
Rotational Motion Platform for Emulating Spacecraft Attitude Control

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Abstract

This research develops and evaluates a robotic rotational motion platform to test lunar-landing-like attitude, sensing and control. The platform is equipped with thrusters, sensors, and computer control and is restricted to orientation maneuvers. The platform is mass balanced and suspended on a bearing that accommodates 60 degrees of excursion in roll, pitch and yaw. The platform operates in a controlled indoor environment where one spotlight represents the sun, another represents earth and a pattern on the floor represents a star field. Sensor fusion and control are accomplished and motion is commanded. The robot follows intended attitude trajectories with high fidelity. Fused sensor data exhibits superior pose estimation beyond what is possible with any single sensor. This platform emulates the actuation capabilities of spacecraft, such as Apollo 11 landers, CLEMENTINE lunar orbiter and the Space X Dragon, which use attitude thrusters as a means for attitude control. This research illustrates that a propulsive roll, pitch, yaw platform with scaled mass properties of a lunar lander can emulate attitude trajectories required for cruise, entry, descent and landing on the moon.

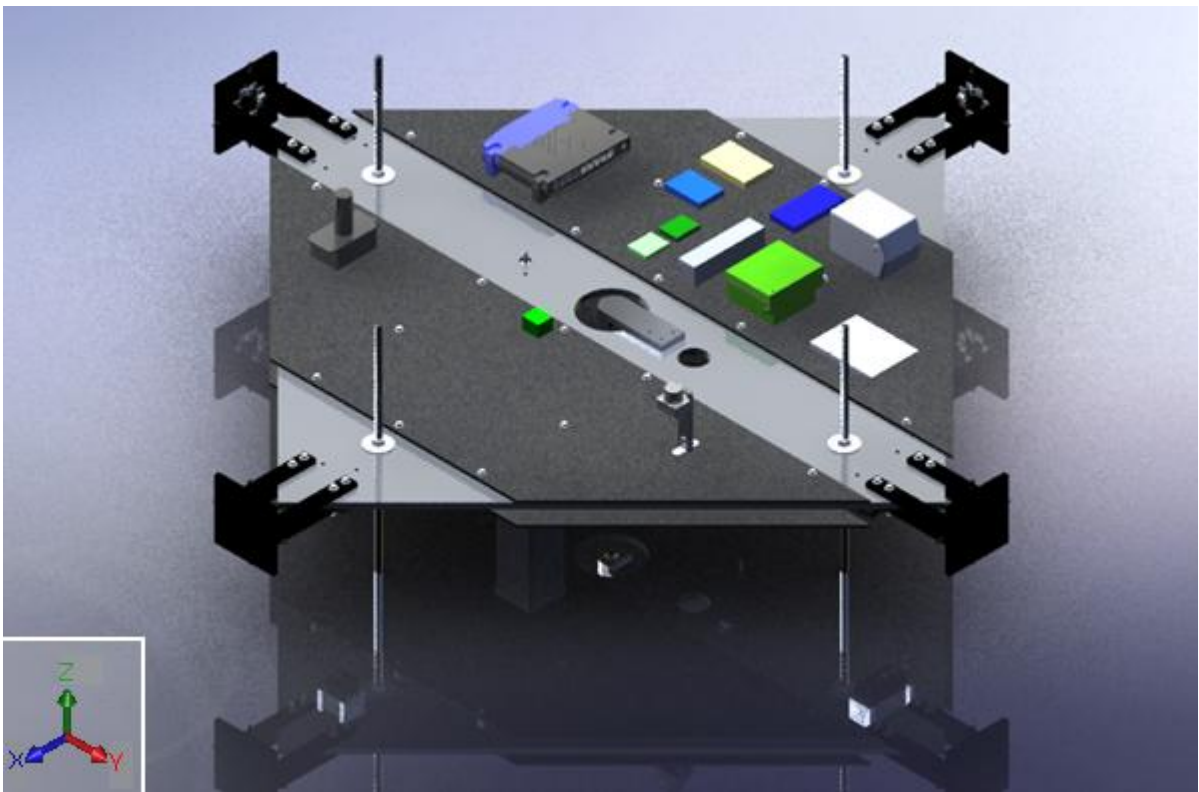


Figure 1a: Tilt Table – Sensing and Attitude Control Platform, CAD Model

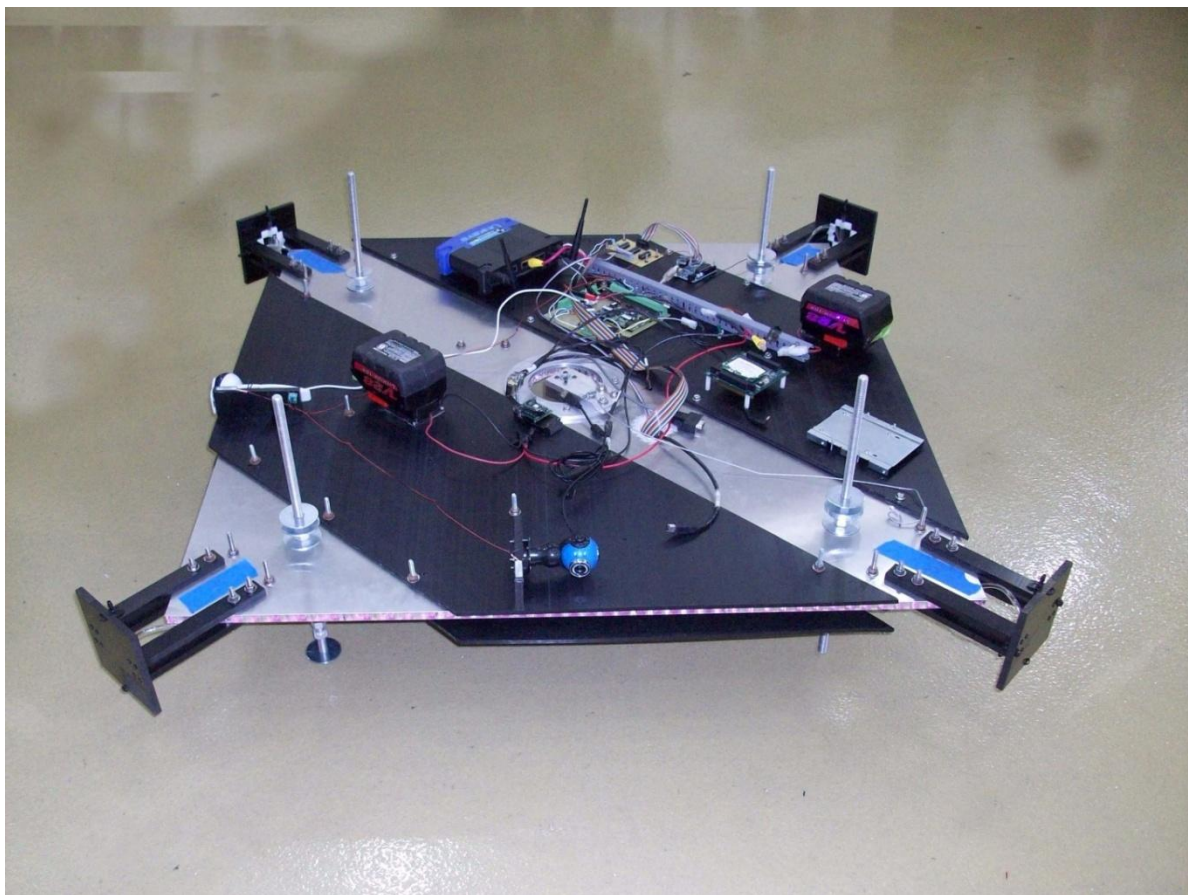


Figure 1b: Tilt Table – Sensing and Attitude Control Platform Physical Model

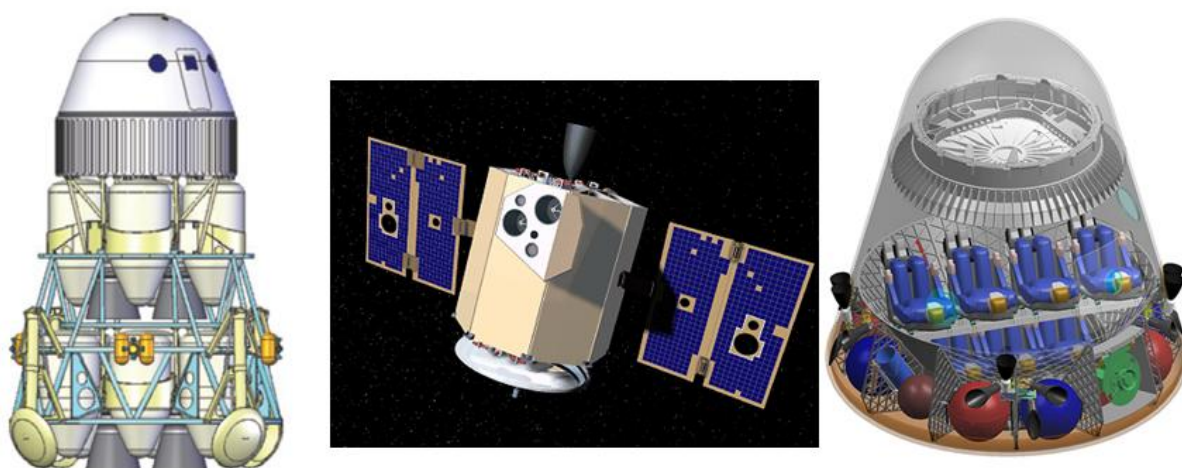


Figure 2: Pictured from left to right
Apollo 11, CLEMENTINE, Dragon

1 Introduction

1.1 Motivation

Hardware models provide a means to investigate the behavior of spacecraft in an earth environment, as opposed to studies that occur in software simulation alone. A simulation is only as good as its model; alternately, physical testing incorporates tangible attributes. While emulating spaceflight may require some assumptions, it is still a much more reliable model because the physical properties of the model and environment can be measured rather than chosen, as is done in a simulation. A tilt platform with three rotational degrees of freedom is needed to perform long-duration tests of attitude control and sensor fusion algorithms, as well as space-relevant hardware. The platform must be designed with mass properties similar to spacecraft mass properties. The platform follows attitude trajectories for cruise, descent, and touchdown of a lunar spacecraft in an emulated lunar environment. Creating and evaluating a hardware model has revealed software limitations and bugs that were not apparent using idealized software modeling; this has inspired software updates. Additionally this research has developed an emulation that optimizes feasibility and realism. Hence, a lander hardware model platform proves to be an essential stepping stone to creating a lunar flight article. This motion platform makes an important extension to the planetary robotics field of research by emulating the sensing and actuation capabilities of a spacecraft which could autonomously perform precision landing.

