# Development of a Low-Cost, Open-Hardware Attitude Control System for High-Powered Rockets

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**Attitude control systems are an important enabling technology for amatuer and university class high-powered rockets to be more useful as platforms for high-altitude science, but are presently too costly and technically complex to implement for many groups. With the intention of making this technology more accessible to the high-powered rocketry field a mechanical engineering senior capstone team at Portland State University developed an open-source, scalable attitude control system leveraging COTS components, robust controls, and additive manufacturing. A qualitative narrative describing the system design process is presented here.**

## Nomenclature

| | | |
|---|---|---|
| COTS | = | Commercial Off The Shelf |
| DoF | = | Degree of Freedom |
| IMU | = | Inertial Measurement Unit |
| LQR | = | Linear Quadratic Regulator |
| LTI | = | Linear Time Invariant |
| PSAS | = | Portland State Aerospace Society |
| PWM | = | Pulse Width Modulation |
| RCS | = | Reaction Control System |

## I. Introduction

The Portland State Aerospace Society (PSAS) is an engineering student group and citizen science project at Portland State University dedicated to building low-cost, open-source, and open-hardware high-powered rockets and avionics systems. The group's stated long term goal is to place a 1 kg cubesat into low Earth orbit with their own launch vehicle. This goal is set amidst the incredibly rapid expansion of the small satellite industry in this decade. Between 2013 and 2014 launches of nanosatellites, defined as satellites in the 1-10 kg mass range, increased by 270% according to SpaceWorks Small Satellite 2014 annual market analysis**.** Presently the small satellite market is handicapped by the limited selection of dedicated launch services options; satellite operators must choose between launch rideshares as a secondary payload (either on commercial launches or through NASAs Cubesat Launch Initiative) or deployment from the ISS Nanoracks system. In either case the satellite operator must cede ultimate control over the satellite orbital parameters to the launch services provider's primary customer. Because this place a substantial limitation on the utility of small satellites a number of efforts are currently underway to develop dedicated launch vehicles to service the small satellites market, including a NASA request for proposals for "Venture Class Launch Services" capable of inserting up to 60 kg of U-class satellites (e.g. cubesats) into Low Earth Orbit. One fundamental technical requirement for these orbital rockets is a system for guiding the rocket along an orbital insertion trajectory; such systems are known as attitude control systems.

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Dedicated small satellite launch vehicles share cladistic similarities, at the extrema of their range, with both large orbital launch vehicles and the comparatively small high-powered rockets that have been operated by hundreds of amateur and university groups such as PSAS, for decades. Typically high-powered rockets fly ballistic trajectories with apogees nearly always less than 30 km and more commonly less than 10 km altitude. However, several of these amateur and university groups harbor aspirations of sub-orbital flight above the von Karman line. In the context of amateur and university high-powered rocketry groups, attitude control systems have many near-term potential applications and usage cases:

1. active stabilization,
2. trajectory control, dispersion envelope control and range safety,
3. science, payload, and instrumentation requirements,
4. atmospheric reentry energy management,

One direct application of an attitude control system in high powered rocketry is counteracting the deleterious effects of weather cocking (that is, the tendency of rockets to steer into the wind). Aerodynamic fins are often used in conjunction with nose cone weights to ensure the rocket's center of pressure is well behind the center of mass such that corrective moments are produced for non-zero angles of attack. Weather cocking is a side effect of this need to use large fins for passive stabilization. Local wind speeds change the fluid velocity vector so that it is no longer strictly vertical for a rocket in flight. Ultimately this causes rockets to squander impulse in accelerating laterally. By using an attitude control system for active stabilization fin sizes can be reduced and the high-powered rockets maximum altitude at apogee can be improved.

Relatedly, very high altitude launches are constrained by range safety issues. Generally obtaining a FAA waiver for a Class 3 'Advanced High-Powered Rocket' launch is contingent on being able to rigorously justify that the rocket will return to the Earth within some radius of the launch site that is safely distant from populated areas. This area within which the rocket must land is called the dispersion envelope. Unfortunately, ensuring an acceptably small dispersion radius becomes more and more difficult with increasing altitude at apogee, both due to weather cocking and the tendency of high altitude winds to translate the launch vehicle downrange. This introduces a novel usage case for an attitude control system. Using a combination of publically available NOAA data on high altitude winds and Monte Carlo simulation an initial heading and launch angle can be determined that will cause the rocket to land very near the launch site with a known level of statistical confidence. Using this information the boost guidance on the launch vehicle would, upon clearing the tower, immediately roll to align one of the pitch axes with the desired heading and then pitch over to the initial launch angle. This is known colloquially as "calling the shot", and would be unprecedented as an in-situ capability for a launch vehicle in the high powered rocketry class. Presently such capability is attained by gimballing the entire launch tower rail.[1]

In addition to boost guidance, rocket attitude control enables support for sensors or instrumentation with specific angle or rate pointing requirements. For large suborbital sounding rockets a significant portion of the flight time is spent above the atmosphere (often as long as five minutes). At this altitude, free-fall conditions prevail and perturbing aerodynamic torques are small such that an attitude control system can provide a stable actively pointed platform for experimentation with minimal disruption from controller vibrations. Research areas that benefit from such technology include microgravity fluid physics, meteorology and atmospheric science, infrared and x-ray astronomy. Should an inexpensive, open-hardware attitude control system be developed that is scaled for university class sounding rockets, then some of these rockets may eventually be evolved into more

