A Low-Cost Method for Reaction Wheel Torque Characterization in Small Satellites

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ABSTRACT

Characterization testing of reaction wheels is necessary for requirement verification and to verify manufacturer specifications. Torque accuracy verification techniques include wheel speed based methods that assume perfectly made wheels or the use of torque transducers, which are expensive and difficult to set up. A low-cost optical torque characterization method is being developed to solve these issues. In the setup the reaction wheels are placed on a frictionless spin table, commanded an output torque, and then a Pixy-Cam optically tracks the angular position of the table. The data is curve-fitted to obtain angular acceleration and, in turn, the torque outputted by the wheels. In all complete trials the acceleration curves has R^2 values of >.97 indicating accurate characterization of the torques. This setup benefits from the Pixy-Cam's built in GUI and ability to interface with Arduino microcontrollers. While these results are promising, further development is required. Improving the nature of the test setup so that the center of mass of the reaction wheels can be easily located, and characterizing the error in the Pixy-Cam, are areas for future improvement. Despite these issues, this method of torque characterization still presents a promising, low-cost method for use in small satellite programs.

INTRODUCTION

An Attitude Control System (ACS) is an important part of many spacecraft missions. The hardware responsible for controlling a satellite's attitude varies depending on the needs of the mission and can take many forms, including an on-board propulsion system or magnetic torquers. One set of actuators that are found in virtually all spacecraft that require fine attitude control are reaction wheels.

Reaction wheels operate on the principle of conservation of angular momentum. Using an electric motor to spin one of the wheels will cause the satellite to rotate in the opposite direction of the wheel [1]. Using 3 wheels, and usually magnetic torquers for momentum dumping, accurate 3-axis attitude control can be achieved. Reaction wheels have been used on a wide variety of missions including high profile NASA spacecraft such as the Hubble Space Telescope [2]. However until recently these actuators remained prohibitively expensive for use in small satellites, especially low-budget University programs.

Due to the continued growth of the small satellite industry [3], many new manufacturers of satellite hardware have emerged. Several of these companies now produce reaction wheels that are more suited to small satellite missions in terms of size, power consumption, and price. Despite the fact that these new vendors provide specifications for their reaction wheels, it is still important for small satellite projects to perform independent verification and characterization testing of the actuators to ensure that the actuators meet mission requirements. It is also important to verify that the manufacturer specifications are correct as many of these new vendors do not yet have extensive flight heritage.

One important reaction wheel specification to characterize is torque output. As the final effect of the reaction wheels is to exert a torque to rotate the satellite, it is important to verify that the reaction wheels are capable of outputting the correct torque throughout the entirety of their range. Some methods of torque characterization are indirect and require extensive motor characterization, wheel speed analysis, and data acquisition [4-6]. Wheel speed based methods of characterization also assume the wheels are perfect and do not account for any mass imbalances or defects that might affect actual torque output [7]. Direct characterization of torque can require the use of a torque transducer, an instrument that is difficult to set up correctly and often a prohibitive cost burden on a University program.

To combat these issues, a novel and low cost approach to characterize reaction wheel torques is being developed. Using a device called a Pixy-Cam, which optically tracks a programmed color signature, a standard air-bearing spin table, and an Arduino microcontroller, the angular position of the wheel assembly with respect to time is tracked. Fitting this data to a second order curve, the angular acceleration of the setup, and in turn the torque, can be determined. This test setup was used to characterize the Maryland Aerospace (MAI) 101 reaction wheels for the University at Buffalo's Glint Analyzing Data Observation Satellite (GLADOS). The test methodology, results, and conclusions as they relate to the evaluation of the test setup are discussed further in the following sections of this paper.

METHDOLOGY

Setup Description

The test setup consists of 3 main parts: 1) the spin table assembly, 2) the reaction wheel assembly, and 3) Pixy-Cam assembly.

The spin table is a standard air-bearing spin table that is hooked up to pressurized air so that the table can spin without friction. A piece of circular white paper is then placed on top of the spin table with a colorful marker on the outer edge so that the Pixy-Cam can optically track the table's rotation.

