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Design and Experimental Evaluation of a Tilt-Angle Propeller Test Rig for Vertical Thrust Characterisation of the TRQ-1 Quadcopter

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ABSTRACT

This study presents the design and experimental evaluation of a custom-built test rig that was specially developed for vertical thrust measurement of the TRQ-1 quadcopter prototype, The test rig was designed to replicate the TRQ-1's tilt mechanism. The custom-built test rig enables accurate and repeatable thrust measurements under varying tilt-angles. In this work, a series of experiments were conducted using an APC 10×5 propeller to quantify vertical thrust at 0°, +15°, and -15° tilt-angles across a range of rotational speeds starting from 1500 RPM up to a maximum of 5500 RPM. Validation against available manufacturer thrust data confirmed the rig's measurement accuracy, and deviations from manufacturer thrust data were generally within ±5%, with a maximum deviation of 7.12% at low RPM (2010) and minimum deviation of 1.33% at higher RPM (3060–5010). These values confirmed the accuracy of the rig within acceptable engineering tolerances. The results indicated that a +15° forward tilt configuration consistently reduces vertical thrust due to thrust vector redirection. Meanwhile, the -15° rearward tilt configuration yielded a modest increase in vertical thrust, especially at lower RPMs range. These findings are consistent with aerodynamic theory, which highlights the trade-off between thrust vectoring for manoeuvrability and vertical lift performance. The proposed test rig demonstrates reliable performance and provides a consistent tool to evaluate the aerodynamic behaviour of tilt-propeller quadcopter configurations.

Keywords: Tilt-Angle Propeller; Vertical Thrust Measurement; Quadcopter Aerodynamics;Experimental Test Rig; Thrust Vectoring Mechanism

Nomenclature (Greek symbols towards the end)

Yp	Y-axis of the rotor frame
Zp	Z-axis of the rotor frame
Xp	X-axis of the rotor frame
T	Propeller thrust force (N)
F_{thrust}	Vertical thrust converted from $F_{contact}$ (N)
$F_{contact}$	Contact force measured by the weight scale (N)
d_{left}	the distance from the pivot point to the left-side displacement (m)
d_{right}	the distance from the pivot point to the right-side displacement (m)

Abbreviations

APC	Aeroplane Propeller Company
ESC	Electronic Speed Controller
TRQ-1	Tilt Rotor Quadcopter
RPM	Revolution Per Minute
ESC	Electronic Speed Controller
3D	3-Dimensional
SD	Standard deviation
SE	Standard error

1.0 INTRODUCTION

A tilt-angle propeller quadcopter drone utilizes the thrust vectoring concept to change its flight direction [1]. This ability allows the quadcopter drone to perform more agile and efficient flight maneuvers [2], [3]. Enabling this capability encourages the drone to move in different directions without additional control surfaces. Tilt propeller mechanism allows quadcopters to change the angle of their propellers during flight [4]. This mechanism

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enables them to change direction and maneuver more effectively. In practical application, the mechanism can improve the drone stability [1], [5] and agility in flight [6]. This feature enables the drone to perform complex aerial maneuvers and navigate precisely through various confined space environments. This also permits the drone to hover more steadily, fly faster, and perform complex maneuvers with greater accuracy. The mechanism is commonly controlled by the flight controller based on user input or pre-programmed flight paths [7]. It plays a significant role in enhancing the performance and versatility of quadcopters in different applications such as aerial photography, surveillance, and recreational flying.

Recent development in drone technology has addressed the challenges contributed by the tilt-angle propeller mechanism [8]. More research was focused in designing tilt systems with more robust and durable designs [9], [10]. Those research aimed to minimize the flight failure and reduce the maintenance requirements of these mechanisms. Integration of smart technology and sensors into the tilt systems mechanism has enhanced the drone stability and control to perform extreme control conditions [2], [10]. However, the technology enhancement with sensors can also make the drones prone to malfunctions or technical control issues [10]. Such issues may lead to potential safety concerns during flight. Despite its advantages in maneuvers, tilt-angle quadcopters with smart technology require complex tilting mechanisms for tilting the propellers which furthermore adds difficulties to the overall design and adds to the drone’s overall weight [11], [12].

Recent studies have highlighted the importance of specialized test rigs for propeller thrust evaluation in UAVs, especially when tilt mechanisms are involved. For example, Ismail et al. [13] proposed a Propeller Measurement Test Rig (PMTR) designed to capture static thrust of micro-propellers, emphasizing stability, simplicity, and adaptability for tilt-angle investigations. Similarly, Henwood [14] developed a multi-axis testing rig that allows propellers to be rotated within a wind tunnel, enabling thrust measurement at varying angles of attack, which is directly relevant to tilt-rotor aircraft studies. More recently, Liu et al. [15] designed a test bench to experimentally and numerically investigate tilt-angle effects on small-scale propellers in confined environments, showing how tilt alters thrust generation under ceiling proximity conditions. These efforts illustrate the growing interest in experimental rigs capable of simulating tilt-angle conditions, but many designs remain complex or laboratory-bound. In contrast, the present study introduces a simplified, lever-based test rig tailored to the TRQ-1 quadcopter, offering a practical solution for repeatable vertical thrust measurements at variable tilt-angles.

Based on the above issues, Tilt Rotor Quadcopter (TRQ-1) prototype (Fig. 1) was developed by Universiti Teknologi MARA to explore the drone design with simpler propeller tilting mechanism. The prototype was developed to explore the influence of tilt-angle propellers on drone lifting thrust (vertical thrust). The magnitude of vertical thrust or lifting thrust is very crucial for every quadcopter hovering performance [8], [16], therefore TRQ-1 design was developed to produce variable angles for various hovering flight conditions. The new tilting design mechanism is simple yet robust, durable and effective to produce variable effective tilted angle on TRQ-1. However, to understand the influence of this tilt-angle, a suitable experimental test rig must be developed to understand and determine the thrust magnitude for a single propeller at different tilt-angles. Thus, the main objective of current work is to propose a new test rig design to measure the vertical thrust produced by single propeller at different tilt-angles for the TRQ-1 prototype. The tilt mechanism for the test rig was maintained similar to the TRQ-1 platform to ensure identical conditions between them. The rig was developed through rapid prototyping methods by using 3D printing technology and integrated with standard micro size propeller of APC 10 x 5. To verify the thrust outcome, the vertical thrust results produced by the test rig were compared with available data from manufacturers for validation purpose.