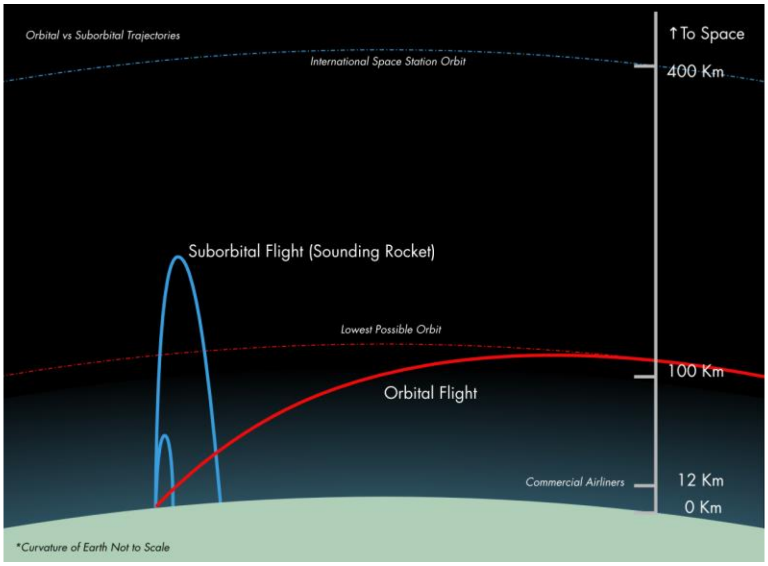


**Figure 1. Comparative schematic of orbital and suborbital trajectories (image courtesy of PSAS).**


**Figure 2. LV2.3 Roll Control System (image courtesy of PSAS).**

generally capable platforms for research in these fields. Other payloads and subsystems can benefit from directional pointing as well, such as cameras and telemetry downlink antennas.

Another application is energy management during payload reentry. During the atmospheric reentry phase of a suborbital trajectory enormous heat and dynamic pressure loadings develop as the launch vehicle decelerates from several kilometers per second ground relative velocity. Mitigating the effect of these loadings is critical for comparatively small scale single-stage launch vehicles that are intended to be recovered and reused, such as many university group operated high powered rockets. An attitude control system can be used to place an initial spin on the launch vehicle; as it reenters the atmosphere aerodynamic drag induces small torques on the spinning vehicle. Because of rotational energy dissipation, these small torques cause the spin to precess or nutate to the axis with the highest moment of inertia, in this case the pitch/yaw axes. This flat-spin aerodynamic mode has the effect of increasing drag coefficients for the launch vehicle. The resulting increase in drag can be harnessed to bleed off excess velocity of the vehicle during reentry at an acceptably low dynamic pressure.

A yet more ambitious application of boost guidance and attitude control is trajectory optimization for orbital launches. Ascent trajectories for orbital launch vehicles differ in several key respects from sounding trajectories which otherwise do not require inertial guidance; these are schematically illustrated in Figure 1. Optimal ascent trajectories are designed to minimize overall launch delta-v requirements, however this is difficult because the relative magnitude of various losses, such as drag, gravity and steering losses are path dependent. Active control thus becomes a powerful tool for optimizing orbital launch trajectories.

Inside Earth's atmosphere the most often used attitude control strategy is to actuate steerable aerodynamic control surfaces, such as fins or canards. Unfortunately, such systems are constrained by the dynamic pressure at which they can produce useful amounts of lift. Generally, this corresponds to a limiting flight envelope of about 30 km altitude.

**Figure 3. Portland State Aerospace Society LV2.3 and LV3 high powered rockets (images courtesy of PSAS).**

PSASs current generation sounding rocket, LV2.3, is capable of a 5 km apogee and low supersonic velocities. It uses a module with servo-actuated steerable canards for roll axis attitude control, shown in Figure 2. In 2014 PSAS began work on a new very high-altitude high powered rocket, the LV3, with a design apogee of over 40 km. These vehicles are pictured in Figure 3. Pursuant to their mission of developing inexpensive, open-source technologies for small-scale orbital launch vehicles PSAS issued a call for a 6 degree of freedom attitude control system which could operate at these very high altitudes. This became the basis of a mechanical engineering senior capstone project at Portland State University.

## II. Top-Level Design

### A. Requirements

The essential design requirement for the attitude control system is that it must control the launch vehicle pitch, yaw and roll angles and velocities at all conceivable altitudes and in vacuum conditions, with particular emphasis placed on the roll axis. The system should have at least 150 N•s of stored impulse. The system should use inexpensive COTS components. The system should also be expressly designed with extensibility and scalability in mind. This requirement follows from PSASs general interest in open-source development of technologies for high powered rocketry, and the fact that LV3 is presently in the preliminary design phase and its mass characteristics and trajectory design are still subject to change.