1.2 System Overview

Data received from absolute and inertial sensors are sent to an Extended Kalman Filter which fuses the data together in order to get an estimate of the platform's orientation. This estimate is compared against the desired guidance trajectory. The difference between these two orientations is sent to control which corrects for this difference by firing thrusters.

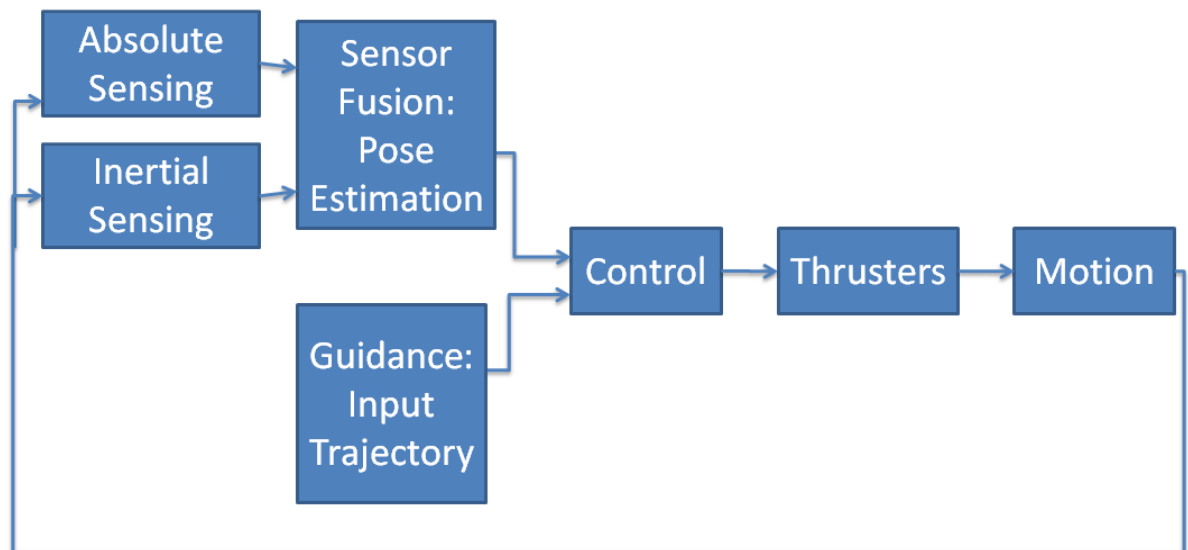


Figure 3: Functional Diagram

This robotic platform is equipped with twelve cold gas thrusters to achieve three degrees of rotational freedom. These thrusters operate from a shop air supply which provides a measured 30 cubic feet per minute (CFM) of air at 110 psi consistently for at least 10 minutes to the platform. Twelve thrusters are controlled by one of twelve solenoid valves. Each thruster has its counterpart, similarly colored in figure 4. In order to achieve only rotational acceleration, coupled thrusters must provide equivalent torques on the structure.

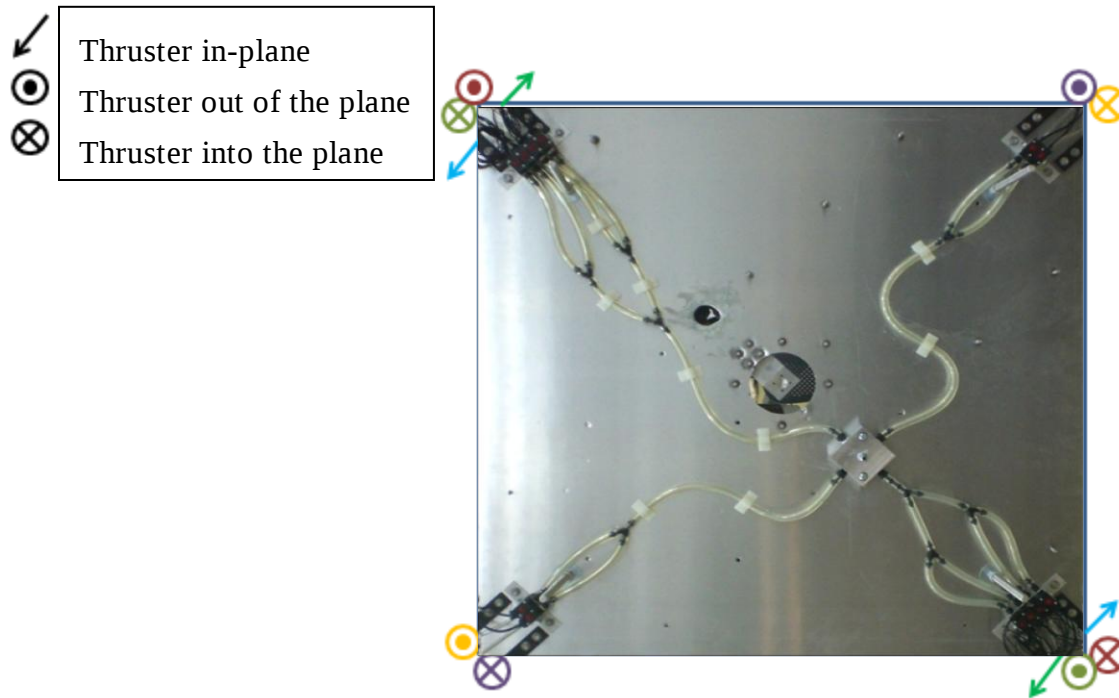


Figure 4: Thruster configuration

An Inertial Measurement unit (IMU) provides relative orientation and other sensors emulating sun, earth and star trackers, provide absolute attitude updates for the system. These measurements are fused with an Extended Kalman Filter which integrates acceleration data from inertial sensors and pose estimation from absolute sensors to give incremental updates of attitude in order to get a better state estimate.

One of the main purposes of this platform is to test capabilities of a variety of control algorithms. Closed loop control is achieved through a Proportional-Integral-Derivative (PID) feedback control loop with values adjusted to control the system based off of its inertia tensor and thrust capabilities. This serves as a baseline for comparison to other control algorithms.

Computation is done by a PC-104 computer with an Intel atom N270 processor with 1.6 GHz clock speed. Data is streamed via a wifi connection to a mission controls computer which is able to send commanded trajectories and compare them against sensed trajectories. Data is backed up on a solid state drive aboard the platform.

2 Prior Work

A preliminary control system for a lunar lander, as well as a simulation environment for testing designs and future work on lander guidance, navigation and control systems have been developed. The preliminary control system made use of a fuzzy logic controller for base thrust control and phase plane controllers for attitude control [10] [11]. These controllers are pictured in figures 5 and 6 respectively.

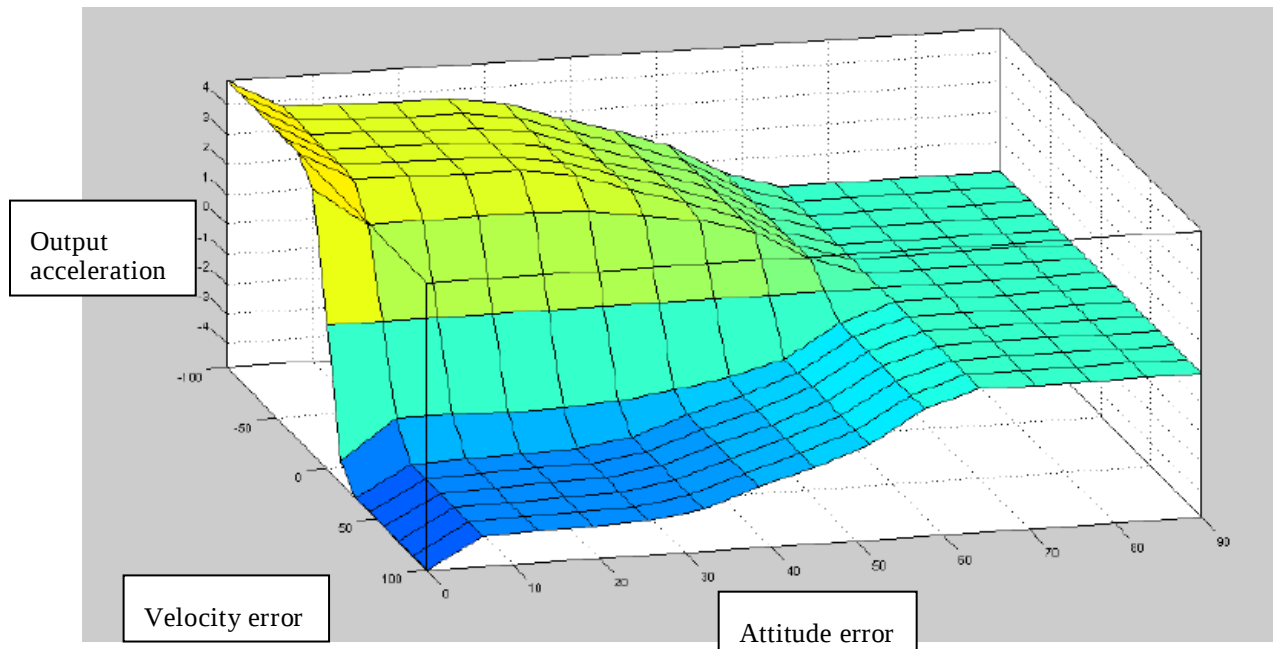


Figure 5: Fuzzy logic descent controller

The fuzzy logic controller controls a position and velocity trajectory based on position and attitude. The inputs of this controller are the error between desired velocity and current velocity and the error between the desired attitude and the current attitude of the controller. The first output is the desired acceleration of the lander, pictured on the vertical axis on the left of figure 5. The second is a Boolean-value that turns on attitude control at errors above 2 degrees. As seen in figure 5, the controller dictates less acceleration of the base thruster at larger angular errors. This prevents the attitude error from increasing due to large accelerations. [11]

