Design and implementation of low cost thrust benchmarking system (TBS) in application for small scale electric UAV propeller characterization

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Abstract. Thrust Benchmarking System (TBS), a low cost and easy to manufacture instrument for electric UAV propulsion system performance measurement is being proposed. With one of its uses for determining the static thrust of a propeller based on simple empirical characterization modeling. In this paper, characteristic modeling is performed on 3 APC-Electric propellers with different pitch and diameter dimensions. As a result, there are 2 constants $K_1$ and $K_2$ which can express similar propeller characteristics with different dimensions. It costs IDR 1.6 million and took two-and-a-half months of manufacture and assembly process.

1. Introduction

In the last few decades, development for UAV has been improved rapidly. One of the key aspect for a UAV is the propulsion system. Typical electric UAV propulsion system consist of battery, motor driver, motor, and propeller. Some problems may occur during the phase of determining the propulsion system combination, especially choosing the right propeller. In general, the motor manufacturer will provide the recommended propeller combination for a given motor. However, the unavailability of the performance data of the motor and propeller may cause problems in choosing the right propeller for the desired flight performance.

One way to determine the thrust characteristic being produced by a propeller is by modeling and performing aerodynamic analysis using a dedicated simulation software, however in order to get a proper and satisfying results, airfoil geometry and other parametric dimensions of the propeller are needed. Acquiring such data from the manufacturer itself is considered to be arduous. More empirical approach is considered to be more practical to determine the characteristic of propellers and or motors.

This paper discusses about design and implementation of Thrust Benchmarking System (TBS) for electric UAV propulsion system. TBS itself is made from low cost and easily obtained materials and easy in manufacturing process. TBS is equipped by various sensors to conduct data acquisition which is needed to determine an optimal combination of electric UAV propulsion system. This instrument has extensive capability and development potential as a static propulsion testing instrument. Measurement of static thrust, torque, battery voltage, battery current output, motor temperature, motor
speed controller temperature, propeller rotational speed (RPM), and vibration are some of the basic functions which have been developed and implemented.

One of the basic functions discussed in this paper is the capability to measure data relating to propeller characteristics, with one application being the determination of the static thrust of similar propellers but different dimensions (airfoil shapes resembling each other but different in diameter and pitch) empirically [1][2][3][4]. TBS measurement validity is determined by comparing it to manufacturer datasheet [5]. The measured data is then used to determine the empiric static thrust model. After that, the model is implemented to estimate the static thrust of an unmeasured propeller which then validated by comparing the estimation with manufacturer data.

2. Propeller characteristic

In modeling the propeller, dimensionless coefficients such as thrust, torque, power, advance ratio, and efficiency is often used as characterization. The coefficients are determined experimentally with static and dynamic testing. Each coefficient can be represented in the equation (1) to (5) [6].

\[ C_T = \frac{T}{\rho n^2 d^4} \] 
\[ C_P = \frac{\omega Q}{\rho n^3 d^5} \] 
\[ C_Q = \frac{Q}{\rho n^2 d^5} \] 
\[ \eta_P = f \frac{C_T}{C_P} \] 
\[ J = \frac{\omega}{n d} \]

where:
- \( C_T \) = thrust coefficient
- \( C_P \) = power coefficient
- \( C_Q \) = torque coefficient
- \( \eta_P \) = propeller efficiency
- \( J \) = advance ratio
- \( T \) = thrust
- \( Q \) = torque
- \( V \) = velocity
- \( \rho \) = air density
- \( n \) = revolutions per second
- \( d \) = propeller diameter
- \( \omega \) = radians per second

Thrust Coefficient (\( C_T \)) is generally determined using experiments as well as an in-depth analysis and understanding of the geometry of the propeller itself. For simplification, another approach is used which expressed by the equation (6) [7]

\[ T = \rho \pi \left( \frac{0.0254 d}{4} \right)^2 \left( \frac{0.0254 N p}{60} \right)^2 \left( \frac{d}{K_1 p} \right)^{K_2} T = \text{Static Thrust (N)} \]

where:
- \( \rho \) = air density (kg/m³)
- \( N \) = revolutions per minute
- \( p \) = propeller pitch (inch)
- \( d \) = propeller diameter (inch)
- \( K_1 \) and \( K_2 \) are characteristic constants that can be used as a reference to determine the value of static thrust of a propeller that rotates at a certain speed.
3. **Hardware design and implementation**

3.1. **Mechanical**

TBS consists of 3 main parts specifically motor mount, sensor mount, and TBS base. The parts that cannot be obtain on the market are manufactured from 8 mm and 3 mm multiplex. This material is chosen because of its cheap cost and strong structure. In addition, the ability of the available manufacturing tools is also considered in the selection of multiplex thickness. TBS is mounted on a strong base which function as a supporting structure.