### B. Baseline Design

The baseline attitude control system design is a cold-gas vernier jet type Reaction Control System (RCS) as seen in Figure 4. The RCS module is designed to fit ⌀6.o" payloads. The RCS module itself is physically composed of a high-pressure nitrogen propellant tank, a regulator, a series of 6 solenoid valves (two for roll, and four for pitch/yaw) plumbed to 8 3D printed rocket nozzles, a power supply and MOSFET relay board, an Intel Edison microcontroller with an Arduino breakout board, an inertial measurement unit, a set of pressure transducers, miscellaneous plumbing (gas lines, push to connect fittings, compression fittings, a fill valve, a latch valve, a high pressure tank adaptor, a gas distributor manifold, burst disks, etc.) a structural frame, and a carbon-composite aeroshell. The set of 8 vernier jet rocket nozzles are arranged such that they are perpendicular to the 3 principle axes of rotation of the rocket. When the solenoids are energized nitrogen gas exhausts supersonically through the rocket nozzles producing thrust. These thrust forces act across a lever arm to the vehicle center of mass to produce moments of force which then steer or orient the vehicle in whatever direction is desired. Cold-gas propulsion systems, while of generally low performance, are inexpensive, mechanically simple, and safe to operate such that they can be used by high turnover university student groups. The open-source/open-hardware and scalability requirements for different missions led to the selection of a modular system layout

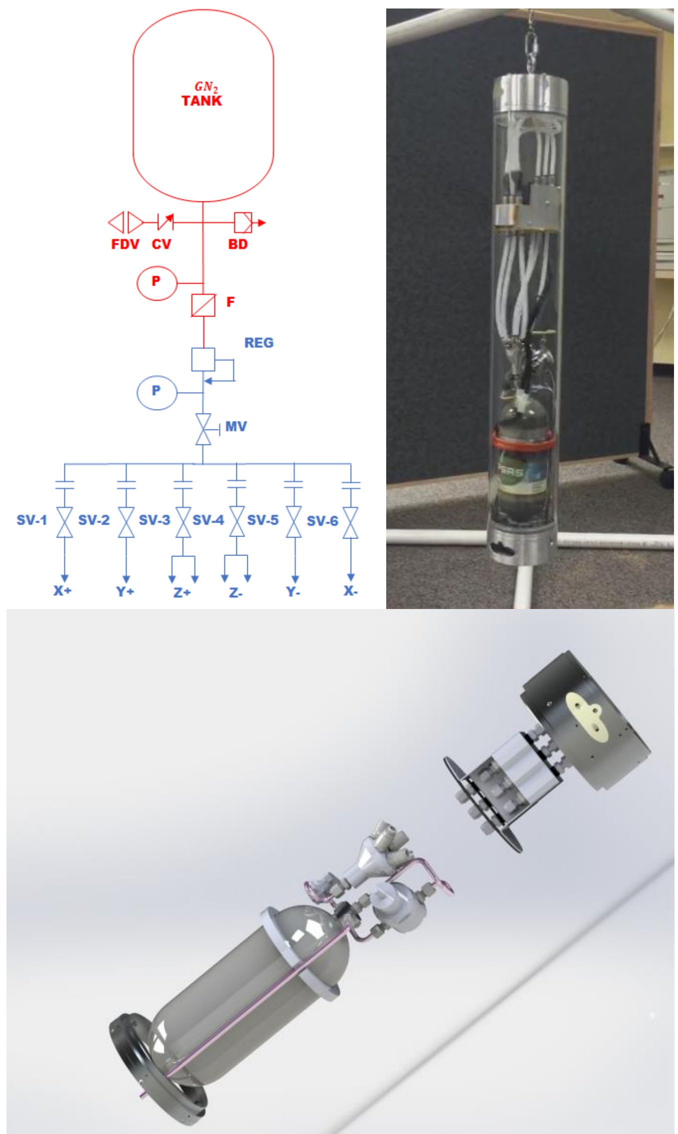


**Figure 4. RCS Piping and Instrumentation Diagram, RCS roll test module in acrylic display case, and Solidworks® render of RCS assembly.**

with 3D printed nozzles, and a controller robust enough to tolerate large variances in system dynamics and model uncertainty, and that is relatively straightforward to determine gains via simulation.

## III. Propulsion

Nitrogen cold-gas has comparatively low theoretical specific impulse of about 70 s at 100 psi chamber pressure and standard temperature. This means that the ratio of mass flow rate to developed thrust is high and thus is inefficient. Since there are both volume and mass constraints on the total amount of propellant that can be carried on the rocket some analysis was required to optimize nozzle performance where possible. Additionally for a scalable, open-source system a way is required to ensure that the numbers that are put into the plant model in the controller are accurate.

An essential property of rocket nozzles is that their design expansion ratio is optimum for only a single ratio of back pressure to chamber pressure. This optimal performance therefore corresponds to a single specific altitude of operation. Problematically, for any sub-orbital sounding trajectory the altitude, and thus the back pressure, changes rapidly with time. One primitive, but analytically straightforward approach to determining the back pressure is simply to use an averaged 'characteristic altitude' value associated with a mission design flight envelope in combination with the US 1976 standard atmosphere model. Using additive manufacturing techniques we gain the flexibility to rapidly manufacture optimal nozzles on the fly to fit any specified mission trajectory, or launch vehicle mass characteristics by varying nozzle throat area, and expansion ratio parameters.

