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DEVELOPMENT AND PRELIMINARY CHARACTERISATION OF A MULTI-ORIENTATION PROPELLER TEST BENCH FOR STATIC THRUST-VECTOR MEASUREMENT IN TILT-CAPABLE UAV APPLICATIONS

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ABSTRAK

Studi ini mengembangkan dan secara preliminier mengkarakterisasi bangku uji baling-baling multi-orientasi berbiaya rendah untuk pengukuran vektor dorong statis yang relevan dengan penelitian propulsi kendaraan udara tak berawak (UAV) yang mampu miring. Platform ini menggabungkan mekanisme kemiringan 0-90 derajat yang digerakkan servo, unit akuisisi data Arduino Uno, instrumentasi sel beban nominal 1 kgf dengan pengkondisian HX711, sensor orientasi MPU6050, pemantauan RPM, dan pengukur daya listrik inline. Prototipe dievaluasi menggunakan baling-baling HQProp T63-6 63,5 mm yang digerakkan oleh motor iFlight XING 1404 4600 KV pada sudut kemiringan diskrit 0, 30, 45, 60, dan 90 derajat pada beberapa pengaturan kecepatan rotasi. Pengukuran awal menunjukkan redistribusi vektor gaya dorong yang diharapkan dalam kerangka acuan laboratorium: komponen horizontal dominan pada 0 derajat, komponen vertikal dominan pada 90 derajat, dan komponen yang hampir seimbang terjadi di dekat 45 derajat. Peningkatan kecepatan rotasi meningkatkan besaran gaya yang terukur di seluruh orientasi yang diuji. Eksperimen ini sengaja diinterpretasikan sebagai karakterisasi vektor gaya multi-orientasi statis daripada reproduksi aerodinamika penerbangan transisi, karena tidak ada aliran bebas eksternal yang diterapkan. Hasilnya menunjukkan fungsionalitas praktis dari arsitektur bangku uji berputar dan kesesuaiannya sebagai dasar untuk karakterisasi sistem propulsi yang lebih ketat.

Kata kunci: propulsi UAV; UAV yang mampu miring; bangku uji baling-baling; pengarahan vektor dorong; instrumentasi eksperimental.

ABSTRACT

This study develops and preliminarily characterises a low-cost multi-orientation propeller test bench for static thrust-vector measurements relevant to tilt-capable unmanned aerial vehicle (UAV) propulsion research. The platform combines a servo-actuated 0-90 degree tilt mechanism, an Arduino Uno data-acquisition unit, nominal 1 kgf load-cell instrumentation with HX711 conditioning, an MPU6050 orientation sensor, RPM monitoring, and an inline electrical power meter. The prototype was evaluated using a 63.5 mm HQProp T63-6 propeller driven by an iFlight XING 1404 4600 KV motor at discrete tilt angles of 0, 30, 45, 60, and 90 degrees over several rotational-speed settings. The preliminary measurements show the expected redistribution of the propulsion-force vector in the laboratory reference frame: the horizontal component is dominant at 0 degrees, the vertical component is dominant at 90 degrees, and approximately balanced components occur near 45 degrees. Increasing rotational speed increases the measured force magnitude across the tested orientations. The present experiment is intentionally interpreted as static multi-orientation force-vector characterisation rather than a reproduction of transition-flight aerodynamics, because no external freestream was imposed. The results demonstrate the practical functionality of the rotating test-bench architecture and its suitability as a foundation for more rigorous propulsion-system characterisation.

Keywords: *UAV propulsion; tilt-capable UAV; propeller test bench; thrust vectoring; experimental instrumentation.*

1. INTRODUCTION

Tilt-rotor, tilt-wing, and other tilt-capable unmanned aerial vehicles (UAVs) require propulsion systems that can operate across substantially different vehicle attitudes and thrust orientations. Unlike a conventional multirotor that is predominantly characterised in a fixed hovering configuration, a tilt-capable vehicle continuously redirects the propulsion-force vector between vertical and horizontal flight requirements. This creates a strong need for experimental platforms that can quantify propulsion performance while the motor-propeller axis is positioned at different orientations [1]-[5].

The aerodynamic behaviour of a rotor during actual transition flight is more complex than a simple change in orientation. When a rotor encounters a non-zero external inflow component, the rotor disk may experience asymmetric velocity distribution, non-uniform blade loading, wake skew, and local changes in blade angle of attack [6], [7]. Ground proximity can introduce additional changes in rotor performance [8], [9]. Consequently, aerodynamic models and flight-control strategies benefit from empirical data obtained under clearly defined operating conditions.

