency (%)	Motor	Motor Efficiency (%)
M1	64.285	**M1**	62.010
M2	51.802	**M2**	47.127
M3	46.228	–	–

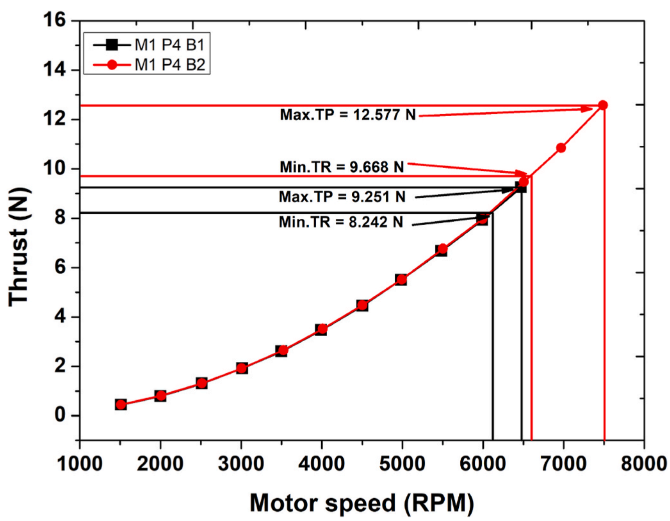


Fig. 15. Thrust required and thrust produced by most efficient motor and propeller for battery B1 and B2.

Battery discharge: Battery discharge allowed during the flight. As LiPo batteries can be damaged if fully discharged, it's common practice never to discharge them by more than limit. The limit can be estimated as, each cell in the battery has 4.2 V while it can be discharged until 3.3 V, so the battery discharge is $\frac{3.3}{4.2}$ is approximately equal to 0.78 or 78 %.

AAD: Average ampere draw by the multicopter, calculated in amperes.

To determine the quadcopter hover endurance, the battery capacity is known (Table 4), the battery capacity is 78 % (known), and the unknown parameter is ADD.

ADD is the current drawn by the motor at an RPM that allows the quadcopter to hover. Because the current study employs four motors, the thrust and current values derived from Figs. 4 and 5, respectively, are multiplied by four and shown in Fig. 17. The endurance has been estimated by substituting the values from Fig. 17 into Equation (9), and the results are shown in Fig. 18 and also reported in Table 17. The maximum endurance has been found to be 21.435 min and 14.778 min with B2 without and with payload, respectively.

If the payload is considered to be the battery, then endurance of the quadcopter can be increased based on the number of batteries it can accommodate. For M1P4B1, the maximum payload it can carry is 2.018 N while the battery weighs 2.618 N. As a result, the battery cannot be used as a payload. For M1P4B2, the maximum payload it can carry is 5.816 N and the battery weight is 5.472 N, thus one battery payload can be accommodated, and the endurance can be twice, which is approximately $14.778 \times 2 = 29.556$minutes. When the battery payload and maximum payload are subtracted, the result is 5.816 N–5.472 N = 0.344 N. Although it is small, it can be stated that M1P4B2 with two batteries can carry a 0.344 N payload and the flight time is 29.556 min.

Finally, it can be concluded that the most efficient propulsion system for quadcopter with 450 mm frame size is M1P4B2, which can carry a higher payload and has a longer endurance.

Table 16
Payload and MTOW for T/W = 2.

	Max. payload (N)	MTOW without payload (N)	MTOW with payload (N)
M1P4B1	2.018	16.484	18.502
M1P4B2	5.816	19.338	25.154