![TBS assembly](image1)

**Figure 1. TBS assembly.**

![Motor mount](image2)

**Figure 2. Motor mount.**

The motor mount, as shown in figure 2, serves as the platform to attach the propulsion system which is going to be tested. 8mm multiplex which has been laser-cut is used as the motor mount frame. The motor mount base section is designed to resemble a plus sign. The horizontal part of the motor mount, especially the far end, has an important role in the data acquiring process by the load cell (both thrust and torque readings). The vertical part of the motor mount base acts as a reinforcing structure. The motor mount base plays a role in distributing the pressure from the thrust generated by the motor to a vertical load cell and also the torque to two pieces of horizontally positioned load cells. Instead of using L-shaped plates, hinges are used on the motor mount section to minimize the wasted torque to bend a L-shaped plate. In addition, the hinges are selected to minimize the negative effect of vibration.
The part behind the motor mount is the top mount. On the top mount itself, there are 3 pieces of CNC coolant pipe mounted as the arm to place the sensor base in a customized position so that data can be read accurately and precisely on any location around the tested propulsion system. The CNC coolant pipe is chosen as the sensor’s arm because it is easy to adjust the position of the sensor base, quite stiff when used in the measurement process, the length of the pipe is easily adjustable, lightweight, and easy to obtain. For the sensor base section, located at the end of CNC coolant pipe arm, multiplex with thickness of 3 mm is being used. At the bottom of the top mount there are two load cell grips that serve as a platform to install a vertical load cell.

For the TBS base, multiplex with thickness of 8 mm is being used. A main base is positioned vertically. This section serves to place TBS on a stronger structure. There are triangular support structures at the TBS base section. This structure serves to strengthen the position of the TBS base. A horizontal beam is positioned amid the triangular support structures. In addition, TBS is designed to have several sections that are intended to provide support for the overall structure as well as some parts that are mechanically reinforced to provide additional protection.

Spring washers are used to prevent any looseness between joints due to vibration. The reason for the use of spring washers and hinges is because the cost is cheap, easy to install, and provide good vibration damping. Other than those components mentioned before, we also use wooden adhesive to assemble the TBS base. Cyanoacrylate adhesive is used because it has the adhesive power that matches the glued component such as multiplex. The TBS full assembly can be seen in the figure 5.
3.2. Electrical

3.2.1. Block diagram

Figure 6 shows the interaction between TBS’s electrical components. The following explanation will explain about workflow, communication line, and the function of each sensor. First of all, strain gauge load cell is used as torque and thrust sensor for the rotating propeller(s). Load cells work by changing its resistance as a proportional response to the force applied to the device. The resistance changes are too small to be measured by ordinary ohmmeter because strain gauge load cell measurements usually involve quantities less than 1 centi-strain. To cope with it, HX711 is used to amplify the miniscule changes of resistance. The working principle of HX711 is similar to Wheatstone bridge in which resistances come from compression and tension to the wiring inside the load cell. Thrust is obtained by known relation between certain output voltage and applied force [8]. HX711 communicates to the microcontroller about the reading of torque and thrust with data and clock channels [9].

RPM sensor is a rotational velocity sensor. The RPM sensor consists of a laser module and a photodiode module. Laser module functions are to emit light that composed by homogenous wavelength and focused into a point. After reflectors is mounted on the surface of the propeller or motor body, or any rotating body of the tested propulsion system, a photodiode module is positioned to detect the reflected light from the laser module. The photodiode module is used to count the number of reflections that occur. Rotational velocity is obtained by dividing number of reflections by the passed time in minute(s). The counting of the reflected laser light occurrence is done by utilizing the external interrupt function of the microcontroller [10][11].