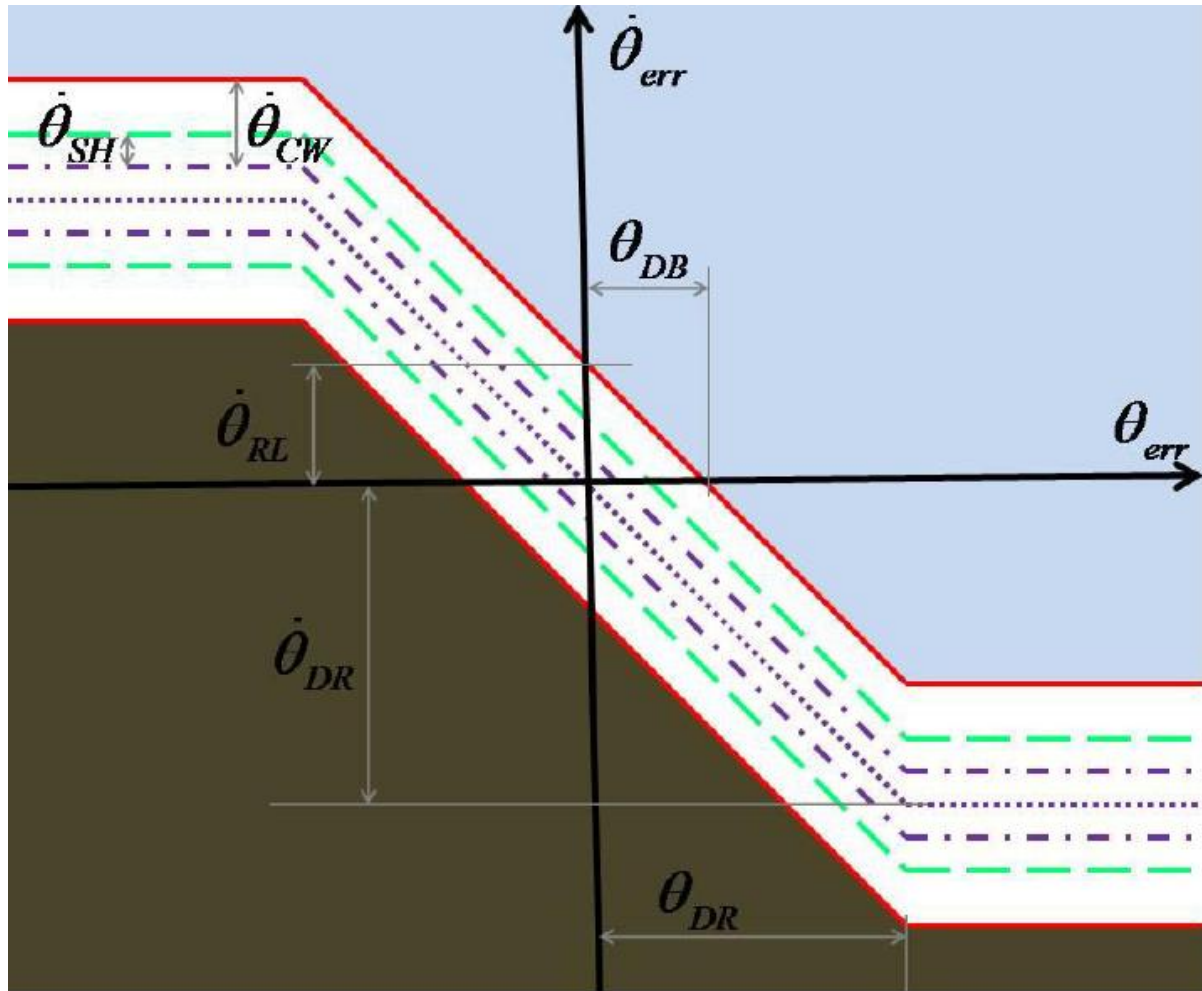


Figure 6: Phase plane attitude controller

A phase plane controller was designed as a solution for attitude control that would couple nicely with the fuzzy logic descent controller. Figure 6 shows the phase plane diagram for the attitude controller. The x-axis represents the attitude error and the y-axis represents the attitude rate error. In the light blue section above the central bands, the thrusters are fired at maximum thrust to reduce the attitude rate. In the dark brown section below the central bands, the thrusters are fired at maximum thrust to increase the attitude rate. Between the solid red lines and the dashed green lines, the thrusters are fired at less than the maximum thrust. The exact thrust percentage is proportional to where the error falls between the red and green lines in the $\pm err$ direction. Between the green dashed lines and the purple dot-dashed lines, the thrusters are fired using the minimum thruster impulse. Between the two purple dot-dashed lines the thrusters are not fired, and the spacecraft is allowed to drift. For cases where the commanded attitude rate is set to the maneuver rate, the attitude error is set to zero before calling the phase plane controller. This causes the phase plane controller to behave as a one dimensional controller along the err axis. [10]

Development of these controllers required a means of testing and modifying them in order to optimize the controllers to find a balance between minimizing fuel usage and settling time. A simulation has been developed to test descent and attitude controllers like the ones described. The next step is to ensure the fidelity of the simulation by testing on a physical model such as the platform developed in this research.

There are a great variety of model spacecraft used for testing a wide variety of hardware and software components. A paper by Choset et al. describes a planar robot prototype autonomously moving about an air bearing table in order to test path planning strategies in space [2]. This system has one rotational degree of freedom because it is meant for two dimensional path planning applications. Georgia Institute of Technology (GIT) has a system with attitude control thrusters aboard a spherical air bearing as a test-bed for integrated attitude dynamics and control research, pictured in figure 7 [4]. This system only has 8

thrusters, since it is restricted to rotational motion. Otherwise unbalanced forces would cause translation at each rotation. GIT's Integrated Attitude Control System has a finite nitrogen tank fuel source on board which only allows for short test durations. The mass of this system is comparable to a scaled down version of a satellite. NASA's Marshall Space Flight Center has a robotic lunar lander that operates on earth with a gravity offload thruster to account for the difference between earth and lunar gravity, this system can only operate under small attitude offsets because of the requirement of the offload thruster to be pointed in the direction opposing the earth's gravitational field, sensing is achieved through the use of an IMU which uses dead reckoning alone and relies on its low drift rate and short test durations to achieve good pose estimation. MIT has a "Terrestrial Artificial Lunar and Reduced gravity Simulator" named Talaris, which is an Earth-based prototype hopping vehicle which they use to test their GNC algorithms. Talaris uses fans rather than thrusters for propulsion which provide different thrust profiles than space relevant thrusters. Attitude control is not decoupled from base thrust making the system relevant for testing spacecraft with vectored base thrusters.



Figure 7: GIT's experimental test-bed for integrated attitude dynamics and control research



Figure 8: NASA Marshall Space Flight Center's Robotic Lunar Lander

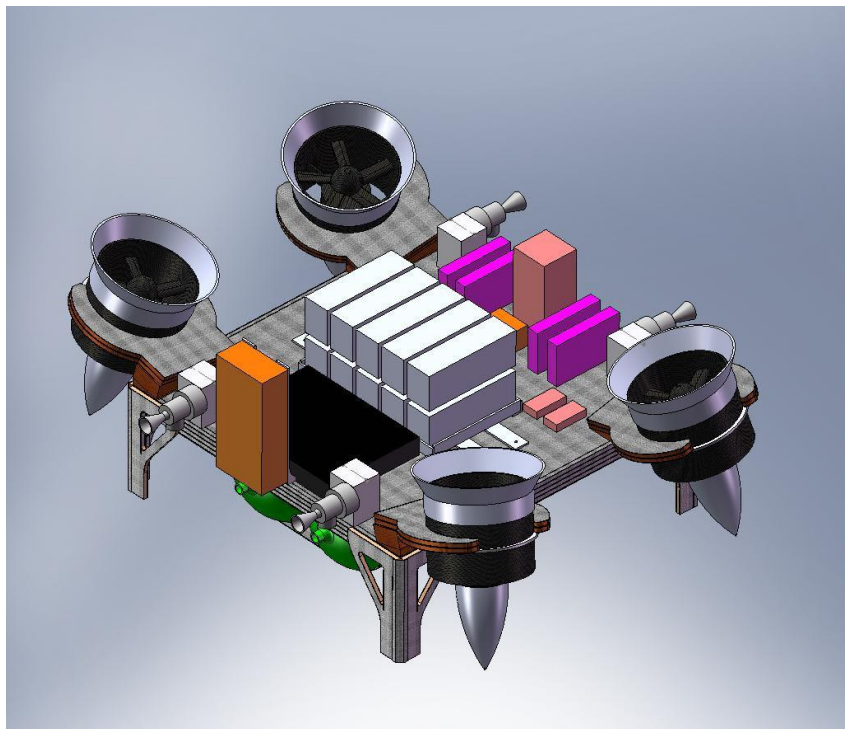


Figure 9: Talaris

Groups such as Masten and Armadillo have competed in the Northrop Grumman Lunar Lander Challenge in which teams built robotic landers that operated in earth gravity and atmosphere, but accomplished

tasks similar to those that would be accomplished by that of a lunar lander. This competition allowed for great leaps in the development of commercial spacecraft technologies. Technologies used aboard these flight vehicles use a vectored base thruster and do not have a separate attitude control thrusters.

This research makes many important extensions to previous research and caters to a design that can test GNC software and space relevant hardware. This 3 degree of freedom design allows for repeatability of experiments as well as long duration experiments at low cost due to its use of an off-board air supply. Thrusters were chosen for their similarity to space relevant-thrusters. Mass properties of the structure reflect a scaled version of a typical lunar lander with a decoupled attitude control system. Inertial and absolute sensors were fused to get accurate orientation measurements over long duration tests. Additionally this design is replicable and possible to build with a low budget in a short amount of time.

3 Structure and Mount

The tilt platforms base structure is a 40" x 40" x 3/8" sheet of aluminum honeycomb with .020 5052 Permatreat aluminum face sheets. This allows for an exceptionally lightweight and high-strength base structure. Polyethylene, a rigid, insulating material, is used for mounting electronics and sensors. The mounts are bolted to the base structure. One mount holds computing and electronic hardware (figure 10), one mounts top sensors (figure 11), and one mounts bottom sensors (figure 12).

