PROGRESS REPORT

A Bang-Bang Active Pressurization System for Liquid Bi-Propellant Rocket Engines

University of Toronto Aerospace Team

Technology Development Challenge

Launch Canada 2020 Competition

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Abstract

Liquid bi-propellant rocket engines are the standard propulsion technology used in rocket launch vehicles around the world. A fundamental process in operating a liquid bi-propellant rocket engine is feeding the liquid propellants to the injector, and subsequently the combustion chamber. The system that performs this process is called the propellant feed system. Feed systems can be operated in a variety of ways, however, two distinct feed processes remain the status-quo. Those are the **pressure feed process** and the **pump feed process.** A rocket engine whose propellants are delivered using a pressure feed process is called a *pressure-fed engine*, and similarly, one whose propellants are delivered via a pump feed process is called a *pump-fed engine*.

Due to many performance and cost considerations, large, heavy weight rocket launch platforms used for delivering payloads to earth orbits or beyond typically use pump-fed propulsion systems. The reasons for this are beyond the scope of this paper. However, for smaller rockets that are not designed to insert large payloads into earth orbit, and are rather used to delivery payloads into a temporary micro-gravity environment, pressure-fed propulsion systems can be beneficial, for various performance and cost reasons. Those rockets carry a non-propellant fluid called a *pressurant* fluid, which is used to feed the propellants to the propulsion system. This is typically done by storing the pressurant at a pressure that is significantly higher than the propellant nominal tank pressure, and feeding pressure-regulated pressurant into the propellant tanks as the engine burn progresses.

The pressurant feed process can itself be performed in many ways, both passively and actively. A passive feed system can, for example, be based on pressure regulators that automatically adjust the pressurant mass flow rate into the propellant tanks to maintain a set pressure. Pressure regulators are passive because they rely on internal mechanical mechanisms to self-adjust the regulators effective orifice size, and thus, adjust the pressurant mass flow rates. All control feedback is provided by the upstream and downstream pressures, and no active pressure readings are required in order to generate any actuation commands. On the other hand, active systems rely on reading the propellant tank pressure and issuing pressurant actuation commands as needed. In these systems, instrumentation for reading tank pressure supplies pressure readings to a processing unit, that commands the actuation of some pressurant delivery mechanism to supply high-pressure pressurant to the propellant tanks. Those systems can be, under certain conditions and for specific performance regions, simpler, cheaper, and more stable than passive pressurization system.

This report presents the concept design for a Bang-Bang active pressurization system for liquid bi-propellant rocket engines. Bang-Bang is a type of control scheme where upper and lower bounds on the controlled parameter are set, and the system only acts to keep the controlled variable within this preset range. The system's preliminary engineering design, high-level testing plan, and the development timeline are presented.

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Abbreviations

BPS	Bang-bang Pressurization System
CPTC	Component Performance Test Configuration
FFBD	Functional Flow Block Diagram
FMEA	Failure Mode and Effects Analysis
FOS	Factor of Safety
FPU	Floating Point Unit
GSE	Ground Service Equipment
ISR	Interrupt Service Routine
LTP	Lower Threshold Point
MOV	Main Oxidizer Valve
OP	Operational Point
P&ID	Plumbing and Instrumentation Diagram
PID	Proportional Integral Derivative
PFSM	Partial Finite State Machines
PPE	Personal Protective Equipment
PWN	Pulse Width Modulation
SBD	System Block Diagram
STFC	System Functionality Test Configuration
UTAT	University of Toronto Aerospace Team
UTIAS	University of Toronto Institute for Aerospace Studies
UTP	Upper Threshold Point

1. Motivation

The University of Toronto Aerospace Team (UTAT) has been a competing in the Base11 Space Challenge since mid-2018. The challenge seeks the first student team that can design, build and launch a liquid bi-propellant rocket to space: an altitude of 100 km. UTAT designed a rocket, Houbolt, capable of reaching an apogee of 120km, and is powered by a semi-pressure fed propulsion system. Houbolt is fueled by liquid nitrous oxide, which is pressure-fed, and ethanol, which is driven by a gear pump.

In the early stages of design, a trade study was performed to choose the propellant feed method. The initial conclusion was to pressure feed both propellants, as it eliminated the need for a heavy pump system, and since the required mass flow rates were not high to require a pump system anyway. Specifically, since the nitrous oxide is self-pressurizing, it was more suitable to complement the self-pressurizing capability with a pressure fed design. This is because upon analysis, it was concluded that only a small fraction of the nitrous oxide's mass was required in pressuring, and furthermore, the addition of an inert gas to the nitrous oxide ullage also functioned as a critical safety feature to dilute the nitrous gas phase, significantly reducing the possibility of catastrophic decomposition. However, as the design progressed and better mass estimates were possible, the rocket's dry mass increased significantly, pushing the pressure fed system to its limits.

Before discussing the proposed design, it is important to establish an understanding of what the initial pressure fed system design was, and why it was changed to the current one. The nitrous oxide was to be pressurized using a pressure regulator, that would maintain the nominal tank pressure throughout the engine burn. This meant that the system would need a pressure regulator that would be capable of accepting an inlet pressure between the range of 4350-1500 psi and provide an outlet pressure of 525 psi. While doing so, the regulator must vary its mass flow rate between 0-250 g/s, the highest being at the end of the burn when the nitrous self-pressurizing capability is practically non-existent (due to the very large ullage volume and small volume fraction that would be evaporated). The main issue was then sourcing a pressure regulator that meet those performance requirements, was within a suitable mass margin, and is within the team's financial budget. Various regulator manufacturers were examined, however, a suitable option for the team was not available. The team then examined the possibility of sub-optimal pressurization schemes were the regulator would be allowed to choke at some point during the burn and act as a choked orifice. However, analysis showed that with the mass flow rates provided by the regulator of interest at choked conditions, several regulators would be needed to achieve the desired performance. It is important to also highlight the safety concerns with operating a pressure-regulator near choking conditions, since they are not designed for this regime. The general trend was that affordable regulators were nowhere near close to providing the mass flow rates needed at the given pressure conditions, and the ones that could were too heavy and expensive. This prompted the team to investigate other pressurization solutions

The team considered two active pressurization system designs, one being a servo-driven ball valve system, and the other being a Bang-bang Pressurization System (BPS), which is driven by solenoid valves. In the first design, a pressure transducer detects a drop in tank pressure, and a central processing unit would thus issue a command to increase the orifice area of the pressurant supply ball value in order to increase the tank pressure back to the set pressure. In a rocket engine scenario, this would translate to the gradual opening of the valve as the burn progresses, to supply a higher mass flow rate over time. On the other hand, a bang-bang active control system simply dispenses pressurant fluid once the pressure-regulated tank's pressure drops below a pre-defined lower bound. The pressurant is dispensed until the pressure-regulated tank's pressure reached a pre-defined upper limit. The team has chosen the bang-bang type pressurization system for variour reasons which will be discussed in this report.

2. System Design

The BPS is labelled as the `system`, and broken down into four `subsystems`, each responsible for unique actions and functions. The overall function of the BPS is the regulation of a propellant tank's pressure during the burn of a liquid bi-propellant engine. This is one of the most critical functions on a pressure-fed liquid bi-propellant propulsion system, since the performance of the system is driven by a few major parameters, one of them being the pressure difference across the engine's injector system. In a pressure fed system, this is directly controlled by the pressure inside the propellant tank. In order to maintain nominal performance during the engine burn, the pressure must remain within the design bounds. This means that a system capable of sensing a change in pressure in the propellant tank, and taking some action to counteract that, is of critical importance on such propulsion systems.

The BPS full-fills this role in a non traditional manner. Instead of the traditional passive pressure regulator approach, the BPS utilizes an active control architecture to perform the function of pressure regulation. In order to perform its main function, the BPS is required to perform other sub-functions that constitute its overall operation. At this point, a distinction will be made between the ground-based and flight systems. From here on-wards, this report will refer to the ground based system, which may or may not be required to perform functions that its flight counterpart isn't. This is because the ground system does not have the various support systems available on a rocket, such as a supply of high pressure pressurant fluid, housing structure, power supply, etc...

The BPS is required to performs the following sub-functions:

- Storing high pressure pressurant
- Supplying high pressure pressurant to pressure-regulated tank
- Expel contents from pressure regulated tank into the environment. Note that these contents will usually be Nitrogen gas (N_2). During advanced testing of the system, Nitrous-Oxide (N_2O) might be used.
- Monitor the state and conditions of all fluids in the system.
- Maintain all pressures within safety margins.
- Gather and store relevant test data.

These fundamental sub-functions allow a functional breakdown of the system to be performed, and consequently, the system design of the BPS to be performed. This functional breakdown is illustrated in figure 1, which is a System Block Diagram (SBD) for the BPS. In order to satisfy the functional requirements of the BPS, four subsystems are required, each performing a subset of functions that can all be classified to some degree. For example, the fluid subsystem performed tasks related to handling and administering the pressurant fluids, etc... These distinctions, along with a description of each subsystem, are subject of the following few sections.

2.1 Flight System Requirements

Table 1 Flight system functional requirements

Req. ID.	Requirement	Child Requirements
FS_F1	System shall provide pressurent fluid to all pressure controlled propellant tanks	FS_P1
FS_F2	System shall maintain its target nominal downstream pressure	FS_P2
FS_F3	System shall provide a discrete range of low to high flowrates	FS_P3
FS_F4	System shall be capable of operating over the full expected inlet pressure range	FS_P4, FS_P5
FS_F5	System shall be capable of operating over the full expected inlet temperature range	FS_P6,FS_P7
FS_F6	System shall provide protection against pogo oscilations	

FS_F7	System shall be fail safe to loss of power	
FS_F8	System shall have redundant isolation capability	
FS_F9	System shall have pressure relief capability on all nominally closed volumes	
FS_F10	System shall be compatible with pressurent fluid	
FS_F11	System shall comply to the mass budget	FS_P8
FS_F12	System shall have a minium factor of safety of 2	
FS_F13	System shall comply to the power budget	FS_P9

Table 2 Flight System Performance Requirements

Req. ID.	Requirement	Parent Requirements
FS_P1	System shall respond to actuation commands within TBD seconds	FS_F1
FS_P2	System shall maintain downstream pressure within +/- 1 bar of the nomninal pressure	FS_F2
FS_P3	System shall be capable of providing a maximum mass flow rate of 200 g/s at the minimum expected inlet pressure	FS_F3
FS_P4	System shall be capable of operating with a maximum inlet operating pressure of 300 bar	FS_F4
FS_P5	System shall be capable of operating with a minimum inlet operating pressure of 100 bar	FS_F4
FS_P6	System shall be capable of operating with a maximum inlet operating temperature of 323K	FS_F5
FS_P7	System shall be capable of operating with a maximum inlet operating temperature of 263K	FS_F5
FS_P8	System mass shall not exceed TBD kg	FS_F11
FS_P9	System shall not induce a power surge greater than TBD W above its nominal power draw	FS_F13

2.2 System Functionality Test Configuration Requirements

Table 3 Functional Requirements

Req ID.	Requirement	Child Requirements
GTS_F1	System shall provide pressurent fluid to all pressure controlled propellant tanks	GTS_P1
GTS_F2	System shall maintain its target nominal downstream pressure	GTS_P2
GTS_F3	System shall provide a discrete range of low to high flowrates	GTS_P3

GTS_F4	System shall be capable of operating over the full expected inlet pressure range	GTS_P4, GTS_P5
GTS_F5	System shall be capable of operating over the full expected inlet temperature range	GTS_P6, GTS_P7
GTS_F6	System shall demonstrate protection against pogo oscilations	
GTS_F7	System shall be fail safe to loss of power	
GTS_F8	System shall have redundant isolation capability	
GTS_F9	System shall have pressure relief capability on all nominally closed volumes	
GTS_F10	System shall be compatible with pressurent fluid	
GTS_F11	System shall have a minium factor of safety of 2	GTS_P8
GTS_F12	System shall comply to the power budget	
GTS_F13	System shall protect all back EMF sensitive components from any generated back EMF	
GTS_F14	System shall be rigidly anchorred to the ground	
GTS_F15	System shall be remotely operable	
GTS_F16	System shall provide live telemetry for all measured parameters	
GTS_F17	System shall measure the pressurant tank pressure	
GTS_F18	System shall measure the pressurant tank temperature	
GTS_F19	System shall measure the pressure controlled tank's pressure	
GTS_F20	System shall measure the pressure controlled tank's temperature	

Table 4 System Functionality Test Stand Performance Requirements

Req. ID.	Requirement	Parent Requirements
GTS_P1	System shall respond to actuation commands within TBD seconds	GTS_F1
GTS_P2	System shall maintain downstream pressure within +/- 1 bar of the nomninal pressure	GTS_F2
GTS_P3	System shall be capable of providing a maximum mass flow rate of 200 g/s at the minimum expected inlet pressure	GTS_F3
GTS_P4	System shall be capable of operating with a maximum inlet operating pressure of 300 bar	GTS_F4
GTS_P5	System shall be capable of operating with a minimum inlet operating pressure of 100 bar	GTS_F4
GTS_P6	System shall be capable of operating with a maximum inlet operating temperature of 323K	GTS_F5
GTS_P7	System shall be capable of operating with a maximum inlet operating temperature of 263K	GTS_F5
GTS_P8	System shall not induce a power surge greater than TBD W above its nominal power draw	GTS_F12