Recent research has examined transition and interference effects in tilt-powered rotor systems. Wu et al. [3] investigated rotor spacing and attitude transition in a tilt-powered coaxial rotor UAV, while Zhu et al. [12] studied the aerodynamic interaction of non-parallel tandem dual-rotor arrangements over different tilt states. Ryll et al. [13] demonstrated the control complexity of an overactuated variable-orientation aerial platform. In parallel, model-based thrust estimation methods such as those reported by Santos et al. [15] and the hybrid aerodynamic modelling approach of Bauersfeld et al. [18] highlight the continuing importance of reliable experimental propulsion data.

Propeller test benches provide a practical route for obtaining such data, but many laboratory platforms are designed for a fixed thrust axis. High-precision directional force systems have been reported [10], and several custom UAV propulsion stands have been developed for static characterisation [11], [16]. Prabowo et al. [17], including authors from the present research group, recently demonstrated an Arduino-based fixed-axis propeller test bench supported by experimental and CFD analysis. The logical next step is to extend this capability from fixed-axis measurement to controlled multi-orientation testing.

The research gap addressed here is therefore not the absence of all tilt-rotor experimental systems, but the need for an accessible laboratory platform that can systematically reposition a small UAV propulsion unit and record force, rotational speed, orientation, and electrical operating data within a single test architecture. The present study develops a servo-actuated multi-orientation test bench and provides a preliminary static characterisation at discrete angles between 0 and 90 degrees. Importantly, the current experiment does not impose an external freestream; therefore, the measured changes are interpreted as static thrust-vector behaviour in the laboratory coordinate system rather than as direct reproduction of transition-flight oblique-inflow aerodynamics. This distinction makes the scope of the present contribution clear and provides a rigorous basis for subsequent wind-on or dynamic-transition studies.

2. THEORETICAL CONSIDERATIONS

For a geometrically fixed propeller operating under static conditions, thrust commonly increases approximately with the square of rotational speed over a restricted operating range. A simplified relation can be written as:

$$T = k_T \omega^2 \quad (1)$$

where T is the resultant propeller thrust, omega is the rotational speed, and k_T is a proportionality term that depends on propeller geometry, air density, and operating condition. The present study uses this relation only as a qualitative expectation for the effect of increasing RPM; it is not used as a complete aerodynamic model.

When the entire motor-propeller unit is rotated through a tilt angle theta, the resultant thrust vector can be resolved into horizontal and vertical components in the laboratory reference frame. With theta = 0 degrees defined as a horizontal thrust orientation and theta = 90 degrees as a vertical thrust orientation:

$$F_H = T\cos(\theta) \quad (2)$$

$$F_V = T\sin(\theta) \quad (3)$$

Equations (2) and (3) describe geometric force-vector decomposition. They do not, by themselves, describe the aerodynamic penalties associated with transition flight. In the present static test, no controlled external freestream is applied, so changing theta primarily changes the direction of the thrust vector relative to the laboratory axes. A future wind-on test would be required to quantify oblique inflow, skewed wakes, asymmetric blade loading, or transition-specific aerodynamic losses.

3. METHOD

3.1 *Test-Bench Architecture And Mechanical Design*

The test bench was designed as a compact laboratory platform for repositioning a small UAV motor-propeller assembly between horizontal and vertical orientations. The base and vertical support are manufactured from 5 mm acrylic sheet, while the tilt-arm and associated fixtures are produced using PLA additive manufacturing. A servo-driven mechanism rotates the propulsion unit over the 0-90 degree range. The mechanical concept was first prepared in CAD to verify component placement, range of motion, and physical clearance before fabrication.

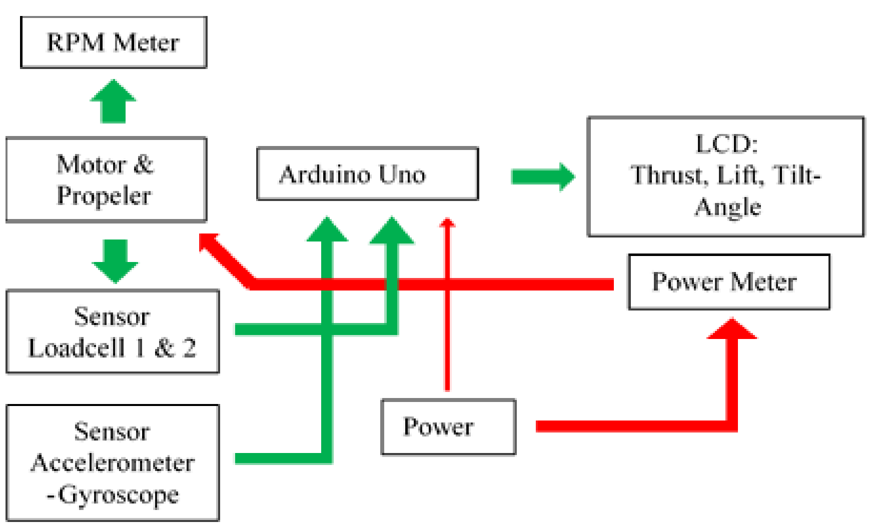

Figure 1. System block diagram of the preliminary multi-orientation test bench.

