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Propulsion System Testing Instrumentation for Multi-Rotor and Lighter-than-Air UAVs

Brendan Cox,* and Or D. Dantsker†
Indiana University, Bloomington, IN 47408

Robert W. Deters‡
Embry-Riddle Aeronautical University - Worldwide, Daytona Beach, FL 32114

Unmanned aerial vehicles (UAVs) and lighter-than-air (LTA) vehicles have seen an increase in popularity from use in civilian, education, government, and military applications. However, these systems are often constrained by limited on-board energy storage, heavily affecting flight time and overall usability. One of the main factors in the energy consumption of UAVs and LTA vehicles are their propulsion systems. This means determining the most optimal combination of possible propulsion system components, i.e. propellers, motors, and electronic speed controllers (ESC) can have a major impact on the performance of these vehicles. Options for each of these components range in the hundreds, yet it can be very difficult, if not impossible, to find proper performance specifications on the majority of them. In order to determine these performance specifications, a cost-effective and reproducible propulsion system testing apparatus has been developed and validated. This testing apparatus was designed to measure the performance and efficiency parameters of electric propulsion system components (propellers, motors, and ESC) in a static environment. The GWS Direct Drive 3×2 propeller was tested, with the results showing that this testing system provides very similar results to known data. Data from this system will be used in the future to aid in optimizing LTA vehicle performance for the Defend the Republic (DTR) competition as well as multi-rotor (quadcopter-style) UAVs.

Nomenclature

ADC	=	analog-to-digital converter
DTR	=	Defend the Republic competition
ESC	=	electronic speed controller
LTA	=	lighter-than-air
PWM	=	pulse width modulation
RPM	=	rotations per minute
RTS	=	reaction torque sensor
UAV	=	unmanned aerial vehicle
C_P	=	power coefficient
C_T	=	thrust coefficient
D	=	propeller diameter
i_s	=	supply current
n	=	propeller and motor rotation rate
p	=	ambient pressure
P	=	electrical power
Q	=	torque
R	=	universal gas constant
T	=	thrust
T	=	ambient temperature
V	=	air flow velocity
U_s	=	supply voltage
ρ	=	density of air

*Undergraduate Student, Department of Intelligent Systems Engineering, AIAA Student Member. brewcox@iu.edu.
†Assistant Professor, Department of Intelligent Systems Engineering, AIAA Member. odantske@iu.edu.
‡Associate Professor, School of Engineering, AIAA Senior Member. detersr1@erau.edu.

I. Introduction

The rising popularity of UAVs in recent years stems from their versatility across a wide range of applications, including precision agriculture, infrastructure monitoring, environmental surveillance, mapping, search and rescue operations, and even weather forecasting. However, a major challenge in UAV design is energy storage, which imposes strict limitations on flight time and overall functionality. As a result, selecting the right propulsion system has become a pivotal decision in UAV development, directly impacting their efficiency and usability.

In previous work, a mission-based propulsion system optimization tool was developed for fixed-wing unmanned aircraft [1] to select the most optimal combination of possible propulsion system components for a given mission profile, i.e., propellers, motors, and ESCs. Currently, there are hundreds of propeller and dozens of motor and ESC options in the radio control model market for small- to medium-sized (1-3 m wingspans) fixed-wing aircraft, yielding thousands of possible choices. Therefore, the problem became gathering component parameters with often scarce performance specifications. Recent propeller testing efforts by the authors have measured electric fixed- and folding-blade propellers from manufacturers such as APC, Master Airscrew, AeroNaut, Graupner, Kavan, etc.,[2–4] which are mostly suited to fixed-wing unmanned aircraft.

Previous works have measured the performance and efficiency parameters of propellers as well as other electric UAV propulsion system components. Brandt[5,6] and Uhlig[7,8] explored the performance of low-Reynolds number propellers at slow speeds and past stall. Lundstrom performed a similar test using an automotive-based testing rig.[9,10] Deters looked into the performance of micro propellers for both small/micro air vehicles,[11,12] later expanding his work to look at static performance of micro propellers for quadrotors.[13,14] Lindahl[15] tested large UAV propellers in a wind tunnel while Chaney[16] and Dantsker[17] did so using automotive based rigs. Lindahl also tested the effects of using different motors with a given propeller. Drela has done extensive work testing and modeling motors and propellers.[18–20] Green[21] and Gong[22] have modeled and tested the efficiency of ESCs. Gong has also tested a propeller-motor combination in a wind tunnel[23] as well as create an in-flight thrust measurement system.[24]