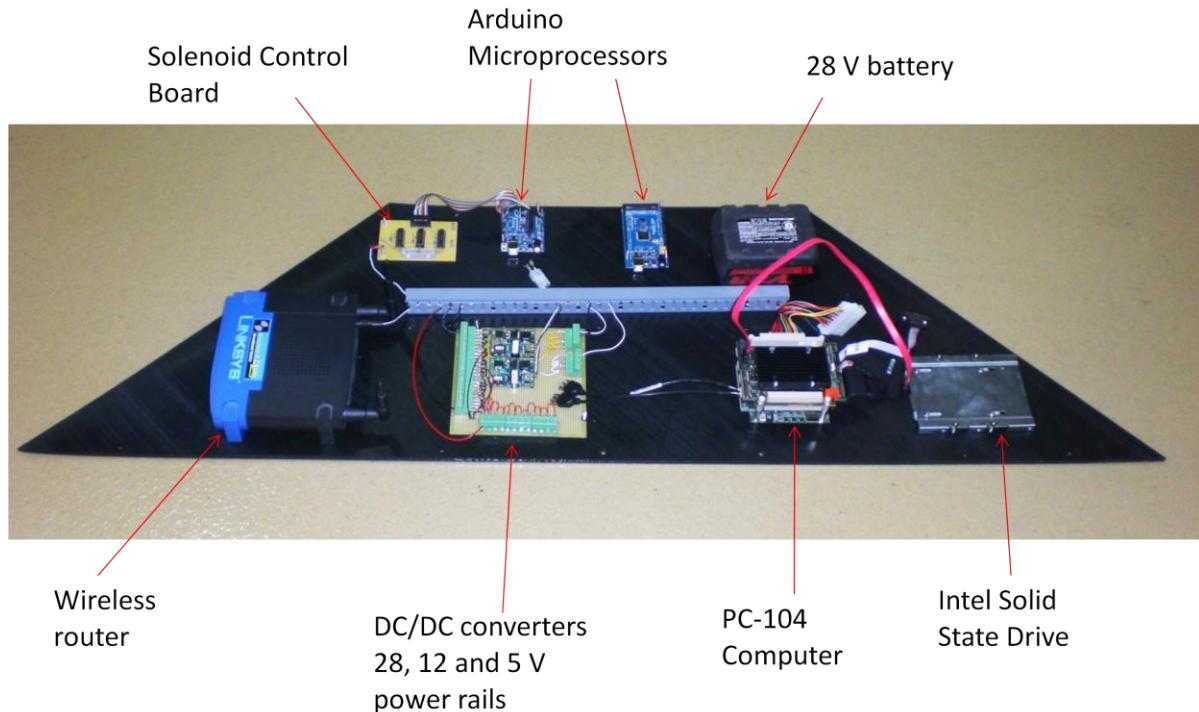


Figure 10: Computing and Electronics Platform

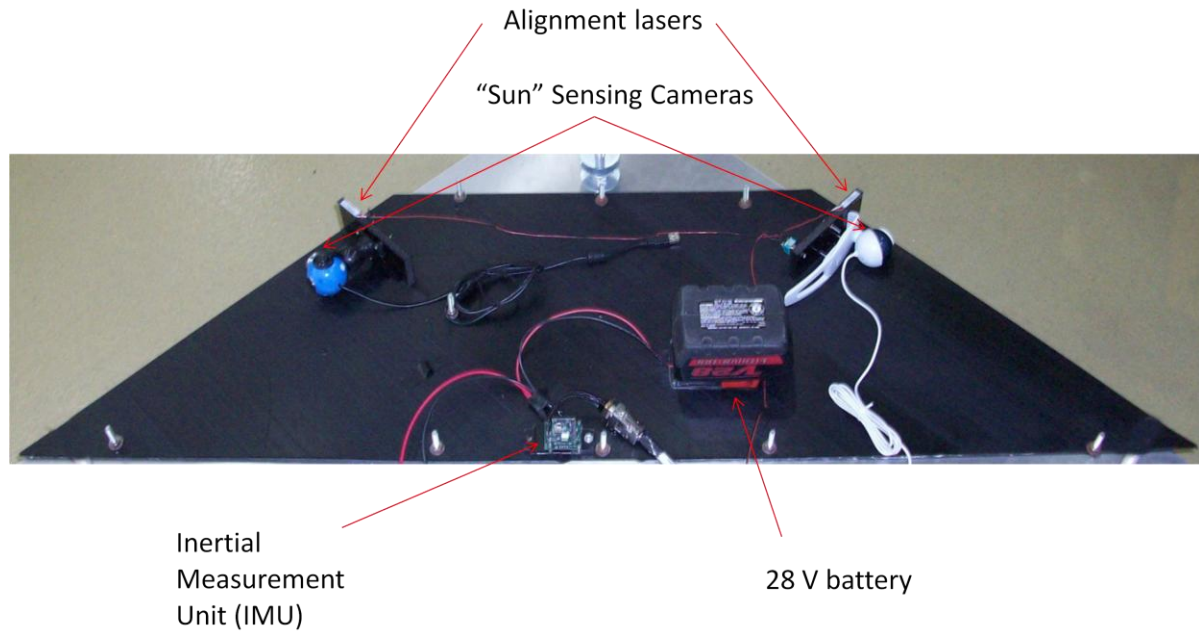


Figure 11: Top Sensing Platform



Figure 12: Bottom Sensing Platform

Polyurethane tubing is connected with nylon barb and National Pipe Taper (NPT) fittings. The tubing mounts to the bottom surface of the honeycomb structure using adhesive nylon hose clamps. The tubing is routed to each corner solenoid cluster from the central hose attachment point. From each solenoid compressed air runs through the tubing to the thruster nozzles.

The robotic platform is mass-balanced by the addition and removal of nuts and washers threaded to standoff poles, located along each of the primary axes of the platform. The platform's center of mass is located at the point where the mounting pin meets the socket cone. The mounting pin is a cone with a span of 60° while the socket cone has a span of 120° which enables a 60° sweep for roll and pitch motions. Both pin and socket are hardened steel, resulting in good rotational freedom and low friction.

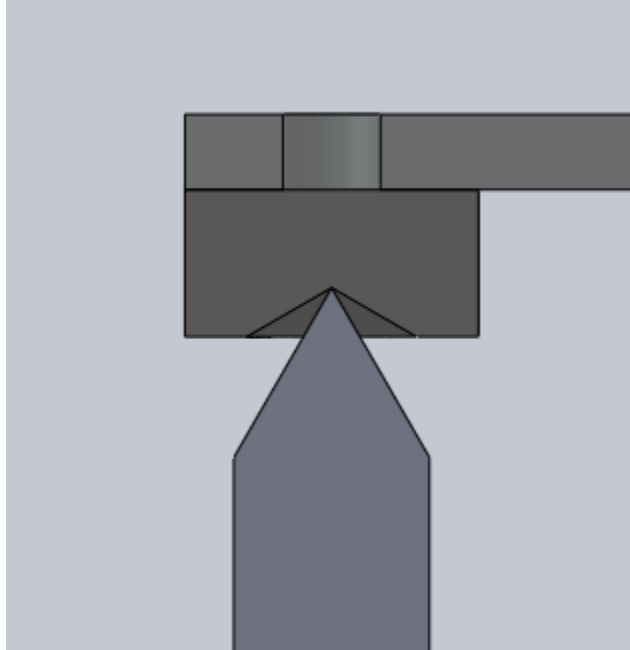


Figure 13: Cut away view of pivot point



Figure 14: Pivot point

Table 1: Motion platform mass properties analogies to Apollo 11 mass properties [19]

	Apollo 11	Tilt platform
Mass (kg)	7,327	23
COM (m) [x, y, z]	[5.42, 0.04, -0.01]	[0,0,0]
Inertia about COM (kg*m ²)	17,061 753 -247 753 21,973 -100 -247 -100 18,804	1.9027 0.0263 -0.0975 0.0263 3.8238 0.0718 -0.0975 -0.0718 1.9865
Thrust of each pitch/yaw/roll jet (N)	2224.1	(see table 2)
[Height, Width, Depth] (m)	[5.5, 4.3, 4.1]	[0.46, 1.1, 1.1]

4 Actuation

Cold gas thrusters actuate the tilt platform. A cold gas thruster consists of a pressurized gas repository which serves as a propellant, a commanded valve to open and close gas flow, and a nozzle designed to increase the exit velocity of the cold gas.

For the tilt platform the gas source is a shop compressed air supply. The regulator on the air supply can deliver up to 100 cubic feet per minute (CFM) of air to flow at 150 pounds per square inch (psi), but is limited by what the shop supply can provide. Flow through quarter inch tubing before being split to individual valves was measured to have a flow rate of 30 CFM. Further reduction in flow could occur due to friction losses in hoses and fittings. When the air supply is held open it is able to maintain 110 psi for duration of 10 minutes without any flow or pressure drop. The pneumatic schematic is represented below in figure 15.

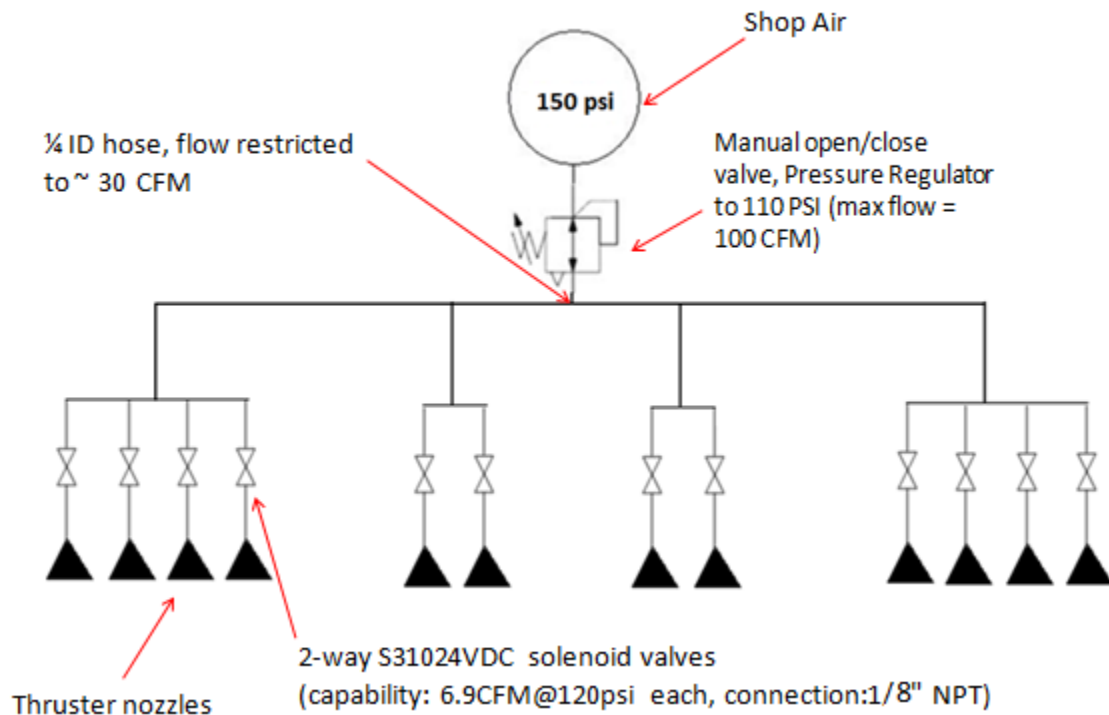


Figure 15: Pneumatic schematic

The tilt platform has 12 cold gas thrusters to achieve three degrees of rotational freedom. Thrusters are each controlled by a 24 Volt solenoid valve. The system is partitioned into two clusters of four valves, and two clusters of two valves. The valve clusters are mounted at the four corners of the structure. The parts layout is illustrated in figure 16.