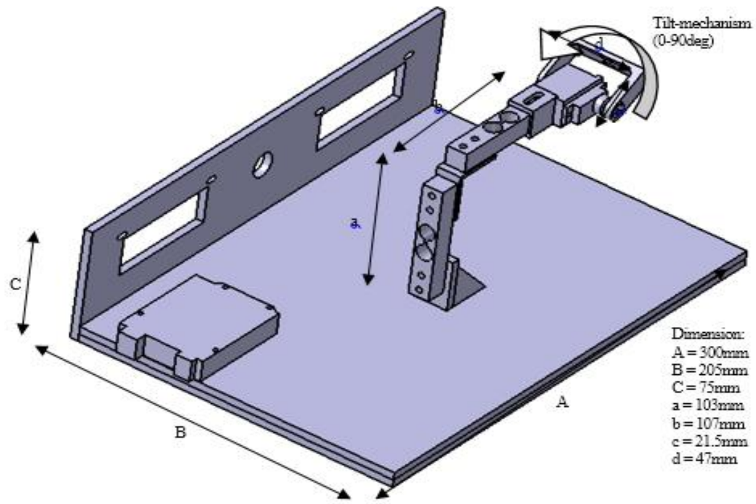

Figure 2. CAD model and principal dimensions of the multi-orientation test-bench structure.

3.2 *Instrumentation and Data Acquisition*

The data-acquisition architecture is based on an Arduino Uno that receives the force and orientation signals and displays the operating variables on local LCD modules. The prototype photograph indicates two nominal 1 kgf load-cell elements in the mechanical assembly, together with HX711 signal conditioning. The source manuscript does not yet provide a complete cross-axis calibration matrix for these channels; therefore, the present study treats the reported horizontal and vertical force values as preliminary component measurements rather than fully validated orthogonal metrology.

An MPU6050 accelerometer-gyroscope module is used to monitor the angular orientation of the rotating assembly. Propeller rotational speed is monitored using the installed RPM measurement system. Electrical operating condition is monitored with an inline wattmeter connected to the propulsion power circuit. Torque is not measured in the current configuration; consequently, shaft power and propulsive efficiency are not reported.

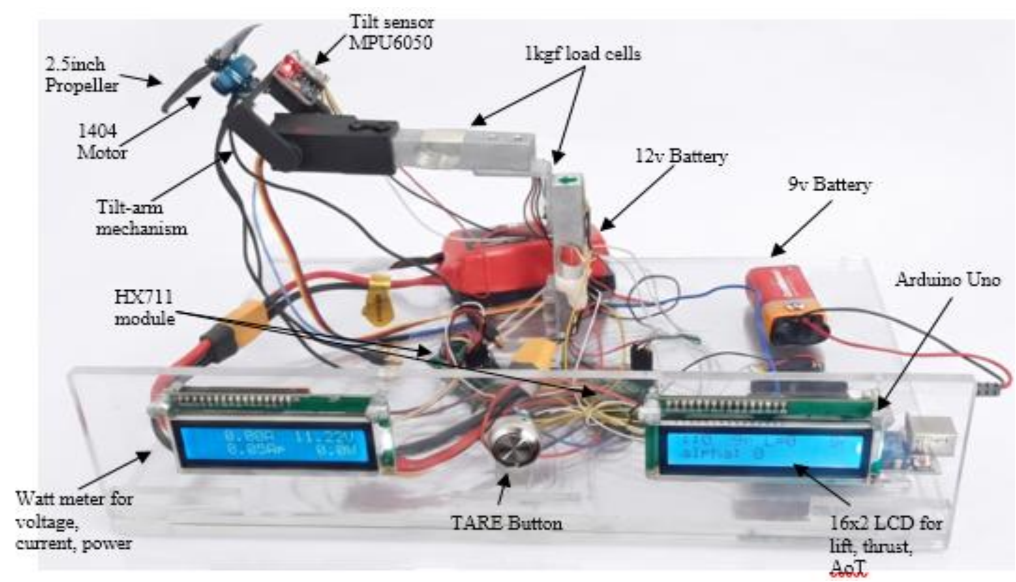

Figure 3. Fabricated prototype showing the propeller-motor assembly, tilt sensor, nominal 1 kgf load cells, HX711 module, batteries, Arduino Uno, wattmeter, and LCD displays.