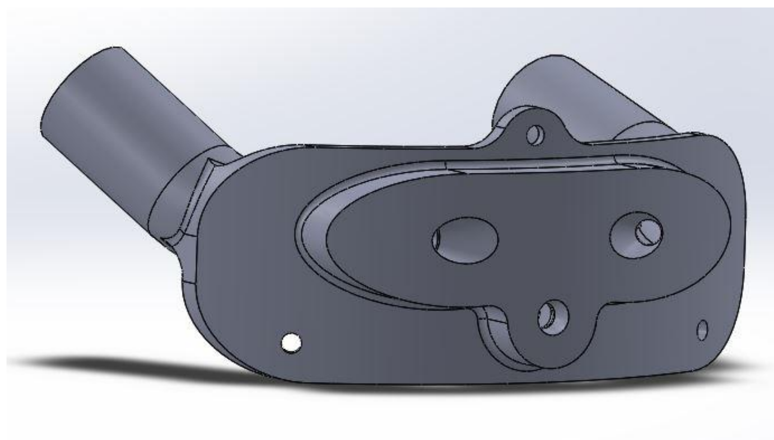

**Figure 5. Roll axis scarfed geometry nozzles SolidWorks® CAD drawing.**

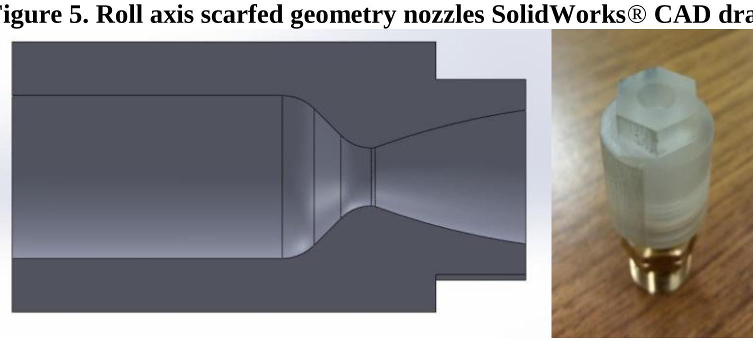

**Figure 6. 3D Printed nozzle SolidWorks® CAD drawing and single-stream test nozzle.**

An ideal nozzle is shaped such that all flow is axial at the exit plane, eliminating divergence losses, however such ideal nozzles are infinitely long and so cannot be used for practical propulsion. Since 1960 Rao's method of characteristics approach has been used to analytically determine the contour needed to achieve optimal (i.e. uniform parallel) flow conditions at the exit plane.[2] This requires that flow be inviscid and 2-D, however since real flow is viscous a boundary layer correction must be applied ex post facto. For large rocket nozzles these losses are comparatively small (generally less than 1.0 %).[3] Nozzles with throat Reynolds numbers greater than $10^6$ are not believed to have significant boundary layer losses.[4,5] For small nozzles there is potentially a much larger effect.

The Rao perfect nozzle is not a parabola, however it resembles one and can be reasonably be approximated as one. Such nozzles are commonly termed 'Bell nozzles'. These nozzles can be shorter than conical nozzles of equivalent expansion ratio. The significant divergence losses in conical nozzles can only be reduced by reducing the divergence angle. For the same expansion ratio this means that the nozzle will have to be longer. As the 3D printed nozzles are real rather than ideal nozzles, added length has the effect of increasing boundary layer and frictional losses, which are compounded by the combination of small throat area, rough interior surface finish and low chamber pressure. A further advantage of additive manufacturing in that it enables use of the Rao bell paraboloid nozzle which are normally difficult to manufacture at very small scales using conventional machining techniques.

A simple procedure was developed which makes this approach very easy to scale. First, the known back pressure and desired thrust are used as arguments in a simple MATLAB® script to determine throat area and optimal expansion ratios for the RCS nozzles. Initial and final angles, and convergence radii of the ideal Rao paraboloid approximation are determined from a lookup table using the expansion ratio and percent bell.[3] These values are input into a SolidWorks® parametric model of the rocket nozzles. As the RCS module is inline, nozzles were scarfed, as seen in Figure 5, to conform to the airframe outer diameter. This unfortunately incurs a small cosine loss as the thrust vector is no longer coplanar with the nozzle axis of radial symmetry. Effective expansion ratios for the scarfing were determined using a straightforward root mean square approach.[6] Lastly SolidWorks® is used to export ".stl" files that can be sent to any commercial 3D fabricator for printing. The RCS nozzles were printed on a 3D Systems ProJet® 3500 HD Max printer. The production media, VisiJet Crystal, is relatively durable, and can be tapped for threaded inserts or fittings. An example of a 3D printed test nozzle can be seen in Figure 6.