LM35 is a contact temperature sensor. With constant current passing by LM35, voltage will change in PN junction diode by 0.1V °C. Before calibration, LM35 provides typical accuracies of ±½°C at room temperature and ±¾°C over a full −55°C to 150°C temperature range [12]. LM35 communicates with microcontroller by analog channel [13]. Next, MLX90614ESF-BCC IR is a contactless temperature sensor. MLX90614 series has a standard accuracy ± 0.5°C over wide temperature measurement range [14]. Infrared ray that produced by the pointed surface will be focused by convergent lens onto thermopile. The result of heat energy conversion into electrical energy by thermopile will be channeled into a detector. The detector will determine temperature by amount of voltage across it. MLX90614ESF-BCC IR communicates with microcontroller via I2C bus [15].
MPU 6050 is used to measure vibration. MPU 6050 is an Inertial Measurement Unit (IMU) with six Degree of Freedom (DOF) which composed by three DOF from an accelerometer and another 3 DOF from a gyroscope. MPU 6050 is based on MEMS technology. MPU 6050 IMU gyroscope sensitivity is up to 131 LSB/º/s and accelerometer sensitivity up to 16384 LSB/g [16]. MPU 6050 communicates with microcontroller via I2C bus [17]. The last is 3DR power module which is used as voltage and current sensor. It communicates with microcontroller via two analog channels.

As for safety consideration, a safety switch is used to provide emergency operational shutdown. If the button is in armed (pressed) condition, then the whole system will be terminated. Also additional buzzer is provided to give notification sound to the user.

3.2.2. Extension board (PCB breakout)

The function of extension board is to breakout all of the I/O function pin from the main board (Arduino Mega PRO), as well as components modularization and to prevent from direct physical damage to the microcontroller. The double layer extension board was created with size of 73.2 x 129.5 mm.
3.3. Firmware

Arduino Mega Pro is chosen as the microcontroller due to the pin capability, small form factor, input and output pin quantity and storage of 256 kilobytes Flash memory, 8 kilobytes SRAM, and 4 kilobytes EEPROM [18].

To provide a user interface, TBS is equipped with Command Line Interface feature via USB, where users can provide input to change mode, system parameters, as well as tuning.

![TBS command line interface.](image1)

Figure 7. TBS command line interface.

There are several modes in the TBS such as INIT which is the mode for system initiation, DEBUG for debugging selected subsystem, FAIL which is a failsafe mode if the sensors measurement limit are exceeded, STBY which is the default mode while in idle condition, MSRE which is a mode to measure with all sensors with specific measurement periods and propulsion load scenario, as well as CALB which is a calibration mode for selected sensors.

TBS measurement result is delivered as a .log file. The file has a specific format, which is made to resemble the format used by Ardupilot flight controller system to store data flash log. This is done to facilitate the graphing process of the measurement result with Mission Planner GCS software [19][20]

![TBS measurement result being analyzed using the data flash log review function in Mission Planner software.](image2)

Figure 8. TBS measurement result being analyzed using the data flash log review function in Mission Planner software.
3.4. Expense Cost

| Item                                           | Cost       |
|------------------------------------------------|------------|
| Arduino Mega Pro                               | IDR 152,500.00 |
| 3x Load Cell + HX711                           | IDR 285,000.00 |
| MLX90614ESF-BCC IR Thermal sensor              | IDR 120,000.00 |
| MPU6050 IMU                                    | IDR 25,000.00 |
| LM393 Photodiode Module                        | IDR 15,000.00 |
| Laser Module                                   | IDR 5,000.00  |
| LM35                                           | IDR 15,000.00 |
| 3DR Power Module                               | IDR 100,000.00 |
| Emergency switch                               | IDR 20,000.00 |
| 3x CNC Flex Hose                               | IDR 70,000.00 |
| 3mm and 8mm Wood Sheet (Multiplex)             | IDR 140,000.00 |
| PCB Manufacture                                | IDR 222,000.00 |
| Laser Cut Service                              | IDR 175,000.00 |
| Cables, Pin Headers, Fasteners, Nuts, Washers, and Adhesive | IDR 245,000.00 |
| **Total**                                      | **IDR 1,589,500.00** |

Table 1 shows the total cost for the construction of TBS. From the table, we can see that as the total cost of TBS roughly on IDR 1,600,000 with easy-to-find material, thus TBS could be a good alternative for research and development on small-scale UAV electric propulsion system.