Examining non-fixed wing unmanned aircraft, for example multi-rotor and lighter-than-air vehicles (LTA), there is a similar need to optimize their propulsion system to meet both performance and endurance requirements. The authors have previously static performance tested micro propellers for quadcopters.[14] However, a larger set of propeller data is needed to enable widespread optimization of multi-rotor and lighter-than-air (LTA) UAVs (discussed further below). Based on examination of existing unmanned aircraft of interest, Gemfan,[25] HQProp,[26] DALProps, and APC[27] fixed-blade electric propellers were identified as good candidates. Fig. 1 shows several examples of propellers that are of interest for testing.

(a) (b) (c) (d)

Figure 1: Example propellers of interest for testing (a) Gemfan Hurricane 3020 (3-blade, 3” diameter, 2” pitch), (b) Gemfan Bi-Blade 1610 (2-blade, 1.6” diameter, 1” pitch), (c) DAL New Cyclone T3528 (3-blade, 3.5” diameter, 2.8” pitch), and (d) HQ Prop Tri-Blade 4×3×3 (3-blade, 4” diameter, 3” pitch).

As part of a multi-university effort between Indiana University and Embry-Riddle Aeronautical University, a multi-use propulsion system testing rig is being developed with the primary purpose being static performance testing of propellers and propulsion system elements. Below are two applications that the developed propulsion system testing rig will be used for — multi-rotor (quadcopter-style) UAVs and light-than-air (LTA) vehicles. The ultimate goal is to develop a reproducible testing fixture, encompassing both hardware and software elements, which can be used by the broader community.

This paper begins by exploring potential applications for a cost-effective electric propulsion system testing apparatus. It then examines the system's key requirements before outlining the equipment, testing procedures, and data reduction methodology. The design and development process is detailed next, followed by the validation testing conducted on the apparatus. Finally, the paper concludes with a summary and a discussion of future work.

II. Propulsion Testing Applications

A. Multi-Rotor UAVs at Embry-Riddle Aeronautical University

For multi-rotor UAVs, the propellers are the source for all lift and thrust required by the aircraft. Of particular importance is the static performance of the propellers which directly relates to the hover capabilities. By knowing the thrust and power from the propellers along with the power consumption of the electric motors, the hover performance can be predicted as well as the amount of time the UAV can stay airborne based on the available battery capacity.

B. Lighter-the-Air UAVs at Indiana University

One ongoing effort that requires significant propeller data is the design of LTA vehicles for the Defend The Republic (DTR) competition.[28,29] At the DTR competition, collegiate teams strive to create the most competitive LTA vehicles with significant physical constraints in a head-to-head competition as an exploration into the research necessary for autonomous aerial vehicles.[30,31] Fig. 2 shows LTA vehicles navigating the game space during a DTR match. During the competition, students aim to have their vehicles capture neutrally-buoyant goal balloons, and place them through colored, multi-shaped hoops on the opposing end of the playing field with limited sensing, actuation, and computational

Figure 2: LTA vehicles navigating the game space during a DTR match

capabilities. Previously, researchers[32–39] have explored aspects such as the design and development of LTA vehicles as a whole. However, as these systems are novel and are continuously being iterated upon, optimization is an area that has not yet been thoroughly explored. The major constraints on physical designs is a maximum helium budget and a maximum negative buoyancy of 100 grams.[40] Thus, the lift requirement drives the need for efficient propulsion systems design and therefore appropriately-sized propeller performance data.

III. Testing Requirements

It is desired that the propeller testing apparatus be able to measure the performance and efficiency characteristics for a wide range of propeller shapes and sizes. With that being said, three key requirement areas of interest that drove the design were (1) overall consistency, (2) cost efficiency, and (3) system reproducibility.

A. Operational Similarity

The propeller testing apparatus should be able to simulate the conditions which the propeller, motor, and ESC will experience in-use. One aspect of concern is whether or not the air flow the propeller experiences will mimic what is exhibited in actual flight. As this paper aims to create a system valid for testing propeller performance multi-rotor and LTA UAVs, a static testing setup will be created with the ability to add external flow generation at a later time.

