Environmental and Performance Testing of Hard Disk Drives as Low-Cost CubeSat Reaction Wheels

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Introduction

Reaction wheels are an important component for attitude control of small satellites. Many low-budget CubeSat developers, particularly universities, face the issue of the high costs of reaction wheels. Missions that can not afford commercial reaction wheels often turn to manufacturing their own in-house, which historically have had a high failure rate. To disrupt the dilemma of cost vs. reliability of reaction wheels, UC Davis' first CubeSat, REALOP, will perform a technology demonstration of a hard disk drive (HDD) reaction wheel to raise their technology readiness level (TRL) to TRL 9.

Commercial small satellite reaction wheels cost from 10^3 to 10^4 USD, while HDDs cost on the order of 10 to 100 USD and are available as COTS products. Currently, the HDDs are at TRL 4, with the components validated in a laboratory environment through thermal, vacuum, and shock testing. The HDDs have also been modified to allow variable speed bidirectional control, and successful single-axis control tests have been performed. By raising the status of HDDs as reaction wheels to TRL 9, REALOP aims to lower financial barriers associated with small satellite development.

Figure 1: HDD with disks and motor hub removed, exposing copper-colored stator coils surrounding a bearing in the center of the motor.

Cost & Performance Study

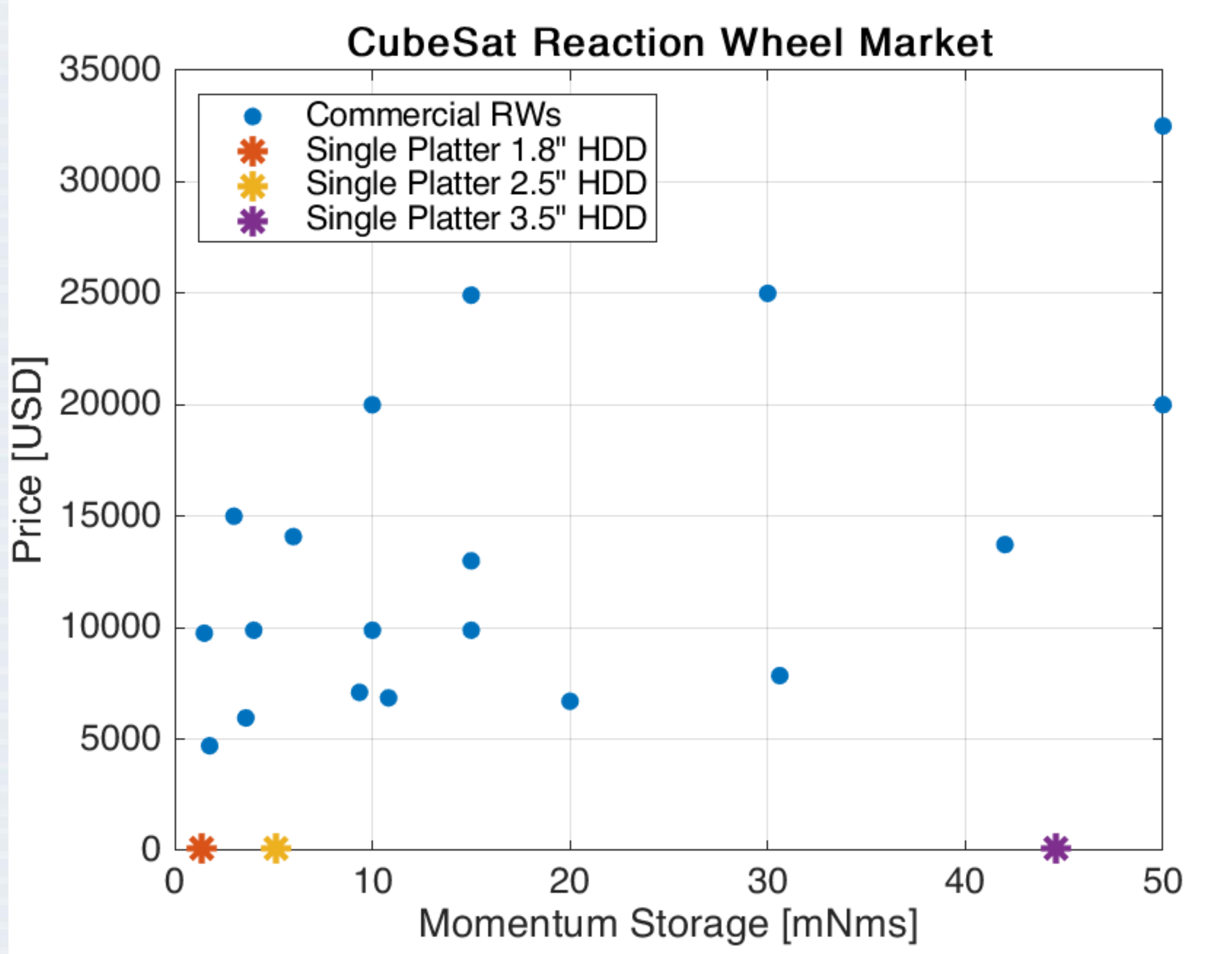

Figure 2: HDD reaction wheel performance & cost in comparison to commercial options

HDD Form Factor	Dimensions [mm x mm x mm]	# of Disks	Momentum Storage [mNms]	Torque [mNm]	Price [USD]
1.8”	71 x 54 x 5	1	1.4	0.33	$30
2.5”	100 x 70 x 7	1	5.1	0.29	$55
3.5”	147 x 102 x 20	1	44.6	TBD	$80