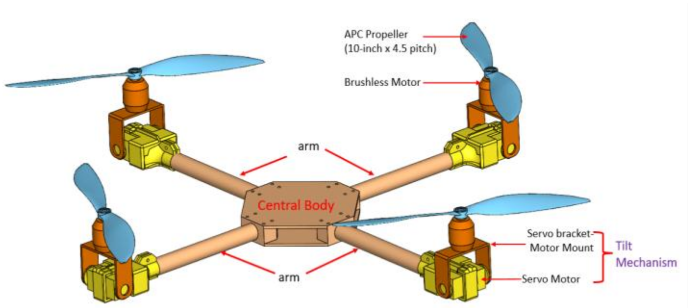

Figure 1.TRQ-1 quadcopter drone prototype.

2.0 METHODOLOGY

2.1 TRQ-1 Prototype Design

The TRQ-1 prototype (Fig. 1) has a sophisticated design with advanced tilt mechanisms that propose to improve the quadcopter maneuverability and its performance efficiency. The TRQ-1 quadcopter prototype shares common features with four propellers located at each arm. The prototype arms are made from a lightweight material that extends from the central body. Each arm supports one propeller and is associated with a tilt-angle mechanism. The tilt-angle mechanism allows each propeller to change the vertical thrust direction which permits thrust vectoring and alter hovering maneuvers. Each tilt-angle mechanism is controlled by a single servo motor and mounted in a 3D printed servo bracket-motor mount located at each arm end. The tilt-angle mechanisms are specially designed to ensure robust and durable thrust vectoring movement.

The introduction of tilt-angle mechanism (thrust vectoring) on TRQ-1 can enhance its lift generation and its maneuverability. The thrust vector mechanism induces optimal thrust direction which is more effective in generating lift and beneficial during vertical takeoff or hovering conditions. The tilt mechanism permits real-time adjustments during flights, especially under the influence of external forces such as wind or turbulence [6]. It can maintain the optimal lift needed to stabilize the TRQ-1 during hover flight.

2.2 The Working Principle Of Tilt-Angle Mechanism

Fig. 2 shows the working principle of the tilt-angle mechanism on TRQ-1. The tilt-angle mechanism has servo bracket-motor mount, servo mount and servo motor components which are connected to the propeller and brushless motor. The mechanism is assembled at the end of the arm structure. The working principle behind this mechanism is to rotate the servo bracket-motor mount assembly around the Yp axis of the rotor frame (shown in Fig. 2). The rotational movement starts with the input control (by user transmitter) to control the servo motor rotation. This rotational movement transmits to the servo bracket-motor mount to rotate on its Yp axis according to the servo rotation. The servo bracket-motor mount that holds the motor-propeller translates the rotational movement into the propeller's thrust vector angle orientation known as propeller’s tilt-angle as shown in Fig, 3. In the current study, propeller’s tilt-angle is set between -15˚ to +15˚ range, measured from its neutral (0˚) position. This is to avoid the collision between the propeller and the drone arm if negative angle rotation exceeds the -15˚ angle.

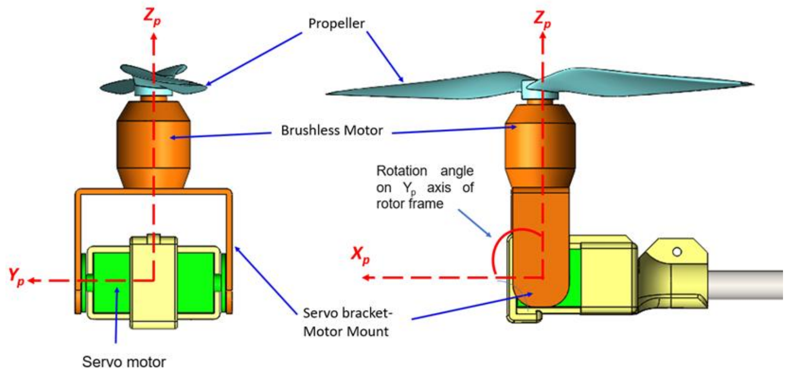

Figure 2. The tilt-angle mechanism components and rotational angle.

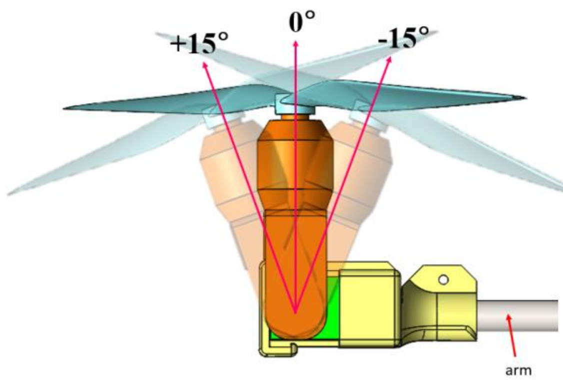

Figure 3. Propeller’s tilt-angle.

2.3 The Custom Test Rig Design

Fig. 4 shows the custom test rig design to measure vertical thrust force generated for TRQ-1. The rig consists of several components such as a rig base, fulcrum leg, fulcrum swing, vertical connector, balancer (counterweight), vertical rod, arm (rod), tilt mechanism and weight scale to measure the thrust force generated by the propeller. The test rig uses the same components found on TRQ-1 for the tilt mechanism which mounts the propeller and brushless motor. The identical components are important to ensure movement and changes in the tilt-angle of thrust are similar between the TRQ-1 and the test rig. The components all work together in a cohesive system to translate the mechanical energy produced by the propeller into readable data. The detailed dimensions of this test rig are shown in Fig, 5 in unit m.

2.4 Test Rig's Working Principle

Fig. 6 shows the working principle of the test rig. The rig adopts the lever mechanism and a pivot point to translate the thrust force produced by the propeller into measurable force readings data. As the motor drives the propeller, the resulting thrust force produces an upward movement on the right-side of the rig. Thus, it creates a vertical displacement on the right side as illustrated in Fig. 6. This right-side arm displacement is transferred to the left side as displacement due to the pivot mechanism at the fulcrum swing. The downward displacement on the left side creates a vertical movement of a vertical rod and contact with the weight scale. The weight scale measured this as contact force in gram-force units, representing the thrust force generated by the propeller.