B. Measurement Capabilities

In order to conduct a proper comparison between possible propellers, the propulsion system testing apparatus must be capable of recording all relevant/required measurements. Based on previous work, the following measurement capabilities were identified as required for testing:

- motor–propeller thrust T, torque Q, and rotation rate n
- supply voltage U_s and current i_s

It was also desired that the instrumentation be able to acquire the above fields at the highest realistic frequency possible. This requirement follows that noise can be averaged out more effectively as the acquisition rate increases. Based on the range of commercially available components (i.e., size, compatibility, price, and availability) as well as previous experience integrating data acquisition systems into aircraft (e.g., interfacing with ESC),[17,41–46] a desired acquisition rate is in the order of 100Hz.

C. Test Component Compatibility

The propulsion system testing apparatus should be able test propellers and motors for all of the desired unmanned systems. For example, for the DTR LTA vehicles, propellers with 1.5 mm mounting holes are desired. Tables 1-3 provide a list of the 1.5 to 6 in. propellers and Table 4 provides a list of motors that are of interest to be tested for the LTA vehicles.

Table 1: Gemfan Fixed-Blade Electric Propellers of Interest for Testing

Gemfan Propellers				
Hurricane	**Ducted**	**Bi-Blade**	**Flash**	**Tri-Blade**
2009 (3b, 2×0.9)	1815 (3b, 1.8×1.5)	1610 (2b, 1.6×1)	2540 (3b, 2.5×4)	3530 (3b, 3.5×3)
2008 (2b, 2×0.8)	1815 (2b, 1.8×1.5)			
3020 (3b, 3×2)	2530 (3b, 2.5×3)			
2023 (3b, 2×2.3)	3030 (3b, 3×3)			
4024 (2b, 4×2.4)				
2512 (3b, 2.5×1.2)				
2520 (3b, 2.5×2)				
3018 (2b, 3×1.8)				
3016 (3b, 3×1.6)				

Table 2: DALProp Fixed-Blade Electric Propellers of Interest for Testing

DALProp Propellers
New Cyclone
3528 (3b, 3.5×2.8)
2530 (3b, 2.5×3)
3018 (3b, 3×1.8)

Table 3: HQ Prop Fixed-Blade Electric Propellers of Interest for Testing

HQ Prop Propellers		
Tri-Blade		**Bi-Blade**
3525 (3b, 3.5×2.5)	5125 (3b, 5.1×2.5)	5030 (2b, 5×3)
3030 (3b, 3×3)	2515 (3b, 2.5×1.5)	3015 (2b, 3×1.5)
3025 (3b, 3×2.5)	3520 (3b, 3.5×2)	3522 (2b, 3.5×2.2)
3535 (3b, 3.5×3.5)	3530 (3b, 3.5×3)	1510 (2b, 1.5×1)
3020 (3b, 3×2)	3015 (3b, 3×1.5)	2015 (2b, 2×1.5)
5020 (3b, 5×2)	4030 (3b, 4×3)	
2535 (3b, 2.5×3.5)	2520 (3b, 2.5×2)	
2525 (3b, 2.5×2.5)	2015 (3b, 2×1.5)	
4020 (3b, 4×2)	3018 (3b, 3×1.8)	
1510 (3b, 1.5×1)	2010 (3b, 2×1)	

Table 4: Motors of Interest for Testing

Motors
iFlight Xing2 1404 4600KV
HGLRC Specter 1404 2750KV
HGLRC Specter 1303.5 5500KV
BETAFPV 1103 11000KV
Flash Hobby King 1303 5000KV

IV. Experimental Methodology

A. Equipment

The propulsion system testing rig is being developed at Indiana University. A diagram showing the load and torque cell configuration can be seen in Fig. 3. The propellers are mounted to the motor so that the thrust force is pointed downwards, toward the load cell. With this propeller configuration, the propwash is directed away from the rig so that it does not interfere with the measurements. Thrust is measured using a load cell and torque from the propeller is measured using a reaction torque sensor (RTS). Each propeller is tested using an appropriately-sized brushless motor using a speed controller. To provide power to the motor, a power supply is used. Propeller RPM is measured via the ESC's auxiliary pin.