4. Results and discussion

4.1. Development results

Low cost and easy to manufacture are two main benefits of TBS. It costs IDR 1,589,500 which including electrical components, mechanical parts, and laser-cut service. It took two-and-a-half months for completing TBS into final product. All electrical components that listed in Table 1 was bought simultaneously from local e-commerce.

Frame and mechanical parts were designed and evaluated by using CAD. CAD made it possible to have fast yet proven design of TBS. Frame and mechanical parts were manufactured by using laser cut method. Consideration of choosing laser cut method was its rapid and high-precision process. The duration itself took an hour.

Work on electrical systems was divided into PCB design and manufacturing, sensor wiring, and troubleshooting. In the final process, multi-sensor integration testing was performed to verify data acquisition.

Firmware development was done step by step, started from sensor interfacing, state machine, Command-Line Interface (CLI), calibration, failsafe, measurement, and additional feature. Arduino and dummy sensor had been used for testing firmware before subsystem integration was completed. In term of obtaining excellent and consistent result, it took two months for firmware development. In brief, CAD implementation, task breakdown, and parallel firmware development are three reasons of low cost and easy TBS manufacturing.

4.2. Data analysis

Based on the previously obtained equation (6), to characterize a propeller, two data are required, that is static thrust and RPM, where for every static thrust data will be expressed in RPM function in data
processing. The results of data acquisition are in the form of external files that can be processed to provide data visualization.

Tests were performed for 3 different dimensions but form-alike (APC-electric) propellers. The Propellers dimensions are 12x6, 13x6.5, and 14x7, respectively. Then, measured static thrust data for each RPM are compared with manufacturers’ performance datasheet to determine the measured data accuracy [21].

For each propeller the values of $K_1$ and $K_2$ will be estimated, based on the comparison of test result data and the estimation result using equation (6) for the static thrust value at a certain RPM. Then the standard deviation value is calculated from the estimation result to the actual result of measurement. Last, the average values of all $K_1$ and $K_2$ are reused to estimate the resulting static thrust, and then the standard deviation is recalculated for each propeller.

![Figure 9. APC Electric propellers (12x6, 13x6.5, and 14x7, respectively).](image)

Implementation of the data acquisition system has a weakness that is, not all data exists in a certain timestamp as shown in figure 10, due to data acquisition was done periodically where the data acquisition period can be set based on the reading and processing speed of each sensor.

![Figure 10. TBS measurement result being loaded in Mission Planner software. For a certain timestamp only contain one data packet, although one data packet may consist of several sensor readings.](image)

In data processing, the data from external files first imported into Microsoft Excel. Then the desired data in this case static thrust and RPM is chosen, which both data is contained in the line with the data format prefix THR and RPM. THR data format itself not only has static thrust data but also torque data (as shown in the figure 11 there are 2 parameters inside THR data format, the static thrust
data is contained in the second parameter), for that required further processing for data extraction required for calculation.

| FORMAT | TIME STAMP | PARAM1 | PARAM2 | THR | RPM |
|--------|------------|--------|--------|-----|-----|
| THR    | 79221852   | 1910   | -0.21  | 0.3557340352 | 0   |
| RPM    | 79010432   | 0      | 0.52   | 2.069182302  | 344 |
| THR    | 79036558   | 4900   | -0.9   | -2.41 | 72130360 |
| RPM    | 79184568   | 344    | 5.682695570 | 689 |
| THR    | 79270268   | -11896 | -0.01  | 5.882695570  | 689 |
| THR    | 79538545   | -13731 | 7.6    | 5.882695570  | 689 |
| THR    | 79444896   | 30860  | 18.67  | 5.882695570  | 689 |
| RPM    | 79533004   | 1032   | 16.43348464 | 1033 |
| THR    | 79533004   | 19120  | 17.24  | 16.43348464  | 1033 |
| THR    | 79618528   | 12655  | 19.15  | 16.43348464  | 1033 |
| RPM    | 79707100   | 1034   | 19.15  | 16.43348464  | 1033 |
| THR    | 797303016  | 12655  | 19.15  | 16.43348464  | 1033 |
| THR    | 79792776   | 11365  | 22.49  | 23.24846638  | 1378 |
| RPM    | 79812772   | 1378   | 22.49  | 23.24846638  | 1378 |