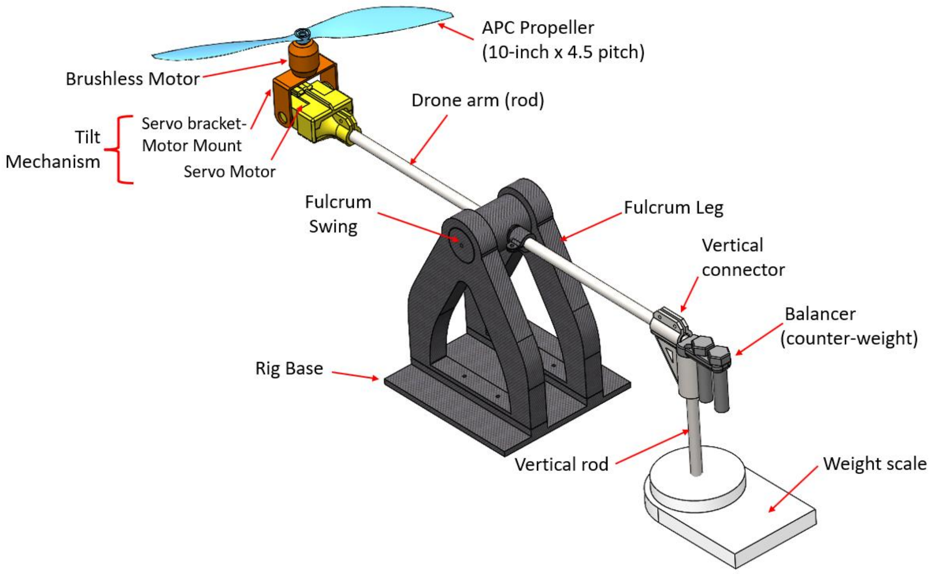

Figure 4. Custom test rig to measure vertical thrust force generated for TRQ-1

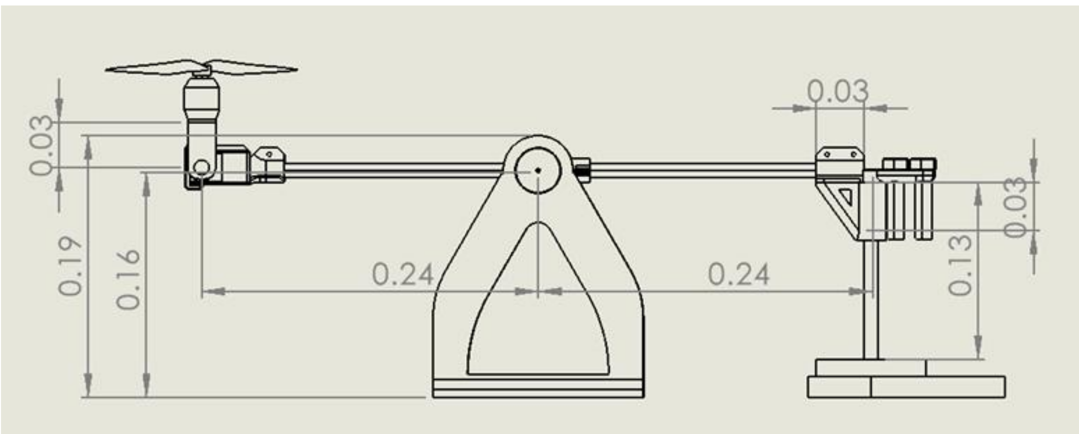

Figure 5. Custom test rig dimensions in unit meters.

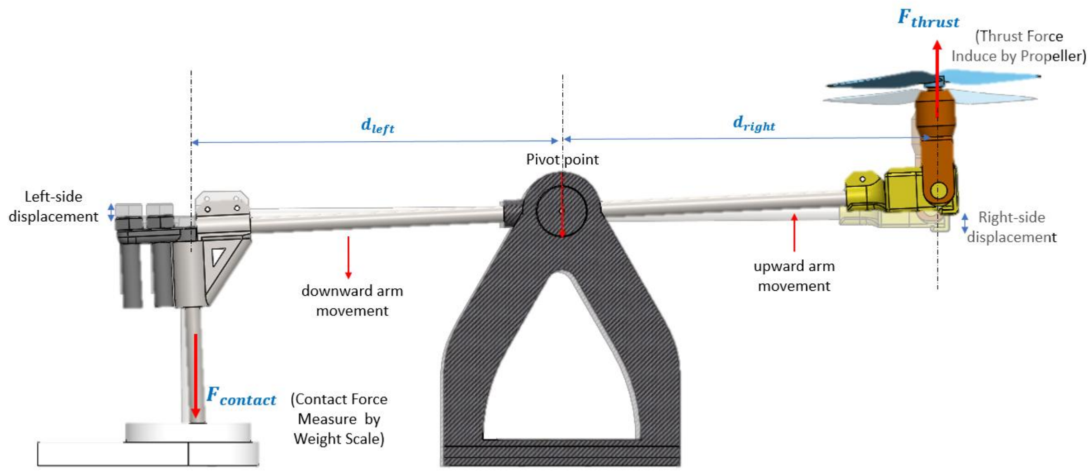

Figure 6. Working principle of the test rig.