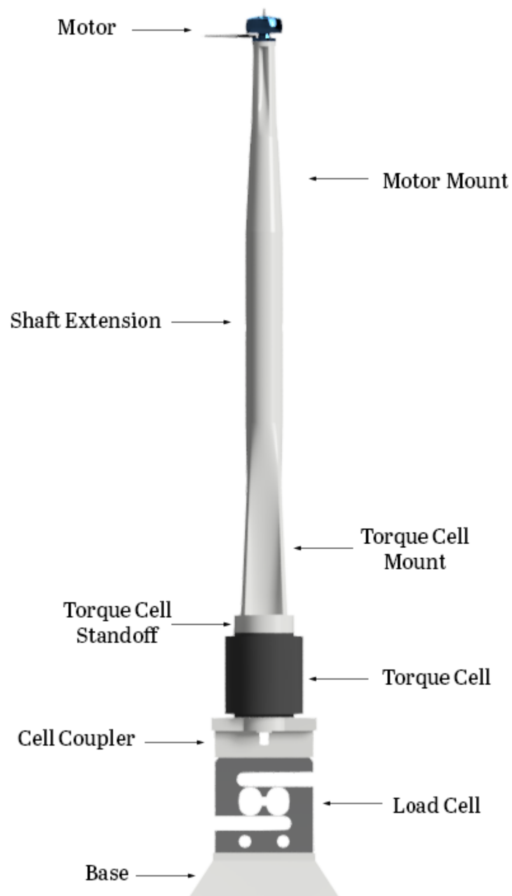


Figure 3: Torque and load cell configuration.

B. Testing Procedure

As a static performance test, the thrust and torque is measured over a range of RPMs. To control RPM, a micro controller is used to generate a PWM signal between 1000 and 2000 μsec in 10 μsec increments, which is sent to the speed controller. Each increment is commanded for 15 sec, allowing for many data points to be collected for each RPM.

C. Data Reduction

The ambient pressure and temperature are measured using an external pressure and temperature sensor. Air density is then calculated from the equation of state

$$p = \rho RT \tag{1}$$

where R is the universal gas constant. The standard value of 1716 $\mathrm{ft}^2/\mathrm{s}^2/{}^\circ\mathrm{R}$ (287.0 $\mathrm{m}^2/\mathrm{s}^2/\mathrm{K}$) for air was used.

Propeller power is calculated from the measured propeller torque by

$$P = 2\pi nQ \tag{2}$$

Performance of a propeller is typically given in terms of the thrust and power coefficients, defined as

$$C_T = \frac{T}{\rho n^2 D^4} \tag{3}$$

$$C_P = \frac{P}{\rho n^3 D^5} \tag{4}$$

where nD can be considered the reference velocity and D^2 can be considered the reference area.

V. Design and Development

The design and development of the propulsion system testing apparatus was split between two efforts: (1) static testing assembly and (2) instrumentation.

A. Testing Assembly

The core of the propulsion system testing apparatus is the physical testing assembly, which contains both load and torque cells and provides a variable mounting system for the motor and propeller. An isometric rendering is shown in Fig. 4. The assembly is composed of a 3D-printed base, of which the load cell is mounted to. Above the load cell is another 3D-printed component that serves as a coupler between the load cell and the torque cell. A long, 3D-printed three-piece shaft is then mounted above the torque cell, the top of which serves as the mount for the motor. The modular shaft section allows for multiple extensions to be added when testing larger propellers, and also enables modular tops to seamlessly switch between motors of different sizes. All parts were printed in PLA on a Prusa MK4 printer.

B. Instrumentation

The propulsion system testing apparatus was instrumented with a variety of sensors to record the required data during testing. As mentioned before, the testing rig contains a load cell and torque cell to measure the thrust and torque produced by the propeller when running. The remainder of the sensors are located below the testing assembly region and include: an ESC data interface (which provides RPM), a supply voltage measurement sensor, and a supply current measurement sensor (between power supply and ESC).

Figure 4: Isometric view of the propulsion system testing apparatus.

An Arduino Giga R1 WiFi was used to record the supply voltage and current measurements from their respective sensors, RPM from the ESC, and also drove PWM to the ESC in consistent known intervals. A computer was used to interface with a wheatstone bridge ADC to intake raw voltage measurements from the torque cell and load cell during testing. The component specifications for the propulsion system testing apparatus instrumentation are provided in Table 5.

The instrumentation, combined with a known air density value and the data reduction described in Section VII.C., enables calculation of the following: inline measurement of thrust (T) and torque (Q) at the motor; ESC data collection of rotation rate (n); upstream measurement of supply voltage (U_s) and current (i_s). Thus, these enable the propeller thrust coefficient (C_T) and power coefficient (C_P) curves to be determined.