4. Conclusions

The present study was focused on investigating the efficient propulsion system (motor-propeller-battery combination) that would be beneficial to the designer/engineer to develop an efficient multicopter UAV. The study considered three motors, five propellers and two batteries. It was observed that regardless of battery capacity or motor type, the thrust and torque produced for a given RPM are identical. All parameters, including the ESC signal, current, power, thrust, and torque, are directly proportional to the size of the propeller. It was found that a higher capacity battery consumes less current and can attain higher RPMs to produce the required thrust force than a lower capacity battery. The descriptive approach for estimating weight was discussed. A detailed procedure to evaluate the most efficient motor and propeller was reported. The P4 propeller (12 inch in diameter) was found to achieve efficiency levels of 12.9 % when used with the B1 battery (3s, 3300 mAh) and 11.4 % when used with the B2 battery (4s, 6000 mAh). Similarly, the M1 motor (700 KV) was determined to exhibit efficiency levels of 64.29 % when used with the B1 battery and 62.01 % when used with the B2 battery. It was observed that the use of the B2 battery resulted in an increased payload capacity of 5.82 N, as opposed to 2.02 N when the B1 battery was used. Furthermore, greater endurance was noted when the B2 battery was used, with durations of 14.7 min and 21.4 min for scenarios with and without payload, respectively. In contrast, the B1 battery resulted endurance durations of 9.6 min and 11.1 min for scenarios with and without payload.

Data from present experiments is expected to be used for a wide range of purposes. The outcomes will provide designers with a sizable database that can be utilized to choose the best propulsion system for quadcopter, hexacopter, VTOL UAVs, etc. designs. Also, the data can be exploited to enhance design capabilities by studying the effect of propeller pitch and propeller spacing, co-axial and ducted propeller systems. Further, the outcomes could potentially be utilized to enhance the prediction techniques, such as computational fluid dynamics (CFD), control algorithms, and empirical or semi-empirical methods.

Table 15
Thrust, motor speed and MTOW for payload calculation.
(A) Payload calculation for battery B1

	Min. TR (N)	Max. TP (N)	TR (N) for 4 motors	TP (N) by 4 motors	RPM at TR	RPM at TP	RPM difference	MTOW
M1P4B1	8.242	9.251	32.968	37.004	6098	6472	374	16.484
M1P4B2	9.668	12.577	38.672	50.308	6580	7485	905	19.336

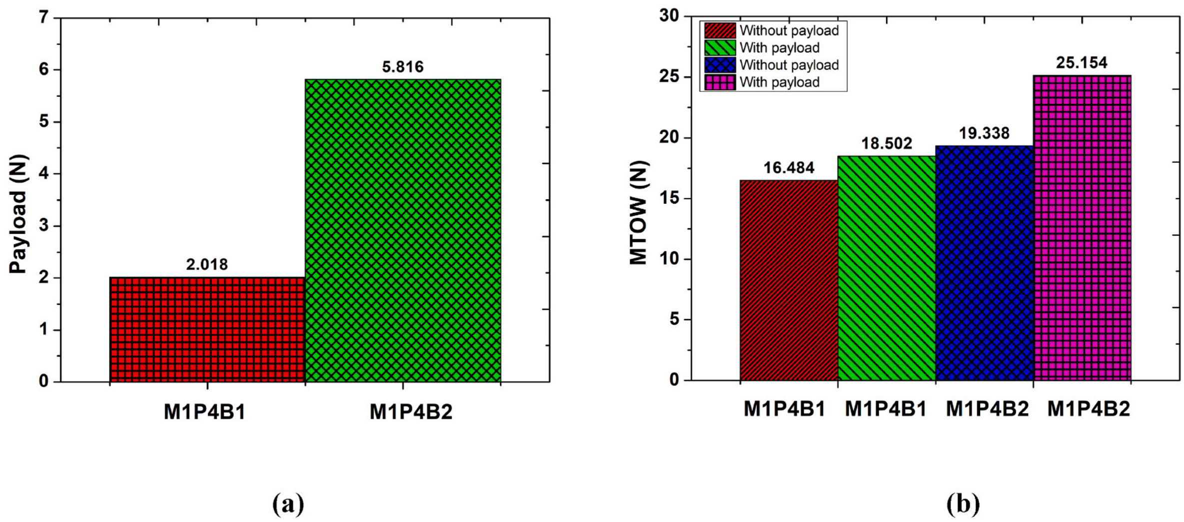


Fig. 16. Quadcopter (a) maximum payload and (b) maximum take-off weight (MTOW).