2.3 Component Performance Test Configuration Requirements

Table 5 Component Performance Test Stand Functional Requirements

Req ID.	Requirement	Child Requirements
CTS_F1	System shall be capable of operating over the full expected inlet pressure range	CTS_P1, CTS_P2
CTS_F2	System shall be capable of operating over the full expected inlet temperature range	CTS_P3, CTS_P4
CTS_F3	System shall be fail safe to loss of power	
CTS_F4	System shall have redundant isolation capability	
CTS_F5	System shall have pressure relief capability on all nominally closed volumes	
CTS_F6	System shall be compatible with pressurent fluid	
CTS_F7	System shall have a minium factor of safety of 2	
CTS_F8	System shall protect all back EMF sensitive components from any generated back EMF	
CTS_F9	System shall be rigidly anchorred to the ground	
CTS_F10	System shall be remotely operable	
CTS_F11	System shall provide live telemetry for all measured parameters	
CTS_F12	System shall measure the pressurent tank pressure	
CTS_F13	System shall measure the pressurent tank temperature	
CTS_F14	System shall measure the expelled mass flow rate	
CTS_F15	System shall measure the component inlet pressure	
CTS_F16	System shall measure the component outlet pressure	

Table 6 Component Performance Test Stand Performance Requirements

Req. ID.	Requirement	Parent Requirements
CTS_P1	System shall be capable of operating with a maximum inlet operating pressure of 300 bar	CTS_F1
CTS_P2	System shall be capable of operating with a minimum inlet operating pressure of 100 bar	CTS_F1
CTS_P3	System shall be capable of operating with a maximum inlet operating temperature of 323K	CTS_F2
CTS_P4	System shall be capable of operating with a maximum inlet operating temperature of 263K	CTS_F2

2.4 System Block Diagram

The System Block Diagram (SBD) is a block representation of the BPS and its major system interfaces. It breaks down the system into subsystems, and indicates the interfaces between them. Each subsystem is indicated using a block, which indicates the subsystem's type, roles and components.

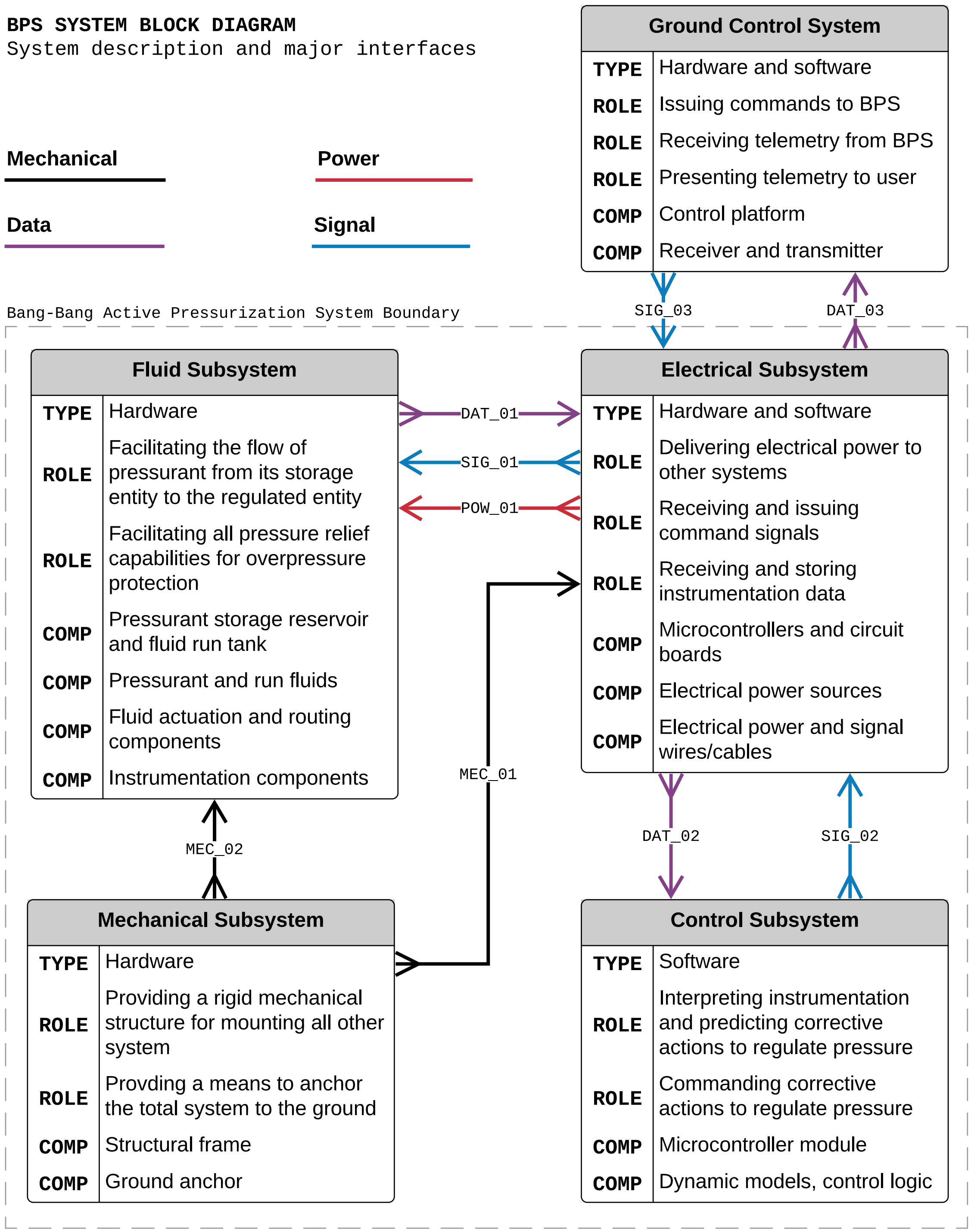

Fig. 1 System Block Diagram (SBD) and major system interfaces

The SBD illustrates the boundaries of the BPS, and within that boundary, it represents four subsystem blocks that describe each of the four subsystems in the BPS. Those subsystems are the `fluid`, `electrical`, `mechanical`, and `control` subsystems. The subsystem blocks are graphically explained in figure 2.

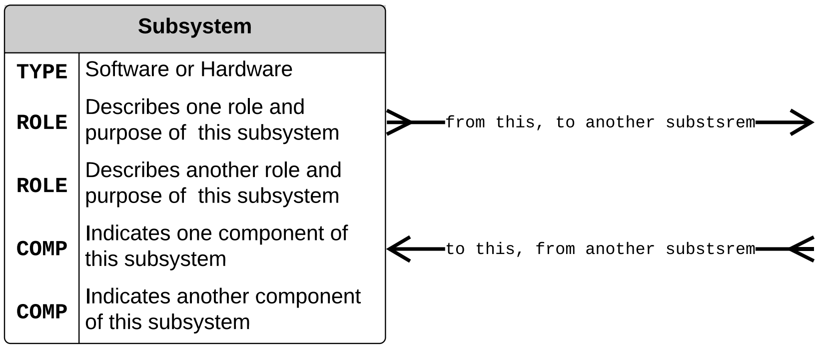

Fig. 2 System Block Diagram subsystem block description

2.4.1 Fluid Subsystem

The fluid subsystem performs all operations associated with the pressurant fluid. This includes storage, delivery to pressure regulated tank, instrumentation, and pressure relief capabilities. At this point, it is appropriate to make the following definitions. The `reservoir` will be from hereon defined as the tank that stores the high pressure pressurant fluid that will be administered to the pressure-regulated tank. The pressure-regulated tank, which receives pressurant from the reservoir, will be referred to as the `tank`. Components of the fluid subsystem include the tank, reservoir, high-pressure tubes, actuation valves, relief valves/disks, pressure transducers, thermocouples, and pressure gauges. This is the only subsystem that comes into direct contact with any fluid under normal operations.

2.4.2 Electrical Subsystem

The electrical subsystem is responsible for all electrical operations performed by the BPS, including power supply to all components, data acquisition from sensors such as thermocouples and pressure transducers, data storage and processing, and control/command signal delivery from the central microprocessor to components like solenoid valves and servo driven ball valves. The electrical system protects all sensitive components from current spikes and other damaging electrical transients via multiple electrical safety design features. The electrical subsystem interacts with the fluid subsystem in three major ways. Through interface `POW_01`, the electrical subsystem provides electrical power to all components on the fluid subsystem the need it. Through interface `SIG_01`, the electrical interface sends command and control signals to the fluid subsystems, which command actuation's or a certain action from components the need them. Finally, through interface `DAT_01`, the electrical subsystem receives instrumentation data from the fluid subsystem, which will be processed, stored, and/or utilized for further actions. Data from pressure transducers will be used to perform calculations that enable the BPS to regulate the tank's pressure, and will also be used for safety related purposes like automatic pressurant dump and mission abort. The electrical subsystem does not perform any actions and doesn't not make any decisions directly related to the pressurization of the tank. Those are performed by the control subsystem.

2.4.3 Control Subsystem

The control subsystem is a pure software-based subsystem that exists on the central microcontroller. It is comprised of a set of routines and logic that make all decisions related to the process of regulating the tank's pressure. The control system utilizes processed data from the electrical subsystem via interface `DAT_02` to make pressurization decisions, which are then communicated back to the electrical subsystem via interface `SIG_02`. Note that interfaces `DAT_02` and `SIG_02` are virtual interfaces, meaning, they are pure software interfaces in the form of message passing routines and or reading data data/variables from memory.

2.4.4 Mechanical Subsystem

The mechanical subsystem contains all of the physical structures that provide mechanical anchoring and structural support to all other components. There are no mechanical actuators outside of the valves in the fluid subsystem, and the mechanical subsystem's components are all static.

2.4.5 Major Interfaces

The SBD also presents all the external systems and and their interfaces with the BPS. Major communications and interactions/interfaces between each subsystem are classified as either mechanical, data, power and signal. The following are descriptions of all the major interfaces between all subsystems:

- **DAT_01:** Transfer of instrumentation data from the fluid subsystem to the electrical subsystem.
- **DAT_02:** Transfer of instrumentation data from the electrical subsystem to the control subsystem.
- **DAT_03:** Transfer of instrumentation data from the electrical subsystem to the ground control system.
- **SIG_01:** Transfer of electrical signals from the electrical subsystem to the fluids subsystem. This issues all fluid component actuation and monitoring commands.
- **SIG_02:** Transfer of control command signals from the control subsystem to the electrical subsystem. These signals are generated and commanded by the controller.
- **SIG_03:** Transfer of electrical signals from the ground control station to the electrical subsystem. Allows the user to issue various control commands to the BPS.
- **POW_01:** Transfer of electrical power from the electrical subsystem to the fluid subsystem for powering all fluid control, actuation and instrumentation components.
- **MEC_01:** Mechanical interfacing of the electrical subsystem onto the mechanical subsystem's frame.
- **MEC_02:** Mechanical interfacing of the fluids subsystem onto the mechanical subsystem's frame.

2.5 Physical Architecture

The BPS is ultimately meant to be used on a rocket, however, on the ground its physical architecture and component arrangement may differ greatly from the flight system. The ground-based system's major goal is to test the BPS capability of regulating a tank's pressure. A secondary function, which is a part of the overall development and testing process, is to test the performance of the solenoid valves. This is done to gather data and build mass flow rate predictive models that can be used in software simulation and tuning. Thus, the BPS will be arranged in two manners: the `System Functionality Test Configuration (SFTC)` and the `Component Performance Test Configuration (CPTC)`.

2.5.1 System Functionality Test Configuration

The SFTC is the configuration that will be used to perform full system functionality and performance testing. This means that the system will be required to actively regulate the pressure inside a depleting tank by administering high pressure pressurant from the reservoir. It is important to note that by the time the SFTC is used for full system testing, the component testing will already be concluded, and all the necessary data will already be gathered.

The SFTC's physical architecture is given in Figure 3. The system is arranged on top of a single platform, contrary to the initial design iteration submitted in the design concept document. This decision was made because the multi-platform design added unnecessary complications to the frame design, while not proving as fruitful as initially anticipated (in terms of simplifying the physical architecture and safe separation of systems). Initially it was believed that separating the fluid subsystem and the electronic subsystems would allow more space and freedom in positioning the fluid subsystem components, and would make the assembly process easier. However, once the detailed design of the BPS was underway, it became clear that the multi-platform design would only complicate design and assembly. Having everything on one platform, given adequate physical safety barriers are in place for protection, will streamline the assembly and member training processes. Furthermore, the initial amount of space budgeted for the electronics was much higher than what is actually needed, and a dedicated platform for the electronics was deemed unneces-

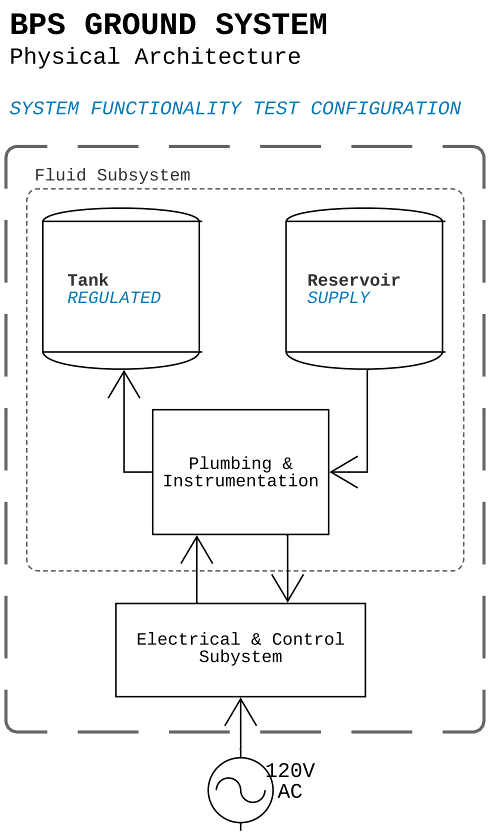

Fig. 3 BPS System Functionality Test Configuration Physical Architecture

sary. The single platform design proved to be much simpler and cheaper, and it is the chosen design moving forward.