Table 5: Specifications of the Propulsion Testing Apparatus

Data acquisition system	Arduino Giga R1 WiFi
Sensors	
Thrust Cell	Phidgets S-Type Load Cell - 2kg
Torque Cell	Transducer Techniques 10 oz-in RTS reaction torque sensors
Wheatstone Bridge	Phidget Bridge 4-Input
RPM	Castle Aux Output
Current	DFRobot Isolated AC/DC 50A Current Sensor
Voltage	Analog Pin (ADC) on Arduino using Voltage Divider Circuit
Drivers	
Motor	iFlight XING2 1404 4600KV brushless motor
Speed Controller	Castle Phoenix Edge Lite 50
Power Supply	BK Precision
PWM Generator	Digital Pin on Arduino

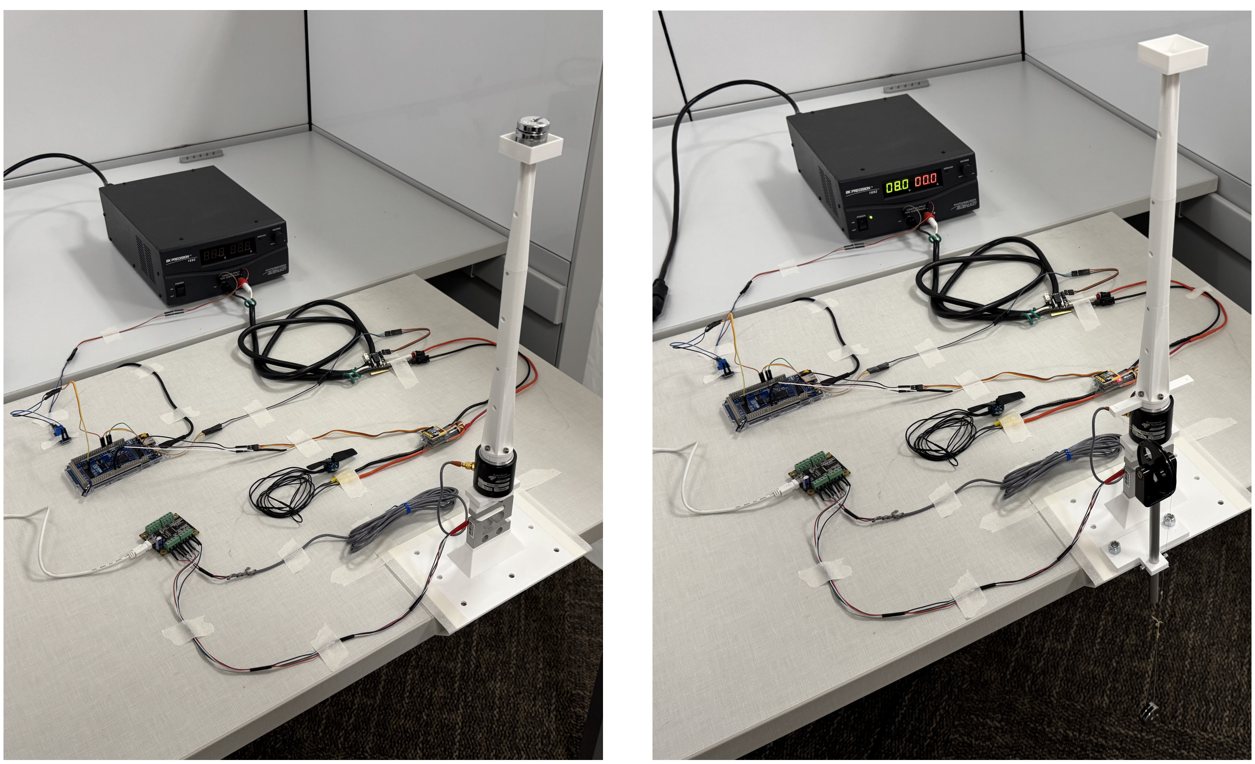
VI. Validation Testing

The propulsion system testing apparatus underwent validation testing, confirming its ability to accurately measure performance and efficiency data under static conditions. The validation testing focused on verifying that the testing apparatus is able to correctly measure propeller thrust and torque, as the mechanical design is new and untested. Calibration was also performed to verify load and torque cell, supply voltage, and supply current output linearity. The RPM data from the ESC was verified using an external optical tachometer and the voltages and current using calibrated voltage and current meters.

A. Calibration

The propulsion system testing apparatus underwent thrust and torque calibration to verify linear output and determine the required calibration constants. Thrust calibration, shown in Fig. 5 (a), was performed by stacking precision proof weights on top of the rig, thereby simulating thrust being applied to the load cell. A total of 18 precision weights were added sequentially creating simulated load that would be expected during propeller testing. Torque calibration was performed using a 3D printed pulley mount and extended rod attached to the load cell and can be seen in Fig 5 (b). Weights were applied using a low-friction pulley at a known location along the extension. A total of 9 precision weights were added sequentially creating a simulated torque that would be expected during testing. For both the thrust and torque calibrations, linear regression was performed on the data yielding R^2 values of greater than 0.9999.