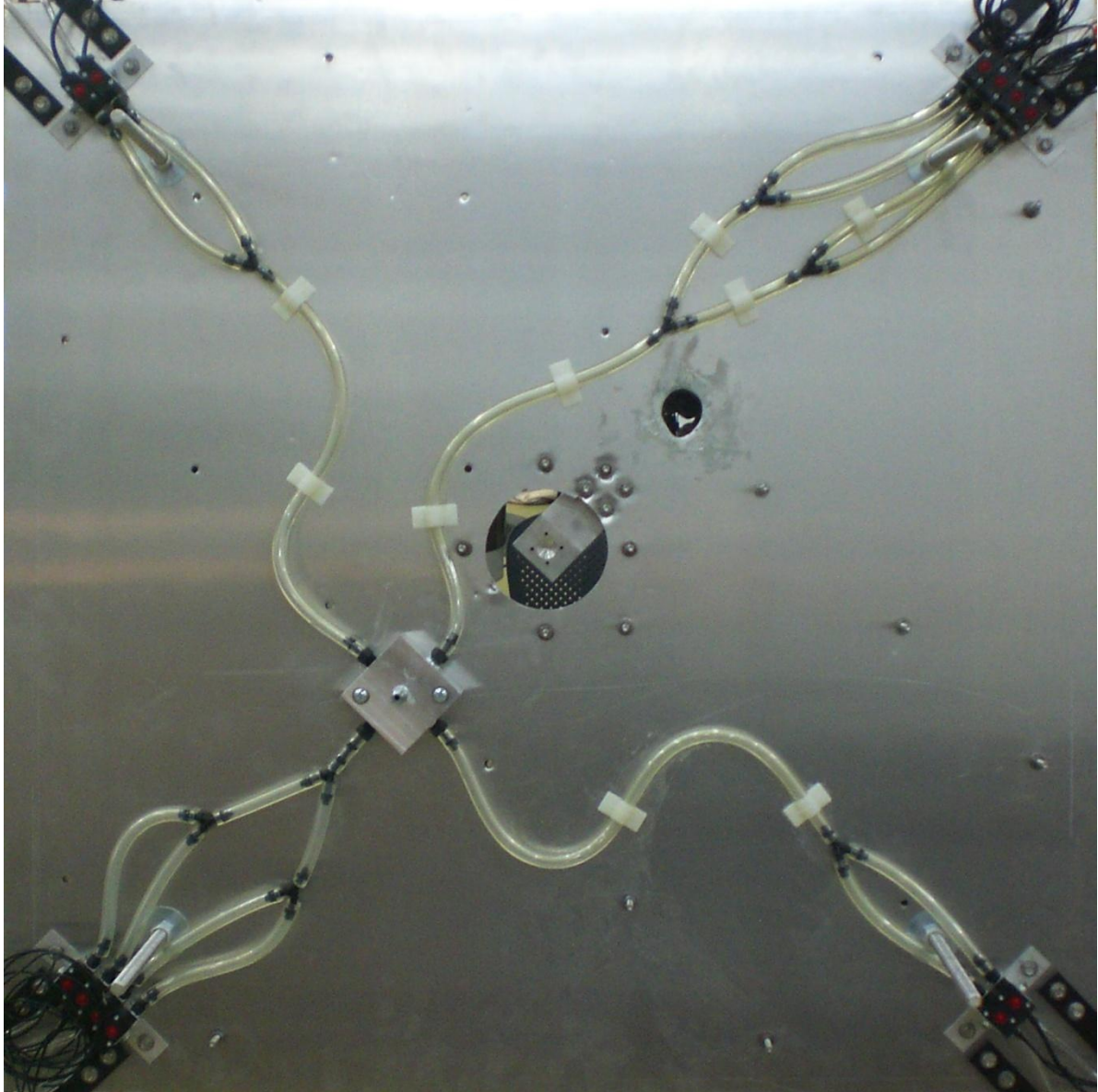


Figure 16: Pneumatic layout

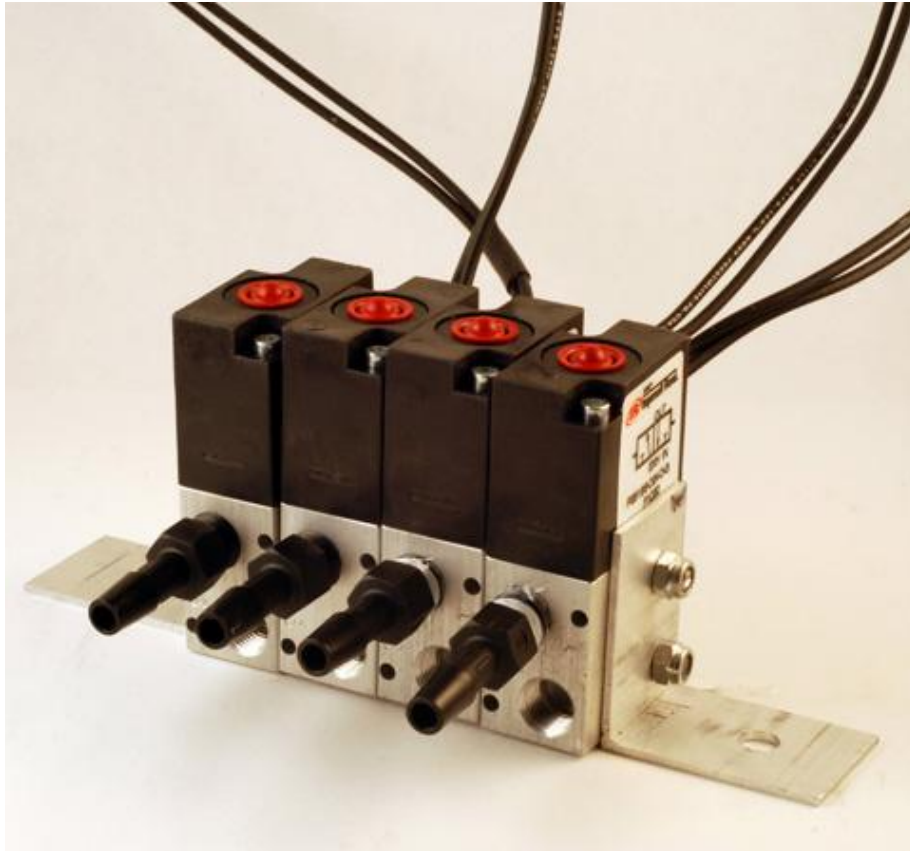


Figure 17: Four solenoid valve cluster

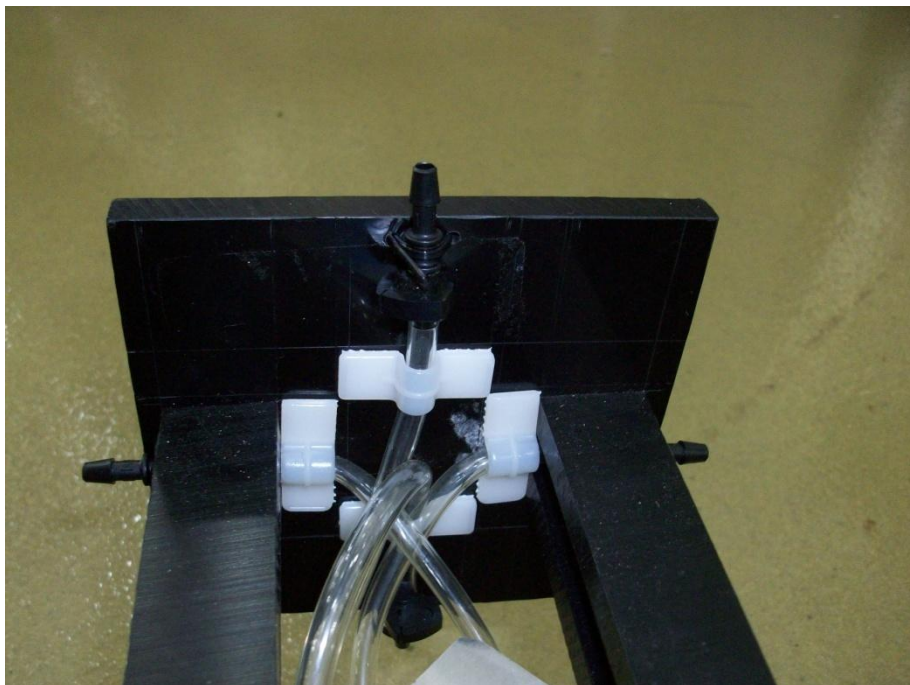


Figure 18: Thrusters

At any instant a maximum of six valves are open to create a torque about each of the three orthogonal axes. Thrust values of a single valve were measured by a load cell while 1-6 were held open. Table 2 reports the average thrust value of a single thruster with a standard deviation of .01N.

Table 2: Thrust values

Number of valves open	Maximum thrust out of a single valve (Newtons)
1	3.09
2	2.77
3	2.40
4	2.06
5	1.86
6	1.81

Given the thrust values from table 2, and the inertia tensor and dimensions from table 1, the theoretical maximum angular acceleration of the platform about each axis can be calculated and compared to those of Apollo 11. Moment arms from the point about which rotation is occurring are calculated using equation 1.

$$r = \sqrt{w^2 + d^2}/2 \quad (1)$$

r is the distance from the center point to the thrust vector, w is the width of the structure and d is the depth of the structure, all calculated in meters. Angular acceleration is found using equation 2.

$$\alpha \approx \frac{2Fr}{I_{jj}} \quad (2)$$

α is angular acceleration in radians/s², F is taken as the thrust force, given in Newtons when six thrusters are on, I is the moment of inertia of the axis which angular acceleration is calculated about given in kg*m².