Based on the equilibrium principle of moment applied at the pivot point, the thrust force, F_{thrust} is calculated using Equation 1:

$$F_{thrust} = \frac{F_{contact} \times d_{right}}{d_{left}} \tag{1}$$

where $F_{contact}$ is the contact force measured by the weight scale, d_{left} is the distance from the pivot point to the left-side displacement, and d_{right} is the distance from the pivot point to the right-side displacement. According to Fig. 6, d_{left} is the distance equal to d_{right}= 0.24 m. Thus, thrust force, F_{thrust} is equal to $F_{contact}$ as shown in Equation 2:

$$F_{thrust} = F_{contact} \tag{2}$$

2.5 The Test Rig Setup

The fabricated test rig (shown in Fig. 7) closely resembles the 3D design of the test rig (shown in Fig. 4) in terms of component arrangement and functionality. Important elements such as the propeller and motor assembly, tilt mechanism, fulcrum and swing, drone arm (rod), base structure, vertical rod, weight scale, and balancer are consistent between the two. To ensure the rig is ready for use, additional shelf electronic equipment is used such as the digital weight scale, tachometer, Flysky remote control transmitter- receiver, 20kg dual shaft digital servo, 30A electric speed controller (ESC), and 4s 5200mAh 60c battery. The battery ensures that the rig can operate independently of external power sources, providing flexibility in testing locations and conditions. The tachometer and ESC enable accurate RPM readings and provide fine control over the motor speed at specific RPMs, respectively. The remote-control transmitter-receiver is used here to control the servo movement and rotational speed on the brushless motor to imitate TRQ-1 conditions. A standard digital weight scale is used to measure the contact force in grams unit. The digital weight scale has a resolution of 0.1g, a sensitivity of ±0.05 g, and a measurement range of 0kg to 1 kg.

The test rig is fabricated based on standard 3D printing process. Carbon material is used as the rod component that connects the brushless motor assembly to the fulcrum swing. Meanwhile, the on shelf brushless motor (1000kV) and APC propeller (10-inch x 5 pitch) are used to emulate the actual TRQ-1 configurations.

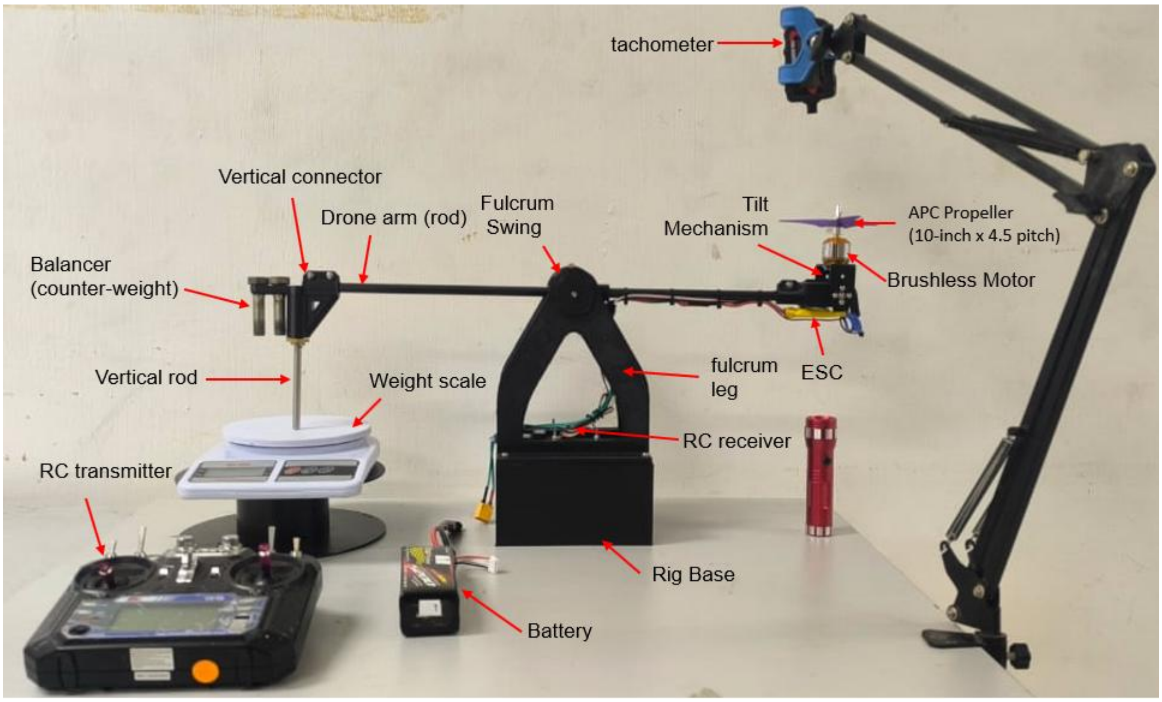

Figure 7. Fabricated test rig.

2.6 The experimental procedure

The test process began with the setup of the battery to power the test rig. Then, the RC transmitter was activated and used to adjust the propeller tilt-angle. A digital tilt-angle measurement device was employed to verify and validate the accuracy of the tilt-angle settings. Initially, the propeller was set to a neutral or baseline position at 0°. Subsequently, the tilt-angle was systematically adjusted to -15° and +15° for further testing. The thrust measurements were taken at various throttle settings, starting from 1500 RPM and incrementally increasing by 500 RPM until reaching the maximum of 5500 RPM. At each throttle setting, the thrust force generated by the propeller was recorded using a weight scale, which measured the contact force in grams. Each experimental condition was repeated three times to ensure data reliability and minimize random errors. Standard deviation and standard error were calculated for each set of measurements for robustness of the data collection.

3.0 RESULTS AND DISCUSSION

3.1 Validation With Manufacturer Data

The validation results are illustrated in Fig. 8, which shows the measured thrust compared to available manufacturer thrust data [17] for the APC 10x5 propeller, that is also used as main propeller for TRQ-1. This comparison is essential to assess the measurement precision of the test rig, particularly to capture thrust variations across a range of rotational speeds (RPM).

The validation involved subjecting the test rig to controlled experiments, where the propeller's RPM was rotated specifically for validation at 2010, 3060, 4020, and 5010 RPM. This is to correlate exactly with the available manufacturer thrust data. The measured thrust values from test rig were obtained and repeated across three trials to ensure statistical reliability. Standard deviation (SD =0.0113 N) and error analysis (SE=2.0873%) were also applied to quantify measurement uncertainty.

The data showed that at 2010 RPM, the test rig measured a thrust force 7.12% lower than the manufacturer's value, indicating a potential underestimation at lower RPMs. In contrast, at higher RPMs (3060 to 5010), the rig consistently recorded slightly higher values, with deviations ranging between 1.33% and 4.98%. These data variations can be attributed to multiple factors such as temperature, air pressure, and mechanical vibration which may differ from the controlled laboratory settings used by the manufacturer. The mechanical lever system in the rig setup may also introduce slight mechanical damping or transient delay in force transmission, especially at lower RPMs. Despite the data discrepancies found in this validation works, the rig affirms its reliability and accuracy for measuring propeller thrust across certain operational RPMs. The data validation discrepancies fell within acceptable tolerances which are below 5%.