The reaction wheel assembly primarily consists of the MAI 101 reaction wheels, which are contained in a cube-shaped pressurized box. The reaction wheel box is mounted onto a small aluminum fixture with standoffs so that the reaction wheels can be easily moved around the spin table. The reaction wheels are then plugged into a power and telemetry module, which consists of a power distribution board, a 9-volt battery, and a Bluetooth board. This module allows the wheels to both be powered wirelessly and send and receive telemetry wirelessly. The need for wired connections for either of these functions would produce a disturbance torque in the system that would affect measurements. This power and communication module is then covered in black electric tape so as not to interfere with the Pixy-Cam's color based tracking. The reaction wheel assembly is placed so that its center of mass is directly over the center of the spin table. Although the exact center of mass of the assembly can difficult to determine, the placement can be assumed to be correct when the spin table is at rest with the assembly on it. The issues with determining center of mass, the reaction wheel assembly placement, and the resulting problems with the frictionless assumption of the spin table, will be elaborated upon in the discussion section.

The most important part of the Pixy-Cam assembly is the Pixy-Cam itself, which is placed with the lens facing downwards into a hole in an arch shaped piece of glass. The arch is then placed over the reaction wheel assembly and spin table so that the Pixy-Cam is pointed down at the reaction wheels. The Pixy-Cam is connected to an Arduino Uno microcontroller, which is in turn connected to a laptop for data acquisition.

Pixy-Cam and Data Acquisition Setup

For both the determination of the inertia of the setup, and the determination of the angular acceleration of the system for a given command torque, angular position data with respect to time is used. To obtain this data a data acquisition system comprised of the Pixy-Cam, an Arduino, and a Laptop is used. The first step in the preparation of the data acquisition setup is to "train" the Pixy-Cam to track the colored marker on the outer edge of the spin table. To do this, the Pixy-Cam is simply pointed at the colored marker against a plain background and the built in software is used to specify that as the color that the camera should track. A small colored marker is then placed on the edge of the spin table and observed through the processed video provided by the Pixy-Cam software to verify that it is indeed tracking the small colored marker. A simple Arduino code is then used to take the data from the Pixy-Cam and display the x and y position coordinates of the small colored patch on the spin table. The laptop then displays the x and y position on a serial monitor. The data is recorded at a rate of 20 data points/second. Using the complete record of the x and y position data over the entire respective trial, along with the dimensions of the spin table, the angular position of the small point of color with respect to time is determined. This approach for obtaining the angular position data is used throughout the whole experiment.

Inertia Determination

The formula used to determine the torque output by the wheels from angular acceleration is:

$$\tau = I\alpha \quad (1)$$

Therefore, in order to determine the torque in subsequent trials, the inertia of the setup must be determined

To do this, the following equation is used:

$$H = I\omega \quad (2)$$

Where H is the angular momentum of the system. For the MAI 101 reaction wheels, the momentum storage capacity is listed on the data sheet. This specification is commonly found in all reaction wheel documentation. With this value known, only the angular velocity term must be determined to solve for the inertia. To determine the angular velocity, the recording of data with the Pixy-Cam is begun, and then the reaction wheels are commanded to their maximum speed. Then, once they have reached that speed for several seconds, data recording halts. The wheels are then turned off. The resulting position data is thus mostly second order, but tails off into a first order line when no more torque, and thus acceleration, is available. By ignoring the beginning of this position curve and extracting the slope of the first order section at the tail, the maximum angular velocity that corresponds to maximum wheel momentum can be calculated. The maximum momentum on the data sheet is divided by this experimentally determined spin speed, in order to find experimentally determined inertia. This value of inertia is then used in all subsequent torque verification trials.

Torque Verification

To verify the torque accuracy of the reaction wheels over their entire range, 8 different torques are commanded to the wheels in 8 respective trials. For each trial the x and y coordinates of the colored patch with respect to time are used to produce the angular position data. This data is then analyzed to obtain the angular acceleration of the colored patch.