**Figure 11.** RPM and THR data from the external file being processed using Microsoft Excel.

As mentioned earlier (and can be seen in figure 11) the overall sensor data is not present at a time, so an approach is required to have static thrust data on a given RPM measurement. It can be seen in figure 11 that the RPM data at a certain timestamp is always flanked by two static thrust data measurements, so a linear approximation can be done to determine the value of static thrust data in a given RPM based on the timestamp. Further data processing is done on the measurement data of the RPM propeller to minimize the noise, which used the average filter of 9 data points shown in figure 12.

**Figure 12.** RPM and filtered RPM value at one-time full measurement scenario for 12x6 APC electric propellers.

After obtaining the generated static thrust data for each RPM value, comparison is performed between the datasheet and the measurement results as can be seen in table 2 to determine the measurement accuracy of TBS for static thrust measurement.
Table 2. TBS measurement accuracy for the tested propellers.

| RPM | THRUST(g) | APC_THRUST(g) | Accuracy of TBS(%) |
|-----|-----------|---------------|-------------------|
| 1000| 32.79     | 50.57         | 64.84             |
| 2000| 151.03    | 203.19        | 74.33             |
| 3000| 367.33    | 457.42        | 80.31             |
| 4000| 766.94    | 815.08        | 94.09             |
| Mean|           |               | 78.39             |

| RPM | THRUST(g) | APC_THRUST(g) | Accuracy of TBS(%) |
|-----|-----------|---------------|-------------------|
| 1000| 34.25     | 39.08         | 87.65             |
| 2000| 144.91    | 156.3         | 92.71             |
| 3000| 333.49    | 351.22        | 94.95             |
| 4000| 551.3     | 626.13        | 88.05             |
| Mean|           |               | 90.84             |

| RPM | THRUST(g) | APC_THRUST(g) | Accuracy of TBS(%) |
|-----|-----------|---------------|-------------------|
| 1000| 17.36     | 29.42         | 59.01             |
| 2000| 97.62     | 118.15        | 82.62             |
| 3000| 241.19    | 266.18        | 90.61             |
| 4000| 430.37    | 473.97        | 90.8              |
| Mean|           |               | 80.76             |

Based on the measurements and comparison for each tested propellers show the accuracy of 80.76% for 12x6 propeller, 90.84% for 13x6.5 propellers, and 78.39% for 14x7 propellers. Variation of the accuracy value occurs because the measurement process does not depend on the constant value of RPM, but the constant PWM signal input value to the motor driver for a certain time interval, so that the desired constant RPM value is difficult to achieve. The static thrust data shown in the table is the average RPM value within ± 100 RPM targets. On the other hand, the placement of sensor arms that block airflow can also decrease the value of reading accuracy.

![Diagram](image)

**Figure 13.** Measured static thrust and estimated static thrust being plotted in filtered RPM value at one-time full measurement scenario for 12x6 APC Electric propellers.

Since the equation (6) depends on the values of $K_1$ and $K_2$, the values of $K_1$ and $K_2$ can be adjusted so that the curve form from the static thrust of estimation can resemble the form of the static thrust curve of the measurement. Manual iterations are performed to obtain $K_1$ and $K_2$ values that can represent the static thrust curve of measurement results.
Both the static thrust measurement data and the static thrust estimation is represented in unit of grams, therefore the previously equation (6) is modified. The plot results from the static thrust curve and the estimation results can be seen in the figure 13.

Figure 13 shows the values of \(K_1\) and \(K_2\) for the 12x6 propeller. For 13x6.5 propeller, \(K_1\) and \(K_2\) constant are valued at 0.409 and 3.661 respectively, for 14x7 propeller \(K_1\) and \(K_2\) constant are valued at 0.383 and 3.412 respectively. All of the \(K_1\) and \(K_2\) constant for each propeller are tuned to give a satisfactory representation, resulting standard deviations which are valued at 18.690 grams, 24.195 grams, and 30.573 grams for 12x6, 13x6.5, and 14x7 propellers respectively.