The main platform is constructed using aluminum extrusions. The surface of the platform is made of a 3/8" thick sheet of plywood, which is then covered with a 1/64" thin sheet of aluminum. The fluid subsystem is positioned on one side of the main platform, and most of it's volume is allocated to the reservoir and tank. The reservoir is a standard 80 Cu ft aluminum scuba diving tank rated to 300 Bar (4350 psi). As a scuba tank, it is designed for direct contact with people when pressurized. The tank is a custom made Al6061-T6 tank rated to operation at 700 psi. This is because this same tank will be used on the rocket, as its oxidizer tank. The tank is constructed from an aluminum pipe welded to two aluminum caps. All welding is done professionally and according to standard practice. The tanks are rigidly secured to the platform, such that they can neither shift laterally nor axially. Two stainless steel clamping u-bolts are used to secure each tank to the platform, and a thin 1/4" rubber ring will be placed between each u-bolt and its adjoining tank surface to prevent contact damage and to also increase the clamping friction force. The rest of the fluid management system, which includes plumbing tubes, valves, and sensors, are assembled and arranged between the two tanks. 3D printed elevated supports will be used to support all the elevated fluid components. Those supports will be mounted to the platform securely by screws. Figure 4 illustrates a 3D representation of the assembled system (minus a few minor components).
The electrical system is located on the other end of the platform. Cables are secured via surface mounted cable holders, while the Controller and Power Control Unit are secured in their own electrical boxes for easy access. A large acrylic box is used to house the electrical subsystem to protect it from potential debris and or fluid contact in case or relief value or burst disk activation.

The fill system is arguably the simplest of all. Although not depicted in the physical architecture diagram, it can be found in the P&ID in sections. Only one Ground Service Equipment (GSE) tank is show in the P&ID, however, it is likely that multiple parallel tanks will be used in order to facilitate the use of a lower GSE tank pressure. This

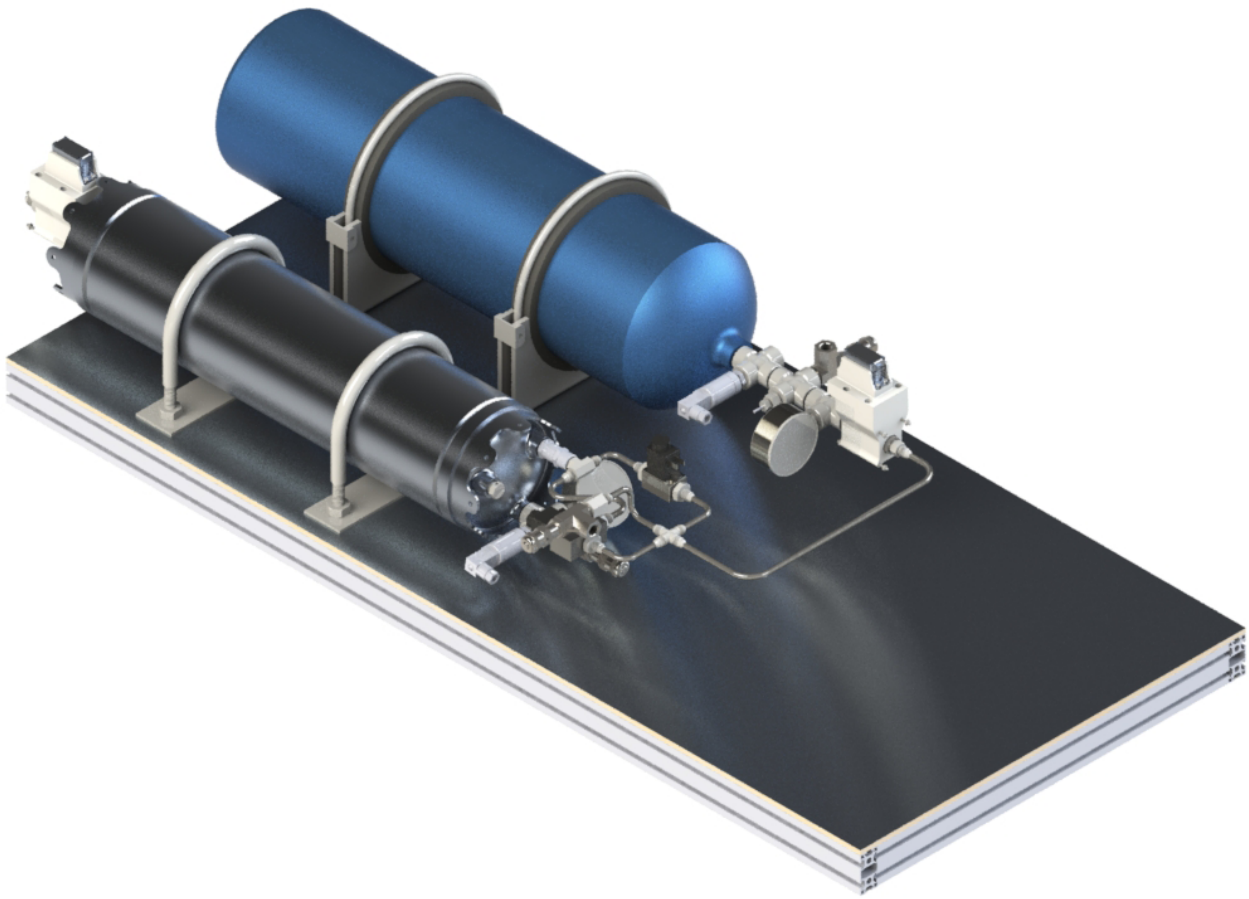

Fig. 4 BPS System Functionality Test Configuration 3D Representation

would be done while still getting a reasonable number of test runs before the GSE tanks require refilling. The tanks will be placed in a cylinder rack near the test operator unit (located where the test personnel will be housed away from the testing area), to which the fill system plumbing is fastened (using pipe strap and routing clamps). The fill system connects to the BPS via a length of flexible hose so that the manual valves on the fill system may be safely operated during the test.

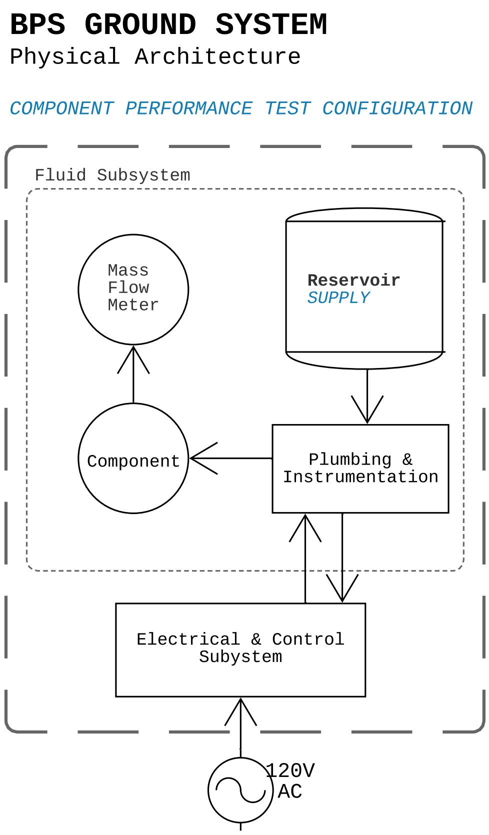

Fig. 5 BPS Component Performance Test Stand Fluid and Electrical Systems Physical Architecture

2.5.2 Component Performance Test Stand Physical Architecture

The CPTC uses the same structural frame as the SFTC, as well as many of the same fluid components and an almost identical electrical system. The first major difference is that it only includes the reservoir and replaces everything downstream of the main isolation valve (excluding the RF_R_N2 relief valve) with a new fluid system arrangement (using the same fluid components when possible). The solenoid valve placed between the two pressure transducers is a place holder for whatever fluid component's flow rate data is desired. A third pressure transducer is added downstream of the fluid component being tested and after this the line terminates at the inlet to the Coriolis mass flow meter.

2.5.3 POGO Mechanism

In the initial design concept report, a mechanism for detecting oscillations/vibrations in the system was briefly outlined. The sole purpose of this mechanism was to detect any sustained vibration/oscillation in the test stand, and switch off the pressurization system if that happened. However, the sliding rail and spring mechanism was too expensive for the team, as other components such as the solenoids and the tank and reservoir were much more critical and thus received financial priority. Furthermore, the tank discharges through a valve that is connected to a T fitting (initially was a straight fitting, which would have created some thrust). For safety issues, the T was added to divert the flow laterally and thus no thrust will be created, rendering the POGO mechanism useless.

3. Engineering Design

3.1 System Functionality Test Configuration

3.1.1 Plumbing and Instrumentation Diagram

The P&ID for the SFTC is presented in Figure 6. The fluid components are arranged in a serial fashion from the reservoir to the tank. The reservoir output leads to a series of 3 cross fittings, called the cross manifold, where the instrumentation components are mounted to measure tank exit conditions. The cross manifold leads to the system isolation valve, which is a servo driven ball valve used to isolate the upstream high pressure system from the solenoids and the downstream system. The `upstream system` is everything before this valve, and everything after it is defined as the `downstream system`. This is a safety feature that is needed to allow the full isolation of both sides of the system. More details and failure scenarios are discussed in Section 5. The isolation valve output leads to two solenoid valves, which are the valves that will actuate upon command from the controller. These are the valves that will supply pressurant to the tank. The lines between the solenoids and the isolation valve are relieved with a pressure relief valve. The lines from the solenoid valves then combine into a check valve that leads into the tank. Instrumentation is attached to the tank via various fittings and adapters. All of the fluid components have been selected. Table 7 describes each component shown in the P&ID. Figure 7 presents a top view of the assembled fluid subsystem.