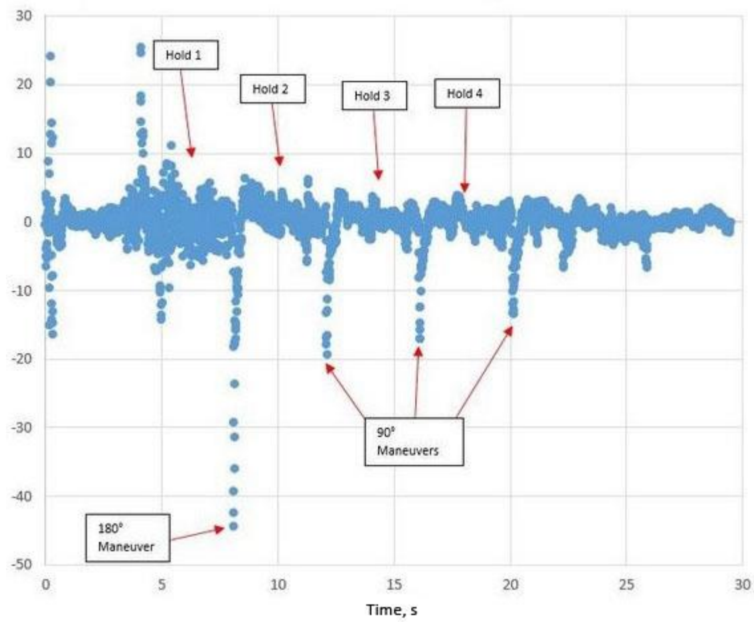


**Figure 7. LV2.3 Roll force telemetry used for estimating baseline for RCS performance.**

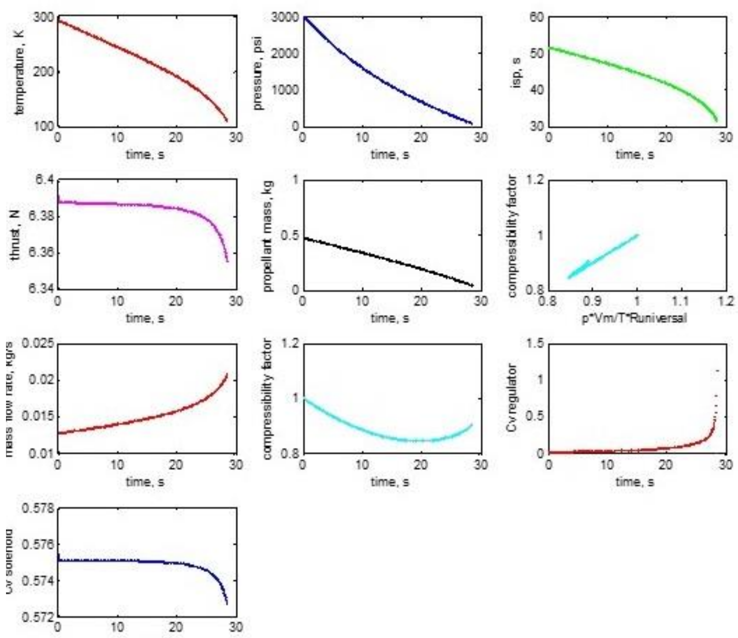


**Figure 8. Simulation output used for flow componentry selection.**

The first major step in the nozzle design process was determining the thrust level required of the system. Starting with the equation of motion

$$I\ddot{\theta} = T \tag{1}$$

where I is the mass moment of inertia, $\ddot{\theta}$ is the angular acceleration, and T is the torque. Furthermore, torque is defined by the equation,

$$Fr = T \tag{2}$$

where F is thrust force and r is lever arm (i.e. launch vehicle outer radius). Substituting (2) into (1) leads to the equation for the required thrust force (uncoupled)

$$F = \frac{I\ddot{\theta}}{r}$$

It was desired for LV3 to be able to conduct snap rolls off of the tower to support the "call the shot" usage case. This called for a maximum case 45° roll program to be completed in 1 s, requiring 0.80 rad/s$^2$ of angular acceleration. Given this value, and the worst case expected values of mass moment of inertia and lever arm of LV3 in roll, the thrust required from the roll nozzles is only 6.0 N.

Another design consideration is an estimate the required delta-v for maneuvering and active attitude stabilization, which is important for trade off analysis of rocket fin size as well as propellant tank size. Unfortunately there does not seem to be a straightforward analytical approach to determining impulse budgets for launch vehicle attitude control. Therefore the impulse budget, along with the magnitude of dynamical perturbations affecting the airframe generally, was estimated using launch telemetry from PSASs LV2.3. It was determined that the average perturbing force acting on LV2.3 was 1.49 N. Integrated over a 30 second period of active control this translates to required impulse budget of 45 N•s to maintain roll rates at 0 rad/s$^2$, neglecting any additional planned maneuvers. Given an initial tank pressure of 3500 psi and isothermal emptying conditions this translates to a required tank volume of 0.885 L. A roll force plot constructed from LV2.3 telemetry is presented in Figure 7. It is desirable that the ratio T/I be large enough to zero out initial rates to the satisfaction of any response time requirements, and to exceed the magnitude of any expected disturbing torques by a large margin, but yet no so large that attitude hold fuel-efficiency is negatively affected with a sub-nominally damped control response. Based on the assumption that the disturbing torques are similar between LV2.3 and LV3 a design thrust of 8.0 N was chosen for the RCS roll nozzles. The propellant tank is a Luxfer composite 2 L cylinder with a specified service pressure of 4500 psi. Given a design pressure of 3500 psi the tank should have a mission impulse budget factor of safety of close to 2.