Table 3: Angular acceleration comparison

	Apollo 11	Tilt Platform
α_x	.7745	1.47
α_y	.6014	.733
α_z	.7027	1.41

5 Pose estimation

Sensors used on the tilt table emulate those of a spacecraft. Sensors include an Inertial Measurement Unit (IMU), pseudo sun and earth sensors, a pseudo star tracker and an actual star tracker. An Extended Kalman Filter is used for sensor fusion. An IMU is used for incremental pose updates while the emulated earth sensor, sun sensor and star trackers give absolute orientation updates which correct for drift in the IMU.

The IMU is sampled at a rate of approximately 1 KHz. The platform utilizes a Crista IMU which uses MEMS gyroscopic rate sensors and accelerometers mounted on orthogonal axes to provide 300° /sec rate and 10g acceleration data. A drift rate of approximately 1°/hour is measured after calibration.

The pseudo sun and earth sensors each consist of 5.0 Megapixel USB PC Webcam Cameras which use computer vision to view a round light and determine orientation vectors from the camera to the light. In the experimental setup the two webcams are mounted orthogonal to each other, as seen in figure 19, so that three degrees of freedom can be determined from the two vectors determined by these two sensors.

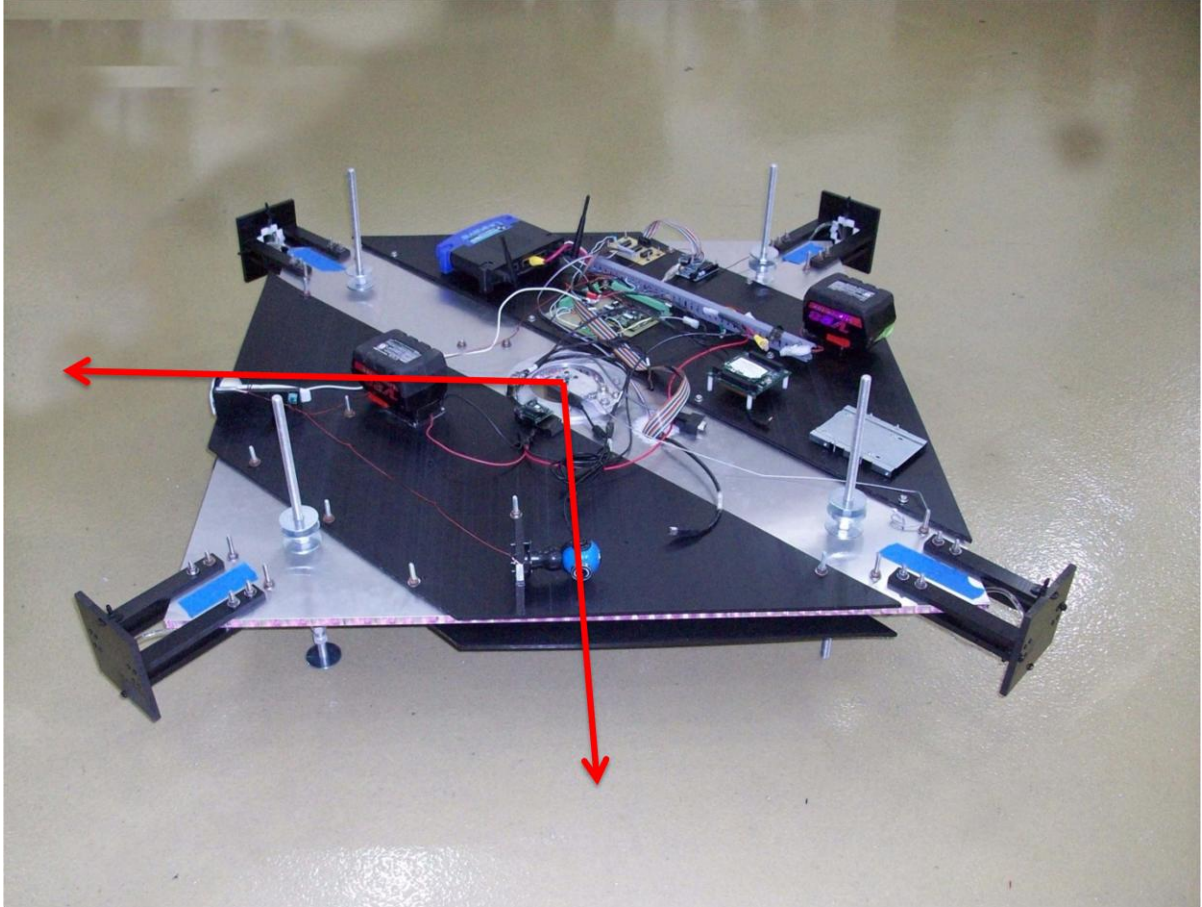


Figure 19: depiction of pseudo star tracker orientation

The pseudo star tracker uses a Point Grey Firefly MV camera and an open source computer vision software package called reactivision to determine six degrees of freedom in the frame of the camera when specially designed fiducial markers are in the cameras field of view [20]. Rotations and translations in this frame are then propagated to the robot frame (figure 1), which is centered at the pivot point.



Figure 20: Pseudo star tracker (fiducial sensing)

The data provided by these sensors is noisy, (in some cases biased) and as a result each sensor is not reliable on its own. An Extended Kalman Filter (EKF) is implemented as a means of combining these measurements to provide an estimate of attitude that has the highest probability of being true.

The Extended Kalman Filter is a probabilistic filter which consists of five equations that propagate state through time. Each sensor is assumed to take measurements with white Gaussian noise. It is based on the Linear Kalman Filter, but has allowances for non-linearity in system transition dynamics. The Linear Kalman Filter works for systems in which elements of the new state are a linear combination of the previous state and any control inputs. The Extended Kalman Filter propagates error using first order Taylor series approximations while ignoring higher order terms [21].

The EKF uses the IMU's gyroscope data at a high frequency for its prediction step which uses dead-reckoning to propagate state through time and uses the lower frequency absolute attitude sensor measurements for its measurement update step.

Measurement latency is handled by storing a large number of recent states, with time correlation. Given a measurement and knowledge about the time at which it was taken, the measurement update is made using the state estimation of the system corresponding to the time at which the measurement was taken.

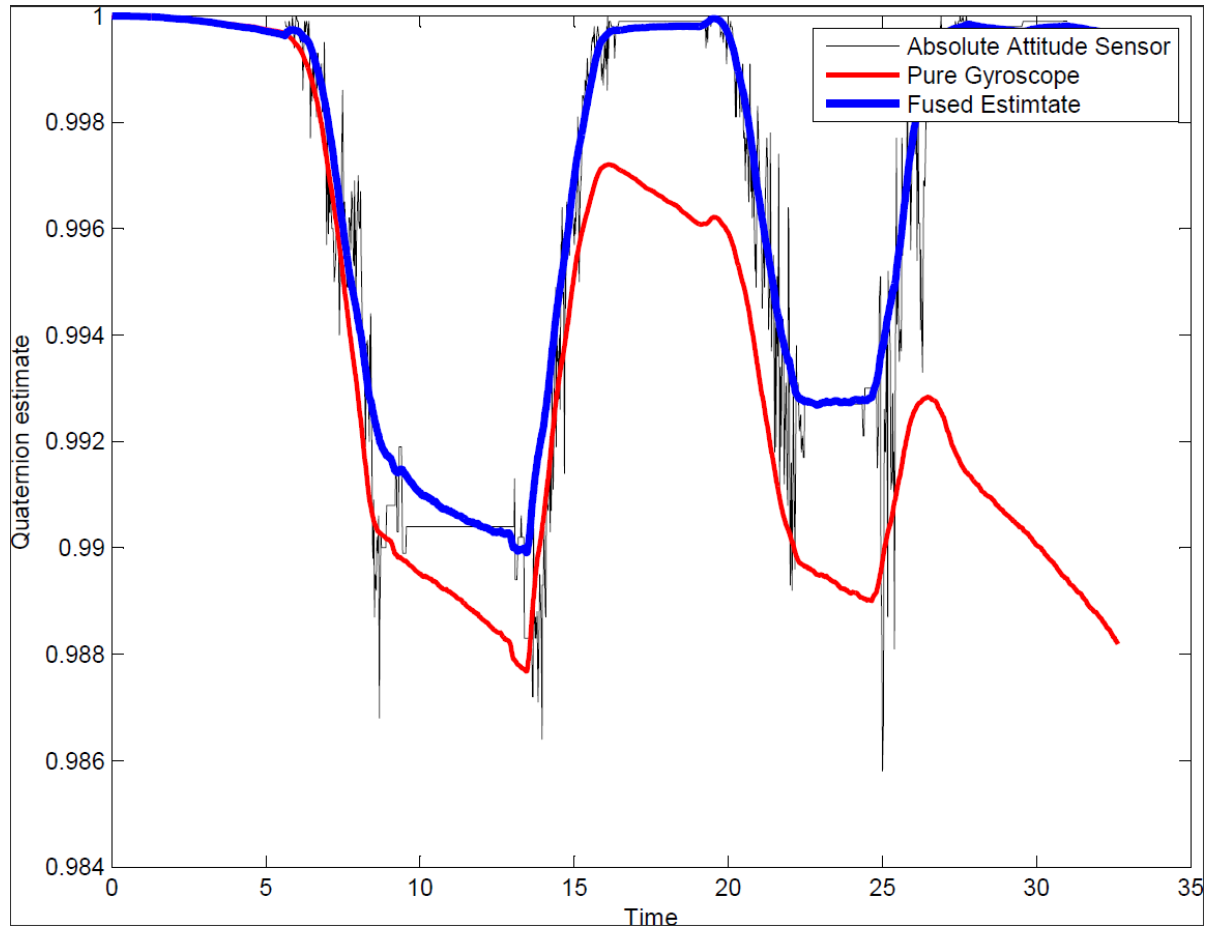


Figure 21: Filtered inertial and absolute sensing data

Preliminary tests reveal that fused pseudo star tracker and gyroscope sensor data give an attitude estimate with less than 3° of error.

6 Control Software

A PID feedback controller is used as a baseline attitude control algorithm for the tilt platform. Other controller's performance can be compared against the performance of this control algorithm. For the purposes of this research control was optimized to reduce settling time as much as possible by altering PID constants. Other optimizations can be done to reduce fuel consumption, or reduce overshoot, depending on the application of the control algorithm being tested.