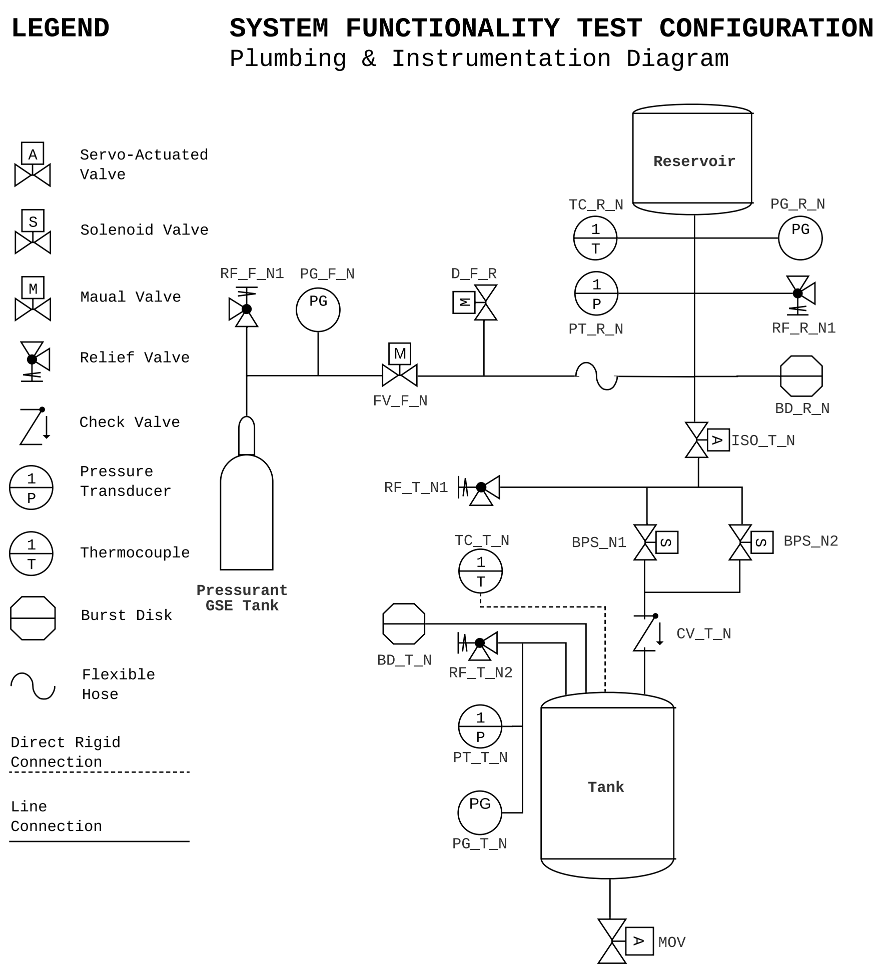

Fig. 6 System Functionality Test Configuration P&ID

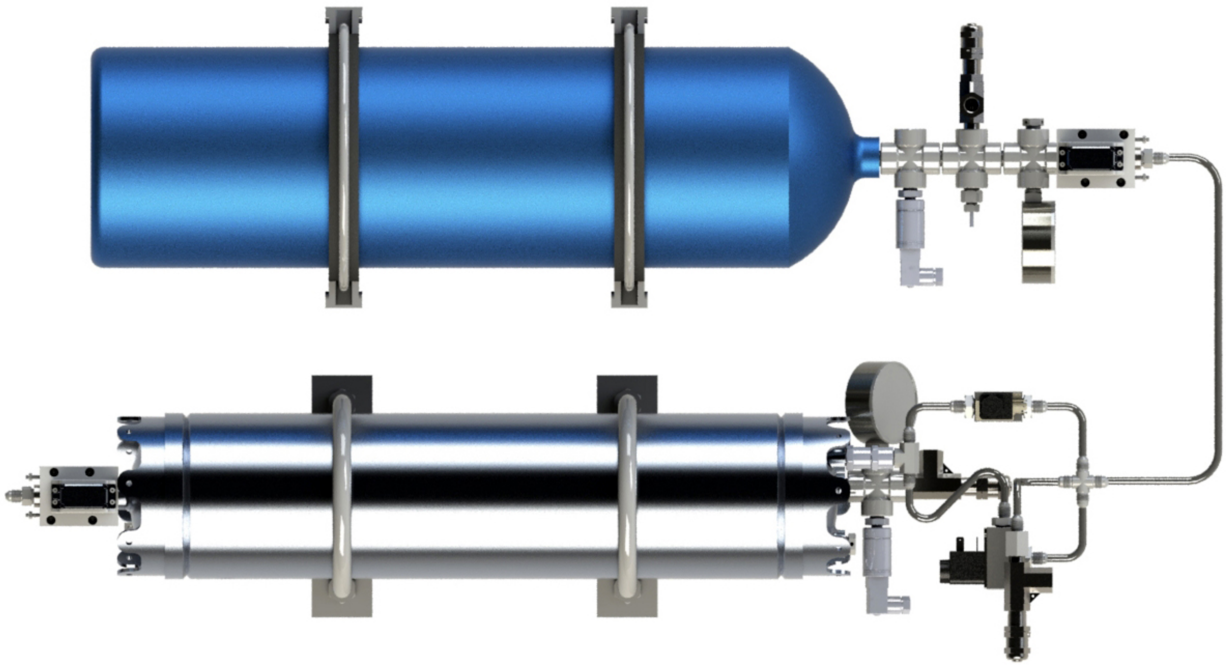

Fig. 7 System Functionality Test Configuration Fluid Subsystem 3D Representations

3.1.2 Description of Components

Table 7 System Functionality Test Configuration - Description of Components

Part ID.	Name	Purpose	Initial State	Nominal State
Reservoir	Reservoir	High pressure tank that supplies nitrogen pressurant to the downstream system	Ambient pressure	N/A
Tank	Tank	Pressure-regulated tank	Ambient pressure	N/A
Nitrogen GSE Tank	Ground service equipment nitrogen tank(s)	Nitrogen source for the reservoir	High Pressure Nitrogen	N/A
TC_R_N	Reservoir thermocouple	Measure the temperature of the fluid flowing out of the reservoir	N/A	N/A
TC_T_N	Tank thermocouple	Measure the temperature of the fluid flowing out of the tank	N/A	N/A
PG_R_N	Pressure gauge of the reservoir system	A pressure indicating device that provides a local readout of reservoir pressure to monitor the operation or condition of a process by locally indicating a quantity of pressure	N/A	N/A

PG_F_N	Pressure gauge of the fill system	A pressure indicating device that provides a local readout of fill pressure to monitor the operation or condition of a process by locally indicating a quantity of pressure	N/A	N/A
PG_T_N	Pressure gauge of the tank system	A pressure indicating device that provides a local readout of tank pressure to monitor the operation or condition of a process by locally indicating a quantity of pressure	N/A	N/A
PT_R_N	Pressure transducer of the reservoir system	Measure the pressure of the fluid flowing out of the reservoir system	N/A	N/A
PT_T_N	Pressure transducer of the tank system	Measure the pressure of the fluid flowing out of the tank system	N/A	N/A
RF_R_N1	The first relief valve of the reservoir system	A safety valve used to control or limit the pressure in a reservoir system	Closed	Dependent on conditions
RF_F_N1	The first relief valve of the fill system	a safety valve used to control or limit the pressure in a fill system	Closed	Dependent on conditions
RF_T_N	Relief valve of the tank system	A safety valve used to control or limit the pressure in a tank system	Closed	Dependent on conditions
BPS_N1	The first solenoid valve	Control the mass flow from upstream to the tank	Closed	Nominal state
BPS_N2	The second solenoid valve	Control the mass flow from upstream to the tank	Closed	Nominal state
ISO_T_N	Isolation valve	Isolates the upstream and downstream systems via a servo actuated ball valve	Closed	Latching
FV_F_N	Fill valve of the fill system	Manual valve for transferring nitrogen from the GSE tanks to the reservoir	Open	Dependent on conditions
CV_T_N	Check valve of the tank system	Ensures one-way fluid flow - upstream to downstream. It provides protection against reverse flow with minimal effect on the system (low pressure drop and low chatter)	Closed	Dependent on conditions
BD_T_N	Burst disk of the tank system	A rupture-disk pressure relief safety device that protects the pressure vessel	Unruptured	Dependent on conditions
MOV	Automatic valve of the oxidizer tank	Automatic valve simulating the Main Oxidizer Valve	Automatically operated	Automatically operated

3.2 Component Performance Test Configuration

3.2.1 Plumbing and Instrumentation Diagram

The P&ID for the CPTC is presented in Figure 5

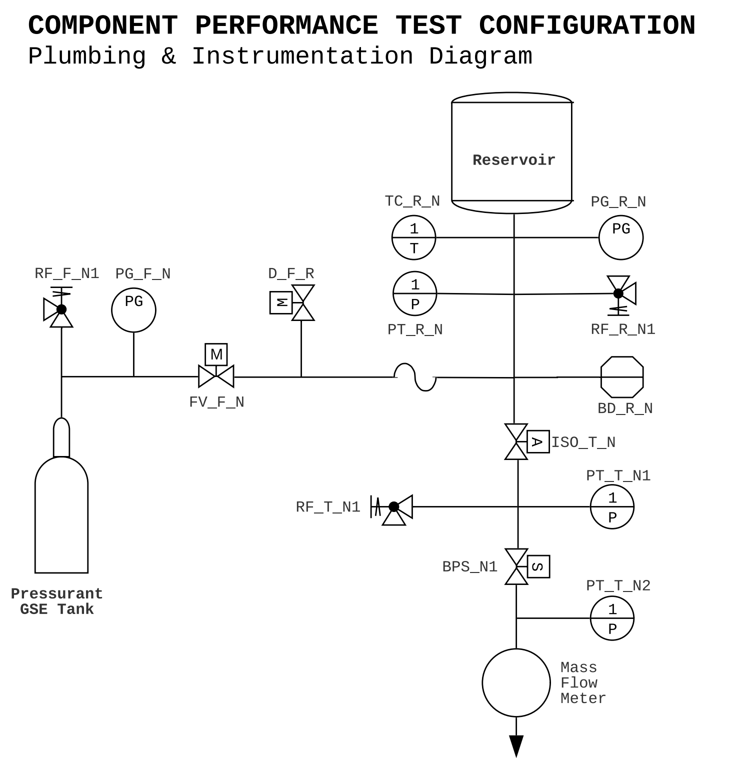

Fig. 8 Component Functionality Test Configuration P&ID

3.2.2 Description of Components

Table 8 Component Performance Test Configuration - Description of Components

Part ID.	Name	Purpose	Initial State	Nominal State
PT_T_N1	Component inlet pressure transducer	Measure pressure of fluid entering the component being tested	N/A	N/A
PT_T_N2	Component outlet pressure transducer	Measure pressure of fluid exiting the component being tested	N/A	N/A
RF_T_N1	Component upstream relief valve	Relieve overpressure in the line upstream of the component being tested	Closed	dependant on conditions
Mass flow meter	Mass flow meter	A Coriolis mass flow meter for measuring the mass flow rate of nitrogen passing through the component being tested	N/A	N/A

3.3 Control Architecture

This section outlines the high-level architecture of the BPS control system. The control system comprises all the software responsible for control logic and decision making. The control architecture diagram outlines each control module and the direction of information flow. The control loop diagram outlines the closed control loop for the feedback system of the BPS control system, identifying the controller, plant to be controlled, sources of disturbances, sensors, and filters.

3.3.1 Control System Concept

To provide comprehensive monitoring, control, and automation, the BPS control system must scale to support up to 20 physical I/O connections and 2 controlled variables that can be correlated to analyze events and provide data for all control aspects. The solenoid valves are modelled such that the minimum cycling (ON/OFF) frequency of are set to 1 Hz and the maximum frequency is set to 16 Hz. Therefore, the BPS control system must support 1 HZ positive-feedback control and must not exceed 16 HZ on/off controlling cycles.

The control architecture is broken down into three layers. This simplifies the implementation of the control loop, increases the modifiability of code and hardware, and makes the architecture more modular. The layers are:

- **Layer 1:** Layer 1 comprises the hardware/protocol integration at a lower level compared to layers 2 and 3. Layer 1 contains dedicated equipment controllers, which in turn interface to specific equipment through point-to-point protocols (e.g, I2C, PWM, SPI) to the electrical subsystem. This layer is responsible for the hardware architecture of the control system and integration with any software protocols, including communication protocol to transmit data, collect data, store data, and control signal delivery.

- **Layer 2:** This layer comprises the algorithm-based implementation required to execute each control module. Layer 2 contains the controller module, tank module and all the valve operation (opening and closing commands), monitoring (sensors) and display activities. The tank module includes the physics and fluid mechanics models that simulate the expected oxidizer tank discharge, the pressure response of valves opening and closing.

- **Layer 3:** This is the highest level layer - the logic layer. This layer includes all the data storage and processing (generated from layer 2) logic (e.g., sorting methods and domain-specific data managements), and all interrupt service routines (ISRs) for various external events. This layer is the integration of layer 2 through to layer 1, such that a control loop is formed. It accepts the reservoir pressure and temperature as inputs (see Figure 9) and outputs the actuation commands. The controller module includes one closed feedback loop consisting of the microcontroller, sensors to detect the dynamic pressure change in the tank module, digital filters to eliminate noise and smooth out the sensor input sample data, calculating the error, and sending the corrected controller output signal to the tank module.

3.3.2 Control Logic Design

The BPS controller's objective is to determine when to open and close the solenoid valves and the duration of each state. There are two solenoid valves available, one with a higher mass flow rate and one with a comparatively smaller flow rate. The logic is to use the valves appropriately such that no undershoot or overshoot of pressurant fluid pressure takes place in the oxidizer tank module. Initially, both solenoid valves are in OFF state. Two desired pressure limits (upper and lower limit of pressure set range) are fed into the controller as input reference signals. These pressure limits serve as extreme bounds and any pressure readings beyond this range is not acceptable. The controller module initiates the process by switching the state of the smaller solenoid valve to ON while keeping the bigger valve OFF. Once this start sequence is initiated, the following control loop steps are executed:

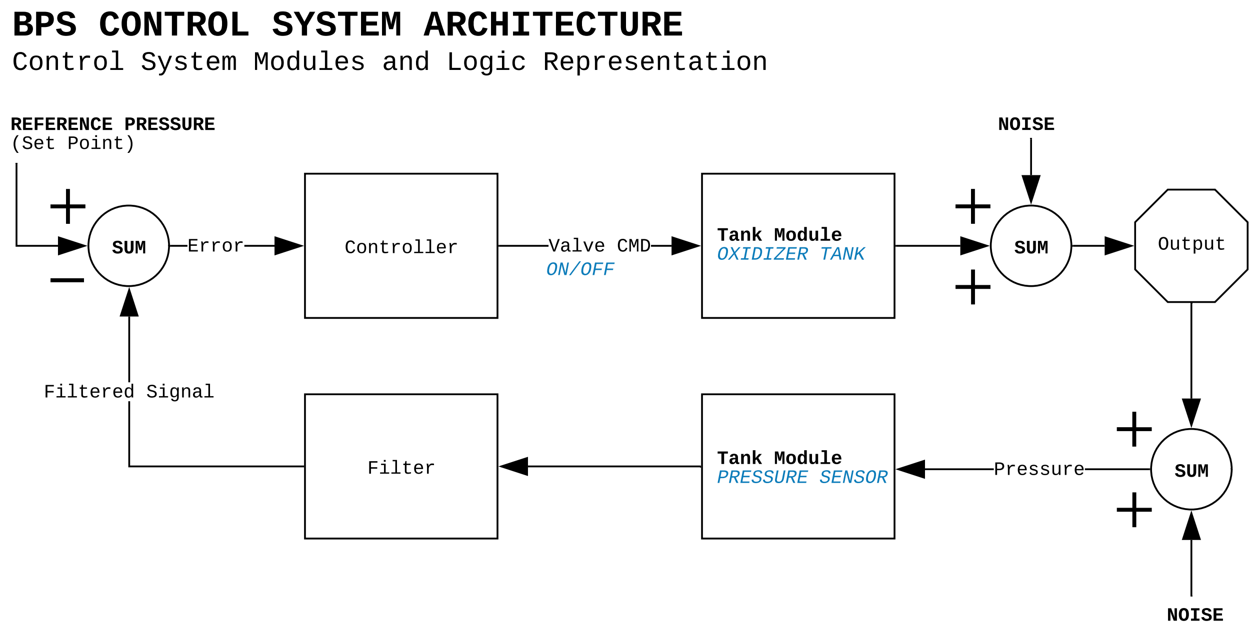

Fig. 9 BPS Control Architecture

1) The oxidizer tank module measures the pressure and temperature responses using pressure and temperature sensors, and stores the sample data in a rolling buffer for the microcontroller to be used. An internal system timer is used to timestamp the collection times in correspondence with the collected pressure and temperature values. This prevents any lag in calculating the error in the signal, which in this case is the difference between the current and desired pressure values in the oxidizing tank.