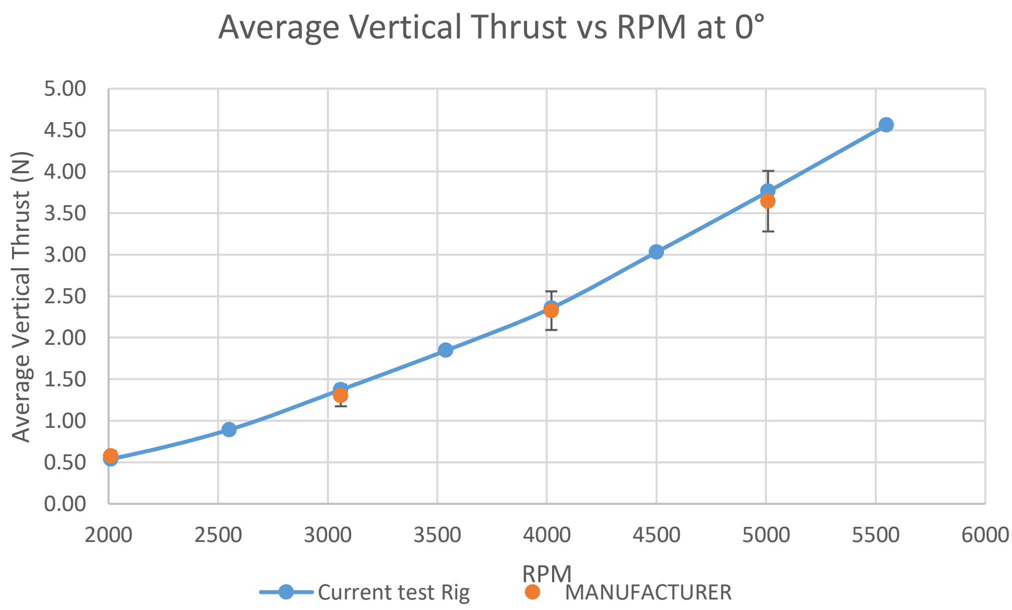

Figure 8. Thrust validation results for the APC 10x5 propeller.

3.2 Thrust Data At 0° Configuration

The experimental thrust data obtained at a fixed tilt-angle of 0° is shown in Table 1. The data served as a baseline to evaluate the performance of the TRQ-1 propeller system. The measurements revealed a clear and consistent increase in vertical lift force with rising propeller rotational speed (RPM). This trend demonstrates the expected aerodynamic performance of a propeller. At the lowest RPM of 1500, the lift force was measured between 0.3012 N and 0.3237 N. As the RPM magnitude increased to 3060, thrust force magnitude rose substantially to 1.3734 N. At maximum RPM of 5550, the thrust value peaked at around 4.5813 N. This steady and nonlinear increase in lift aligns with the theoretical quadratic relationship between thrust and RPM [12], which suggests that the system operates efficiently across a wide speed range.

The data also indicated that the test rig sensitivity was most pronounced at lower RPMs (from 1500 to 2010 RPM). The relative percentage increase in thrust indicated high responsiveness to this lower operating range. As the RPM increased, the rate of change in vertical thrust became more gradual. This behaviour is common for propeller systems which reflects the aerodynamic and mechanical properties of the thrust generation process.

To assess the reliability of the measurements, standard deviation (SD) and standard error (SE) were calculated across all RPM levels. The SD values were consistently low, ranging from 0.0084 N to 0.0204 N, indicating high repeatability across the three trials conducted per RPM setting. Additionally, the percentage of standard error decreased by increasing RPM, dropping from 2.0873% (at 1500 RPM) to only 0.1509% at 5550 RPM. This trend indicated that measurement uncertainty is inversely proportional to the vertical thrust magnitude, thereby confirming improved precision at higher speeds. The reduction in SE suggested that the experimental rig exhibits less variability under higher dynamic loads, likely due to increased mechanical stability and reduced sensitivity to environmental perturbation.

The consistency of the measurements was further validated by the small variance between repeated trials. For instance, at 3540 RPM, the weight readings were 186.0 g, 187.5 g, and 188.2 g, producing nearly identical vertical thrust force values with a standard deviation of just 0.0110 N. Such consistency across trials reinforces the robustness of the test rig, including its mechanical design and integrated electronic systems. The performance of the scale, electronic speed controller, and brushless motor under repeated use indicates the system's effectiveness in capturing accurate vertical thrust data under standardized conditions.

In conclusion, the thrust measurements at 0° provided a reliable reference for understanding the performance characteristics of the TRQ-1 propeller system. The results demonstrated that the test rig produces consistent and accurate vertical thrust data, particularly at mid to high RPM ranges, where precision is critical for vertical flight and hovering applications. These findings establish the foundation for evaluating the influence of tilt-angle on vertical thrust, which is addressed in subsequent sections.

Table 1: Vertical Thrust Data at 0° configuration

RPM	Weight scale reading (g)			Converted Value for Vertical Thrust Force (N)			Standard Deviation	Standard Error (%)
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3		
1500	32.0	30.7	33.0	0.3139	0.3012	0.3237	0.0113	2.0873
2010	58.0	57.0	55.0	0.5690	0.5592	0.5396	0.0150	1.5563
2550	93.0	92.0	90.9	0.9123	0.9025	0.8917	0.0103	0.6594
3060	137.0	136.0	140.0	1.3440	1.3342	1.3734	0.0204	0.8730
3540	186.0	187.5	188.2	1.8247	1.8394	1.8462	0.0110	0.3466
4020	242.0	241.0	240.3	2.3740	2.3642	2.3573	0.0084	0.2046
4500	307.0	306.8	309.0	3.0117	3.0097	3.0313	0.0119	0.2283
5010	381.0	381.9	383.5	3.7376	3.7464	3.7621	0.0124	0.1913
5550	467.0	464.8	465.0	4.5813	4.5597	4.5617	0.0119	0.1509

3.3 Thrust Data At +15° Configuration

The vertical thrust performance of the TRQ-1 propeller system at a +15° tilt-angle was evaluated to assess the effect of forward propeller inclination on vertical thrust generation. The experimental result for this configuration is plotted in Fig. 9. The +15° tilt-angle result demonstrated a clear dependence of vertical thrust on rotational speed (RPM) and showed comparative basis against the 0° tilt configuration. For the purpose of analysis, the RPM range was categorized into three distinct regions: low RPM (1500–2520 RPM), mid RPM (3000–4020 RPM), and high RPM (4500–5520 RPM).