Table 1: HDD reaction dimensions, momentum storage, and cost

Modifications

While in their designed use case, hard disk drives are set to spin in one direction at a constant speed (i.e., 7200 RPM), this is in fact a limitation of their default control circuitry and not the HDD motor itself. The motor design is that of a three-phase brushless DC (BLDC) motor, which accepts as input three separate periodic signals used to turn multiple electromagnetic coils inside the motor on and off in succession. This pattern of electromagnets being turned on and off exerts a force on magnets also built into the motor, in such a way that these magnets are pulled towards one coil, followed by the next, and so on. This is what causes the motor to spin — therefore, the direction and speed of the motor can be controlled simply by modulating the signal being fed to the three motor inputs. However, the built-in control electronics of the commercial hard drive do not allow for this type of flexible control, so it is necessary to bypass and remove the HDD circuit board and interface directly with the motor via its three connection points that can be found under the board.

The HDD was modified to allow for testing. First, all unnecessary parts were stripped from the hard drive. This included the reading arm, any removable magnets, and the default control circuit. Next, wires were soldered to the three exposed motor pads on the HDD so that they could be put in a breadboard along with a custom ESC. The ESC and HDD were not compatible out of the box - to test this fact, the HDD and ESC were wired together on a breadboard and a power supply was connected. A PWM signal and a single digital output was used from a microcontroller to provide the speed command to the ESC, which resulted in sporadic, inconsistent movement from the HDD motor itself.

