SPACE SYSTEMS DESIGN STUDIO

# REPORT ON THE INITIAL TESTING OF THE HIGH AGILITY ATTITUDE TEST BED

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# 1 Premise and Concept

The spacecraft flight simulator implements two perfectly-smooth spherical granite air bearings in order to counteract gravity and achieve a torque-free environment that simulates a spacecraft in deep space. The simulator test bed structure is comprised of an 80/20 bar frame. The structure is divided between its base, test bed, and suspension system. The base houses the bottom component of the air bearing and remains stationary at all times. The test bed houses the top component of the air bearing as well as attitude control actuators, sensors, cold-gas system, and in the future, a mass balancer system. The suspension system was redesigned from previous semesters by now relying on a lead screw motorized system. The purpose of the suspension system is to lift and lower the test bed onto the base only when pressurized air is flowing through the air bearing. The cold gas subsystem was redesigned in order to meet an angular momentum requirement. Regarding circuit design, a new design integrates all sensors, collecting their gathered data, transmitting the data to a flight computer, and depicting the system on a user-interface. The spacecraft flight simulator will be used for algorithm development and new hardware implementation.

# 2 System Requirements

For success, the spacecraft flight simulator must be designed to meet the following requirements:

## 2.1 System Top Level Requirements

SYS 1. *The spacecraft flight simulator shall simulate the attitude mechanics of a vehicle in deep space.*

SYS 2. *The spacecraft flight simulator shall simulate attitude control of the spacecraft.*

SYS 3. *The spacecraft flight simulator shall achieve rotational, not translation, motion.*

SYS 4. *The spacecraft flight simulator shall weigh less than 145kg.* The air bearing used to achieve a torque-free environment has a maximum load of 160kg. There exists a 15kg contingency that also serves to support future work on the spacecraft simulator. For example, new technology such as sun sensors and star trackers can be mounted in the future semesters without exceeding the mass limit.

SYS 4. *No closed-loop software shall exist on the test bed.*

## 2.2 System Functional Requirements

SYS 1 F01. *The simulator flight simulator must achieve a torque-free environment*

SYS 1 F02. *The spacecraft flight simulator shall counteract the gravitational force*

SYS 1 F03. *The spacecraft flight simulator shall have 3 degrees of freedom.*

SYS 1 F04. *The spacecraft flight simulator shall have its center of mass 2 centimeters below its center of rotation.*

SYS 2 F01. *The spacecraft flight simulator shall simulate attitude sensing.*

SYS 2 F02. *The spacecraft flight simulator shall implement on-board actuators*

SYS 4 F01. *A flight computer shall exist off of the test bed.*

## 2.3 Subsystem Operational Requirements

STRUCT F01. *Compressed air shall flow between two perfectly smooth, spherical granite air bearings.* **Source:** SYS 1 F01, SYS 1 F02, SYS F03

STRUCT F02. *The air bearing shall be attached at the center of rotation.* **Source:** SYS 1 F01, SYS 1 F02, F03

STRUCT F03. *A circular bumper attached to the spacecraft simulator shall prevent damage to ADCNS sensors and actuators.* The circular bumper will be the first component to impact the vertical support post, which will prevent any further motion, thereby protecting the various technologies. No other components shall be housed in the cone formed by this circular bumper. This will achieve $\pm 45^o$ of motion in all directions.

STRUCT F04. *A mass balancer system shall control the spacecraft flight simulator's center of mass.* The mass balancer system will slide masses moving along 3 orthogonal directions in order to manipulate the total system's center of mass. **Source:** SYS 1 F04

ADCNS F01. *The spacecraft flight simulator shall be controlled by three reaction wheels and six thrusters.* The reaction wheels will be the key instrument to manipulate momentum to influence rotational movement whereas the cold gas thrusters will primarily be used to dump momentum.

ACDNS F02. *The reaction wheels shall be oriented orthogonally.* The pancake motors used as wheels will rotate about $\pm x$, $\pm y$, and $\pm z$ axes.