Additional simulations of tank and nozzle thermodynamics were used to determine required flow coefficients for the various flow components in the system, particularly of the solenoid valves and the pressure regulator. The model used discrete time iteration to model the changing tank conditions using the Van der Wall equations of state and the isentropic relations, in addition to the non-choked flow coefficient equations. This was done to ensure that choked flow conditions would hold only at the nozzle throat and thus that the nozzle would operate supersonically. This helped inform the COTS component selection of the detailed design phase of the engineering process. An example model output plot for the case of a flight-like nozzle with a 100 psi chamber pressure nozzle operated at sea level with an expansion ratio of 2, inlet temperature of 290 K, initial tank pressure of 3500 psi, and a throat area of $1.26\times10^{-5}$ m$^2$ is shown in Figure 8. These simulations indicated that for the isentropic tank emptying condition at the expected duty cycles, and initial conditions propellant temperatures would rapidly drop to the region 70-90 K. This is close to the saturation temperature of nitrogen at 1 atmosphere. Though it was understood that the tank would not empty in a purely isentropic mode, a naively applied lumped capacitance analysis of the thermal response of the solenoid valves was conducted**.** This analysis conservatively assumed that only the solenoid armature absorbs heat, and made use of the Dittus-Boelter Nusselt number correlation (i.e. assuming that the flow is turbulent and fully developed though the solenoid). It was determined from this analysis that Biot numbers were large and that the characteristic time was of the same order of magnitude as the solenoid open time. This led to the selection of solenoid valves with Buna-N seals, which are expected to maintain integrity against leaks at temperatures as low as -40 C.

## IV. Controller

### A. Modeling

For the rotational tests, a simple proportional controller was used. This controller satisfied the key requirements without adding unnecessary complexity to the overall system. The creation of the RCS roll controller is broken into two methods: the theoretical modeling of individual blocks formed into a working system, and the physical implementation of the model applied to the dynamic mechanical system. The model consists of 5 major blocks, the DC limiter, controller, PWM generator, solenoid model, and the rotational system transfer function (e.g. the rigid-body dynamics of the airframe). The system model is shown in Figure 9.

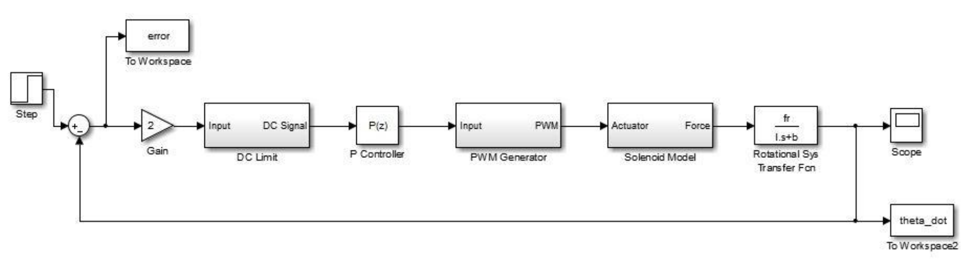


**Figure 9. Simulink® block diagram of the rocket in roll.**

A simplified transfer function, dubbed the *flying cylinder*, was created using system dynamics equations with respect to roll rate and disturbance force. Starting with the equation of motion and solving for the transfer function with the input as angular velocity and the output as force we obtain

$$\frac{\dot{\theta}}{F} = \frac{r}{Is + b}$$

where $\dot{\theta}$ is the rotational velocity, F is the force, r is the radial position of the nozzles, I is the mass moment of inertia about the rotational axis, b is the damping ratio of air, and s is the Laplace frequency domain variable.

The On/Off solenoid valve block, used as the actuator, is modeled with the equation

$$\frac{1}{\tau s + 1}$$

where $\tau$ is the solenoid time constant; this model was used to simulate the discrete time lag of the solenoid. The time constant was determined through the manufacturer's lag time claims and verified by single-stream testing the system.

A PWM block was also included to simulate the force out of the solenoid as it is cycled. This then had to be normalized from a 0 to 1 range (PWM duty-cycle). A PWM frequency of 5 Hz was selected by optimization between the fastest response time and widest duty-cycle range. A duty-cycle of 10% was determined to be the fastest rate at which the solenoid could be reasonably pulsed at 5 Hz, to achieve low-end force control (i.e. to minimize the size of the smallest impulse bit).

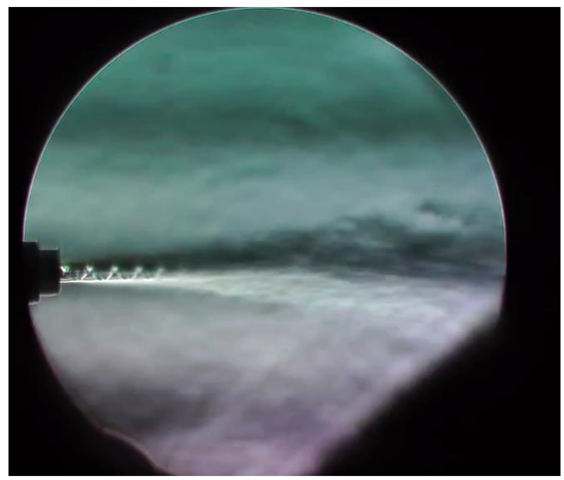

**Figure 10. Single-stream testing Schlieren interferometry.**

The DC limiter constrained the control duty-cycle to a workable range, from 10% to 80% pulse width. This block transforms the required thrust force into solenoid duty cycle by use of a linear regression determined through PWM single-stream testing of the propulsion system. The range of the workable low-end duty-cycle was determined through thrust force data collected during single-steam propulsion testing using a load cell, and through qualitative analysis of the transient developing flow during PWM solenoid operation using Schlieren interferometry, as seen in Figure 10. This single-stream analysis also included characterization of the open and close lags, time constant, and controllability of the duty-cycles for the solenoid. The maximum thrust developed by the nozzles was also determined through single-stream testing and compared to predictions from isentropic theory. The single-stream test apparatus is shown in Figure 11.

