53rd International Conference on Environmental Systems
21-25 July 2024, Louisville, Kentucky
ICES-2024-383

Flexible Motor Controller Architecture for Spacecraft Applications

Connor Myers[1], Russell Wallace[2], Bradley Cowgill[3], Casey Rorabeck[4], Elias Tarver[5], David Carney[6], Sam Moffatt[7], George Heindl[8], Mike Bourget[9]
Sierra Space, Madison, WI 53717

Brushless DC (BLDC) motors are ubiquitous to spacecraft operation. BLDC Motors provide the driving force for many different components within ECLSS and TCS such as: valves, fans, blowers, pumps, and rotary separators. Specific to valve operation, several considerations come into play when developing a control system for a BLDC motor. Position sensing/indication, mass, power, volume, cost, radiation susceptibility, and maintainability are among primary design driving factors for developing a BLDC motor controller. Looking at the potential needs for valve control and design, a common product was developed to balance the design driving factors towards the end goal of cost reduction and simplifying on-orbit logistics and maintenance for future spacecraft. The flexible design supports a wide array of valve functions and can be maintained/removed without exposing the internal fluid to the spacecraft environment. The microcontroller-based design provides a simplified and abstracted serial data interface to the flight computer, enables low level hardware and software fault detection, allows modularity for adding additional application specific sensors and features without impacting vehicle avionics, simplifies channelization and wire harness to vehicle avionics, and allows for in field software updates. The design supports different part grades from automotive to grade 1 to optimize for the application. Additionally, key internal components have been tested to support the radiation and vibration environment encompassing many potential valve applications.

Nomenclature

BLDC	=	Brushless Direct Current
COTS	=	Commercial Off The Shelf
DAC	=	Digital to Analog Converter
ECLSS	=	Environmental Control and Life Support System
EEE	=	Electrical, Electronic and Electromechanical
EMI	=	Electromagnetic Interference
FOD	=	Foreign Object Debris
HED	=	Hall-Effect Devices
ILA	=	Internal Lighting Assembly
I/O	=	Input/Output
MBSE	=	Model-Based Systems Engineering
MCU	=	Microcontroller Unit
PWM	=	Pulse Width Modulation
S2A2	=	Smart Space Actuator Assembly

[1] Electrical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[2] Electrical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[3] Software Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[4] Mechanical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[5] Electrical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[6] Systems Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[7] Mechanical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[8] Mechanical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717
[9] Electrical Engineer, Space Applications, 1212 Fourier Dr. Madison, WI 53717

SADA = Solar Array Drive Assemblies
SEU = Single Event Upsets
TCPS = Trash Compaction Processing System
TCS = Thermal Control System
TID = Total Ionizing Dose

I. Introduction

Control of electric motors is an enabling function for many components and subsystems on spacecraft both crewed and uncrewed. Electric motors allow for actuation of numerous critical spacecraft components such as: valves, fans, pumps, Solar Array Drive Assemblies (SADA), among others. Brushless DC (BLDC) motors can trace their spacecraft heritage back to the Apollo Era used in Environmental Control and Life Support System (ECLSS) blowers for circulating oxygen[1]. When compared with brushed DC motors, BLDC motors offer significant benefits.

DC motors operate by generating a rotation-dependent magnetic field which produces a net torque on the rotor. The process of controlling the rotating field is called commutation. Before modern electronics commutation was necessarily mechanical. performed by brushes and rotor contacts. These acted as mechanical switches to apply current to the proper rotor coils in sequence as the motor turned. Most brushed DC motors use either a series of permanent magnets or constant electromagnets on the stator.

The rotor is a series of electromagnets wrapped around the rotor core. Brushes are used to conduct current to the rotor electromagnets. As current is applied to one set of rotor electromagnets and the rotor start to turn, the movement of the rotor causes the brushes to commutate (change which rotor electromagnets are energized) keeping the motor moving. These brushes are a wear item and tend to generate Foreign Object Debris (FOD) over the life of the motor. In addition to FOD generation, as the rotor spins every time the brushes move from one commutation to the next, a spark is generated at the brushes. Both FOD and spark generation pose significant risk to high oxygen concentration environments such as the Apollo pump noted above.

In brushless DC motors the rotor is a group of permanent magnets wrapped around the rotor core and the stator is series of electromagnets that are turned on and off to move the rotor. A resolver or Hall Effect Devices (HEDs) are used to measure the position of the rotor and control the application of current to the correct stator winding. As the switching of current is now being controlled by solid state devices outside of the motor, there is no mechanical wear points and no electric arcing potential in the motor making the BLDC motor desirable for oxygen applications. The lack of mechanical wear also provides long life and high efficiency making it the motor of choice for many ECLSS and Thermal Control System (TCS) actuation applications. Additional benefits over brushed motors include speed control and torque maintainability[2].