2) The controller module then uses a digital filter to eliminate noise in the temperature and pressure values before calculating the error.

3) Once the sensor input values are filtered, the controller module then calculates the error in the pressure value by calculating the difference between the current pressure value and the desired reference pressure value. Based on the magnitude of the error, the controller module is pre programmed to take appropriate steps to maintain the pressure within the acceptable range.

4) A positive feedback (hysteresis) loop algorithm is used to maintain the pressure within the acceptable range. This is an optimized version of the Bang-Bang algorithm. The hysteresis loop uses two threshold pressure values within the upper and lower bound pressure limits. This is illustrated in Figure 10. When the smaller valve is in ON state, the pressure in the oxidizer tank rises and as it reaches the upper threshold point (UTP), the valve is switched OFF allowing the pressure to drop until it reaches a lower threshold point (LTP). As soon the pressure reaches the LTP, the small valve is turned ON. This cycle continues until the pressure in the oxidizer tank is unable to reach the UTP and drops to LTP twice without intercepting the UTP. This switches the state of the bigger valve to ON which allows the cycle to continue and maintain the pressure within the UTP and LTP. LEDs are used to provide visual indication of opening and closing of the valves: RED for opening the big valve and GREEN for opening the small valves. The positive feedback ensures that any disturbances such as sudden vibration will not cause the switching of the valves even if the pressure values are affected.

For testing purposes, artificial disturbances or noise can be added to the pressure readings generated by the tank module and then the controller response can be tuned to minimize the effect of disturbances on the process variable. Also, partial finite state machines (PFSM) can be used to automate optimization of various states and

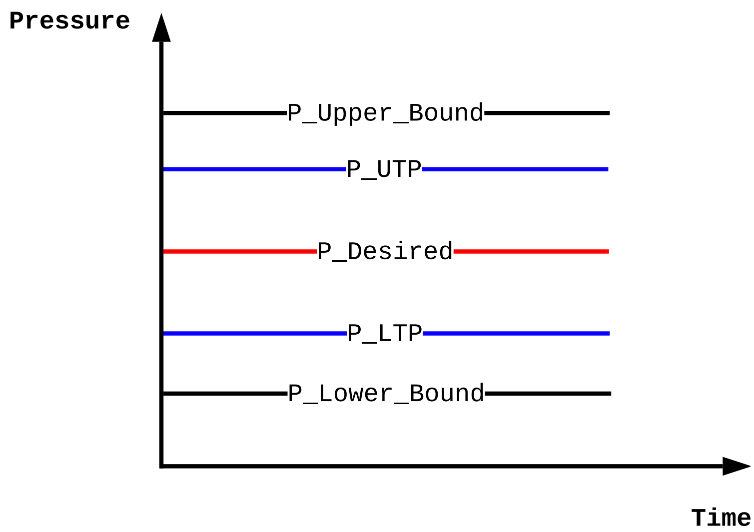

Fig. 10 Pressure bounds used for control logic

transitions, and prevent any dead-ends in the code.

The performance metrics of the BPS controller design process are: input step functions (designed from the upper pressure limit, lower pressure limit, UTP, and LTP), rise time , percent overshoot, settling time and steady-state error. The BPS controller performance can be characterized by applying a step function as the set point variable, and then measuring the pressure responses of the process variable. In this case two step functions are applied to bound a desired pressure range. The response measurements can be quantified by measuring defined waveform characteristics. First, rise time is defined to be the amount of time the system takes to go from 5% to 90% of the steady-state pressure (final expected pressure). Second, percent overshoot is desired to be around 2.5% (or around 0.5 bar) of the final pressure is the amount that the process variable overshoots the steady-state pressure. Settling time is defined to be the time required for the pressure control process variable (pressure variable) to settle within 2% of the desired pressure reference value. Time delay is measured by the output command delay after the input signal is applied (type II and type III delay can be measured as well). Steady-state error is then measured as the desired pressure difference between the process variable and set points.

In the future, to further optimize the controller module, a software implementation of a Proportional-Integral-Derivative (PID) controller is being explored. The PID controller would use the process variable (pressure values) collected from the tank module to calculate error based on proportional, integral, and derivative control. To complement the PID controller, a servo actuated valve shall be used and the opening of the valve will be determined based on the error in the pressure value. The duty cycle of the PWM signal used to actuate the servo motor will be a function of the error calculated by the PID controller. This will minimize the fluctuation of the pressure and frequent switching of the valves between ON/OFF states. To calculate the integral component of the controller, a multi-segment trapezoidal rule can be used with previously stored pressure values. Similarly to obtain the derivative component of the controller, a backward divided difference can be used to obtain the rate of change in pressure in the oxidizer tank.

3.3.3 Microcontroller Selection

The proposed microprocessor is a `Teensy 4.0`. It features an ARM `Cortex-M7` processor at 600MHz, with a NXP iMXRT1062 chip. When running at 600 MHz, Teensy 4.0 consumes around 100mA of current. Teensy 4.0 provides support for dynamic clock scaling; unlike traditional microcontrollers, where changing the clock speed causes can faulty baud rates and other issues, Teensy 4.0 hardware and software support for Arduino timing functions are designed to allow dynamic speed changes. Teensy 4.0 also provides a power shut off feature, which can be useful in implementing emergency power shutoff. Teensy 4.0 also can also be overclocked, well beyond 600MHz. The

ARM Cortex-M7 is a dual-issue superscalar processor, meaning the M7 can execute two instructions per clock cycle, at 600MHz. Teensy 4.0's Cortex-M7 processor includes a floating point unit (FPU) which supports both 64 bit "double" and 32 bit "float".

These features will allow fast implementation of continuous control loops and also execute various interrupt service routines (ISRs). The major computational tasks for the microcontroller are executing the control loop, filtering data, and running algorithms, such as the trapezoidal rule. In addition, it has 31 Pulse Width Modulation (PWM) pins, 40 digital pins all capable of interrupts, and 14 analog pins. This comfortably satisfies the initial objective of the microcontroller having at least 20 GP I/O pins. The pins comprise of supply voltage outputs, grounds, and control pins, and are more than sufficient to adequately interface input and output devices. Furthermore, the light-weight (9.1 g) and compact (36mm by 18mm by 2mm) characteristics of Teensy makes it an ideal microcontroller for the design.

3.4 Electronic Design

3.4.1 Power

All electrical components, with some exception, will be powered from a 480 W, 120VAC to 24VDC switched-mode mode power supply. Two adjustable, step-down regulators (PROPW-336975) will be connected to the power supply output, with one being stepped-down to 12V, while the other to 5V. It should be noted that while the 12V rail will be significantly loaded, all components will never be activated at the same time, therby not saturating the current limit of the regulator.

3.4.2 Components

Schematics for the components connected to the microcontroller can be seen in figure 11. The pressure sensors are powered by the 12V rail, connected to ground, and the $0 - 5$V output of the sensor is read on an analog pin of the microcontroller.

The thermocouples chosen are thermistors, which are devices that relate measured temperature to a change in electrical resistance. In order to measure this resistance value, one end of the thermocouple is connected to the 5V rail, the other end to a pull-down resistor connected to ground, and the point between the thermocouple and the pull-down resistor is connected to an analog pin of the microcontroller. As the resistance of the thermocouple varies, the current flow changes, causing the voltage across the pull-down resistor to also change. In this way, the change in resistance is measures as a change in voltage.

The servo motors are powered through the 12V rail, are connected to ground, and to a PWM pin of the microcontroller, whose signal will control the movement of the servo motor by setting the PWM duty cycle.

The high mass flow rate and low mass flow rate solenoids have different power requirements. The coils on the solenoids require 24V and 12V to activate, respectively. As such, the 24V solenoid is connected directly to the switched-mode power supply, and the 12V solenoid is connected to the 12V rail. In order to control the 12V solenoids from the Teensy microcontroller, which outputs a maximum of 5V, TIP120 Darlington transistors are utilized. A 1N4001 flyback diode is placed in parallel with the solenoids to protect them from flyback (the sudden voltage spike across an inductive load when its current supply is suddenly turned off).

3.4.3 Telemetry

The serial USB output of the Teensy will be connected to a Raspberry Pi 4 Model B and will be passing all telemetry data via the serial port. The Raspberry Pi will have a USB webcam (with microphone) which will be recording live video of the test site. The Raspberry Pi will be hosting a Parsec, low latency streaming server host. An extended ethernet cable will route from the Raspberry Pi to a remote computer, which will be running the Parsec client. This facilitates a real time audiovisual feed of the test site, in addition to a live feed of the telemetry data from the BPS system.

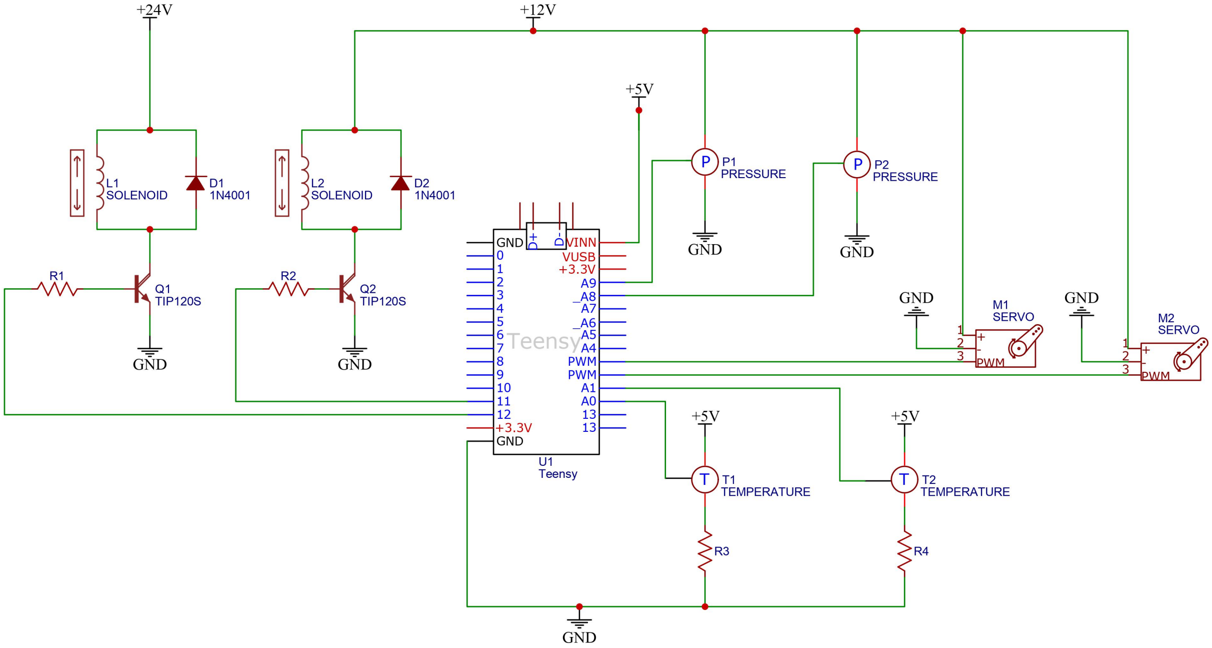

Fig. 11 Electrical schematic of microcontroller connections

3.5 Dynamic Modelling of System Performance

An important part of designing and testing a complex system is modelling its performance to understand its response to various inputs and conditions. This enhances the design process by revealing the strengths, weaknesses, and sensitivities that the system may have. However, it is important to acknowledge the assumptions made while creating a model, and the limitations a certain modelling approach may have.

