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Low-cost, lightweight electronic flow regulators for throttling liquid rocket engines

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Abstract

The need for robust pressure reducing regulators that are able to operate throughout large changes in upstream pressure is becoming increasingly common as more work is done on small-scale pressure-fed liquid rocketry. Accurate and precise pressure regulation of both tank pressures and injector pressures can allow for higher engine efficiency and optimized tank construction with the system operating closer to target design parameters.

Methods currently used for gas regulation are often inflexible, and require extensive characterization [1,3]. These include dome-loaded pressure regulators and cascaded solenoid systems with bang-bang controllers. With these systems, electro-mechanical limitations such as limited orifice size, droop, slow reaction times, and cryogenic incompatibility [2] make them unsuitable for many applications such as throttling, which has become increasingly important as vertical take off vertical landing rockets become more ubiquitous.

To overcome these challenges, we designed an electronic pressure regulator (eReg), a multi-input multi-output system that utilizes closed loop feedback to accurately control downstream pressures. Consisting of a single ball valve actuated by a motor, its robust design allows eRegs to regulate both gaseous pressurant and cryogenic liquid propellants, at high flow rates (1.14 kg/s of liquid; 0.39 kg/s of gas) and upstream pressures (310 bar). By using 4 eRegs in conjunction - 2 regulating propellant tank pressures, and 2 regulating flow of propellants to the engine - we are able to operate our engine at near-optimal OF ratios while throttling over a wide range of thrust.

To reduce system mass, powerful motors and compact planetary gearboxes were used. For high flow rates, serviceability, and manufacturing considerations, COTS full port ball valves were chosen as the flow control orifice. High flight reliability in the face of vibrations and g-forces was accomplished through the use of castellated components and nylon thread locking components.

Each eReg uses a cascaded controller, with the outer PID loop monitoring downstream pressure variations and computing valve angle setpoints for the inner PID loop. However, the control problem is complicated by the constantly changing ullage volume and upstream pressures, which results in a non-linear, time-dependent system. We found that adding feedforward terms and dynamically adjusting PID constants significantly improved controller performance, allowing us to achieve precise control despite the challenging environment.

We also empirically verified the design's performance and reliability through a water and cold-flow testing campaign, culminating in a static fire test demonstrating eReg's ability to regulate pressures precisely (within 0.2 bar) while simultaneously throttling our engine. To our best knowledge, this is the first time any undergraduate team has throttled a liquid bipropellant engine.

References

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