![REPLOTTED APC 12x6](image)

**Figure 14.** Measured static thrust and estimated static thrust being replotted in filtered RPM value using the mean values of \(K_1\) and \(K_2\) respectively valued at 0.398 and 3.548, at one-time full measurement scenario for 12x6 APC Electric propellers.

Further steps can be made by performing average calculation on 3 measurement data to obtain the average value of \(K_1\) and \(K_2\) for APC propeller type, which is then reused to estimate the generated static thrust, and recalculate the standard deviation for each propeller.

It can be seen from figure 14 that by using the mean values of \(K_1\) and \(K_2\) respectively valued at 0.398 and 3.548, from the results of all previous measurements, a sufficiently representative and satisfactory result is obtained for all of the propeller configuration, with standard deviations which are valued at 19.289 grams, 36.723 grams, and 55.309 grams for 12x6, 13x6.5, and 14x7 propellers respectively.

To justify the equation (6) for estimating the static thrust using the propeller characteristic constant is done by comparing another 2 APC electric propeller (10x5 and 15x10) which are not owned, with the static thrust data from the manufacturer using the mean values of \(K_1\) and \(K_2\) from the previously obtained calculations. The estimation accuracy can be seen in table 3.

| RPM | PRED. THRUST(g) | APC THRUST(g) | Accuracy of THR(%) |
|-----|-----------------|---------------|--------------------|
| 1000| 40.63           | 70.8          | 57.38              |
| 2000| 162.5           | 283.65        | 57.20              |
| 3000| 365.63          | 638.09        | 57.3               |
| 4000| 650.02          | 1131.82       | 57.43              |
| Mean|                 |               | 57.35              |

| RPM | PRED. THRUST(g) | APC THRUST(g) | Accuracy of THR(%) |
|-----|-----------------|---------------|--------------------|
| 1000| 12.53           | 15.63         | 80.16              |
| 2000| 50.12           | 62.06         | 80.75              |
| 3000| 112.76          | 139.75        | 80.69              |
| 4000| 200.47          | 249.17        | 80.46              |
| Mean|                 |               | 80.51              |
Based on the estimation result using equation (6) and data comparison, the average accuracy estimation for 10x5 propeller is 80.51%, and 57.35% for 15x10 propeller. It can be seen that the average value of obtained K1 and K2 perform good estimation although there is a decreasing tendency of the thrust estimation accuracy. The average values of K1 and K2 are used as the approximation of the constants on 10x5 and 15x10 propellers by assuming the shapes are identical.

Based on the extrapolation method for 10x5 and 15x10 propellers, there is a significant difference in accuracy value. One of the possible causes is due to pitch value in 15x10 propeller, has significant difference compared to average pitch value from propeller 12x6, 13x6.5, and 14x7. Thus, generalization on 15x10 propeller based on measured propellers from TBS has lower accuracy value (57.35%).

In order to increase the static thrust estimation accuracy, more number of test propellers with various dimensions of diameter and pitch can be used to determine the mean values of K1 and K2 in order to generalize wider range of propeller diameter and pitch dimension with the same shapes and types. Another constant K3 also can be added as needed in to the equation (6) to modify a certain variable such as RPM to provide better estimation accuracy [7].

In order to increase the TBS measurement accuracy some additional features in measurement modes can be implemented such as RPM_HOLD to provide constant RPM value in order to determine static thrust data in more proper method. Also more proper placement for the sensors will provide better airflow to the propeller.

5. Conclusion
A low cost and easy-to-manufacture TBS has been achieved because of various method implemented during manufacture and assembly. It costs IDR 1,589,500.00, and much cheaper than similar system in market. The features of TBS are thrust, temperature, vibration, voltage, RPM, and current measurement. Although TBS is a low cost system, TBS has 83.3% estimated accuracy for thrust measurement with the highest recorded accuracy is 90.84%. With 83.3% accuracy of TBS, propeller characterization could be used to estimate static thrust for similar diameter and pitch propeller.

The modeling of propeller characteristics was successfully performed using a simple empirical approach using static thrust data and RPM measurements from TBS. Propeller characteristic modeling yields 2 values of K1 and K2 constants that can be used to represent propellers of similar shapes and types.

As an electric propulsion system performance measuring instrument, TBS can be utilized widely and further developed for other purposes.

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