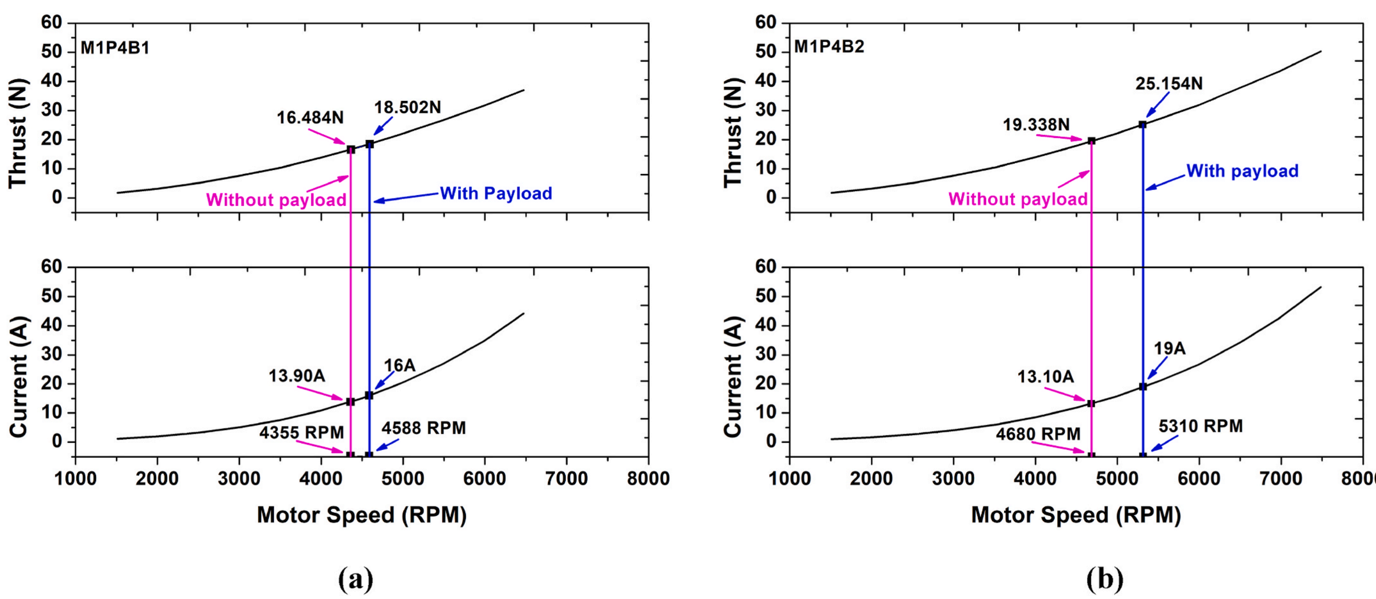


Fig. 17. Thrust and current requirements for without and with payload for (a) M1P4B1 and (b) M1P4B2.

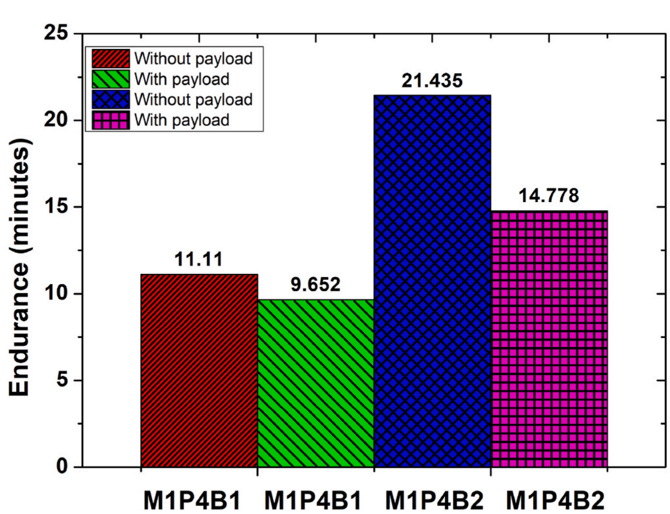


Fig. 18. Endurance of the quadcopter for without and with payload for battery B1 and B2 with most efficient motor M1 and propeller P4

Table 17
Endurance (minutes) for battery B1 and B2 with most efficient motor M1 and propeller P4

	Endurance (minutes)		
	Without payload	With payload	Battery as a payload
M1P4B1	11.110	9.652	NA
M1P4B2	21.435	14.778	29.556

Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

Data will be made available on request.

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