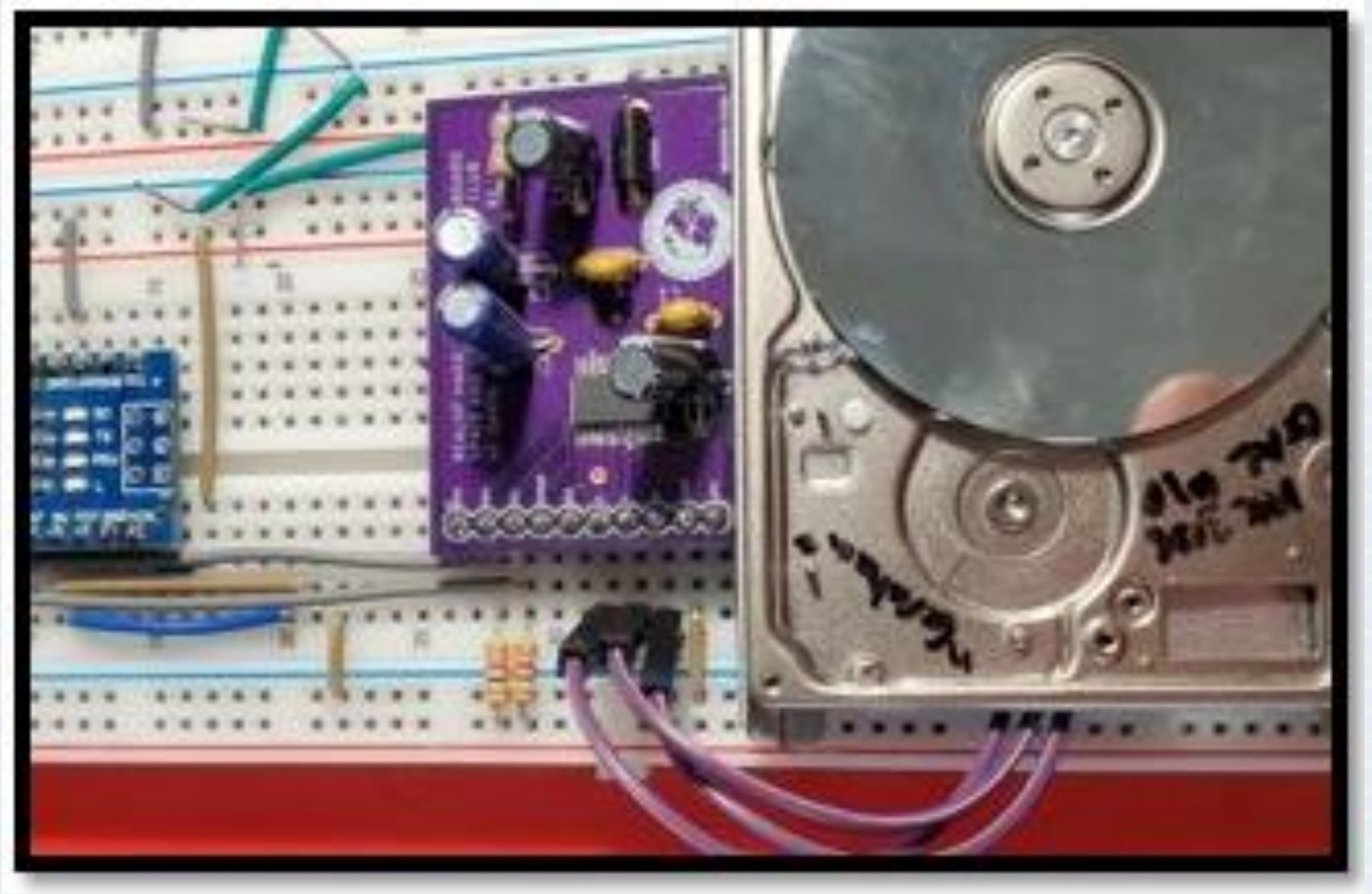

Figure 3: Test setup on breadboard featuring modified 1.8” HDD and custom PCB

Controls

Three-phase BLDC motors are very common in many areas of electronics, from quadcopters to computer fans, so circuits designed to control them are very common and diverse. However, in selecting an ESC for this application, a major consideration was that HDD BLDCs are designed for a highly specific purpose so their electrical characteristics are nonstandard. This meant that a standard ESC could not be expected to be able to control the hard drive. Furthermore, retail ESCs have high-power consumption and inefficiency, which generally makes them nonviable on microsatellites with small power and thermal budgets. Therefore, the design of a custom IC-based ESC is important as it can be tuned to the HDD motor and thus be more power efficient. The DRV10983 from Texas Instruments is selected as the ESC for the HDDs.

Due to the precise nature of the custom ESC, it can not properly control the HDD without some configuration. This requires programming of certain values into the ESC according to the HDD’s electrical and physical characteristics. The DRV10983 is used on a PCB designed to control the HDDs and is being tested and tuned for flight operations of the HDD.

Environmental Testing

Environmental testing is performed on various candidate HDD models to reduce risk by eliminating models that fail under expected mission conditions. Additionally, environmental testing provides better understanding of failures that may occur on orbit and can help diagnose issues during the mission. Although environmental testing at NASA Ames Research Center, initially planned for Spring of 2020, was unable to take place, less sophisticated environmental testing has been performed.