In the low RPM range (1500–2520 RPM), the average vertical thrust measured at +15° ranged from 0.26 N to 0.84 N. Compared to the corresponding 0° case, where the average thrust values ranged from 0.31 N to 0.90 N, a reduction of approximately 18% to 7% in vertical thrust was observed. This reduction is attributable to the vectoring effect, where part of the thrust is redirected horizontally due to the forward tilt [18], resulting in a diminished vertical force component.

In the mid RPM range (3000–4020 RPM), average vertical thrust values at +15° increased from 1.22 N to 2.22 N. Compared to the 0° tilt results of 1.35 N to 2.37 N, this corresponds to a vertical thrust reduction of approximately between 9.8% to 6.3%. The percentage difference narrows as RPM increases, which is consistent with the aerodynamic expectation that the effect of tilt-angle on vertical thrust becomes less pronounced at higher airflow velocities [19], owing to the non-linear relationship between thrust and RPM.

For the high RPM range (4500–5520 RPM), the measured vertical thrust at +15° increased from 2.85 N to 4.40 N. In comparison, the 0° tilt configuration produced average vertical thrust values ranging from 3.02 N to 4.57 N. This reflects a thrust reduction of approximately 5.7% at 4500 RPM, decreasing to 3.6% at 5520 RPM. The results suggest that at high RPMs, the system partially compensates for tilt-induced thrust losses, yet vertical lift remains consistently lower than in the 0° configuration.

The reliability of the measurements at +15° was confirmed through analysis of the standard deviation and standard error as shown in Table 2. Across all RPM ranges, standard deviation values remained below 0.024 N, with the standard error percentage decreasing as RPM increased. Specifically, at low RPM, standard error values ranged from 1.75% to 1.64%, while at mid RPM, values reduced to below 0.48%, and at high RPM, they reached as low as 0.09% at 5040 RPM. These results indicate high precision and repeatability of the test rig, particularly at mid to high RPMs where thrust generation is most stable.

Overall, the observed reduction in vertical thrust at +15° tilt is consistent with theoretical expectations related to thrust vector redirection. The magnitude of thrust loss varies with RPM, with greater reductions evident at low speeds but diminishes at higher rotational velocities [20].

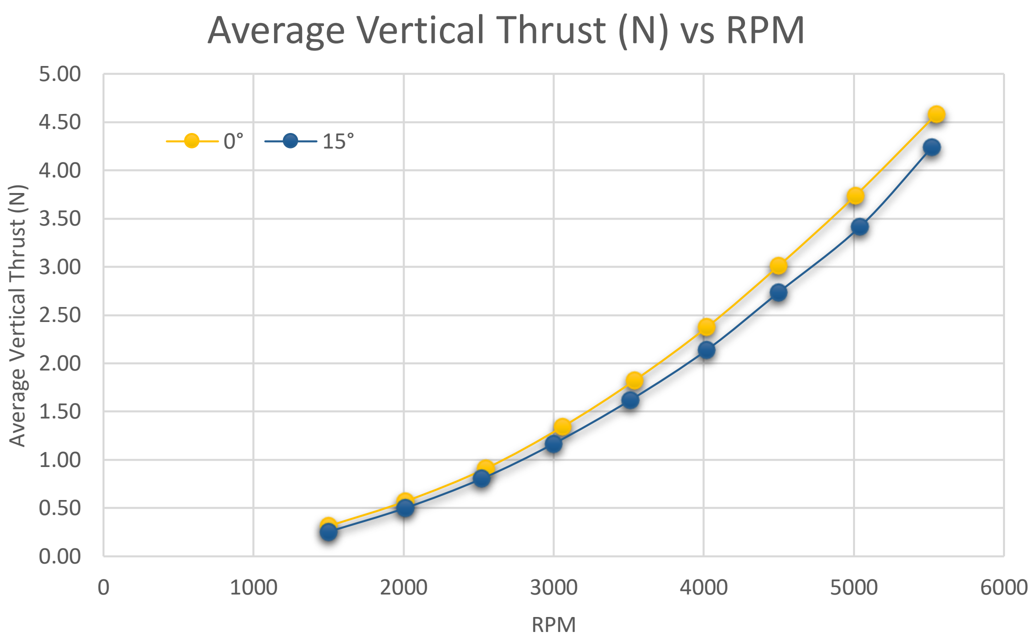

Figure 9. Vertical Thrust Data at +15° configuration

Table 2: Vertical Thrust Data at +15° configuration

RPM	Weight scale reading (g)			Converted Value for Vertical Thrust Force (N)			Standard Deviation	Standard Error (%)
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3		
1500	26.0	24.5	25.0	0.2641	0.2488	0.2539	0.0078	1.7522
2010	51.0	50.9	53.7	0.5180	0.5170	0.5454	0.0161	1.7682
2520	82.0	85.2	80.6	0.8328	0.8653	0.8186	0.0239	1.6481
3000	119.0	120.0	121.0	1.2086	1.2188	1.2289	0.0102	0.4811
3510	165.0	165.0	166.0	1.6758	1.6758	1.6860	0.0059	0.2016
4020	218.0	217.2	219.3	2.2141	2.2060	2.2273	0.0108	0.2805
4500	279.0	280.6	281.1	2.8336	2.8499	2.8549	0.0111	0.2260
5040	348.0	349.0	348.9	3.5344	3.5446	3.5435	0.0056	0.0912
5520	432.0	433.0	435.0	4.3875	4.3977	4.4180	0.0155	0.2035

3.3 Thrust Data At -15° Configuration

The thrust performance of the TRQ-1 propeller system under a -15° tilt configuration was evaluated to assess the effect of rearward propeller inclination on vertical lift generation. The experimental result for this configuration is plotted in Figure 10. Similar with the previous section, RPM values were classified into low (1500–2520 RPM), mid (3000–4020 RPM), and high (4500–5520 RPM) ranges for analytic comparison.