As part of the development of the liquid rocket program at UTAT, a Nitrous Oxide blowdown and pressurization model was created to help simulate the performance of liquid rocket engines. This model can be used to test the performance of the BPS, since it is able to quantify the discharge properties from a tank based, and also able to model the transient pressure profile, and also account for the addition of pressurant gas into the tank ullage. The blowdown model was initially developed by *Fernandez* (2009) [1] and modified to allow for pressurization computations. The model assumes the tank is an adiabatic container that has a vapour and a liquid phase. The liquid phase may or may not evaporate and add more vapour to the vapour phase, this is determined by the tank conditions and the fluid's thermophysical properties. Also, the tank may just have one phase, not necessarily two. This is the case when nitrogen is used, where there exists only a vapour phase in the tank. Although the model was initially created for self-pressurizing Nitrous Oxide, other fluids can be modelled by using their thermophysical properties, instead of the ones for Nitrous Oxide. modelling of different. Figure 12 illustrates the control volume approach to modelling the tank, generalized to two phases. The blowdown model that describes the discharge properties from the tank is illustrated in figure 13. It uses molar (mass) conservation and energy conservation approach to relate the mass flow rate of fluid exiting the tank to various system variables like the amount of vapour and liquid phase, amount of pressurant, their volume fractions, and uses the ideal gas law as a state equation. The routine that is used to couple this blowdown model with the pressurization scheme is illustrated in figure 14.

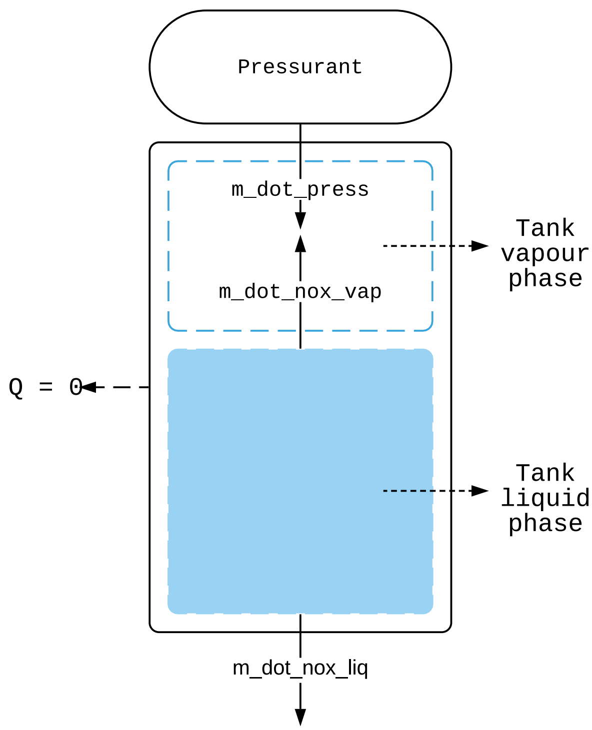

Fig. 12 Control volume approach - tank phases

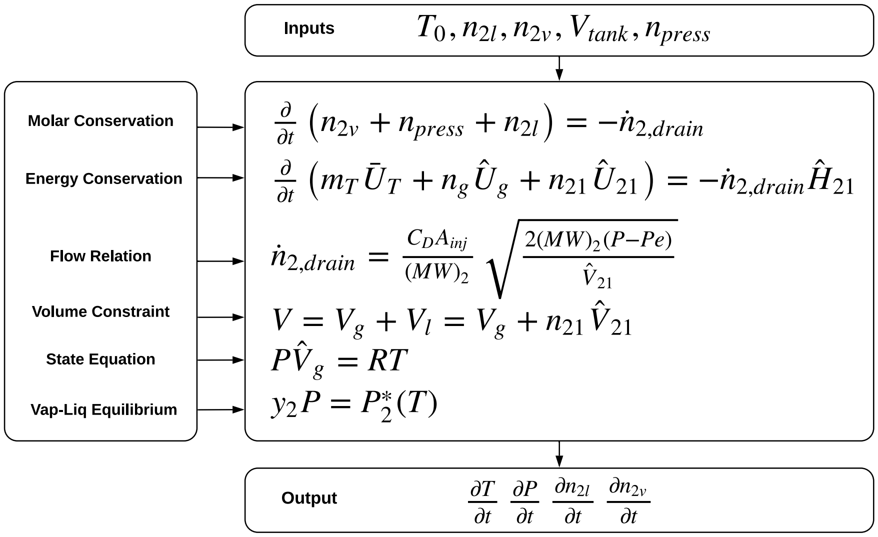

Fig. 13 Equations used in blowdown model

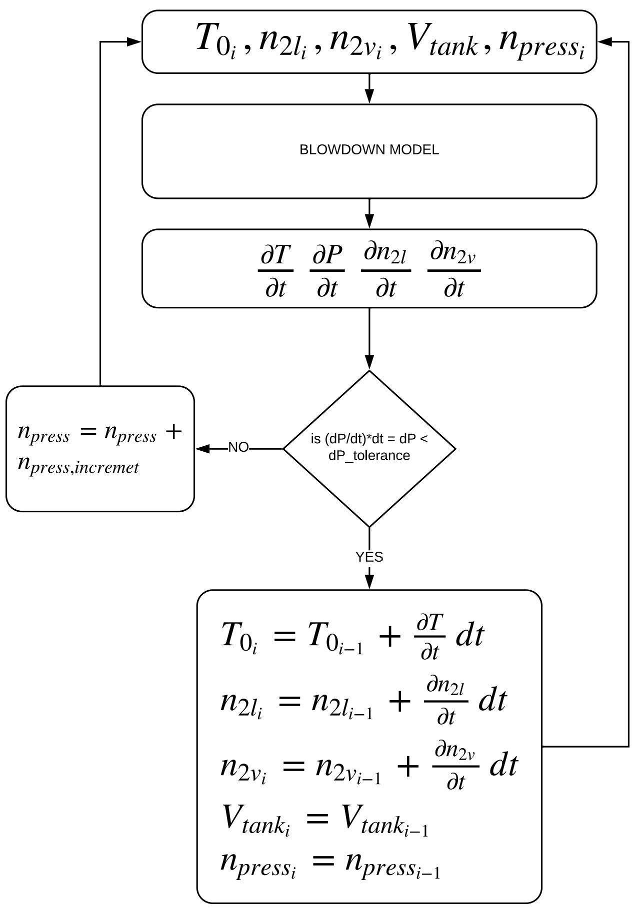

Fig. 14 Routine for computing a pressure-regulated tank's discharge properties

3.6 Safety Features

In Figures 3 and 5, it can be seen that there are numerous features in place in order to ensure the safety of the test stand operators. First and foremost, all volumes which are, or can be, enclosed are fitted with pressure relief valves to protect against over pressure. In the case of the tank, it has been fitted with redundant pressure relief capability in the form of a burst disc, as the tank is being fed nitrogen from the reservoir (which operates at a much higher pressure than the tank). While the relief valve, like all other relief valves in the system, is set for 1.1 times the tank operating pressure, the burst disc is selected to rupture at approximately 1.2 times operating pressure. This allows the relief valve to handle small and transient instances of over pressure, but provides the emergency capability of rapid depressurization in the event that the reservoir cannot be isolated from the tank.

In addition to pressure relief, analog pressure gauges are connected to the nitrogen GSE tanks, the reservoir, and the main tank, in order to provide a power-independent means of determining tank pressures. This serves two key roles. First, it serves as a redundant pressure readout in the case of an unforeseen power loss. Second, these gauges provide personnel working on the test stand a way to visually check whether or not the system is under pressure, without having access the live transducer readings, which would not work if the electrical system were under maintenance (for example).

The next key safety feature is the fill hose. While simple in its operation, it is one of the most important pieces of equipment on the test stand. The fill hose allows the nitrogen GSE tanks to be placed at a safe distance from the test stand, so that filling operations can be performed without needing to be near the test stand itself. This is crucial for safe operation of the test stand because while all parts of the fill system have a FOS of at least 4, there are parts of the reservoir and tank systems where the FOS is designed to be only greater than 2.

4. Testing Strategy

The system will be tested using a two phase process. The first process will evaluate the functionality of each solenoid, with a focus on assessing the response time, pressure drop, and measuring the mass flow rate variation through the solenoid as the reservoir depletes. The second phase will asses the parallel functionality of the solenoids, and also, the ability of the system to maintain nominal pressure in a depleting tank. The mass flow rate data collected will allow the team to build an empirical model for estimating the mass flow rate through the solenoids given reservoir conditions. This is important because it allows the control algorithm to decide which solenoid to use and when, depending on the pressure state in the pressure controlled tank. This could also benefit future projects to upgrade the control scheme from a simple bang-bang controller to a more sophisticated, model-based controlled (using PID or state-space), that uses the empirical test data and models in place of a plant transfer function. This testing strategy aims to validate the performance of the system, and provide critical test data that will be used to upgrade the control architecture in future projects. It is important to note that for safety and environmental reasons, the testing, at least the vast majority of the testing, will be done using only intert nitrogen gas. This is to mitigate the many issues and risks associate with using nitrous oxide. Furthermore, it enables faster testing, and more testing to be performed at once, since no climate control is needed (at least not to the extent it is needed when working with nitrous oxide). Finally, since no oxidizer is used, the system doesn't not need to regularly undergo oxidizer cleaning procedures. However, once the system has been tested and validated for nitrogen, testing with nitrous oxide may become an option. UTAT has extensive experience working with nitrous oxide, and has developed detailed cleaning procedures. Should the team make this decision, cleaning procedures will be submitted to Launch Canada for review in a future report.

4.1 Phase 1: Component Performance Testing

The component performance testing will assess the individual performance of each solenoid, focusing primarily on response time and mass flow rate. The physical architecture of the component test setup is given in section 2.5.2, and its P&ID is given in section 3.2.1, figure 8. The component testing shall provide the required information highlighted in table 9. In order to provide the required information, the component test system is designed with the sensory features given in table 10.

Table 9 Component testing requirements

Test Requirement	Rationale
Solenoid Response time	The system may require high-frequency solenoid actuation to fulfill pressurization requirements. Thus, solenoid response time must be sufficiently short to ensure timely pressurant dispensing.
Evolution of mass flow rate through solenoid	In order to build predictive models for the mass flowrate of the system, the mass flowrate of pressurant fluid through each solenoid must be measured experimentally as the reservoir depletes.
Evolution of reservoir conditions during depletion	The mass flowrate the system can dispense through a given solenoid is a function of the reservoir stagnation conditions. Thus, in order to build an empirical model for mass flow rate, a time evolution of the reservoir conditions must be available. Additionally, reservoir conditions must be monitored for safety reasons during testing.
Component pressure drop	Required to characterize the pressure losses induced by each component.

Table 10 Component test setup sensory features

Feature	Description	Purpose
Reservoir pressure (P_r)	A measurement of the reservoir's pressure history during the depletion	Required to build empirical mass flow rate relationships $\dot{m} = f(T_r, P_r, A)$. Also required for monitoring tank pressure during testing for safety reasons.
Reservoir temperature (T_r)	A measurement of the reservoir's temperature history during the depletion	Required to build empirical mass flow rate relationships $\dot{m} = f(T_r, P_r, A)$. Also required for monitoring tank pressure during testing for safety reasons.
Component upstream pressure (P_{cu})	A measurement of the pressure immediately upstream the tested component	Required for measuring the pressure drop across the component
Component downstream pressure (P_{cd})	A measurement of the pressure immediately downstream the tested component	Required for measuring the pressure drop across the component. Also enables measuring component response time.
Mass flowrate ($\dot{m}$)	A measurement of the mass flow rate expelled out of the tested component	Required to build empirical mass flow rate relationships $\dot{m} = f(T_r, P_r, A)$.

The component testing process will generally be identical for each solenoid, and will take place as shown by the Functional Flow Block Diagram (FFBD) in figure 15. In general, the testing process will look like the following:

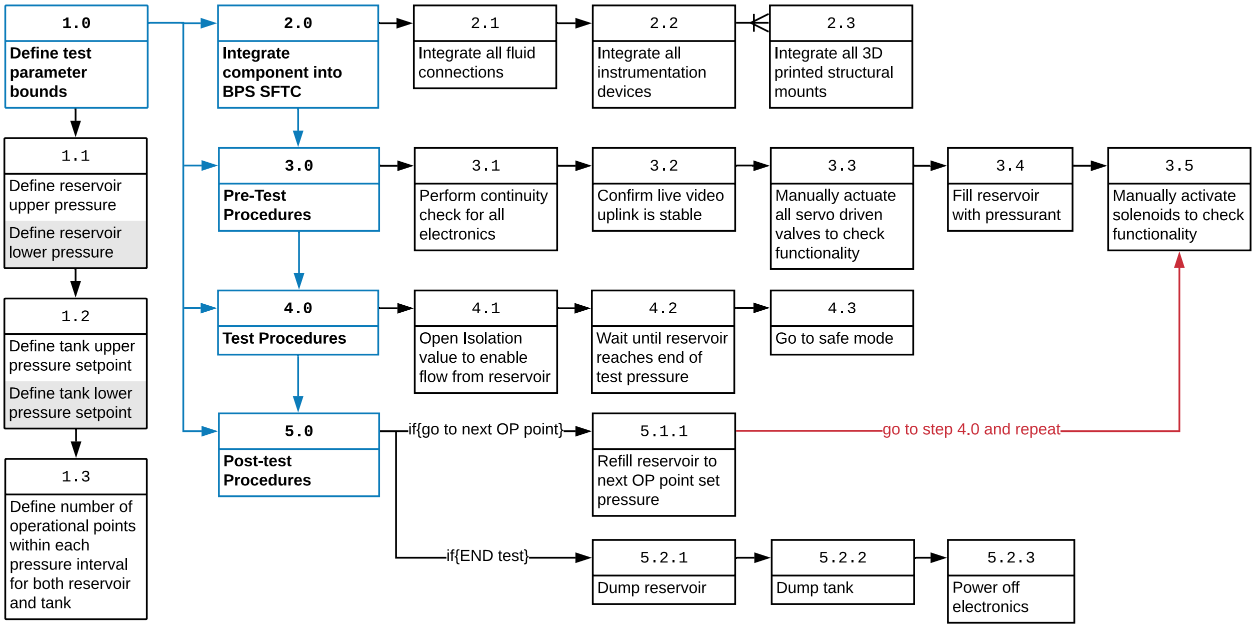

Fig. 15 Component Performance Testing FFBD

1) **Sequence 1.0**: Define a set of required initial reservoir pressures and temperatures, and the set of required tank set pressures. These would then be combined to create a set of operational points (OPs). For example, if there are 5 initial reservoir pressures, and 5 tank set pressures, this would create 25 OPs that would require testing. Care should be taken in defining the OPs since an excessive number of them can lead to unrealistic requirements on testing resources such as pressurant gas, man-power and time.