This analysis is done by extracting the period of acceleration from the full set of position data. The beginning of the acceleration period is identified by the position starting to rise from a near-constant value. The end of the acceleration period is identified by a switch from a second order polynomial curve to a constant slope.

Once the acceleration period is extracted from the full data set, it is normalized to a time and initial position of 0, and a second order polynomial is fit to the normalized position data. Assuming a constant acceleration means that the following kinematic relationship between angular position, angular velocity, and angular acceleration is true:

$$\theta = (1/2)\alpha t2+\omega_0 t \qquad (3)$$

In this equation, the initial angular velocity term corresponds to any rotation that may be present in the spin table setup before the acceleration period. In all trials, the table is initially at rest, effectively making this term zero. The coefficient of the squared term in the polynomial fit is then used to calculate the angular acceleration, α, from the trials. Now that the inertia and the angular acceleration are known, the applied torque can be calculated from the aforementioned equation 1.

In reaction wheel verification testing, the calculated torque is then divided by the commanded torque to determine torque accuracy (as was done for the GLADOS mission). However, as the objective of this paper is not to assess the torque accuracy of particular reaction wheels, but to instead evaluate the merit of this setup as a whole, the results and discussion session will focus on the statistical accuracy of the acceleration results as a metric to assess the test setup.

RESULTS

Calibration

In order to obtain accurate angular position data for each trial, the setup must be calibrated to find the relative center of the x and y coordinates being displayed. To do this, the marker on the spin table is put through a full rotation, and the maximum and minimum coordinates are obtained. Using these coordinates and the physical spin table measurements, the millimeter per Pixy-Cam coordinate relationship is determined. This data is then processed data into a relative coordinate frame with origin placed at center of x and y range. Using the data processed into this new frame, the angular position for the following trials can then be calculated. The following graph shows the x and y coordinates in this frame and inspection of the sinusoidal shape proves that it is an accurate characterization of the circular spin table.

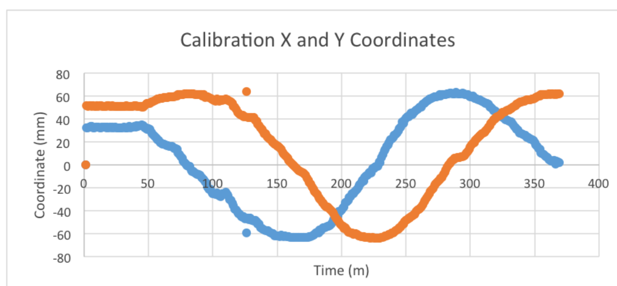

Figure 1: Calibrated Pixy-Cam X and Y Coordinates

Inertia Trial

Using the Pixy-Cam and calibrated coordinate system, the following curve fit for the angular position data for the inertia trial is obtained:

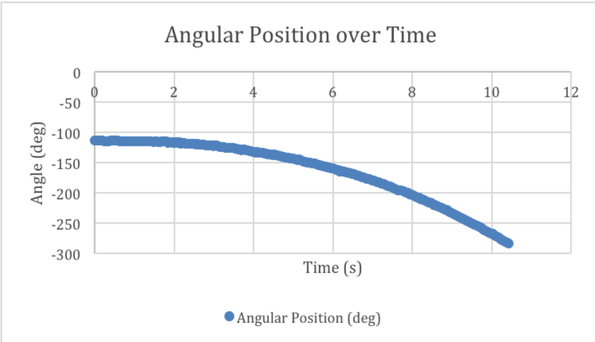

Figure 2: Angular position data for inertia trial

Using the steps described in the inertia determination section, the angular velocity after the wheels are saturated is then obtained and found to be $\omega = 0.5507$ rad/s. The first order section of the data from which the slope is extracted is displayed below.