Because the BLDC motor is electronically commutated instead of through brushes, additional electrical components are required to read the rotor position (through HEDs), control speed and torque, and maintain synchronous excitation for the stator phases. Combined with input from additional position indication sensors (such as rotary encoders) and components for health monitoring, a fully integrated, highly functional controller for the motor can be provided.

Sierra Space heritage BLDC motors and/or controllers have supported numerous space missions with proven success. The Mars 2020 Rover included 8 unique custom actuator designs alone[3]. A sample of recent motor/gearbox applications are noted in Table I-1 below.

Table I-1. Sierra Space Recent Heritage BLDC Actuators

Mission	**Application Supported**
Mars 2020 Rover	Drill Mechanism (5X)
	External Robotic Arm (2X)
	Caching Assembly (2X)
	Helicopter (Ingenuity) Deployment
Dream Chaser	Flight Control
	Wing Deploy
	Wing Lock Insertion
Orion	ECLSS Pump
World View Legion	Very Low Disturbance Gimbal

II. Heritage Valve Motor Controllers

A. Starliner Valve Motor Controllers

Valves with integrated motor controllers were developed for the Starliner program (Figure 1). These valves operate with a simplified control scheme implementing a 28V power input for "open" command and a 28V power input for "close" command. While power is applied the valve moves in the direction per the input signal (open or close). Limit switches provide end of travel indication to determine when the valve is either fully open or fully closed. The limit switch automatically disengages the power feed when end of travel is reached (in either direction). Signal output to the vehicle is analog +5V/-5V depending on the state of the limit switches.

The motor control functionality is provided with a hybrid speed motor controller module that directly drives the BLDC motor. Speed control is input to the module and it then automatically outputs the appropriate motor phase waveforms to drive at the desired speed. The module directly reads the motor hall sensors to determine motor speed and direction and adjusts the phase outputs as needed to maintain. The speed is set electrically in hardware within the board. This overall control approach allows simplification in the electronics and similarly requires no software, however, does not provide the ability to determine valve position between end of travel ranges and does not allow proportional commanding of the valve.

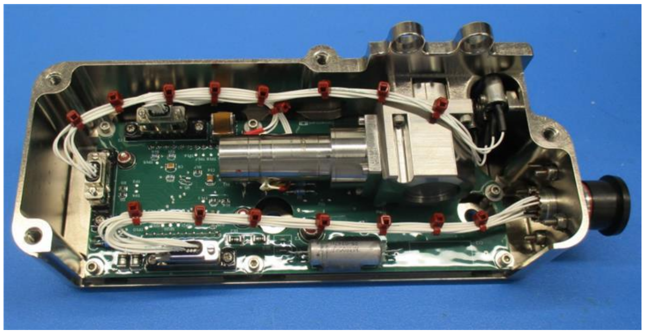


Figure 1. Starliner Ball Valve Motor Controller.
Image Credit: Sierra Space

For other Starliner valves, controller design was driven by a requirement to utilize heritage valves and motors (Figure 2). All valves were two-position (open and close) with limit switches to indicate end of travel. Motors were brushed DC and remote from the controller installation location. The heritage control interface switched each motor terminal to either power or ground, allowing direction control without electronics in the valves. They contained only EMI filtering and wiring for the motors and limit switches and had extremely limited internal space.

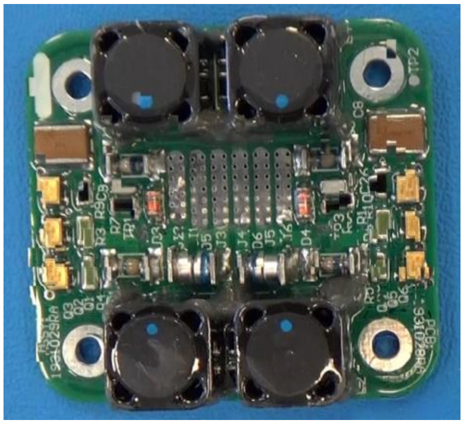


Figure 2. Starliner Adapted Legacy Motor Controller.
Image Credit: Sierra Space

The new control interface was individual open and close relay-switched power feeds. All necessary electronics to adapt the heritage motors to the new interface had to fit inside the valve's existing wiring enclosure. Grade 1 Electrical, Electronic, and Electromagnetic (EEE) parts were required. Other challenges included preventing vibration-induced relay chatter, limiting motor on-time to prevent thermal damage, and additional Electromagnetic Interference (EMI) filtering.

It proved challenging to fit a standard four-transistor H-bridge, EMI filtering, and the necessary control and timing logic in the available volume. Cost and schedule constraints precluded development of a custom hybrid. Significantly reducing part count through creative design proved the only practical option when considering the trade space. Fortunately, performance requirement tradeoffs were allowed to enable implementation. The final design used two MOSFETs, six diodes, and passives to successfully implement all the features described above. Speed and torque were about 10% lower than a standard H-bridge approach, but this was acceptable.