In the low RPM range (1500–2520 RPM), vertical thrust values at -15° increased from 0.34 N to 0.92 N. Compared to the 0° tilt results of 0.31 N to 0.90 N, this represents an approximate 9.0% to 2.4% increase in vertical thrust. The enhancement, though modest at these lower rotational speeds, suggests that rearward tilt marginally improves the effective vertical thrust vector, likely due to improved alignment of airflow with the desired lift direction.

For the mid RPM range (3000–4020 RPM), thrust at -15° increased from 1.34 N to 2.38 N, while the corresponding 0° configuration produced thrust values from 1.35 N to 2.37 N. The observed increase in vertical thrust was between 5.13% and 0.48%, indicating a continued but diminishing performance gain as RPM increased. This trend aligns with aerodynamic principles, wherein the influence of tilt-angle on thrust direction becomes less significant at higher airflow momentum.

In the high RPM range (4500–5520 RPM), thrust measurements at -15° ranged from 3.02 N to 4.62 N. Compared to the 0° tilt case with thrust values of 3.02 N to 4.57 N, the -15° tilt configuration resulted in a slight performance advantage at the upper RPM limit. At 5520 RPM, vertical thrust at -15° exceeded the 0° case by approximately 1.1%, whereas at 4500 RPM, vertical thrust remained approximately 0.10% lower than at 0°, indicating that the benefit of rearward tilt becomes more apparent at maximum rotational speeds but is not uniformly distributed across the high RPM range.

The reliability of the thrust measurements at -15° was confirmed through low standard deviation and standard error values as shown in Table 3. Across all RPM ranges, standard deviations were generally below 0.018 N, with standard error percentages decreasing consistently with increasing RPM. In the low RPM range, standard error values ranged from 1.79% to 0.58%, reducing to below 0.46% in the mid RPM range, and reaching 0.33% at 5520 RPM, reflecting high measurement precision and consistent repeatability at higher operational speeds.

The results suggest that a rearward tilt of -15° offers a marginal improvement in vertical lift, particularly at low RPMs, supporting the hypothesis that backward inclination may optimize lift generation under certain flight conditions. This outcome is consistent with prior studies on propeller vectoring, which reported that slight negative tilt-angles can enhance stability and hovering performance by maximizing vertical thrust alignment. However, the magnitude of improvement remains limited, and the practical benefits must be weighed against potential reductions in manoeuvrability associated with rearward tilt [1], [8].

In summary, the -15° tilt configuration demonstrates a measurable, though modest, enhancement in vertical thrust, particularly at higher RPMs. The results are coherent with aerodynamic expectations and provide empirical evidence to support design considerations for tilt-propeller drones where optimized lift is prioritized.

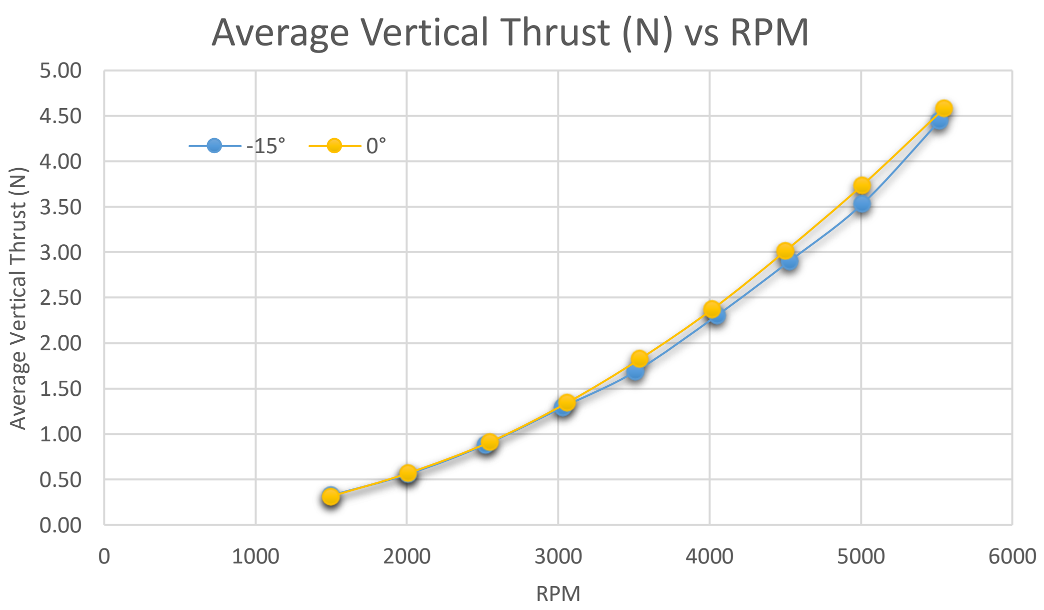

Figure 10. Vertical thrust data at -15° configuration

Table 3: Vertical Thrust Data at +15° configuration

RPM	Weight scale reading (g)			Converted Value for Vertical Thrust Force (N)			Standard Deviation	Standard Error (%)
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3		
1500	33.0	33.0	34.8	0.3352	0.3352	0.3534	0.0106	1.7857
2010	57.0	59.0	60.0	0.5789	0.5992	0.6094	0.0155	1.5033
2520	90.0	91.2	91.8	0.9141	0.9263	0.9324	0.0093	0.5815
3030	132.0	133.0	130.9	1.3406	1.3508	1.3295	0.0107	0.4595
3510	172.0	170.8	171.9	1.7469	1.7347	1.7459	0.0068	0.2241
4050	235.0	235.0	232.0	2.3867	2.3867	2.3563	0.0176	0.4274
4530	296.0	297.0	299.1	3.0063	3.0164	3.0378	0.0161	0.3072
5010	360.0	358.9	361.2	3.6563	3.6451	3.6685	0.0117	0.1845
5520	453.0	454.0	458.0	4.6008	4.6110	4.6516	0.0269	0.3357

3.3 Thrust Data At -15° vs -15° Configuration

The comparative assessment of thrust performance for +15°, 0°, and -15° tilt configurations is shown in Fig. 11. Analysis across low, mid, and high RPM ranges highlighted the distinct aerodynamic influence of propeller tilt on vertical thrust generation.