Separate controllers exist for rotations about each axis. The outputs of the controllers are a function of the error between the current attitude and the intended attitude of the tilt table, and the PID constants. This output is converted to a percentage of the maximum thrust that is available from each thruster at a given time that is needed to correct for this error. This percentage takes into account the number of solenoids on at a given time and takes the maximum thrust from table 2. The percentage is sent as a PWM signal to the solenoid valves and holds them open for the percentage of the duty cycle sent to them after adjustments are made to account for the latency in opening and closing the valve. The solenoid valves are driven by an amplified digital signal from the Arduino microcontroller commanded by the PC-104 computer, the minimum operational cycle is 100 ms, which corresponds to a bandwidth for the thruster of 10 Hz.

Controller performance in simulation with a starting orientation of (0,0,0) and given a step function to achieve an orientation of $(10^\circ, 10^\circ, 10^\circ)$ or $(.17, .17, .17)$ radians is illustrated in figure 22. The controller has about 75% overshoot and a settling time of about 30 seconds for each axis. This controller was tuned

once ported the physical platform because of imperfect system modeling in simulation. The performance of the controller modified for the physical platform is shown in figure 23. In this test illustrated in figure 23 three 10° step functions are applied one after another. Overshoot is about 50% and settling time is closer to 5 seconds on the physical model most likely due to damping caused by friction and air resistance. These damping forces must be characterized and taken into account when modifying controls tested on this platform for space.

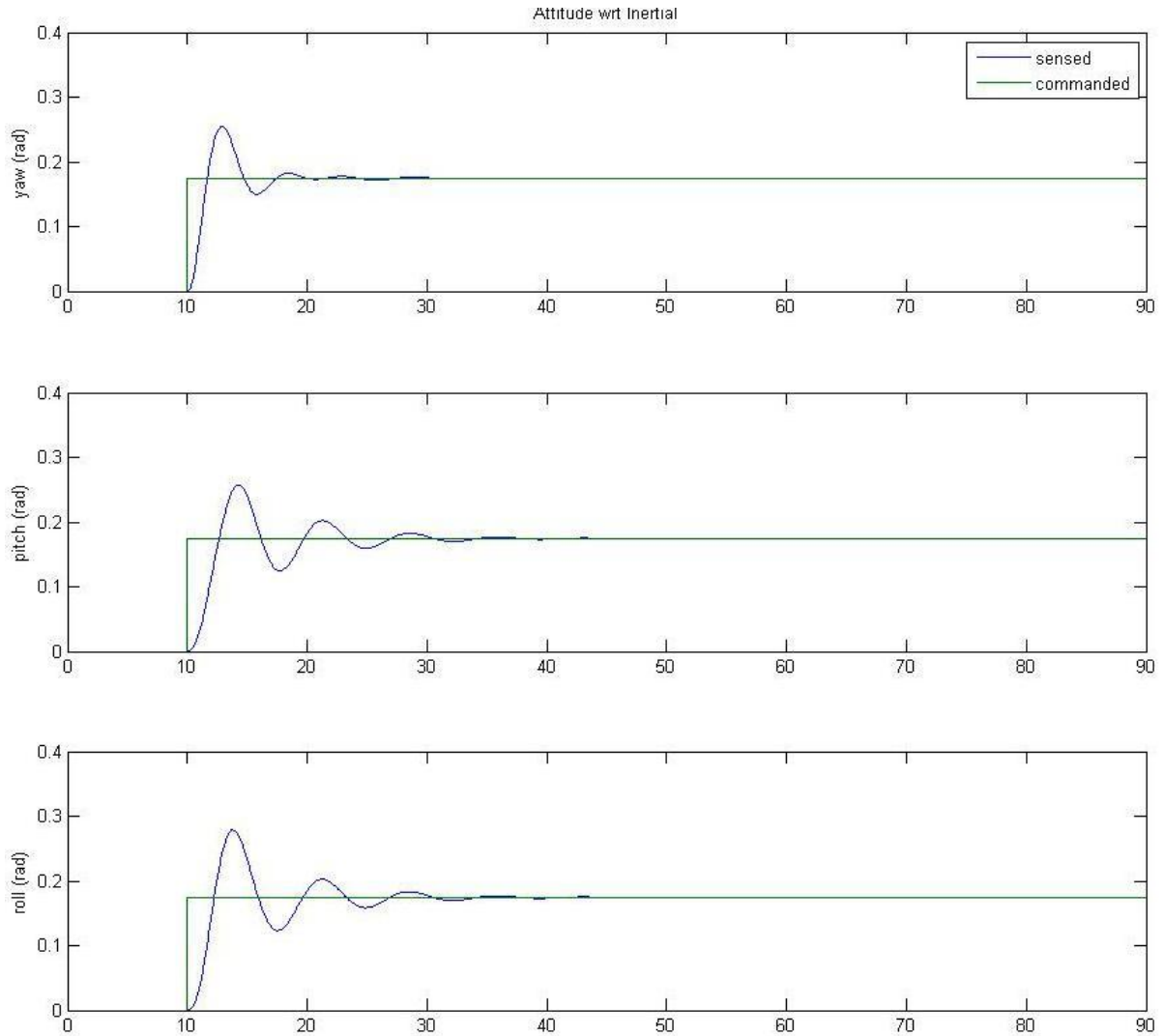


Figure 22: PID performance given a step function in simulation

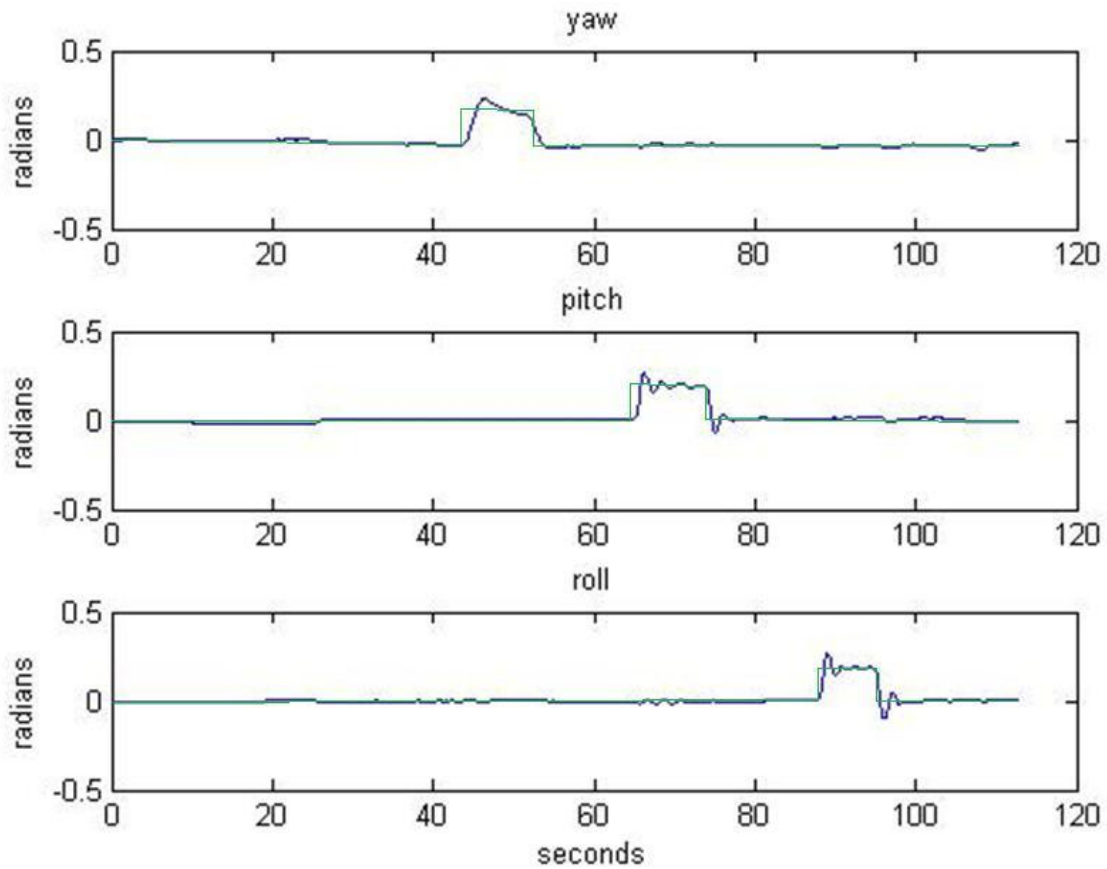


Figure 23: PID performance given a step function on the platform

7 Computing

The tilt platform is equipped with a Lippert Cool RoadRunner-945GSE PC104 computer with an Intel Atom N270 1.6 Ghz processor which provides high speed data processing in a low power, small form factor package. Input/Output devices are handled by an Arduino Duemilanove connected to the PC104 computer through a USB connection. The computer runs a server variant of the Ubuntu Hardy Heron 8.04 Long Term Support operating system mounted on a union file system (AUFS) to emulate a read-only root file system and to increase reliability. Data logs and trajectories are stored separately on a write enabled 32GB Intel Solid State Drive (SSD).

Inter-process communication (IPC) is socket based. TCP/IP packets, containing telemetry and control data, are relayed by CMU IPC between processes onboard the platform's computer as well as to the offboard user interface.