B. Dream Chaser® Valve Motor Controller

The Dream Chaser® spaceplane utilizes a 3-phase BLDC motor as the actuator for fluid control valves used across multiple subsystems. The motor controller designed for Dream Chaser is relatively simple. A hybrid BLDC controller chip commutates the motor, regulates motor current, and performs closed-loop speed control. The motor current limit and set speed are configured in hardware. Like the Starliner valves, position control is limited to end-of-travel indicators which turn off motor drive when tripped. The vehicle interface is dual 28V power feeds. One feed drives the motor clockwise and the other feed drives it counterclockwise. The vehicle interface also includes a discrete signal to override the end-of-travel feedback should an end-of-travel switch fail. The intended operation for the Dream Chaser motor controller is to drive a valve between fully open and fully closed positions, automatically stopping when the valve has reached the commanded position. However, this controller can be used for simple proportional control by pulsing the open or close lines to make small valve movements in the desired direction.

Figure 3. Dream Chaser Valve Motor Controller. *Image Credit: Sierra Space*

The Dream Chaser valve motor controller is a cost-effective approach to driving 3-phase BLDC motors when sophisticated position control is not required. This configuration provides a common approach to multiple valve configurations on the vehicle. The interfaces are simple, and the design is robust to the specified environment for Dream Chaser. However, this design is not suitable for applications where more advanced position control is desired, or if motor speed and torque limits must be adjustable. Additionally, the Dream Chaser motor controller is a stand-alone electronics box which must be mounted to the vehicle separately, with dedicated harnessing routed between the controller and the motor it controls.

III. Next Generation Smart Space Actuator Assembly

A. Overview of Motor Controller Design

The Smart Space Actuator Assembly (S2A2) design eliminates many of the drawbacks of prior generation motor controllers. It reduces the footprint and volume of the previous designs and results in overall mass reduction. Instead of discrete limit switches at end of travel, a rotary encoder is used to provide absolute position control throughout the full 360 degrees of travel. Embedded software allows flexibility in how the valve is utilized, whether for proportional control or on/off operation. Design margins (torque, current, etc.) are built into actuator package to accommodate current and projected valve capability needs. Direct integration with the motor and gearbox simplifies the integration with the downstream valve and eliminate an intermediate wire harness. Actuator connection to valve components don't penetrate the fluid region of the valve, significantly improving on-orbit maintainability for long life applications. The actuator assembly with outer cover removed is shown in Figure 4. Projected component capabilities are noted in Table III-1.

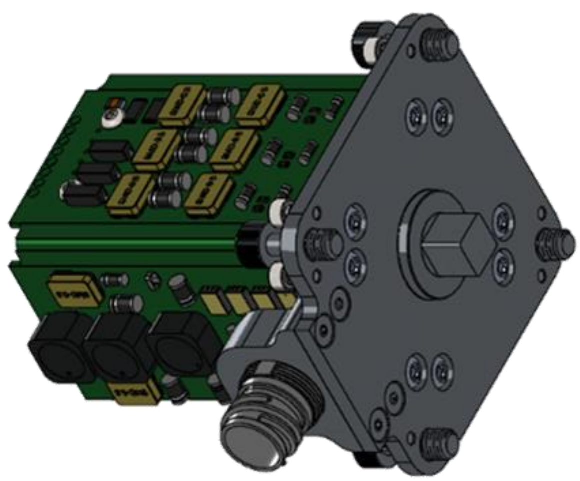


Figure 4. S2A2 Without Protective Cover. *Image Credit: Sierra Space*

Table III-1. S2A2 Capabilities

Component Parameter	Value	Notes
Mass	1.3 kg	Includes Controller, motor, gearbox, sensor and housing
Volume	2.8"x2.8"x3.4"	
Actuating Power	< 56W	Capable of driving up to 2A of motor current. Actual actuation power will depend on torque and speed requirements.
Standby Power	< 3W	Nominal estimated quiescent power. Lower power modes are available by toggling power to peripherals.
Control Accuracy	< 1 degree	
Torque Capability	300 in-lbs	Varies inversely with desired actuation speed, higher torque capability may be achievable
Actuation Speed	0-5.5 RPM	Can be tailored inversely proportional to torque capability.
Data Interface	RS 485/422	Controller and software could support alternate communication protocols as needed
Cycle Life	100,000	Conservative estimate at 150 in-lbs, Infinite predicted life
EEE Part Grade	Grade 1	Automotive grade variant exists for lower cost in less critical applications and environments

B. Mechanical Design

The motor controller electronics consist of a single PCB assembly that uses flex rigid construction, allowing the controller to wrap around the actuator gear box and motor assembly. This allows for compact packaging of the controller without the need for intermediate connectors. The motor is a 50W space rated BLDC motor. It is available in multiple winding configurations in the same physical form factor allowing for easy customization of the motor parameters depending on the end use application.