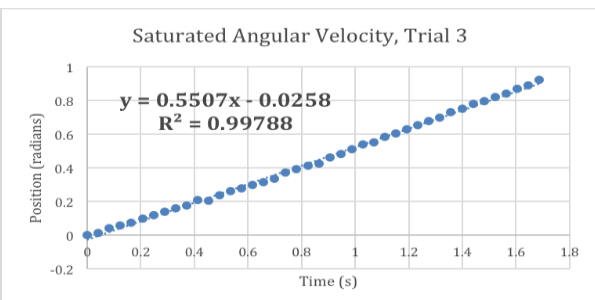

Figure 3: Saturated angular velocity for inertia trial

It can be seen that the data points fit well to the expected linear curve, with an r^2 value of 0.997, indiciating that the results are statistically accurate.

Using the momentum storage capacity value listed on the data sheet (1.1 m*Nm*s), and the aforementioned angular velocity, the inertia of the setup is calculated to be $I = 2*10^{-3}$ $kg*m^2$. This value is used in all the following torque accuracy trials.

Torque Accuracy Trials

In this section, the analysis is completed for one trial to demonstrate the process, and then the results for all trials are presented.

For this trial, a torque of 0.635 mNm is commanded to the wheels and the following angular position data is obtained:

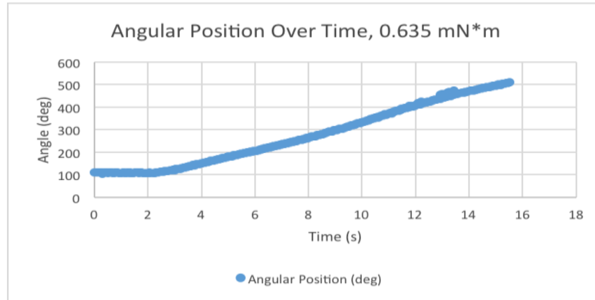

Figure 4: Angular position for torque trial 1

Upon close examination of the raw data, the beginning of the acceleration period is determined to be at 2.044 seconds and the end of the acceleration period is found to be at 3.853 seconds. Looking at this subset of data and plotting the normalized time and position results in figure 5.

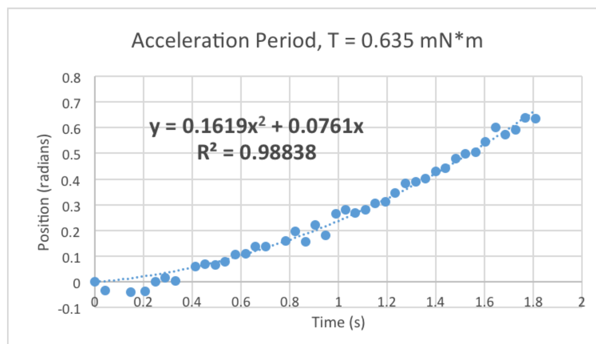

Figure 5: Data from the acceleration period. The initial time and position of this period was subtracted from the raw data shown in figure 4.

Once the acceleration data is plotted, a second order polynomial is fit to the data. Comparing the polynomial fit to the kinematic equation presented in the methodology section shows that the coefficient of the squared term, 0.1619 in this case, is equal to half of the angular acceleration. The torque applied by the wheels is then calculated as follows:

$T_{applied} = I\alpha = 2.0*10^{-3}*2*0.1619 = \text{mNm}$

For the purposes of the original test, the percentage of the command torque is then calculated:

$T_{applied}/T_{commanded} = 0.647/0.635 = 101.95\%$

However, for the purposes of this paper, the interest lies in how accurately the setup is able to obtain the angular acceleration term and, in turn, the output torque. As a metric to measure this accuracy, the R^2 value is selected. An R^2 value is a statistical term that indicates how well a set of data matches a certain line or curve. A value of 0 indicates that the data does not fit the curve at all, while a value of 1 indicates a perfect fit. In this experiment it is used to represent how well the angular position data can be fit to a second order curve to determine angular acceleration. The table below lists the R^2 value for each of the 8 trials:

Table 1: Results from Torque Trials

Trial	**Torque Comma-nded (mN*m)**	**Torque Applied (mN*m)**	**Torque Percentage (%)**	**R^2**
1	0.191	0.169	88.7	0.999
2	0.254	0.191	75.3	0.999
3	0.318	0.36	113.5	0.972
4	0.381	0.38	99.6	0.985
5	0.445	0.454	102.1	0.989
6	0.508	0.517	101.7	0.984
7	0.572	0.522	91.4	0.994
8	0.635	0.647	101.9	0.988

At first glance, it is easy to see that all trials have high values for R^2, even when the output torque does not match the command torque. These results suggest that the setup is able to accurately determine angular acceleration. This is discussed further in the following discussion and conclusion sections

DISCUSSION

Torque Determination Accuracy

It is clear for all trials that the R^2 values indicate statistically significant results. It can be expected that during the acceleration period of the wheels, the data should fit well to a second order curve for acceleration. In all the trials for the experiment these high R^2 show that the data fits exceptionally well to these second order curves, indicating that accurate values for angular acceleration are obtained.

The lowest value of R^2 is 0.972 in trial 3. While this value is by no means disastrously low, it does merit review. For this particular trial, a likely source of error is the Arduino microcontroller not sustaining its data output rate. The Arduino is configured to output more than 20 data points per second, yet it only outputs about 10 per second for much of trial 5. There is a particularly large time gap between data points near the end of the acceleration period; 0.6 seconds passes without any data output. This microcontroller glitch results in there being less data to form an accurate polynomial fit, which then affects the calculated angular acceleration.

Although this trial is of lower data resolution, a relatively high R^2 value is still obtained and the data bears significant resemblance to the second order curve. It can confidently be stated that if this Arduino glitch does not occur, this trial would instead have similar accuracy to the others. In future testing, this can be corrected by examining the data for time gaps immediately after the trial is performed and rerunning the trial if necessary.

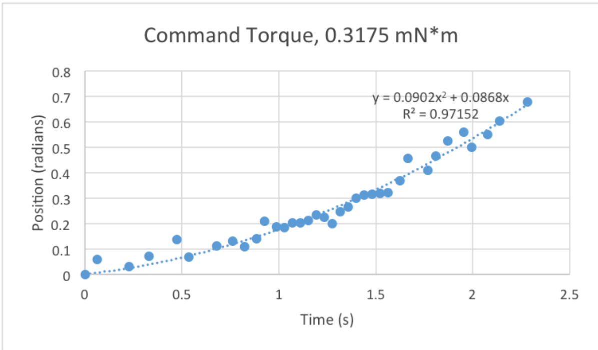

Figure 6: Trial 3 –limited data points for this trial

At first examination of the data presented in table one, one may be concerned that the discrepancies in commanded vs. output torque in trials 1 and 2 may also be a result of the test setup, and not the reaction wheels themselves. However, on closer examination of the trials, this concern can be dismissed.

For instance, in Trial 2, no Arduino microcontroller glitches occur that negatively impact the data resolution. Additionally, the polynomial fit has an R^2 value of greater than 0.99. The effect on torque percentage of making small adjustments to the acceleration start time and end time can be explored, and the reported value of 75.3% is never exceeded. No errors in the calculated angular acceleration can be seen, and the accuracy of other trials indicates that there is not an error in the measured inertia. This indicates that the error is in the reaction wheels ability to carry out the commanded torque. The acceleration period data for this trial is shown in figure 9 to demonstrate that there are no data resolution issues.