2) **Sequence 2.0**: This involves integrating either solenoid valve into the BPS in CPTC. All various fluid components, from tubes to the mass flow meter, shall be installed according to team defined standard procedures. Those procedures are still under development, and will naturally be updated as tests are performed to reflect learning from field experience.

3) **Sequence 3.0**: Perform pre-test procedures to ensure safety and correct functionality, and to bring the BPS to test-ready state. These checks include checking electrical continuity to every electrically powered component, checking the stability of the live video feed, manually actuating servo driven valves to check operation, fill and pressurize reservoir, then test the solenoids for functionality by actuating and noticing a pressure rise in the tank.

4) **Sequence 4.0**: The test starts by opening the isolation valve, followed by triggering the solenoid valve and allowing nitrogen to flow from the reservoir, through the solenoid and the mass flow meter, and then expelled to the environment. While this is happening, all instrumentation is actively performing data acquisition, which is stored and used for analysis later. In case of an anomaly, follow either a pre-defined emergency checklist or a test abort process. Those are yet to be defined in any detailed form. Once the end of test criteria is reached, the system is placed in safe mode.

5) **Sequence 5.0**: Perform post test procedures, which splits into two branches. If the intention is not to perform anymore tests immediately, then all pressurized tanks will be dumped, and the system will be shutdown. If the intention is to move to another OP, the the reservoir will be brought to the next OP pressure via the fill system. Then, return to step 3.5 and proceed as outlined previously.

The purpose of this is to collect data for a range of initial conditions, which would facilitate the development of empirical models for predicting mass flow rate. The test process is repeated for every solenoid valve that is to be used on the BPS for full functionality, and the models are developed after all testing is completed.

4.2 Phase 2: System Functionality Testing

The system functionality testing will assess the system's ability to regulate a depleting tank's pressure. More specifically, the testing aims to evaluate how well the system keeps the tank's pressure between the defined upper and lower bounds, and how fast it can respond to changes in mass flow rate demand. The testing will be performed using the ground testing system, whose details are provided in section 2.5.1, and P&ID in section 3.1.1, figure 6. The system functionality tests must provide the information detailed in table 11. In order to provide the required information, the system test system is designed with the sensory features given in table 12.

Table 11 System testing requirements

Test Requirement	Rationale
Solenoid Response time	The system may require high-frequency solenoid actuation to fulfill pressurization requirements. Thus, solenoid response time must be sufficiently short to ensure timely pressurant dispensing.
Evolution of mass flow rate through solenoid	In order to build predictive models for the mass flowrate of the system, the mass flowrate of pressurant fluid through each solenoid must be measured experimentally as the reservoir depletes.
Evolution of reservoir conditions during depletion	The mass flowrate the system can dispense through a given solenoid is a function of the reservoir stagnation conditions. Thus, in order to build an empirical model for mass flow rate, a time evolution of the reservoir conditions must be available. Additionally, reservoir conditions must be monitored for safety reasons during testing.
Transient pressure behavior in pressure-controlled tank	The behavior pf pressure in the tank upon pressurant injection must be measured due to the potential transients that may develop. Those transients can be driven by various mechanisms, one being the temperature difference between the injected pressurant and the tank's temperature, the tank temperature being higher than the pressurant temperature. This is due to choking effects at the solenoid orifice.
Component pressure drop	Required to characterize the pressure losses induced by each component.

Table 12 System test setup sensory features

Feature	Description	Purpose
Reservoir pressure (P_r)	A measurement of the reservoir's pressure history during the depletion	Required to build empirical mass flow rate relationships $\dot{m} = f(T_r, P_r, A)$. Also required for monitoring tank pressure during testing for safety reasons.
Reservoir temperature (T_r)	A measurement of the reservoir's temperature history during the depletion	Required to build empirical mass flow rate relationships $\dot{m} = f(T_r, P_r, A)$. Also required for monitoring tank pressure during testing for safety reasons.
Tank pressure (P_t)	A measurement of the tank's pressure history during the depletion	Required to evaluate system functionality and performance.
Tank pressure (T_t)	A measurement of the tank's pressure history during the depletion	A measurement of the tank's pressure history during the depletion

The system functionality testing sequence will follow the FFBD outlined in figure 16.//

1) **Sequence 1.0**: Define a set of required initial reservoir pressures and temperatures, and the set of required tank set pressures. These would then be combined to create a set of operational points (OPs). For example, if there are 5 initial reservoir pressures, and 5 tank set pressures, this would create 25 OPs that would require testing. Care should be taken in defining the OPs since an excessive number of them can lead to unrealistic requirements on testing resources such as pressurant gas, man-power and time.

2) **Sequence 2.0**: Perform pre-test procedures to ensure safety and correct functionality, and to bring the BPS to test-ready state. These checks include checking electrical continuity to every electrically powered components, checking the stability of the live video feed, manually actuating servo driven valves to check operation, fill and pressurize reservoir, then test the solenoids for functionality by actuating and noticing a pressure rise in the tank.

3) **Sequence 3.0**: The test starts by pressurizing the tank up to the set pressure, and once that is completed, the pressure regulation can start. This begins by actuating the MOV to discharge nitrogen from the tank, after which the pressure starts to drop, prompting the control system to react and command corrective action by actuating the solenoids to administer pressurant to the tank. In case of an anomaly, follow either a pre-defined emergency checklist or a test abort process. Those are yet to be defined in any detailed form. One the end of test criteria is reached, the system is placed in safe mode.

4) **Sequence 4.0**: Perform post test procedures, which splits into two branches. If the intention is not to perform anymore tests immediately, then all pressurized tanks will be dumped, and the system will be shutdown. If the intention is to move to another OP, the the reservoir will be brought to the next OP pressure via the fill system. Then, return to step 2.5 and proceed as outlined previously.

This testing strategy ensures that the control system, as well as the fluid components respond correctly to the changing conditions in the tank. Phase 1 will be performed until a mass flow rate model can be built for both solenoids, covering a wide range of OPs. That that point, Phase 2 can start, and will be performed until the control system is tuned to perform acceptably (i.e meets the performance metrics mentioned in section 3.3.2. More detailed procedures for both testing Phases are still being developed however, and they are expected to change as the team builds field experience.

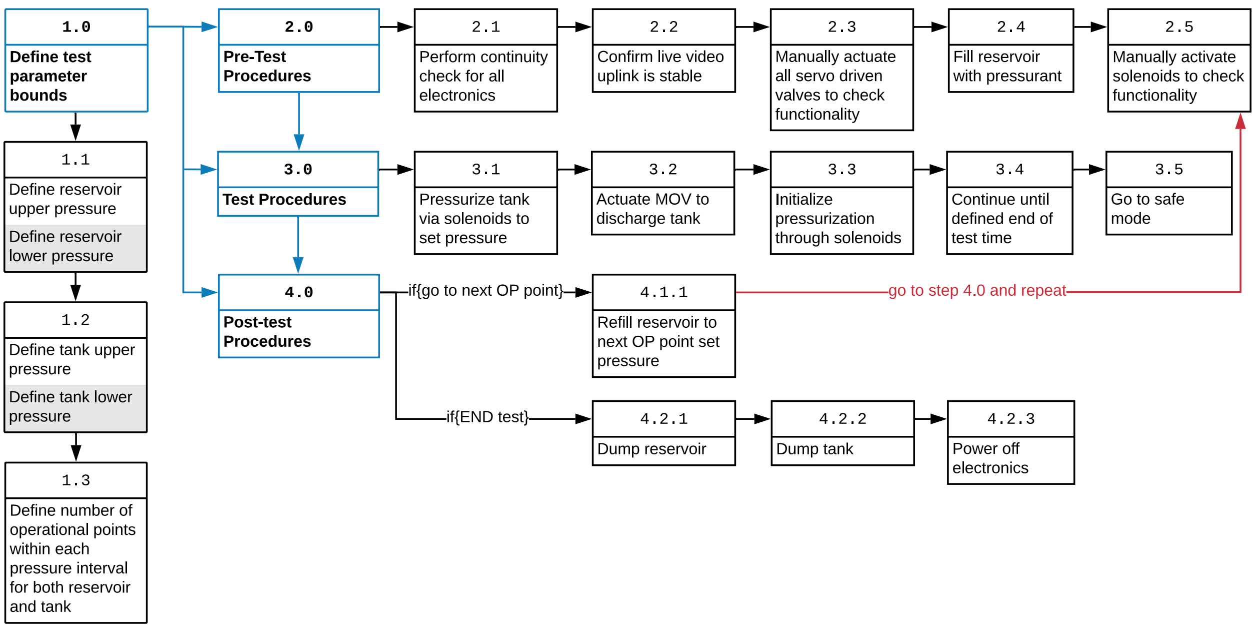

Fig. 16 System Functionality Testing FFBD

5. Risks and Mitigation Strategies

There are two main categories of risk: human- and equipment-related. The former refers to the poor training of operators in handling the rocket, improper component inspections, insufficient preventative maintenance (resulting in equipment-related failures), and overall human error when working with the rocket. An especially relevant human error is improperly following the planned and correct design, construction, and installation procedures during the operation period of the rocket.

The second category of risk, equipment-related, refers to the malfunctioning of components. Since high pressure fluids are being used, leaks due to improper sealing are especially dangerous. Other risks include the chance of failure of safety devices installed, mechanical failure of components due to overall wear, and possibly the use of poorly-suited equipment.

To help mitigate the human risk, prior to the assembly of the system, relevant members are trained in the assembly and operation of high pressure equipment used on the test stand. The training focuses on the planned assembly process, proper Personal Protective Equipment (PPE) usage, and identifying possible safety hazards and how to deal with them. Along with such training, a clear organization of parts to be assembled and a series of quality assurance checks on said parts ensures that all components are to spec before assembly begins. If any parts suffer damage after they are prepared, they should be swapped with a spare and clearly labelled as defective. In some cases, where defective features are not obvious, parts are purposefully damaged further in order to ensure no one accidentally tries to use the part in the future.

During the assembly, providing thorough instructions and safety checklists minimizes the risk of hazards. After the assembly, all points of connection are inspected and any points with a chance of leaking are checked with leak check fluid. A dry run without any pressure is first performed to make sure the parts interact with one another as expected. Lastly, the system has a safety switch which can be used to safely stop the actual firing of the system from a distance. It does so by shutting off power to the test stand. Nominally closed solenoids have been chosen to ensure that, if an emergency power cut is required, the the tank is immediately cut off from the reservoir to prevent over pressure.

The risks associated with subsystems of the BPS must be analyzed in two ways. It is important to address which subsystems have the most severe risks, ones that can largely impact the safety of personnel or jeopardize mission success. However, it is also equally important to assess the probability of risks occurring in each subsystem. While some subsystems have the capability of producing highly severe risks, and nothing can be done to reduce the risk itself – then steps must be taken (such as testing and computer modelling) to reduce the probability that such risks occur. While some subsystems produce less severe risks, such risks could still cause a less than favourable performance – therefore the probability of these smaller risks should also be lowered as much as possible. Below is a risk matrix used to quantify risks in each subsystem:

To assess the risk of the system, a failure mode and effects analysis (FMEA) is performed. This FMEA is performed using a bottom up approach by analyzing each of the fluid components on the BPS stand and assessing all the potential modes of failures. The effect on the system due to this failure is then assessed using a severity scale from 1 to 4 and a probability scale from 1 to 5; the product of these scores indicate what level of risk these failure modes present. Lastly, a mitigation strategy is discussed for each of these failure modes and their associated effcts on the system. The results of this FMEA is seen in Table 13.