The geartrain consist of a custom built, multi-stage, fixed common ring, planetary gear system. The common ring allows for multiple sun and planet combinations to be used in the same housing. With options to use two, three or four gear stages, gear reduction ratios from 20:1 to 2000:1 are possible depending on the use application. The packaged geartrain, motor, position sensor and control electronics are shown in the cut view of Figure 5.

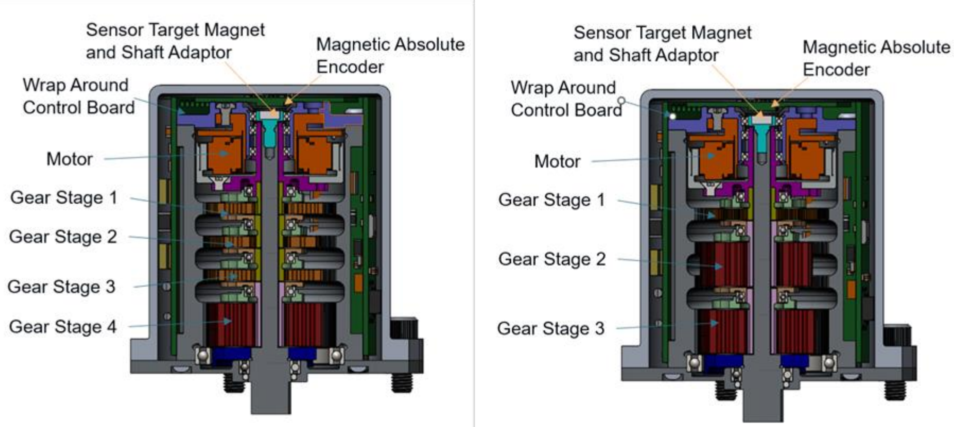


Figure 5. Motor and Geartrain Assembly Cross Section with Different Gear Reduction Options

Unlike prior motor controller applications, the S2A2 design incorporates position sensing that allows for absolute position control throughout the full range of motion for the actuator.

C. Electrical Design

The electrical design for S2A2 is enabled by two key components. The first is a radiation tolerant BLDC controller which implements the 3-phase commutation logic, Pulse Width Modulation (PWM) controller, and current sensing with over-current protection. Four-quadrant operation is selected to allow greater control of the motor during acceleration and deceleration periods. Commutation feedback is provided by Hall sensors in the motor. The PWM controller is configured to control motor torque, with sensed motor current provided as feedback. Motor chopping frequency and current limit are configured in hardware using peripherals to the BLDC controller.

The second is a radiation tolerant Microcontroller Unit (MCU). The MCU is responsible for implementing the speed and position control loops. Motor speed feedback is provided by a tachometer from the BLDC controller. The tachometer is pulsed each time a Hall sensor changes state. Pulses are fed into a counter timer in the MCU to measure speed. Position feedback is provided by a sensor on the motor output shaft. The control loops are nested with position control dictating speed, and speed control dictating motor torque. The interface between the MCU and the BLDC controller is managed by a Digital to Analog Converter (DAC), with the output analog voltage setting the target motor torque referenced by the PWM controller.

The MCU is also responsible for interfacing with the flight computer through a hardware configurable RS-485/422 UART interface. All commands and telemetry are conveyed over the serial interface. On-orbit reprogramming is also available over the serial interface. A three-bit digital address can be configured in the harness to the vehicle to allow for multi-dropping up to eight controllers on the same digital communications bus.

The MCU monitors on board and motor state of health, such as: all voltage rails, board temperature, motor temperature, motor current, and the motor Hall sensors to provide diagnostics for error handling. The MCU itself has an external processor supervisor configured as a watchdog. Power to the BLDC controller and to the position sensor can be toggled by the MCU to clear upsets or reduce quiescent power.

The electrical design includes additional peripheral features to accommodate a wide array of applications. A custom power stage compatible with four-quadrant operation is included to commutate the motor phases. Drive signals are provided by the BLDC controller directly. Power stage components are selected to allow significant margin for required motor torque while limiting dynamic losses. A custom EMI filter is designed to comply with MIL-STD-461 requirements. The EMI filter utilizes a two stage, damped LC topology to minimize conducted emissions and reduce susceptibility to transients on the power bus. A resistive heating circuit is included to enable a simple temperature controller for applications where low environmental temperature extremes are expected.