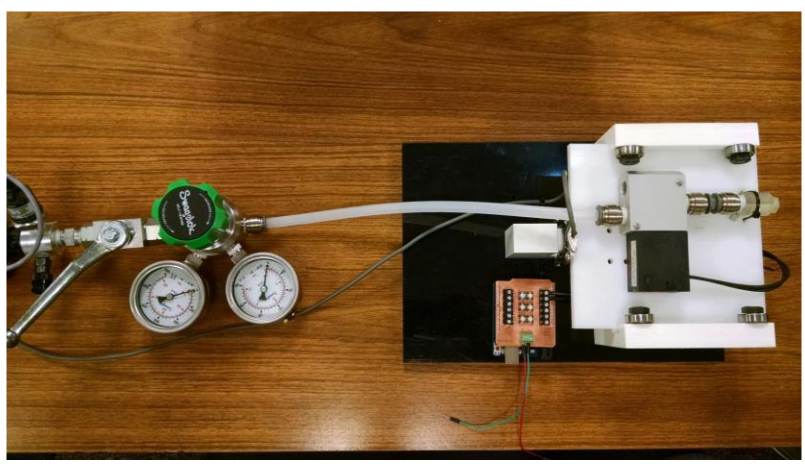

**Figure 11. Single-stream test apparatus.**

### B. Implementation and Results

To help parallelize development, an open loop controller was initially used to qualitatively test the assembled system for operational performance, specifically scalable control forces, and equal forces from opposing nozzles. Additionally an LED simulator with full feedback control was rapily prototyped to qualitatively analyze the control law, sensor characteristics, and electronic system response. This proved useful quickly buying down development risk, identifying bugs, and avoiding unnecessary pressurization of the full roll-control RCS in advance of a test, which could be a time-consuming exercise. The feedback controlled simulator used an Arduino Uno microcontroller and a 6-DoF IMU (MPU-6050) for the on-board sensor. The 6-DoF LED simulator is shown in Figure 12.

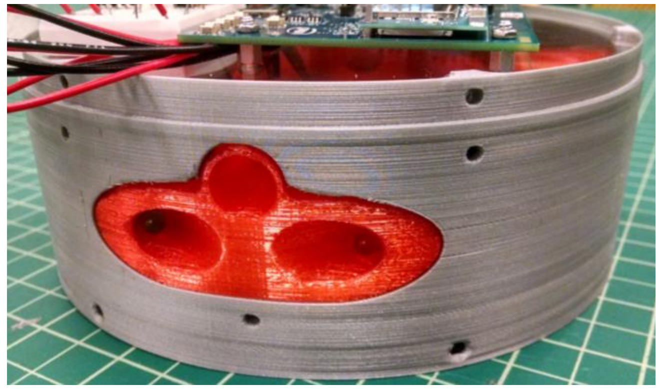

**Figure 12. LED 6-DoF simulator.**

For the full roll-control RCS system an Intel Edison microcontroller was used in lieu of the Arduino Uno. Running the Ubilinux operating system, a Debian distribution targeted for use in embedded device applications, the RCS controller leveraged the Edison's substantially improved performance and its wireless functionality. During captive wire-suspended tests a moment was applied to the rocket body, and the controller would then decrease the roll rate to zero. The data collected from the roll tests was then compared against simulation outputs. The roll rate accuracy was determined to be ±2 deg/s. The expected critical damping and settling time of under 80 ms from the model aligned well with the experimental test results as seen in Figure 13. The model is validated further by comparing model and experimental disturbance rejection as seen in Figure 14, simulating real world forces that are counteracted by the RCS. Using Bode analysis in MATLAB® we estimate that the controller has over -6 dB of gain and 60° of phase margin. This satisfies the robust control requirement, as the controller will tolerate dynamical changes in the plant and/or model uncertainty of over %50.[7]

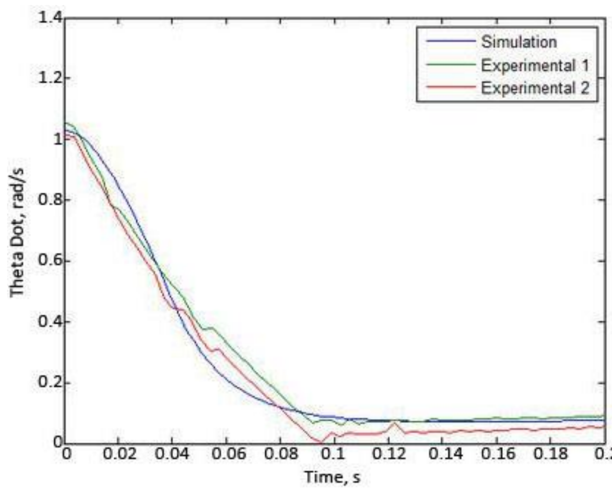


**Figure 13. Impulse response of the RCS in roll. The simulation data is plotted against the collected experimental data.**

## V. Ongoing and Future Work

The RCS controller satisfies the baseline requirements outlined in the original project scope, however further development is necessary to enable robust 6-DoF control. Validating the roll model allows us to project the control logic to the pitch and yaw angles. A rigid-body 6-DoF dynamical model of the entire launch vehicle, shown in Figure 15, was developed in Simulink to provide a medium to simulate the rocket's flight path and controller dynamics. This model contains multiple models that function as independent systems of the rocket throughout varying flight regimes; it serves as a stepping stone moving forward with the development of a fully controlled six degree of freedom RCS.