ACDNS F03. *The thrusters shall be mounted in order to achieve rotation of the test about its center of mass in $\pm x$, $\pm y$, and $\pm z$ directions*

ACDNS F04. *The reaction wheels shall be mounted on the test bed using vibration damping mounts.* This will prevent the whole system from vibrating, potentially affecting the data acquired.

ACDNS F05. *The reaction wheels shall not exceed a maximum speed of 6000rpm* This is the maximum recommended speed of the GPM16LR 005016 motor.

ACDNS F06. *The rate of rotation of the reaction wheels shall be measured in order to calculate the change in momentum.* The maximum recommended speed is 6000rpm. The rated speed is 3000rpm. The arduino used to collect data has a sample rate of 80MHz. Tachometers shall be used to measure the motor shaft axis rotation speed.

ACDNS F07. *In the span of an hour, the thrusters shall be able to induce within 50% of the angular momentum caused by the reaction wheels spinning up and spinning down 30 times for 30 seconds each time.*

COMM F01. *The simulator shall transmit data to the flight computer* This will be achieved via Xbee Radio communication. **Source:** SYS 4 F01.

COMM F02. *The flight computer must be able to give commands to the simulator.* This will be achieved via Xbee communication. **Source:** SYS 4 F01.

COMM F03. *A visual or aural notification will occur if the air tank or batteries reach a low level.*

POWER F01. *The batteries shall last for an hour of operation.* This allows for effective use.

POWER F02. *The voltage level of the batteries shall be monitored.* This will prevent failure of the simulation due to power loss.

POWER F03. *The batteries shall be able to be swapped out in less than 30 seconds.* This allows for efficient simulations.

POWER F06. *The batteries shall be able to charge off the test bed.* The batteries simply plug into a wall power socket to charge.

POWER F05. *Additional batteries shall always be charged to replace the batteries in use.*

PROP F01. *There shall exist onboard air tanks to supply the thrusters with air.*

PROP F02. *The pressure in the tanks shall not exceed 4500psi.* The spacecraft flight simulator shall use paintball tanks with 4500psi storing pressure, and 800psi output pressure.

PROP F03. *The air tanks shall be refilled in the laboratory to a pressure of 4500psi using a compressor.*

PROP F04. *There shall exist 5 additional pressure tanks that are filled at all times.* These tanks shall replace the current tanks on the test bed when the air level is low.

PROP F05. *A pressure transducer shall be implemented after a pressure regulator to monitor when the pressure falls below 140psi.* Once the pressure falls below this point, the notification will be sent to the user to stop the simulation and switch the tanks.

PROP F06. *The pressure into the pressure regulator shall not exceed 6000psi.* The regulator takes an input up to 6000psi and outputs 140psi air.

PROP F07. The pressure into the solenoid valves shall not exceed 250psi.

PROP F08. *The inlet pressure of the thrusters shall not exceed 6000psi.*

PROP F09. *The air pressure in the tubing shall not exceed 750psi.* The tubing used for the system is 3/6" Nylon Tubing with a burst pressure of 750psi.

PROP F010. *The air bearing operating pressure will be in the range 30psi-90psi.*

PROP F011. *The air bearing shall use the shop air supplied in the laboratory at 90psi.*

PROP F012. *The shop air shall pass through an air filtration system before entering the air bearing.* This protects the air bearing.

# 3 Summary of Tests Performed

The following tests were conducted on the attitude test bed while in operation:

| Test Performed | Results |
|---|---|
| The z-axis reaction wheel was accelerated from rest to full speed clockwise. | The test bed successfully rotated about the z axis in a counter-clockwise direction. |
| Thruster 3 was fired once for 100ms to produce a rotation about the z-axis. Thruster 5 was fired to stop the rotation. | Thruster 5 was fired twice, each 100ms in duration in order to stop the movement about the z-axis. |
| Thruster 5 was fired 16 times, each for 100ms. to produce a clockwise rotation about the z-axis. The z-axis reaction wheel was rotated clockwise in order to stop the rotation. | After thruster 5 was fired 16 times, the z-axis accelerometer output 0.98g and the z-axis gyroscope output -9.6 deg/s, which means "purely" rotation about the z-axis. The z-axis reaction wheel was unable to stop the rotation. |
| The y-axis reaction wheel was accelerated from rest to full speed, counter-clockwise. The same reaction wheel was then accelerated in the clockwise direction. | The gyroscope data indicated a y-axis rotation of +2 deg/s, but no perceivable rotation about the y-axis by visual inspection. The test bed then started to rotate about the z-axis as well. |