The power supply voltage and current measurement sensors were both calibrated using an external calibrated multimeter and current sensor. To calibrate the voltage sensor, raw measurements were gathered over a period of 5



(a) (b)

Figure 5: Calibration setup for the load cell (a) and torque cell (b).

seconds at a single voltage measured using a multimeter. The raw values were averaged, and this process was repeated for voltages from 0 to 16 volts. For the current sensor, a static voltage was set, and a motor was powered at various PWM values from the voltage supply, inducing current to flow through the sensor from 0 to 4.5 amps. For each PWM value, raw values were taken in over a period of 5 seconds, after which they were averaged and noted down alongside a multimeter's measurement of the current. For both the voltage and current sensor calibrations, linear regression was performed on the data yielding R^2 values of greater than 0.99.

B. Testing

The complete and calibrated testing rig is seen in Fig. 6. Static propeller testing was performed using a propeller with known performance curves for points of comparison. The propeller chosen was the GWS Direct Drive 3×2. This propeller was previously tested by Deters and the performance data is available in the UIUC Propeller Data Site.[2]

Fig. 7 shows a comparison of the static run results for the propeller. The results show similarity in slope between both data sets, though the UIUC Propeller Data Site data seems to consistently start at higher values for both graphs. One other notable observation in the thrust coefficient graph is that there is a slight constant offset after the slopes normalize between the two sets of data. Fig. 8 shows a plot of thrust vs electrical power, while Fig. 9 shows plots of thrust, torque, and electrical power vs RPM.

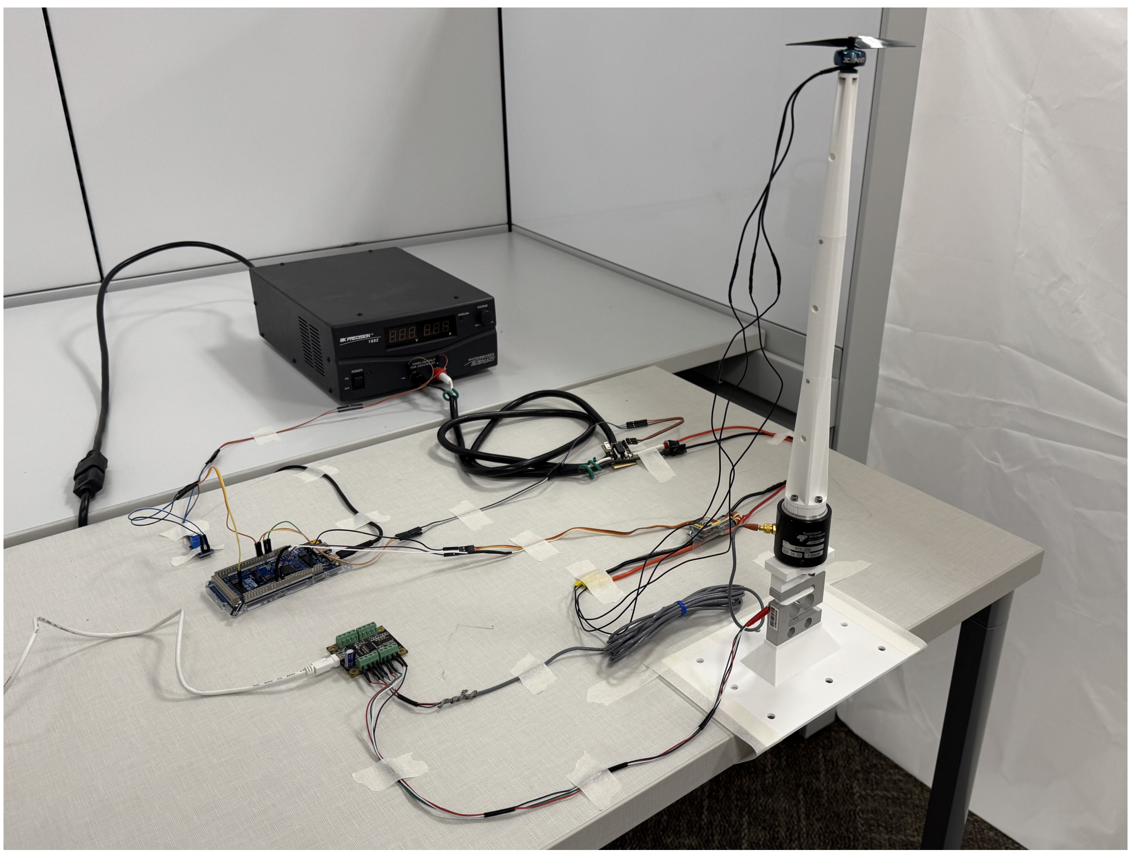
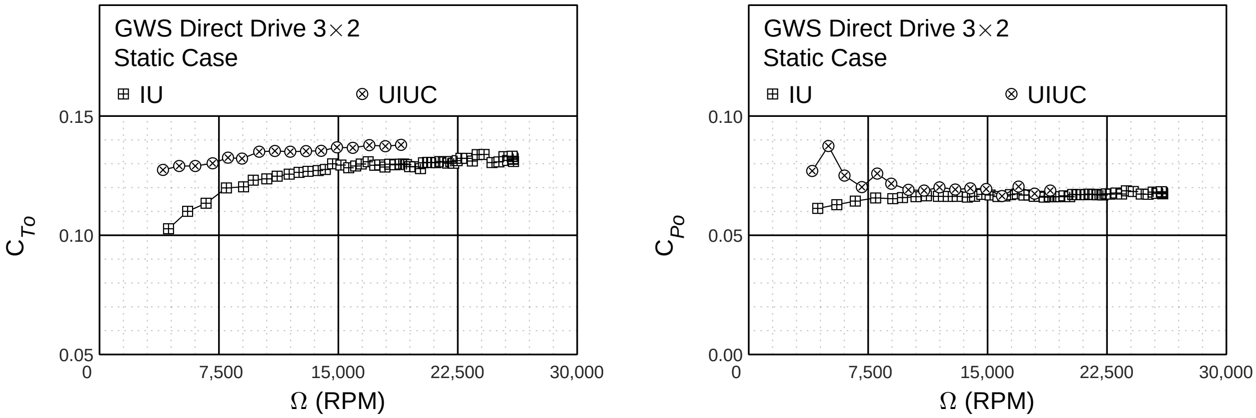