During early bench testing, the reading arm was found to crash against the disk and stay pressed against it after slightly touching the arm. Based on this observation, the decision was made to remove the reading arm of the HDD to avoid a failure caused by the launch loads damaging the reading arm.

To observe the resilience of the HDDs after applying high shock loads, HDDs were dropped from a height of 5m to simulate shock during launch. The impact of the HDD with the ground was recorded in slow motion to determine the duration of impact, from which the impulse was calculated. The HDDs were found to run after sustaining decelerations of up to 160 g’s, 20 times greater than the expected maximum 8 g’s on the Antares rocket. When powered again after dropping them, the HDDs were running with no indication of damage. Further testing will include inducing shocks in the HDDs in different orientations and performing a more thorough analysis post-drop.

To observe the HDD performance at high temperatures, hot air was pumped over HDDs to raise their temperature up to 140°C. It was found that when the HDD was powered with its dongle, some models would stop running above 137°C, but start running again once they were allowed to cool. This was indication of an overheat switch that automatically shut off the HDD when a threshold temperature was exceeded so that memory stored on the disk wasn’t corrupted. To run HDDs above this threshold temperature, their original circuitry is bypassed and the custom control board is directly connected to the HDD motor, as mentioned earlier.

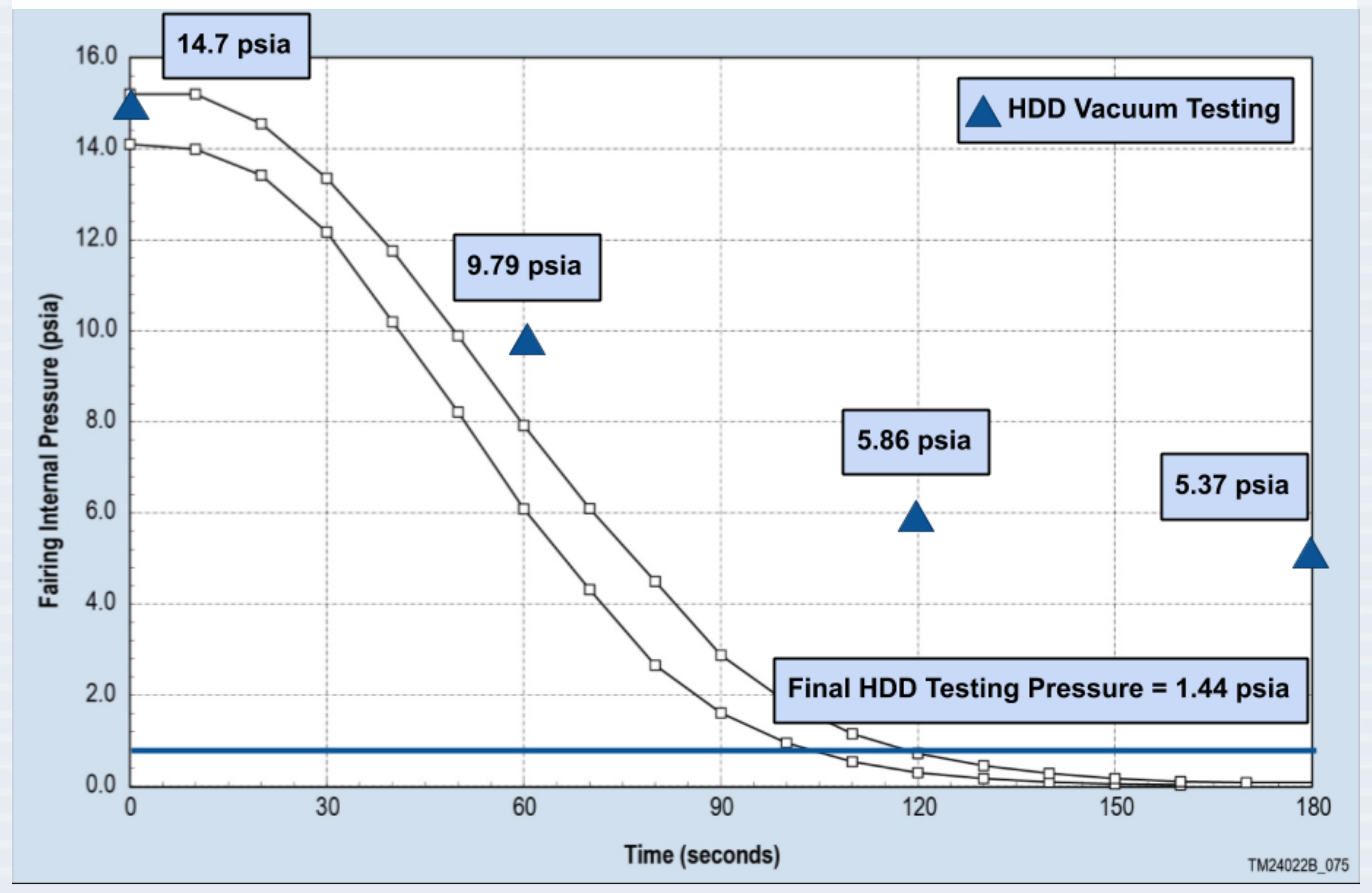

Figure 4: HDD Vaccuum Testing overlaid on Antares payload fairing pressure envelope

To test HDD performance in vacuum environment, preliminary testing was performed in low-vacuum. HDDs were powered to spin before beginning the test, during depressurization, and for 2 hours at 10% of atmospheric pressure. The HDDs were spun with no issues during depressurization and while in low pressure; however, upon repressurization, one of the HDD models stopped running. The cause of the HDD stopping is hypothesized to be a mechanical failure caused by the momentum of the air rapidly entering the system. Although repressurization is not an event that will occur at any point in the mission, the failure during repressurization implies that it may also occur during depressurization. The depressurization rate of the performed vacuum test is much slower than the expected pressure envelope during launch. A proper ascent vent test that matches the rocket pressure profile is required to investigate the effect rapid depressurization may have on the HDDs.