**Table 1:** Operational Tests Performed.

# 4 Subsystem Reports

## 4.1 Simulator Test Bed Suspension System

The suspension responds well to the controller, with no apparent delay or stalling. The tension pulleys mounted to the vertical structure do not remain in position as the weight distribution causes the tensioner assembly to tilt out of position. This can be fixed by adding mass to the free end of the setup to maintain horizontal alignment (i.e. the tension wheel needs a counterweight to remain balanced). During operation, some small vibration of the suspension occurred briefly when lowering the suspension, but corrected itself after a minute.

The belt did not slip, the motor did not stall, and the screw remained turning, so the issue did not impact the performance of the system. This had not occurred in previous testing, but will take note in future if the problem persists.

## 4.2 Air Bearing & Torque-Free Environment

In order to simulate attitude control of a spacecraft orbiting a celestial body or on a deep space mission, a friction-less, torque-free environment must be achieved. The friction-less environment is a result from the air bearing. However, a torque-free environment is far more difficult to achieve, primarily because of the external torque due to the test bed's center of mass. The center of mass was estimated based on the CAD model of the test bed. Balance masses were placed on the test bed in order to achieve a center of mass 2cm below the center of rotation. Because of inaccuracies in the CAD model, additional balance masses were mounted on the test bed to achieve the desired center of mass. A key difficulty in maintaining this center of mass is the cold gas subsystem. With every use of the thrusters, the mass of the propulsion manifold decreases slightly, causing the center of mass to shift off center. The mass of a single tank filled to 3000psi is 1.4kg whereas an empty tank is 1.14kg. Considering all five air tanks, 1.3kg is lost at the furthest distance from the center of rotation, causing the center of mass to shift significantly.

The solution for this changing mass is utilizing the mass balancer system, comprised of sliding masses on linear actuators, to "re-calibrate" throughout the simulation in order to ensure that the behavior exhibited is due to the attitude control system, not the external torque.

## 4.3 Attitude Determination and Control System

### 4.3.1 Reaction Wheels

From Table 1, it can be deduced that the reaction wheels produce no significant rotation of the test bed. One possible solution is altering the motor controller software which includes a default maximum acceleration and deceleration. By increasing the maximum acceleration, the theoretical induced moment should be greater. Another possible solution is increasing the moment of inertia of the reaction wheel. This can be achieved by attaching a large-faced rotor to the rotating axle.

### 4.3.2 Cold Gas System

The cold gas system performed successfully during initial testing. The system works with any number of air tanks. It is possible to open and close each air tank, allowing the user to utilize a select number during simulation. This allows for the refilling or replacement of one air tank at a time instead of all of the air tanks emptying simultaneously. Refilling the tanks one to two at a time is the preferred method due to overheating of the air compressor during prolonged usage.

A LED successfully indicated when air dropped below 140psi, indicating that the tanks need to be refilled. The simulation can still continue for a brief period of time before the tanks are empty, depending on the frequency of use of the thrusters.

## 4.4 Communications and Data Handling

The wireless computer-to-testbed communication scheme was found to work effectively. Because of limitations in latency, real-time, wireless pressure and battery level readings were unable to be implemented on the current version of the user interface. It was also found that sending too many instructions to the testbed through the interface led to high latencies due to the buildup of unexecuted instructions. Refined versions of the wireless communication scheme will consist of better instruction management and data handling, as well as support for real-time battery and manifold pressure monitoring.