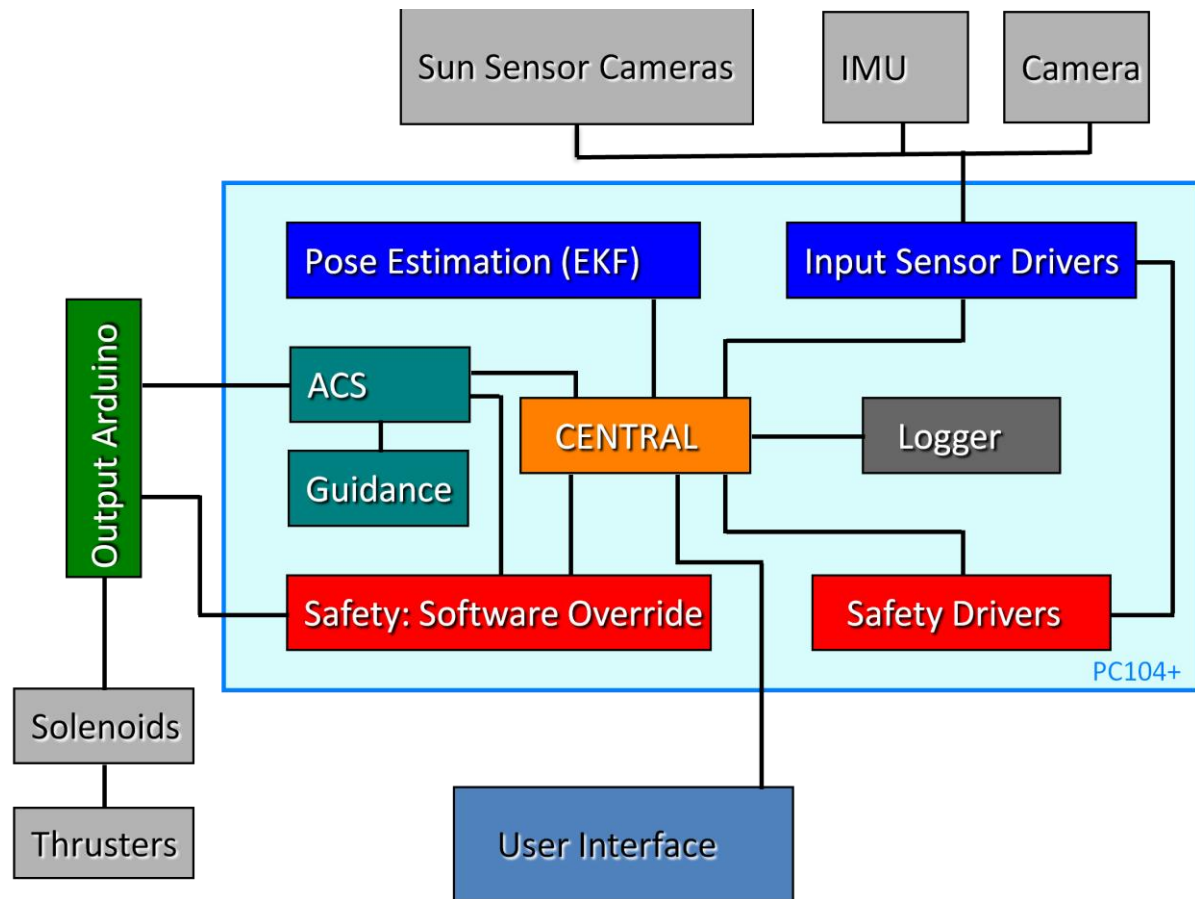


Figure 24: Software module diagram

8 Modeling fidelity

It must be noted that there are differences between a terrestrial motion platform, such as the one presented in this paper, and a system that would fly through space. Friction in the pivot point, air drag, and the restoring force and added inertia from the attached plumbing line are differences between the terrestrial platform and a spacecraft which should be taken into account when determining the quality of tested software and hardware. Varying flow rates and line splits from thruster to thruster could change thrust more than a well regulated space ready system would. Inconsistencies in thruster responses could also change thrust provided even when solenoids receive similar signals and air flow. Sensor errors and drift rates are different from those of space rated components. These system properties all must be characterized and accounted for before implementing software developed on this platform on a spacecraft.

9 Conclusion

This research has developed a sensing and attitude control platform for a lunar lander which is capable of testing Guidance, Navigation and Control software. Sensing capabilities comparable to that of a spacecraft and preliminary controls are achieved. Intended trajectories were followed with high fidelity. Through further testing on this platform control software can be validated for attitude control of all maneuvers from Second Stage Separation to Descent of a spacecraft, represented in figure 25.

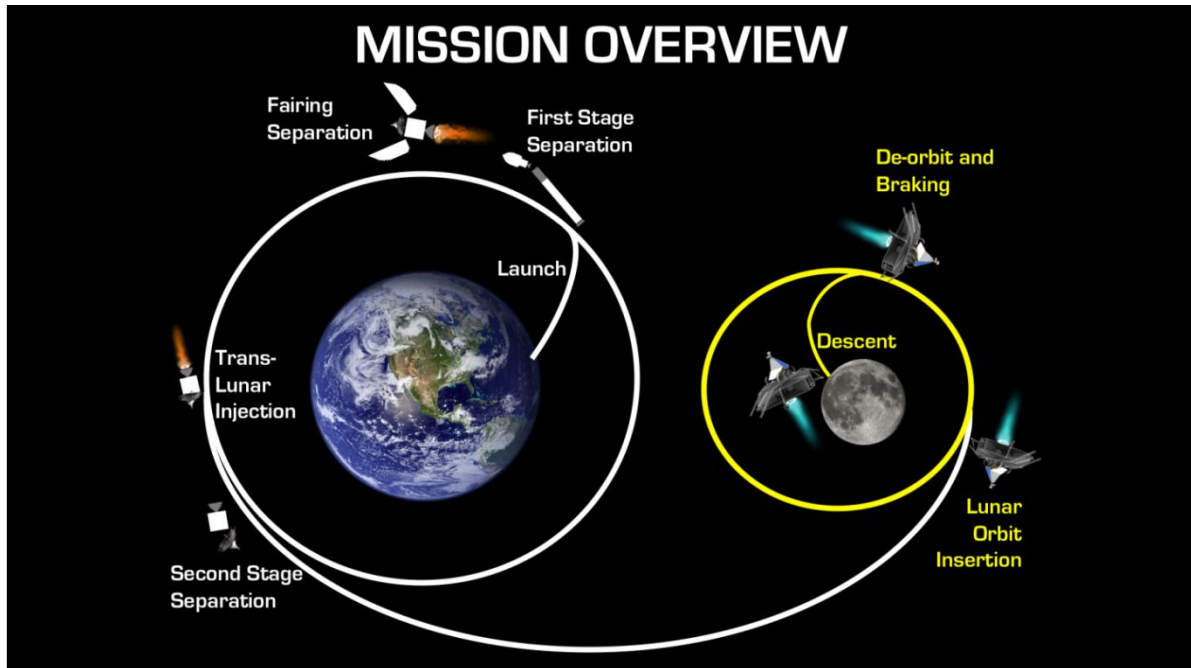


Figure 25: Representation of flight phases

Software developed for filtering sensor data has higher reliability than any individual sensor. With each added sensor data becomes more reliable as a factor of the accuracy of the added sensor. Based on filtered sensor data the tilt platform is capable of achieving rotations of 10° in fewer than 10 seconds.

A propulsive roll, pitch, yaw platform can emulate attitude trajectories required for cruise and lunar entry, descent, and landing.

Lunar relevant sensing and pose estimation can be emulated by a roll, pitch, yaw platform in a controlled high bay environment.

Lunar relevant attitude control is achievable on a terrestrial roll, pitch, and yaw platform.

A roll, pitch, yaw emulator is viable for evolutionary testing of GNC algorithms and devices destined for lunar missions.

10 Future Work

The platform described in this research will be used to test a variety of attitude control and sensor fusion algorithms. Control software that varies the PWM cycle length depending on attitude error can be implemented. Other types of controllers can be tested, such as the phase plane controller described in prior work. Sensor fusion algorithms other than EKF, can be implemented in order to acquire better state estimation.

Many upgrades are available for this robotic platform. A means of gravity offload could be achieved and a base thruster could be added so that the platform could achieve six degrees of freedom in lunar gravity. Software is easily upgraded for space-qualified sensors: the pseudo sun and star trackers could be replaced with celestial sun and star trackers, while a space-rated IMU could replace the Crista IMU. These hardware changes could occur with minimal software changes. If the platform is developed such that six degree-of-freedom motion is possible, a method of determining absolute pose estimation could be developed. A variety of sensor fusion and control algorithms could be tested on this robotic platform. Finely tuned software developed on this system could be ported over to spacecraft which require attitude determination and control and have attitude thrusters which are decoupled from a base thruster.

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In loving memory of Ruth and Bernard Moidel.

Appendix A: Experiments

A.1 Determining errors in attitude estimation

Procedure:

1. *Mark points on the wall that the lasers will make when the platform is zeroed*
2. *Mark points on the wall that the lasers will make when the platform is rotated 20° about each individual axis*
3. *Zero the tilt platform*
4. *Manually rotate the platform 20° about the x axis*
5. *Hold for 5 seconds*
6. *Zero the tilt platform*
7. *Manually rotate the platform 20° about the y axis*
8. *Hold for 5 seconds*
9. *Zero the tilt platform*
10. *Manually rotate the platform 20° about the z axis*
11. *Hold for 5 seconds*
12. *Repeat for each combination of sensors*

Metrics:

- *Mean error*
- *Variance*

A.2 Thruster shock influence on attitude estimate

Procedure: (Let platform spin and reset to zero)

1. *Set the tilt platform on the pin, turn on only IMU*
2. *Zero the tilt platform*
3. *Pulse each moment pair of thrusters for 10 cycles ($10 @ 10\text{Hz} = 1\text{ s}$) for 10%, 20%, etc.*
4. *Zero the tilt platform (determine error between sensed and actual orientation)*
5. *Add absolute orientation measurements to the filter orientation estimate*
6. *Pulse each moment pair of thrusters for 10 cycles ($10 @ 10\text{Hz} = 1\text{ s}$) for 10%, 20%, etc.*
7. *Zero the tilt platform (determine error between sensed and actual orientation)*

Metrics:

- *Drift rate*

A.3 Determining Inertia Tensor

Mission Objectives: Determine Inertia Tensor

1. *Thrust one moment pair of pitch thrusters at full force and measure maximum acceleration*
2. *Hard stop with hand*
3. *Thrust two yaw thrusters at full force and measure maximum acceleration*
4. *Thrust two roll thrusters at full force and measure maximum acceleration*
5. *Determine moments of inertia:*

$$F = 2.77\text{N}$$

A.4 Determining Controller quality

Mission Objectives: Determine Controller performance when given step impulses

1. *Zero the tilt platform*
2. *Rotate 10° about x while holding rotations about y and z to 0° , hold for 10 seconds after oscillations are within a 3° dead band*
3. *Zero the tilt platform*
4. *Rotate 10° about y while holding rotation about x and z to 0° , hold for 10 seconds after oscillations are within a 3° dead band*
5. *Zero the tilt platform*
6. *Rotate 10° about z while holding rotation about x and y to 0° , hold for 10 seconds after oscillations are within a 3° dead band*

Metrics:

- *% deviation from intended roll, pitch and yaw angle after settling*
- *Settling time*
- *% Overshoot*
- *# of cycles to settle into dead band*

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