In the low RPM range (1500–2520 RPM), both +15° and -15° configurations exhibited measurable deviations from the baseline 0° results. The +15° tilt consistently reduces vertical thrust due to the forward redirection of the thrust vector, whereas the -15° configuration yields a modest improvement in vertical thrust, consistent with enhanced alignment of the propeller's airflow with the vertical axis. The percentage difference between +15° and -15° configurations ranged from approximately 25.1% at 1500 RPM, decreasing to 9.2% at 2520 RPM, indicating a diminishing relative advantage for rearward tilt as RPM increases within this range.

For the mid RPM range (3000–4020 RPM), the influence of tilt-angle on vertical thrust became less pronounced but remained observable. At these speeds, aerodynamic momentum partially mitigates the thrust losses associated with forward tilt and limits the performance gain of rearward tilt. The percentage difference in vertical thrust between the +15° and -15° configurations narrowed further, ranging from approximately 9.1% to 3.6%, suggesting that tilt-induced effects are reduced at moderate operating speeds.

In the high RPM range (4500–5520 RPM), the performance trends exhibited a more complex interaction between tilt-angle and thrust generation. The data indicated that at 4500 RPM, the +15° configuration produced significantly lower vertical thrust than both the 0° and -15° cases, with the percentage difference between +15° and -15° exceeding 5.7%, underscoring the pronounced impact of forward tilt at this operating point. However, as RPM increased to 5520 RPM, the disparity between +15° and -15° configurations reduced to approximately 4.8%. This aligns with aerodynamic observations showing that at high rotational speeds, the increase in overall thrust partly compensates for the losses caused by thrust vectoring.

These findings suggest that the aerodynamic influence of tilt-angle on vertical thrust is most significant at low to moderate RPMs. In this region, thrust vector orientation directly affects lift performance. However, its relative influence diminishes as total thrust increases [21].The results further indicate that rearward tilt provides a measurable advantage in vertical thrust force, particularly at low RPMs. Conversely, forward tilt consistently reduces vertical thrust across all operating ranges. These trends align with previous studies on thrust vectoring mechanisms, which show similar trade-offs between lift generation and directional control [22].

The comparative analysis confirms that careful consideration of tilt-angle is essential to optimize quadcopter performance. Forward tilt may enhance horizontal manoeuvrability but comes at the expense of vertical lift. In contrast, rearward tilt improves lift capacity, potentially benefiting hover and ascent operations. Future work should extend these findings to multi-propeller configurations and in-flight assessments to fully characterize the dynamic implications of tilt-angle on drone stability and control.

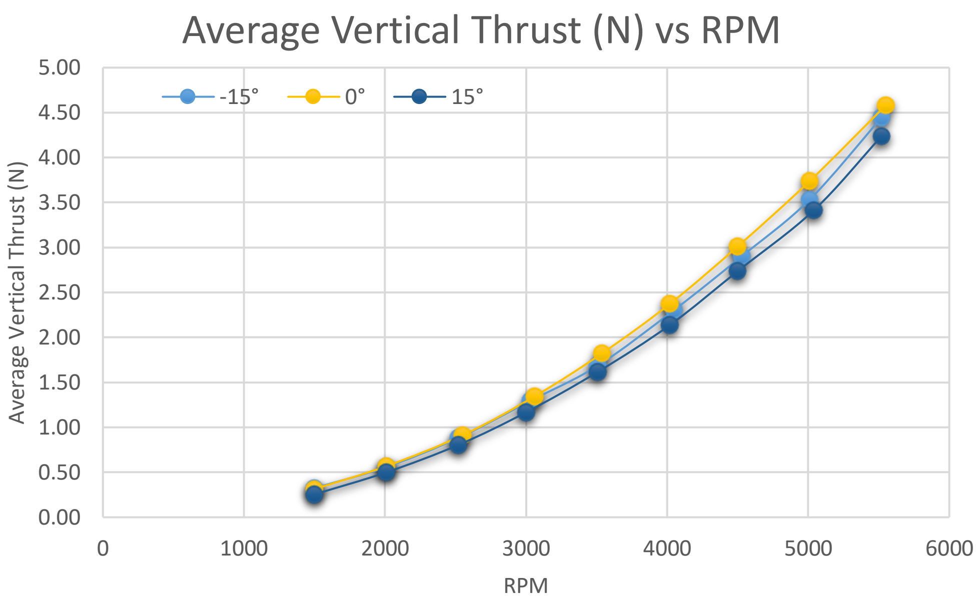

Figure 11. Vertical thrust data comparison between -15°, +15° and -0° configuration

4.0 CONCLUSION

This study presents the design, fabrication, and experimental evaluation of a novel test rig developed for vertical thrust measurement of the TRQ-1 quadcopter which is equipped with a tilt-angle propeller mechanism. The primary research objective was to propose and validate a simplified, robust test rig capable of accurately quantifying vertical thrust under varying propeller tilt-angles. The study simulates the actual operating conditions of the TRQ-1 platform.

The experimental results confirm that the test rig demonstrates high measurement reliability and precision across all tested RPM ranges. Validation against available manufacturer data for the APC 10×5 propeller indicates that the test rig produces thrust measurements within acceptable tolerances, with deviations generally below 5%. This outcome affirms the test rig's suitability for reliable thrust evaluation.

Further analysis reveals that propeller tilt-angle significantly influences vertical thrust performance. A +15° forward tilt consistently reduces vertical thrust, particularly at low and mid RPM ranges, attributed to thrust vector redirection. In contrast, a -15° rearward tilt yields a modest enhancement in vertical thrust, most pronounced at low RPMs, consistent with improved alignment of the thrust vector with the vertical axis. These findings are coherent with established aerodynamic theory and previous studies of tilt-propeller systems.

Overall, the proposed test rig provides a practical and effective solution for evaluating the impact of propeller tilt-angles on vertical thrust in quadcopter applications. The results provide valuable data to inform the design and control strategies of tilt-propeller drones, particularly for optimizing hovering performance and stability. Future work should extend this investigation to dynamic in-flight conditions and multi-propeller configurations to further validate and enhance the applicability of the proposed system.

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DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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