Following from the extensibility and scalability requirement is the planned implimentation of a Linear Quadratic Regulator (LQR) controller**.** This controller implementation is attractive due to their intrinsic robustness and ease of determining gains which are important advantages for a system that cannot be feasibly tested in physically realistic conditions prior to first flight. The ease of determining gains should also smooth the process of adapting the controller for use on other sounding rockets. Further capabilities enabled by LQR include gain scheduling via Linear Time Invariant (LTI) techniques, which has the potential to further improve the controller robustness as the fundamental dynamics of rocket flight change in different aerodynamic (subsonic, transonic transition, supersonic) regimes. While the rocket is not a Linear Time Invariant system, it can be modeled as one by scheduling optimized gains at different altitude ranges offering the more control authority over continuously changing flight conditions. Gain scheduling helps make the control logic tolerant of the time varying dynamics of the system plant. LQR also allows the use of cost minimization functions which provides an elegant approach to preventing waste of the finite supply of consumable propellant.[8]

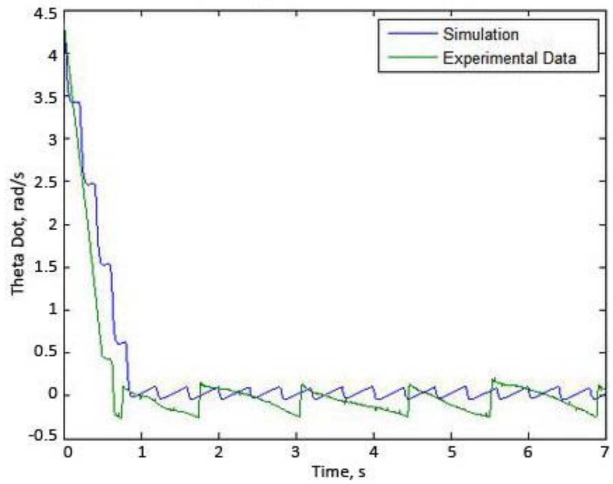


**Figure 14. Disturbance rejection of the RCS in roll. A constant torque was applied to the RCS, inducing a constant disturbance. The controller was set to keep the angular velocity at zero. As shown in the disturbance rejection of error graph, the simulation closely models what is happening in the real world.**

To increase controllability of the system, state-space equations for rigid body attitude dynamics will be implemented; these can be found in some advanced aerospace controls texts.[9] They account for the damping on the rocket in different aerodynamic regimes. These can still be used effectively with the LQR controller. The controller can also be assigned a hierarchy of desired control states with varying weight. The controlled states consist of rotational position and velocity, translational position, and quaternions. Quaternion representations are useful in that they help avoid gimbal locking and account for dynamic cross coupling between different control axes. Further research is planned to model this behavior and implement it in the 6-DoF flight controller.

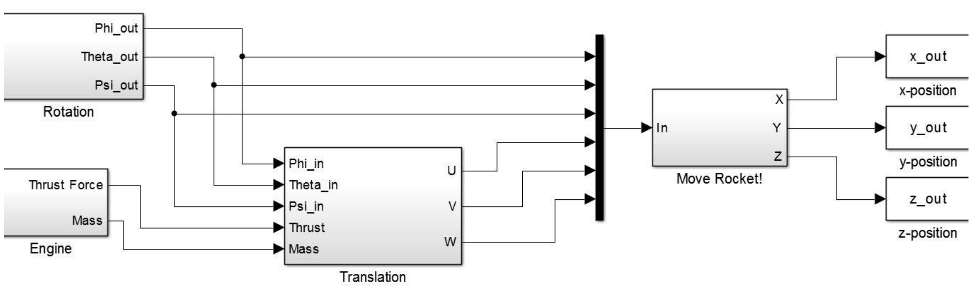


**Figure 15. Simulink® model of a 6 DoF rigid-body rocket.**

## VI. Conclusion

As it stands the LV3 RCS is one of the only operational high powered rocketry class cold-gas attitude control systems in the world, and is also to the best knowledge of authors, the first such system designed entirely by a team of undergraduate students. The RCS module will be integrated on the PSAS LV3 stack for a demonstration flight in spring of 2016. Test risks associated with active control in the pitch/yaw axes will be mitigated by using the RCS in a roll control capacity only for its inaugural flight, however the system will be capable of full attitude control.

Ultimately, there is very little inherently new in designing cold gas attitude control systems; such systems already have a very high technology readiness level. Currently attitude control systems are not widely used by university rocketry groups largely for cost and technical complexity reasons. However, in view of its many applications, RCS remains a key enabling technology for the burgeoning field of high powered rocketry and ultimately, low cost space access as well.

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