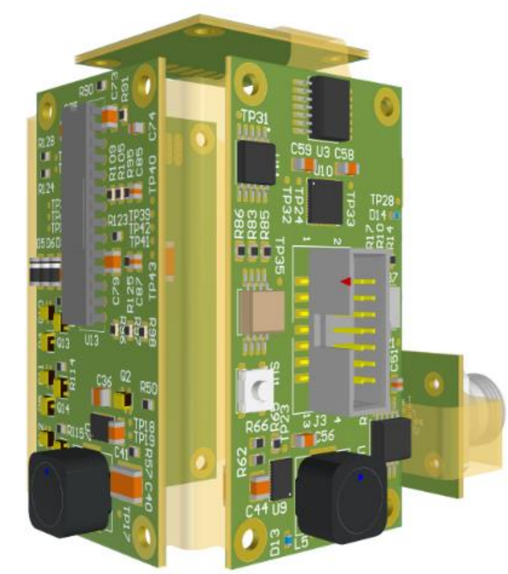


Figure 6. Motor Controller Flex Board Assy.
Image Credit: Sierra Space

The control of the motor consists of an inner current control loop implemented in the BLDC controller and outer control loops of speed and position implemented in the MCU with software. For valve designs, the MCU uses a fixed speed when the SA2A receives a command to open, close, or move the valve. The MCU performs a PID speed control with this fixed speed, driving an analog current command to the BLDC controller. The speed feedback to the MCU for this outer speed control loop is based off the hall effect sensors. When the desired position is reached, the speed is commanded back to 0. The BLDC controller has a braking function that the MCU can use when stopping the motor after the desired position is reached to prevent damage. The presence of the MCU in the design allows for more complex position and speed control for different applications if needed.

To reduce mass and envelope of the next generation motor controller, the electronics are packaged on a rigid-flexible printed circuit board. This board is packaged with the motor and position sensor to form a single actuator package. The flex board assembly is shown in Figure 6.

The motor controller is designed for high reliability. For mission critical applications the motor controller uses Grade 1 components to facilitate proven high reliability and lowest risk. For applications with relatively benign environments, short mission durations, or where maintenance is an option, Automotive Grade components are implemented to retain high reliability, but with lower cost. The Automotive Grade version uses the same MCU and

BLDC controller as the Grade 1 version, but with lower grade semiconductors and passives in peripheral circuitry to reduce cost.

D. Software Considerations

The S2A2 software is critical to enabling functionality and optimized performance. It closely integrates with the hardware design, fully leveraging the microcontroller's capabilities. The software incorporates state-based functionality, telemetry reporting, and a minimal memory footprint bootloader for on-orbit reprogrammability. It receives and acknowledges commands from the upstream controller, monitors and/or manages board and motor parameters, controls the BLDC hardware to achieve desired motor and valve set points with current-based power optimization, and reports telemetry data upon request from the host.

Configurable parameters can be modified over the RS-485/422 standard to change the desired motor controller’s behavior – which includes set point values for valve position or motor speed, lower and upper limit current values, and other configurable settings. All communication with the host device (including telemetry) are accomplished through the Modbus RTU protocol. Telemetry reporting includes monitoring motor parameters such as motor speed, valve absolute position, motor current, and motor and board temperature/voltages. The telemetry data is periodically sent to the upstream controller upon request, enabling real-time monitoring and analysis of the motor's performance. The motor controller does not asynchronously send messages upstream to the host, but instead must only respond to a command or telemetry request.

One key aspect of the software is its upgrade capability. The motor controller software includes a bootloader functionality that allows for the validation and update of the application code stored in FRAM (radiation resistant, non-volatile memory). This ensures flexibility and adaptability, as the software can be reprogrammed or updated without requiring hardware modifications. The bootloader performs a Cyclic Redundancy Check (CRC) check on the application image during initialization to prevent the execution of erroneous code caused by Single-Event Upsets (SEUs) due to ionizing radiation. In the case of an unexpected CRC upon reset, the microcontroller will immediately enter reprogram mode and inform the host controller on next check-in of the error. Additionally, the software incorporates error detection and reporting mechanisms to identify and correct bit errors when possible, enhancing the overall robustness and resilience of the motor controller. An uncorrectable bit error will force a reset which will return an incorrect CRC if application data was affected, also forcing the device into reprogram mode.

The software allows for either a hardware (voltage sampling) or software defined device ID, which is selected as a configurable parameter. This is necessary to utilize the Modbus RTU protocol and allows for multiple motor controllers to be controlled and communicated with on a single RS-485/422 bus. Communication baud rates are configurable but must be uniform across a given bus network.

The motor controller software operates in different modes, which are modeled as a state machine with states as shown in Figure 7 and described in Table III-2. Each state represents a specific operational mode and defines the behavior and functionality of the motor controller. This state-based approach allows for efficient control and management of the motor controller's operations with deterministic behavior between state transitions. The states are modeled in an integrated Model-Based Systems Engineering (MBSE) environment using Cameo.