Table 13 Failure Mode and Effects Analysis Matrix

Part ID.	Failure Mode	Effect on System	Sever.	Prob.	Total	Mitigation
Nitrogen Run Tank	Non-airtight seal (i.e. leak).	Inability to properly pressurize downstream system and unable to achieve full self pressurization.	2	1	2	Leak test during a hydrostatic test or during the fill procedure.
	Critical flaw in the tank shell.	Bursting of the tank.	4	1	4	A hydrostatic test can be performed to verify the structural integrity of the tank.
Oxidizer Run Tank	Non-airtight seal (i.e. leak).	Inability to source oxygen to the system and unable to achieve full self and unable to achieve full self pressurization.	2	1	2	Leak test during a hydrostatic test or during the fill procedure.
	Critical flaw in the tank shell.	Bursting of the tank.	4	1	4	A hydrostatic test can be performed to verify the structural integrity of the tank.
Nitrogen GSE Tank	Critical flaw in tank shell.	Bursting of the tank.	4	1	4	A hydrostatic test can be performed to verify the structural integrity of the tank.
TC_R_N	Measures temperature higher than the true value.	Provide inaccurate results for data analysis and for test safety.	1	1	1	Can calibrate sensor before test and verify against a known temperature.
	Measures temperature lower than the true value.	Provide inaccurate results for data analysis and for test safety.	1	1	1	Can calibrate sensor before test and verify against a known temperature.
TC_T_N	Measures temperature higher than the true value.	Provide inaccurate results for data analysis and for test safety.	1	1	1	Can calibrate sensor before test and verify against a known temperature.
	Measures temperature lower than the true value.	Provide inaccurate results for data analysis and for test safety.	1	1	1	Can calibrate sensor before test and verify against a known temperature.

PG_R_N	Displays an internal pressure lower than the true value.	If PT_R_N also measures a lower pressure than the true value, may over-pressure the reservoir, triggering burst discs and/or relief valves. Inconsistency between pressure gauge and transducer (PT_R_N) will result in aborting test and an inability to gather data to determine mass-flow rate.	1	1	1	Can preform a hydrostatic test before the test to calibrate sensor and can also verify correct reading at the start of the test.
	Displays an internal pressure higher than the true value.	Inconsistency between pressure gauge and transducer (PT_R_N) will result in aborting test and an inabiliy to gather data to determine mass-flow rate.	1	1	1	Can preform a hydrostatic test before the test to calibrate sensor and can also verify correct reading at the start of the test.
PG_F_N	Displays an internal pressure lower than the true value.	Result RF_F_N1 being triggered without warning.	1	1	1	Can preform a hydrostatic test before the test to calibrate sensor. Can also verify correct reading at the start of the test.
	Displays an internal pressure higher than the true value	Unable to pressurize the reservoir due to internal pressure of fill system being lower than displayed.	1	1	1	Can preform a hydrostatic test before the test to calibrate sensor and can also verify correct reading at the start of the test.
PG_T_N	Displays an internal pressure lower than the true value.	If PT_T_N also measures a lower than true value pressure, may over-pressure the tank, triggering burst discs and/or relief valves and test failure. Inconsistency between pressure gauge and transducer (PT_T_N) will result in aborting test and an inability to gather data to determine mass-flow rate.	1	1	1	Can preform a hydrostatic test before the test to calibrate sensor. Can also verify correct reading at the start of the test.

PT_R_N	Displays an internal pressure lower than the true value.	If PT_T_N also measures a lower than true value pressure, may overpressure the tank, triggering burst discs and/or relief valves and test failure. Inconsistency between pressure gauge and transducer (PT_T_N) will result in aborting test and an inability to gather data to determine mass-flow rate.	1	1	1	Can calibrate sensor before test and verify with know pressure. Can also verify correct reading at the start of the test.
	Displays an internal pressure higher than the true value.	Inconsistency between pressure gauge and transducer (PT_T_N) will result in aborting test and an inability to gather data to determine mass-flow rate.	1	1	1	Can calibrate sensor before test and verify with know pressure and can also verify correct reading at the start of the test.
PT_T_N	Measures an internal pressure lower than the true pressure value	Over pressurization of the tank.	2	1	2	Can calibrate sensor before test and verify with know pressure and can also verify correct reading at the start of the test.
		The difference in reading between PG_T_N and PT_T_N will be detected and will cause an abort sequence.				
		Inaccurate results for data analysis.				
	Measures an internal pressure higher than the true value.	Fluid leaving the tank system will not reach the desired pressure.	1	1	1	Can calibrate sensor before test and verify with know pressure and can also verify correct reading at the start of the test.
		Inaccurate results for data analysis.				
		The difference in reading between PG_T_N and PT_T_N will be detected and will cause an abort sequence.				
RF_R_N1	Fails closed.	Over pressurization of the nitrogen GSE tank.	2	1	2	Check valve is very reliable and there is another relief valve upstream.

	Relief pressure set too low.	Under pressurization of the nitrogen GSE tank.	1	1	1	Can verify relief pressure using a hydrostatic test up to the operating pressure.
RF_F_N1	Fails closed.	Over pressurization of the nitrogen GSE tank.	2	1	2	Check valve is very reliable and there is another relief valve.
	Relief pressure set too low.	Fill system is under pressurized.	1	1	1	Can verify relief pressure using a hydrostatic test up to the operating pressure.
RF_T_N	Fails closed.	Over pressurization of the reservoir.	2	1	2	Check valve is very reliable and there is another relief valve, burst disk and manual relief valve that can be opened to relieve pressure and inability for the tank to reach proper pressurization.
	Relief pressure set too low.	Under pressurization of the reservoir.	1	1	1	Can verify relief pressure using a hydrostatic test up to the operating pressure.
BPS_N1	Fails open.	Over pressurization of the tank.	3	1	3	Verify actuator functionality before test is preformed. Relief valve RF_T_N1 will handle any over pressurization.
	Fails closed.	Under pressurization of the tank.	2	1	2	Verify actuator functionality before test is preformed.
	Valve jams.	Over or under pressurization of the tank depending on when the system is manually aborted.	3	1	3	Verify actuator functionality before test is preformed. Relief valve RF_T_N1 will handle any over pressurization.
	Improper coordination with BPS_N2.	Over or under pressurization of the tank depending on type of improper coordination.	2	1	2	Over pressurization handled by the relief valve RF_T_N1 and under pressurization will simply result in a failed test.
BPS_N2	Fails Open.	Over pressurization of the tank.	3	1	3	Verify actuator functionality before test is preformed. Relief valve RF_T_N1 will handle any over pressurization.

	Fails closed.	Under pressurization of the tank.	2	1	2	Verify actuator functionality before test is preformed.
	Valve jams.	Over or under pressurization of the tank depending on when the system is manually aborted.	3	1	3	Verify actuator functionality before test is preformed. Relief valve RF_T_N1 will handle any over pressurization.
	Improper coordination with BPS_N1.	Over or under pressurization of the tank depending on type of improper coordination.	2	1	2	Over pressurization handled by the relief valve RF_T_N1 and under pressurization will simply result in a failed test.
ISO_T_N	Isolation valve is closed too much.	Insufficient flow rate to both BPS valves, cause inaccurate results.	1	2	2	Incorporate a lock on the isolation valve preventing movement from the operating position.
FV_F_N	Left open during test	Full drain of pressurant tank, invalidating test and could damage fill components.	2	1	2	Ensure the fill procedure includes a check of the fill valve to ensure it is closed.
CV_T_N	Valve fails to open	Build up in upstream pressure which could lead to damage and burst of components.	3	1	3	Check valves are very reliable and there is a relief valve upstream of the BPS valves.
BD_T_N	Burst disk fails to burst.	Over pressurization in tank and potential for severe damage.	3	1	3	Very low risk of a burst disk failure as it the purpose of the burst disk is to break once a given pressure is exceeded.
	Burst disk ruptures early.	Test is aborted and is unable to be ran.	2	1	2	Perform hydrostatic test to operating pressure to confirm validity of burst disk.
MOV	Actuator fails to open valve.	Overpressurization in the tank and potential for severe damage.	3	1	3	Relief valve would compensate.
	Unable to send command to solenoid valve	Over pressurization in the tank and potential for severe damage	3	1	3	Relief valve would compensate.
RF_T_N1	Inability to relieve pressure upstream of BPS and isolation valve	Unable to depressurize lines	2	1	2	Can test burst pressure using a hydrostatic test.

	Relief set too low and relieves at a low pressure	Flow is diverted away from the BPS valves and the test is invalidated.	1	1	1	Can verify relief pressure using a hydrostatic test up to the operating pressure.
Mass Flow Meter	Flow meter reads incorrect values	Test is invalidated	1	1	1	Can calibrate measurements before test to ensure an accurate reading.

Many risks are associated with the instrumentation, however there exist some parts with much higher risks than most. These parts include the BPS solenoid valves, isolation valves, and the tank pressure transducer. Each of these parts have the possibility of experiencing highly severe risks. The tank pressure transducer may read an incorrect value; reading lower than the true value can lead to a severe risk while a reading higher than the true value leads to a much less severe outcome. If the transducer measures a higher pressure, less pressurant will be fed to the tank and thus the test will be unsuccessful. At the other end, with high severity, if the transducer measures a lower pressure, this can cause the solenoid valves to open more than necessary. If this happens, the tank will experience pressure above it's maximum allowable working pressure, triggering it's relief devices, making the test unsuccessful. The larger risk comes when the relief devices fail. If these devices fail, the tank can get damaged or even rupture. Incorrect readings will also effect the feedback into the plant which will then incorrectly adjust the BPS solenoids potentially over pressurizing the system.

The solenoid valves may also experience mechanical failure such as "jamming". If a solenoid valve gets jammed open or closed, consequences can be severe. If the valve gets stuck closed, the tank will not reach desired pressure and the test will not be successful. If the valve is jammed open, however, the tank can over pressurize, and thus damage or rupture (if relief devices fail, otherwise will lead to activation of relief devices). As two solenoids must coordinate, a lag in coordination can lead to over pressurization as well.

The isolation valve is key in retrieving information regarding mass flow rate. If the isolation valve remains closed for too long, there will be an insufficient flow rate to both solenoid valves. This will yield inaccurate results, and therefore will create an unsuccessful test.

Conclusion

This section gives summary of the design presented in previous sections, amalgamating the general engineering concepts and guidelines for a comprehensive testing strategy of the proposed Bang-Bang Pressurization System. It states the contribution of this aerospace engineering research by proposing a Bang-Bang Active Pressurization System for Liquid Bi-propellant Rocket Engines. The report also suggests future research that may extend the concept and implement the pressurization system on a next generation liquid rocket.

The report starts by presenting the high-level system testing design of the BPS and illustrates how all subsystems interact to achieve the goal of actively controlling the tank pressure, in place of more traditional passive regulator solutions. The BPS ground operations will be performed via two system configurations, the system functionality test configuration (SFTC), and the component performance test configuration (CPTC). The SFTC serves the purpose of testing the overall pressure regulating capability of the BPS, which the CPTC is designed to collect test data that will be used to build empirical models for each solenoid's mass flow rate. The empirical models can then be used to accurately predict system performance in simulations and during software testing and tuning of the BPS control system.

Next, the engineering design of the BPS is presented. First, a plumbing and instrumentation diagram P&ID for the SFTC is presented, along with a 3D representation of the assembled SFTC fluid system. Description for all components of the SFTC fluid system are provided. Similarly, and P&ID and a table of component descriptions are provided for the CPTC. Then, the proposed control architecture is presented, highlighting the flow of information and control logic within the control system. The system is broken down into three layers and their tasks are described. The operational bounds for the control system, performance, and tuning parameters are are presented. The chosen microcontroller, along with the design of the electrical subsystem are both outlined.

Then, a two phase testing strategy is presented to test the functionality of each component, build predictive mass flow rate models, and test the over all capability of the pressure regulation system. The required test results, along with the required sensory information is presented.

Finally, a Failure Mode and Effects Analysis (FMEA) is performed to identify potential failure modes of BPS components, the risks associated with those failure modes, and mitigation strategies.

Progress since last report

The progress can be summarized as follows:

1) Redesign of the structural frame and architecture to utilize only one platform.
2) Removal of the POGO mechanism.
3) Upgrades to the fluid subsystem, and selection of all fluid components, including solenoid valves.
4) Finalised design of the tank, along with detailed FEM studies of stress response and manufacturing design.
5) 3D placement of fluid components and tube routing.
6) Design of BPS electrical subsystem.
7) Design of BPS control system, selection of the positive feedback hysteresis approach, and selection of the microcontroller.
8) First draft of a bang-bang control system implementation in MATLAB. The positive feedback control system has been recently started on C++.
9) Failure Modes and Effects Analysis.

6. Next Steps

COVID-19 has put a huge amount of uncertainty in the BPS project. The team was gearing up to purchase most of the components, and build the BPS CPTC to start Phase 1 of the testing process. However, until quarantine can be safely lifted, the team is limited to design tasks. Thus, the team will be focused on the following:
1) Completion of the 3D CAD, and ensuring all components fit within the available space.
2) Design the software architecture that will contain the code for executing all BPS functions. This is the highest level of software on the BPS, and will likely run on the Raspberry Pi 4, and will be responsible for actions like switching states, telemetry, live video feed, emergency shutoff, initiating a test, etc.
3) Implement the positive feedback control system in MATLAB and commence testing by using the proposed blow-down and pressurization modes as the control system plant (replaces real tank for software testing purposes).
4) Complete detailed testing procedures
5) Design emergency procedures, including emergency abort procedures.

References

[1] Fernandez, M. M., "Propellant tank pressurization modeling for a hybrid rocket," *M.A.Sc Thesis*, 2009.