3.3 *Propulsion system and preliminary test matrix*

The main components of the propulsion system and corresponding preliminary test conditions are summarized in Table 1. The test matrix wes defined to evaluate the propulsion unit under different tilt orientation and rotational-speed conditions.

Table 1. Propulsion system specification and preliminari test conditions

Item	Specification	Role in test
Propeller	HQProp T63-6, 2.5 in (63.5 mm)	Small-UAV test propeller
Motor	iFlight XING 1404, 4600 KV	Brushless propulsion motor
Battery	3S 1850 mAh 100C LiPo	Primary propulsion power source
ESC	Skywalker 40 A	Motor speed control
Tilt angles	0, 30, 45, 60, 90 degrees	Static multi-orientation test points
RPM points	8000-16000 RPM as reported in Figure 4	Preliminary speed sweep

The propulsion unit was operated at discrete tilt angles of 0, 30, 45, 60, and 90 degrees. Measurements were collected over several RPM settings, reported in the existing dataset from 8000 to 16000 RPM. Because the present manuscript is a working revision, the current data are treated as preliminary until the number of repeats, sampling duration, averaging procedure, and environmental test conditions are formally documented.

3.4 *Preliminary Calibration and Measurement Procedure*

Before testing, the force-measurement system was commissioned using known masses of 50 g, 100 g, and 150 g. The corresponding HX711 output was used to establish the initial calibration factor. This calibration range is sufficient to check the low-force region occupied by the current 2.5 in propeller dataset, but it must not be interpreted as validation of the full nominal 1 kgf sensor capacity. The final manuscript should report the calibration equation, coefficient of determination, loading/unloading behaviour where available, and uncertainty across the range used for the experiment.

The MPU6050 was referenced to the physical test-bench coordinate system so that 0 degrees represented the horizontal thrust orientation and 90 degrees represented the vertical thrust orientation. At each selected angle, the motor was operated at the required RPM condition and the force, orientation, RPM, and electrical quantities were observed. For final publication, each operating point should be repeated at least three times and reported as a mean value with an appropriate scatter or uncertainty indicator.

4. RESULTS AND DISCUSSION

4.1 *Prototype Realization and Functional Behaviour*

The fabricated system successfully combines propulsion, rotation, force sensing, angle measurement, and local data display in a single compact platform (Figure 3). The mechanical arrangement allows the motor-propeller axis to be positioned through the intended 0-90 degree range without changing the main base structure. This is the principal development beyond a conventional fixed-axis static thrust stand and extends the capability established in the authors' earlier fixed-axis work [17].

The current prototype should be described as a preliminary research instrument rather than a fully validated measurement standard. In particular, the source manuscript does not yet document independent full-channel calibration, cross-axis coupling, repeatability, or a formal measurement-uncertainty budget. Nevertheless, the available data are adequate for a functional demonstration of the multi-orientation architecture and for defining the final verification programme.

4.2 *Preliminary Thrust-Vector Trends*

Figure 4 shows the reported horizontal and vertical force components for the five tested orientations. The overall trend is physically consistent with geometric thrust-vector reorientation. At 0 degrees the force is predominantly horizontal, whereas at 90 degrees the force is predominantly vertical. At 45 degrees, the reported horizontal and vertical components are of similar magnitude. Intermediate orientations at 30 and 60 degrees progressively redistribute the measured force between the two laboratory axes. This behaviour is consistent with the vector relations in Equations (2) and (3).