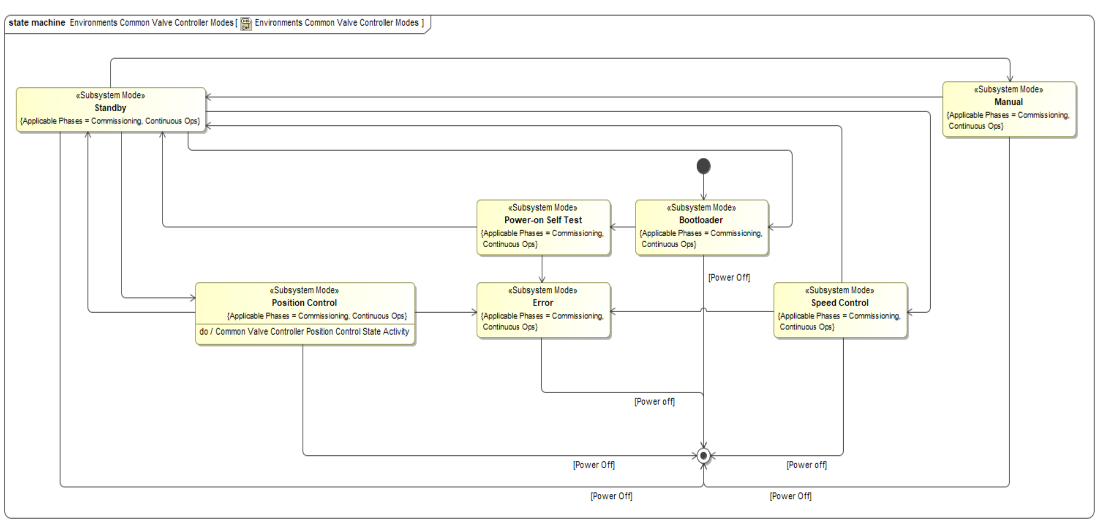


Figure 7. Valve Controller State Machine. *Image Credit: Sierra Space*

Table III-2 - Valve Controller State Description

State Name	Description
Bootloader	The controller enters this mode at power up and checks the CRC of the currently programmed image. If valid, it continues to execute the image. If not valid, it remains in this state waiting for a new image to be sent by the commanding controller. The commanding controller can also command this motor controller to this state when it wants to perform a software update. The commanding controller sends software updates to the motor controller. The motor controller updates its own software image.
Error	The motor controller will automatically transition to this state when it detects an error. The error is reported to the commanding controller. This state contains safe behaviors that the motor controller can be put into until the commanding controller, crew, or ground operations deal with the error.
Manual	The motor controller is monitoring telemetry and sending to the commanding controller. Instead of normal operational commands, the commanding controller has direct register peek and poke access to perform manual control. This mode is used for off nominal condition handling and troubleshooting by ground control or crew.
Position Control	The controller drives the valve motor to put the valve into the specified position. The valve controller awaits for position commands from the commanding controller.
Power-on Self Test	After powering up and exiting the bootloader to execute the valid software image, the motor controller performs a self-test and proceeds to the Error state or the Standby state when finished.
Speed Control	The Controller drives the valve motor to a specified speed and direction. The controller automatically stops driving once either end of travel is reached. This is for special valve applications where valve speed is important (most applications will just use the position control state).
Standby	The motor controller is powered but is not actuating the motor. The motor controller is monitoring telemetry and capable of interfacing with the high-level control (e.g. flight computer) over the RS-485 interface.

The software behavior of the controller is further modeled using activity diagrams for behavior in each state as shown in Figure 8 for the Position Control state. The modeling shows the interaction of the software with the valve hardware and with a commanding controller. The position control algorithm can be further modeled as an activity diagram inside of the Control Valve Position. This form of behavior modeling[4] has the benefit of clearly communicating behavior assumptions between hardware design, software design, and systems engineering stakeholders.