Figure 6: Complete and calibrated propulsion system testing rig.



(a) (b)

Figure 7: Comparison of static performance of the GWS Direct Drive 3×2 propeller: (a) thrust coefficient and (b) power coefficient.

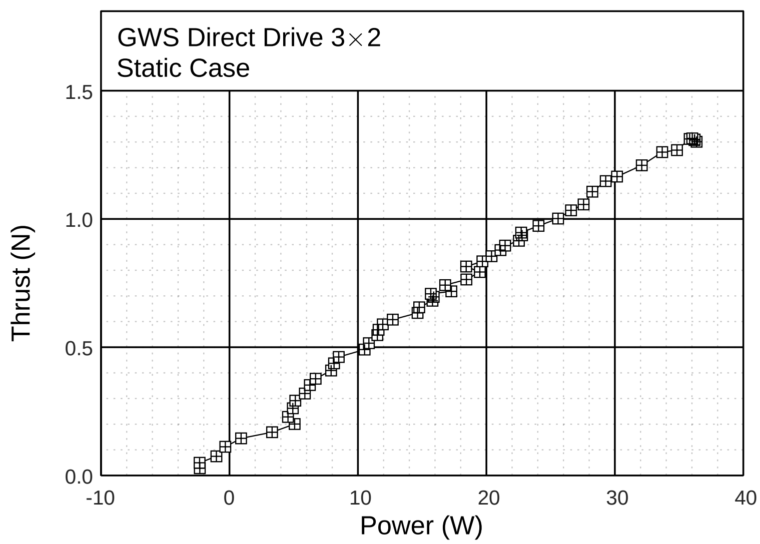
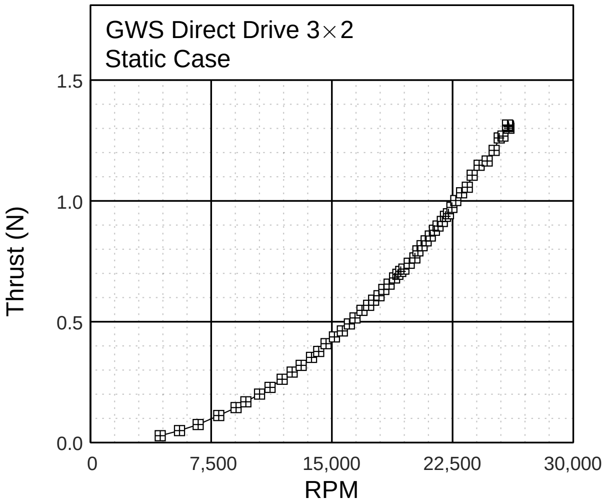
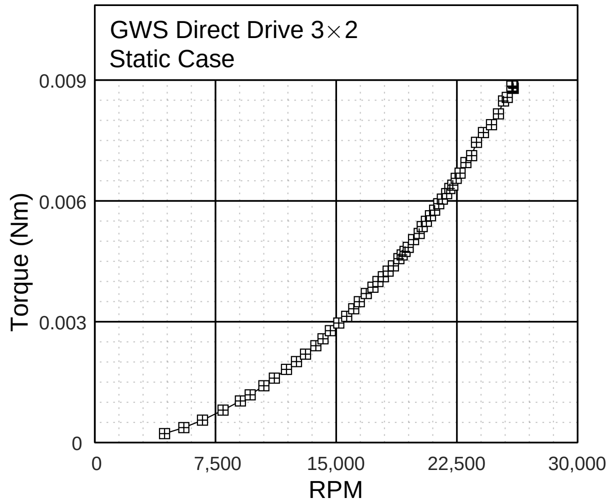