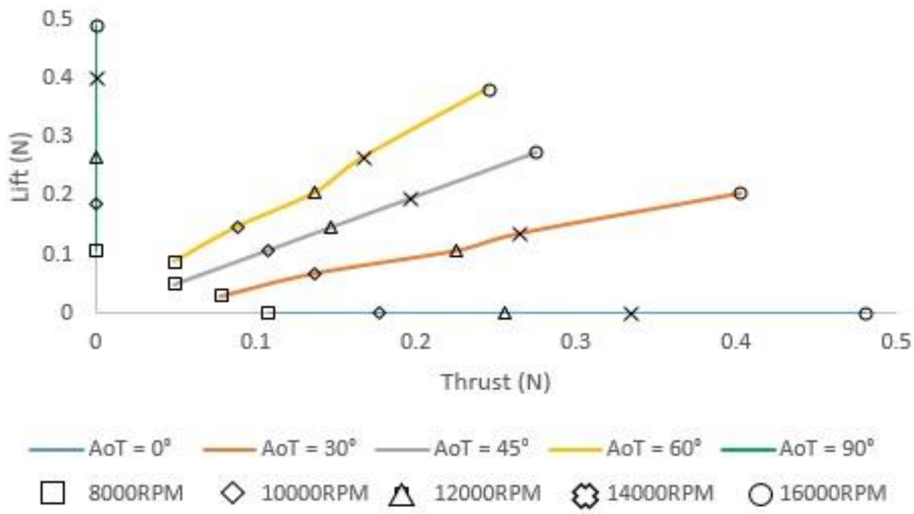

Figure 4. Preliminary reported horizontal thrust and vertical lift-force components at different tilt angles and RPM settings.

The measured force level also increases with RPM. This is consistent with the expected increase in propeller thrust as rotational speed rises. The present dataset therefore demonstrates that the platform can distinguish both orientation-dependent force redistribution and speed-dependent changes in force magnitude. These are the two essential functions required for a multi-orientation static propulsion test bench.

The current data should not be interpreted as direct evidence of transition-flight oblique inflow, retreating-blade stall, or wake-skew losses. No controlled external freestream was imposed in the reported experiment. If the resultant measured force varies with bench angle, possible contributors include force-sensor cross-axis sensitivity, structural alignment, gravity-related tare effects, mounting compliance, proximity of the test structure to the propeller flow, and ordinary experimental scatter. A repeated test programme with calibrated orthogonal channels is required before such deviations can be attributed to aerodynamic mechanisms.

4.3 *Relationship to Existing Test-Bench Research*

The contribution of the present work is best understood as an instrumentation extension rather than a new theory of tilt-rotor aerodynamics. Directional-force test platforms and advanced tilt-rotor facilities already exist [10]-[13], but they can involve specialised architectures. The current prototype targets an accessible small-UAV research environment by combining low-cost microcontroller-based acquisition with an actively reorientable propulsion axis. Compared with the fixed-axis propeller stand previously reported by Prabowo et al. [17], the present platform introduces controlled multi-orientation capability and integrated angle sensing. This creates a practical experimental base from which more rigorous static, wind-on, and dynamic-transition investigations can subsequently be developed.

4.4 *Electrical-Power Measurement Status*

The prototype includes an inline wattmeter and therefore has the hardware capability to record electrical voltage, current, and power during propulsion testing. However, the source manuscript does not provide a complete numerical power dataset for the operating points shown in Figure 4. To avoid unsupported claims, quantitative power-consumption results are not presented in this work. The separate study need to add power-versus-RPM and, where useful, thrust-to-electrical-power (N/W) plots using repeated measurements. Because torque is not measured, the manuscript not claim specificallyshaft-power-based propeller efficiency.

4.5 *Limitations of The Preliminary Study*

Four limitations define the present scope. First, the available measurements are preliminary and require repeatability and uncertainty assessment. Second, the complete calibration and cross-axis behaviour of the force channels are not yet reported. Third, the experiment is static and does not reproduce a controlled transition-flight freestream. Fourth, torque is not measured, so mechanical power and propeller efficiency cannot be determined. These limitations do not invalidate the development work; instead, they define the next verification steps required to convert the prototype into a quantitatively validated research instrument.

5. CONCLUSION

A low-cost, microcontroller-based multi-orientation propeller test bench has been developed and preliminarily demonstrated for small tilt-capable UAV propulsion research. The platform integrates a servo-actuated 0-90 degree rotation mechanism, force sensing, angle measurement, RPM monitoring, and electrical-power monitoring within a single laboratory architecture. Preliminary tests using a 2.5 in propeller show the expected redistribution of the propulsion-force vector: the horizontal component dominates at 0 degrees, the vertical component dominates at 90 degrees, and the two components approach a balanced condition near 45 degrees. Higher RPM also produces larger measured forces across the tested orientations. The principal contribution is therefore the extension of fixed-axis static propeller testing to controlled multi-orientation thrust-vector measurement. The current data are appropriately treated as preliminary and should not be interpreted as validation of transition-flight aerodynamics. Prior to final submission, the force channels were fully calibrated over the operating range, repeated measurements and uncertainty reported, the channel geometry and cross-axis behavior was documented, and the electrical-power dataset analyzed quantitatively. These steps convert the present functional prototype into a stronger experimental platform for subsequent wind-on, dynamic-transition, modelling, and control studies.

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