Vibration testing has not yet been performed; however a research paper has found the first mode fundamental frequency for a similar 1.8” HDD to be 450 Hz. The Antares User Guide recommends payloads to have a first mode fundamental greater than 20 Hz, so the 1.8” HDD is expected to withstand vibration loads of the rocket. Vibration testing will be performed at NASA Ames to verify that the HDD will survive launch.

Results

height (ft)	velocity initial (m/s)	Velocity final (m/s)	Force	Acceleration (m/s^2)	Acceleration (g's)
10	-7.74	0.97	25	1246	127
12	-8.47	1.06	27	1363	139
14	-9.15	1.14	29	1472	150
16	-9.78	1.22	31	1570	160

Table 2: Approximate impact accelerations observed from drop tests

Environmental Test	Results
Shock	Operational after 160g load
Vibration	1st mode freq. above requirement
Thermal	Operational up to at least 137°C.
Vacuum	Operational at 0.1 atm

Table 3: Environmental Testing Summary Table

Conclusion & Future Work

Preliminary bench and environmental testing has raised the TRL of HDD reaction wheels from TRL 2 to TRL 4. A specialized control board has been designed for the HDD reaction wheel and testing has shown that the control board and selected ESC are capable of controlling the HDDs. Preliminary environmental tests have given promising results, increasing confidence in the HDDs’ ability to survive launch loads and expected orbit conditions. Further testing and analysis is necessary and will be conducted at the NASA Ames Research Center to raise the TRL of HDD reaction wheels to TRL 7. UC Davis’ REALOP mission aims to prove the use of HDDs as reaction wheels by raising their status to TRL 9.

Future work for the HDD reaction wheels includes:

- Finalizing design of the control board
- Tuning of the ESC for optimal control of the HDD
- Vibration, shock, and TVac testing at NASA Ames Research Center
- Further modification of the hard disk drive to improve integration
- Tuning of control algorithms
- Integrated environmental and performance testing
- Detailed documentation of the modification processes, designs, and tests results to make HDD reaction wheels an accessible technology

Acknowledgements

We would like to thank Dr. Stephen K. Robinson for his continuous support as our faculty advisor, Vamsi Eyunni for pioneering the HDD modifications, and the members of Space and Satellite Systems for their dedication.

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