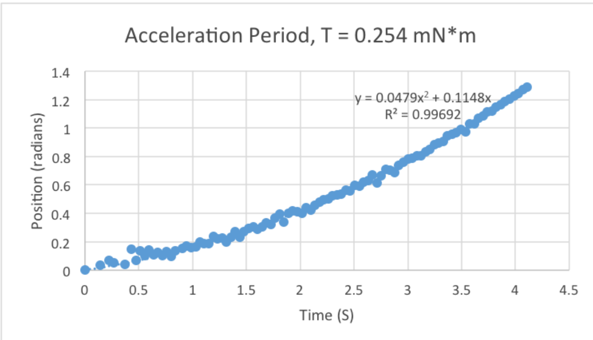

Figure 7: Trial 2 – No data resolution issues exist

Trial 1 is similar to Trial 2. There are no issues with the data resolution, the polynomial fit has an R^2 value of greater than 0.99 and the sensitivity of the torque percentage to varying the acceleration start and end times is explored. As with trial 2, the maximum torque percentage found from this sensitivity sweep never exceeds the reported value of 88.7%. Again, it appears that the source of torque percentage discrepancy is in the reaction wheels ability to torque as commanded. The position data for the acceleration period of trial 3 is shown in figure 10 to demonstrate that there are no data resolution issues.

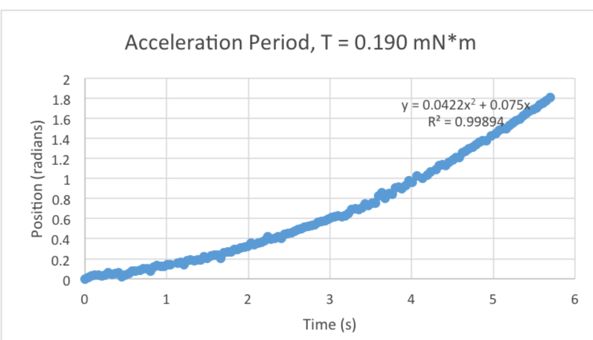

Figure 8: Trial 1 – No data resolution issues exist

From this examination of the trials in which there were large discrepancies in torque accuracy, it can be seen that it was the inaccuracy of the MAI 101 reaction wheels at low torque values (an inaccuracy, that along with unacceptable power consumption by the wheels, merited an eventual hardware change for the GLADOS mission), not an error inherent to the test setup, which produces these results.

From this thorough examination of the data, it can be seen that when the test setup performs correctly (no data resolution issues) it is able to accurately obtain the angular acceleration of the system, from which the torque can then be calculated.

Test Setup Advantages

This test setup has several advantages over other methods. The setup requires little development and setup on both the hardware and software ends. Additionally, the setup requires no assumptions about the wheels, as are required in wheel speed based characterization methods. Lastly, as cost is often a major concern for University programs, this method is very inexpensive.

This test setup requires virtually no hardware development to complete. The spin table is provided on loan from the physics department, and the Pixy-Cam and Arduino Uno are COTS products that come ready to use. The only physical work required to set up the test is to drill a hole in the arch-shaped piece of glass for the Pixy-Cam lens and assemble the setup.

From the software perspective, there is also very little work required. The software that the Pixy-Cam uses to lock onto and track a color signature comes pre-loaded on the device, and the built in GUI for displaying processed video is compatible with both Mac OS and Windows. All that is required is that a simple Arduino code to acquire the x and y data from the Pixy-Cam is written. The libraries for the interface between Arduino and the Pixy-Cam are readily available online, so little effort is required there as well.

This lack of development and setup stands in contrast to other systems that require either the development of complicated test rigs [6] or in house data acquisition systems [4]. The ease of use of this test setup is undoubtedly an asset for projects under time and personnel constraints.

Another advantage of this setup is its potential to characterize wheels that may have imperfections. Many characterization tests use measurements of wheel speeds to indirectly characterize torque [7]. However these tests inherently assume the wheels are perfect and are unable to characterize the possible defects and mass imbalances in the actuators. These defects may affect the final wheel output. In principle, this test setup can characterize reaction wheels in greater detail than the aforementioned methods. For vendors that are selling reaction wheels at relatively low cost, and have limited flight heritage, this detailed characterization is extremely important.