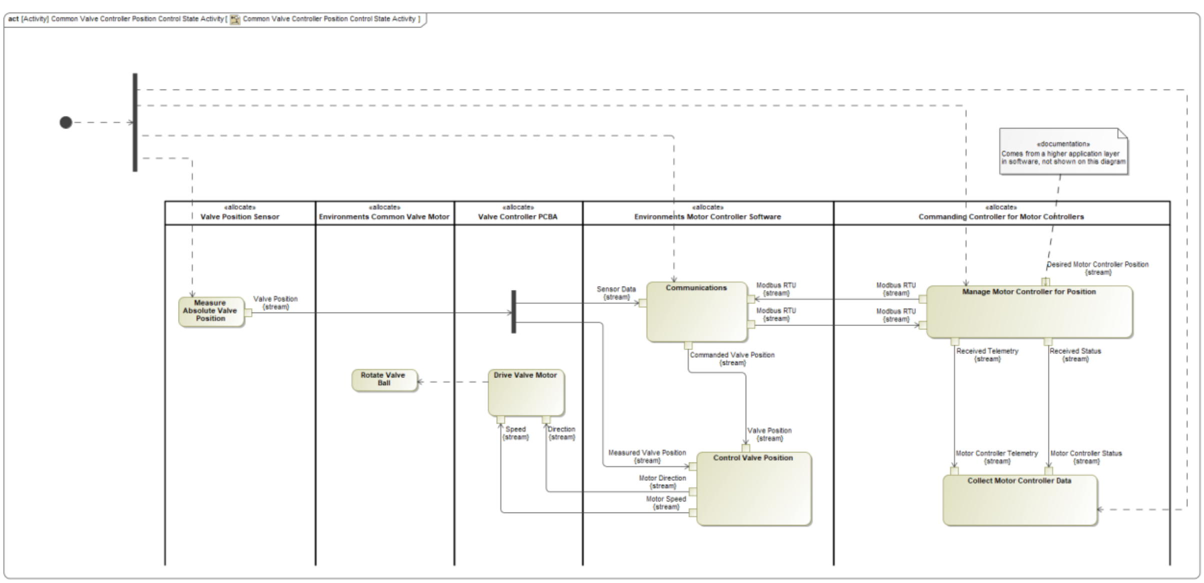


Figure 8. Position Control state activity diagram. *Image Credit: Sierra Space*

With the implementation of reprogrammability, error handling states, single-bit error correction/multiple-bit error detection, and the natural radiation tolerance of components, the motor controller has considerable failure tolerance mechanisms which give the device the necessary resilience to operate in demanding space environments such as lunar and deep space.

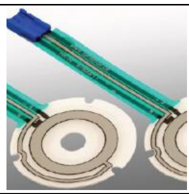
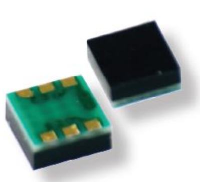
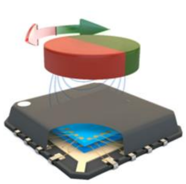
E. Command, Status, and Telemetry Data

The software-based architecture of this valve controller provides the capability for a rich set of command, status, and telemetry data to be defined. This allows for health monitoring of valves, detection of fault conditions, and resilience to off nominal scenarios.

F. Position Indication Sensor Trade

Closed loop position control regulates valve position. A key element of the design is position feedback, which is achieved through an integrated sensor reading the output shaft of the motor and gearbox assembly. A number of different position sensor technologies and interfaces have been assessed for incorporation into the architecture. The primary selection criteria are sensor reliability and robustness to the space environment, cost and lead time, and interfacing complexity. The sensors considered for contention are all absolute, multi-revolution position sensors. The leading candidates for the position sensor are: membrane potentiometer, analog capacitive absolute encoder, analog magnetic absolute encoder, and digital magnetic absolute encoder. The various options considered are described further in Table III-3.

Table III-3. Position Sensor Assessment

Sensor Picture	Sensing Technology	Benefits	Drawbacks
	Membrane Potentiometer	Low Cost, Commercial Off The Shelf (COTS). No radiation susceptibility. Simple electrical interface.	Susceptible to mechanical wear, lower life/reliability. Regular actuation needed to prevent membrane set.
	Analog Capacitive Absolute Encoder	Moderate Price, COTS. Non-contact (no wear). Some space heritage. Radiation Hardened option available.	Analog electronics pose moderate SEU and Total Ionizing Dose (TID) risk. More complicated software required to read output from sensor. Rad hard version high cost.
	Analog Magnetic Absolute Encoder	Very Low Cost, COTS. No radiation susceptibility.	More complicated electronics in controller to process output signal. Harder to integrate mechanically
	Digital Magnetic Absolute Encoder	Very Low Cost, COTS. Internally redundant (higher reliability). Simple electrical interface to MCU using Serial Peripheral Interface (SPI)	Automotive Grade electronics for processing signal (higher radiation concern). Harder to integrate mechanically.

IV. Valve Integration & Capabilities

The common actuator package is designed to be agnostic to the size and type of valve as long as they can accept the drive shaft dimensions and the four-bolt mounting pattern. For the initial LIFE® (Large Integrated Flexible Environment) application[5], all internally designed valves use this common actuator package, with rotary valves ranging from 0.5” to 5.0” line size. The Motor Controller/Actuator is shown integrated to a temperature control valve in Figure 9. In addition to rotary valves, linear actuation is possible with a custom lead screw using the same controller package. Even with different valve configurations[6], commonality in the controller for LIFE TCS and ECLSS allows sharing of controller spares, consequently reducing the quantity needed for on-orbit stowage (decreasing overall stowage volume and mass).