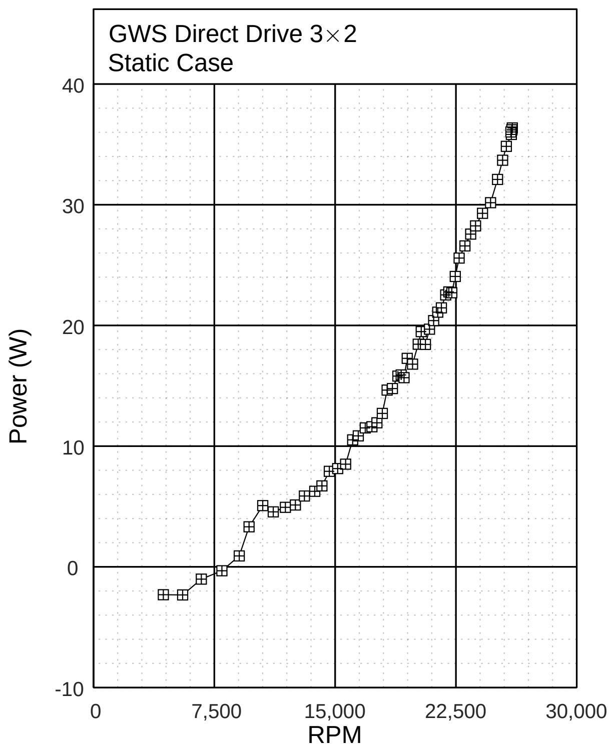
Figure 8: Plot of thrust vs electrical power for the GWS Direct Drive 3×2 propeller.



(a)



(b)



(c)

Figure 9: Plot of (a) thrust, (b) torque, and (c) electrical power vs RPM for the GWS Direct Drive 3×2 propeller.

VII. Summary and Future Work

This paper described the development and validation of a propulsion system testing apparatus that is designed to evaluate potential components for multi-copter and lighter-than-air (LTA) vehicles. Specifically, the testing apparatus was developed to measure the performance and efficiency parameters of possible electric propulsion system components (propellers, motors, and ESC) in a static environment. The propulsion system testing apparatus was instrumented with an accessible, yet reliable data acquisition system made up of an array of sensors allowing for simultaneous load, torque, electrical, and RPM measurement. The testing apparatus underwent calibration and validation testing, confirming its linearity and its ability to accurately measure performance and efficiency data under static conditions. The apparatus was then used to test the GWS Direct Drive 3×2, showing data consistent with that from the UIUC Propeller Data Site. Compared to existing works in the literature, the propulsion system testing apparatus presented in this paper allows for relatively simple and accessible testing of a wide range of electric propulsion system components in a static environment.

In future work, the propulsion system testing apparatus will be consolidated to only include a single microcontroller that can take in and log all data simultaneously, without the any need for an external computer. The system will also include measurements for the motor voltage and current, alongside an added sensor to measure the exact ambient pressure and temperature at the time of measurement. An external optical RPM sensor is also planned on being incorporated into the system to increase the accuracy of the RPM measurements.

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