Lastly, this test setup is extremely low cost. Whereas other setups can require data acquisition devices developed in house (which entail extensive hardware and development costs), this simple plug and play data acquisition system consisting of the Pixy-Cam and Arduino can be purchased for under $100. Trying to directly measure torque (usually a complex endeavor) requires expensive torque transducers or analyzers, which can incur costs on the order of thousands of dollars, which make them prohibitively expensive for University programs. Perhaps the most expensive part of the setup is the air bearing spin table, which can cost a considerable amount when purchased independently. However, the setup does not require a large spin table, and the size and type of spin table used are ubiquitous in any University engineering or physics department. As the risk of damaging the table during this test is virtually non-existent, it is safe to assume that the majority of University cubesat programs will be able to obtain a small spin table with no cost to their program.

The ease of use and setup, potential for detailed wheel characterization, and low cost of the setup are all clear advantages of this method of torque characterization. However, despite these benefits, there are still areas for improvement.

Future Improvements

As the test setup has only begun development, there are several improvements that would even further improve its accuracy in the future.

One important assumption of the setup is that the spin table is frictionless. This assumption is obtained by connecting pressurized air to the table so that it can spin freely. However, there are difficulties with this assumption. If the reaction wheel assembly is not placed so that its center of mass is directly over the axis of the spin table, one side of the table will tilt downwards a small amount and the table will spin without any torques commanded to the wheels. This unwanted spinning can be stopped, but only after significant time is devoted to adjusting the position of the reaction wheel assembly. In future tests, it would important to better characterize the reaction wheel's center of mass. This is particularly difficult given that the MAI 101s are a closed box. Methods to determine the center of mass could include the use of a CAD model or detailed measurements.

On a related note, the method of calculating the inertia of the setup could also stand for improvement. It was initially proposed to use a pulley to characterize the inertia of the setup. It was planned to attach a known mass to a string, which would be wound around the spin table and then draped over a frictionless pulley. The mass would then be released from rest and the string would rotate the spin table and reaction wheels. Using the known mass, the drop height, and the acceleration due to gravity, along with the data gathered from the Pixy-Cam, the inertia of the system could then be calculated. Unfortunately, when the mass is released, the string can pull too hard on the spin table causing it to drag. This ruins the frictionless assumption and makes this method impossible to use. The inertia of the setup is still able to obtained, but the calculations rely on the accuracy of the momentum capacity specification on the data sheet and it is preferable that all variables be determined independently. This issue could be rectified with a spin table that allowed for a large air pocket, therefore preserving the lack of friction in the setup.

The last major area for improvement with the setup is Pixy-Cam error characterization. While the use of the Pixy-Cam proves to accurately characterize the angular acceleration, and its ease of use and price are definite advantages, the fact that the inherent error in the color tracking system has not been thoroughly characterized is an area for improvement. While the Pixy-Cam proves remarkably accurate upon visual inspection and indirectly through data processing, it would still be of benefit to know the exact error in the Pixy-Cam's data so that the system can be characterized as accurately as possible. This can most likely be solved through further analysis of the Pixy-Cam documentation and through further research into machine vision error bounds in general.

Despite these areas for improvement, it can be confidently asserted that this method of optical torque characterization presents an accurate, easy, and low cost method for use in University small satellite programs.

CONCLUSION

The growth of the small satellite industry has led to a growing breadth of missions that university cubesat programs can perform. These missions increasingly require fine attitude control and, therefore, actuators such as reaction wheels that can provide this control. In order to ensure mission success, it is vital that these small satellite programs independently characterize their reaction wheels.

This setup presents a novel and low cost method for these university programs to characterize their reaction wheel's torque outputs. It is shown that this method accurately characterizes the angular acceleration, and in turn the torque, of the system (with all trials displaying high R^2 values). It is also an extremely easy system to setup and requires very little hardware and software development. Its lack of the assumptions intrinsic to wheel speed based methods also leaves open the potential to further develop the test so that it can characterize wheel defects. Lastly, the system consists entirely of COTS hardware that is available at low prices.

This method provides an accurate way to characterize reaction wheel torques. With further development, it could become an even more detailed method for reaction wheel characterization that would provide valuable information to many university programs where fine attitude control is the crux of their mission.

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