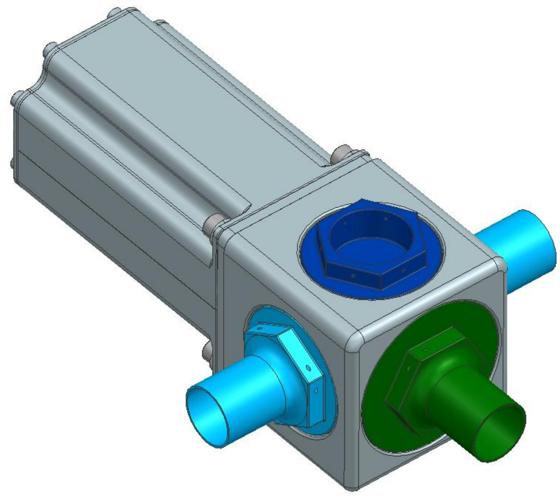


Figure 9. Flexible Motor Controller Integrated With a Valve. *Image Credit: Sierra Space*

Having all the electronics for a valve in a standalone package streamlines higher level packaging. Since the housing encloses the wiring from the motor and position sensor to the board, there is no harnessing internal to an individual valve package. The previous generation electrical boxes and valves required a separate baseplate for controller to valve mounting. With the integrated actuator package, a baseplate is not needed for an individual valve as the valve plus electronics can be fastened into the next higher assembly level directly at the valve body.

Additionally, the actuator does not interface with the working fluid, so it can be removed without disrupting the fluid path. This is beneficial for long duration missions where the electronics may have to be replaced. This can be accomplished without shutting down or risking introduction of foreign objects into the system. Further, when the actuator is removed from the valves, it exposes the drive interface so crew can put a hand tool in its place and manually actuate the valves. Moreover, if there is an electrical failure, all the electronics can be replaced at once so crew does not have to undo internal connectors on station, regardless of which electronic failed. This reduces risk of human error during maintenance.

V. Ancillary Efforts Using Common Microcontroller Architecture

The microcontroller used for the valve controller platform is also used for high voltage speed controllers, Internal Lighting Assembly (ILA) controllers and Trash Compaction and Processing System (TCPS) controllers. Component grade or code storage requirements among designs can drive some deltas (i.e. FRAM vs Flash memory) for a given subsystem design.

Utilizing this common platform over a breadth of applications demonstrates the robustness of the controller design and the potential for code re-use between applications where commonality exists with minimal modifications. Examples being Input/Output (I/O) rewrites, clock initialization, PWM control, watchdog timers, boot loaders, sensor interfaces, etc.

Additionally, common tools for software qualification to meet stringent requirements such as DO-178C[7] can span applications, enabling effective and efficient use across multiple product lines.

VI. Conclusion

The S2A2 design provides future spacecraft developers a flexible and potentially common actuator package for motorized valves within their spacecraft architecture. Besides providing a low mass, integrated motor solution, the S2A2 benefits include: reduction in spares mass and volume, on-orbit reprogrammability, telemeterized health diagnostics, zero fluid path intrusion (and ease of on-orbit maintenance), high position accuracy, programmable speed & torque, high cycle life, high reliability with sensor failure tolerance, and available manual interface. With both commercial space and critical applications options available in a standard package and design, the S2A2 product can support a wide variety of vehicle and mission configurations, increasing capability to meet the needs of the next generation of spacecraft ECLSS and TCS valves.

References

[1]Midwest Research Institute, “Brushless DC Motors” NASA CR-2506, 1975.

[2]Marshall Spaceflight Center, “Selection of Electric Motors for Aerospace Applications” NASA PD-ED-1229.

[3]Suffern, D., Parker, J., “Developmental Bearing and Bushing Testing for Mars Gearboxes,” *44th Aerospace Mechanisms Symposium*, NASA/CP—2018-219887, Cleveland, OH, 2018, pp. 529-541

[4]Carney, David. “MBSE for ECLS and TCS Subsystem Development” 53rd International Conference on Environmental Systems, ICES-2024-303, Louisville, KY, July 21-25, 2024.

[5]Morgan, M., Lin, J., Kirwan, J., Licavoli, E., Valle, G., Buckley, S. “Advancement in Space Deployable Habitat Verification, Validation, and Certification” 53rd International Conference on Environmental Systems, ICES-2024-321, Louisville, KY, July 21-25, 2024.

[6]Rorabeck, C., Schwieso, P., Schlutt, M., Marandola, E. "Benefits of Ball Valves in Thermal Control Systems." 53rd International Conference on Environmental Systems, ICES-2024-381, Louisville, Kentucky, 2024

[7]RTCA/DO-178C “Software Considerations in Airborne Systems and Equipment Certification”