NOVEL FAULT TOLERANT ROBOTIC SYSTEM FOR MARS ROVER

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ABSTRACT

The Sample Manipulation System (SMS) is a robotic system integral to the Sample Analysis at Mars (SAM) instrument suite. SAM is a critical instrument in NASA's Mars Science Laboratory (MSL) Payload. The SMS is an under-actuated 3 degree-of-freedom system. Its function is to receive and transport Martian solid samples from an inlet funnel and seal them in pyrolysis cells for spectroscopic analysis. This paper discusses the command and control architecture designed to achieve flexible command scripts while maintaining a high degree of fault detection and correction. A discussion of the Command and Data Handling System, Motor Control Electronics, and mechanisms describe how fault detection and redundant operating modes were employed.

1. INTRODUCTION

The SAM instrument is designed to assess the habitability, past and present, of Mars by analyzing solid and atmospheric samples. It is a chemical and gas analyzer with three main sensor subsystems: a quadrupole mass spectrometer (QMS), a gas chromatograph (GC), and a tunable laser spectrometer (TLS). SAM can perform both direct atmospheric sampling and solid sample analysis. The SMS is used for solid sample analyses. The SMS stores and manipulates sample cups to receive a sample and hermetically seal it in a pyrolysis oven. The ovens heat soil or rock samples to a temperature of 1100° C as gases are evolved. The released gases from pyrolysis flow through the GC, where they are separated in time by their molecular and chemical characteristics. The separated gases are introduced into the QMS, where their relative abundances and light isotope ratios are determined. Evolved gases and atmospheric samples may also be directed by a series of microvalves into the TLS, which makes high-precision measurements of isotope ratios of C, H, and O in methane, carbon dioxide, and water.

1.1 SMS Driving Requirements

The SMS, Figure 1**,** accepts solid sample from the Solid Sample Inlet Device into any of 74 sample cups and transports the selected sample cup to a pyrolysis oven. Once the SMS inserts the sample cup into the oven, it creates a seal force sufficient to provide a leak tight (1E-5 cc He/sec) seal. The SMS consumes less than 5 Watts continuous and 10 Watts peak power.

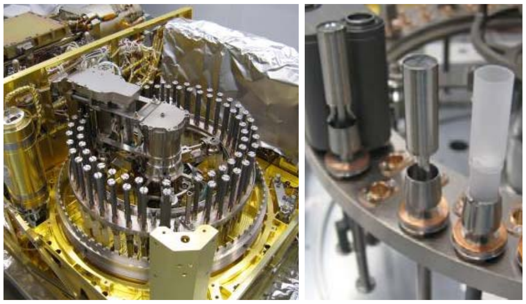

Figure 1. Left: Sample Manipulation System Integrated to SAM ;Right: Metal and Quartz Cups on Sample Carousel

The 74 sample cups are separated into three categories: solid sample quartz cups (60), foil topped metal cups for wet chemistry experiments (10), and foil topped metal cups containing calibration sample (4), Figure 1, right. The SMS must position each cup to within 0.71 mm true position at multiple interfaces including the solid sample inlet device, foil puncture stations for the metal cups, and a pyrolysis oven on each row of the SMS Sample Carousel.

To allow SAM to re-use sample cups in an extended mission scenario, the SMS applies up to 1350 Newtons with an accuracy of +/-10% to seal a sample inside an oven. A seal is created via an annealed copper disk brazed to the sample cup and a titanium knife-edge on the oven. Each successive use of a sample cup requires a larger seal force.

The SMS must transport the sample expeditiously to limit the sample's exposure to the interior of the SMS due to the extremely sensitive (ppb) spectrometers. A given sample cup, once preconditioned in the pyrolysis oven, must not be exposed to the interior of the SMS for an extended time to prevent contaminating the measurement on the solid sample. Contamination concerns led to implementation of a vacuum seal to prevent contamination of the interior of the SMS during Assembly, Test, and Launch operations.

The SMS is capable of recovering from an unexpected power loss. Feedback devices and a robust high level control architecture combined to provide full fault detection and correction capability.

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2. SMS SYSTEM DESCRIPTION

The SMS design is comprised of a high reduction, low backlash actuator, a compliant linear actuator, restraint/release devices, a launch restraint, and a custom incremental encoder. Figure 2depicts the two actuators, Carousel and Elevator, employed in the SMS. The Carousel actuator rotates the sample carousel and the elevator mechanism. The Elevator actuator raises and lowers sample cups at the pyrolysis ovens and sample inlet.

2.1 Carousel Actuator

The Carousel actuator is comprised of a Hall commutated brushless dc motor, 25:1 planetary gearbox, and 100:1 cup style harmonic drive for an overall gear reduction of 2500:1 and 30000 counts per revolution, Figure 2, left. An angular bearing duplexed pair (DF) is located at the harmonic drive output with a trailing Conrad bearing at the interface of the sample carousel support beams to the center rotating hub. The actuator is lubricated via grease-plate Braycote 600 Micronic. A twist capsule carries power and signals to the elevator actuator and feedback switches on the Carousel actuator.

The maximum speed at the output of the harmonic drive is 2 RPM. The maximum continuous torque output is 3.4 N-m. The Carousel Motor is current limited by the motor control board so as not to exceed output torque limits.

The Carousel actuator is used to position both the sample cup elevator and the sample carousel. Two degrees of freedom are achieved via one actuator. When positioning a sample cup, the carousel actuator is coupled to the sample carousel. In this position the sample cup elevator position is fixed with respect to the sample carousel. Once the sample cup is in position, the sample carousel is locked to ground via a caging device and the carousel actuator rotates the sample cup elevator relative to the sample carousel. This is necessary to position the elevator beneath the cup to be used.

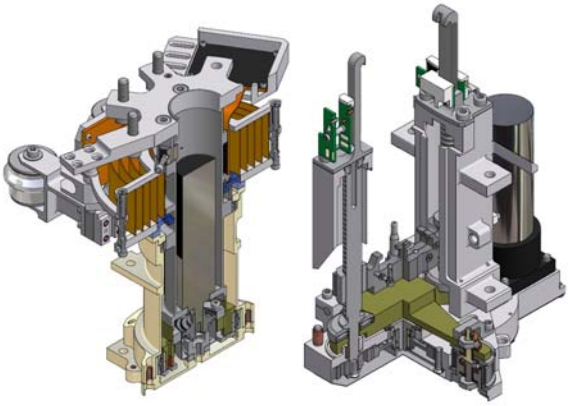


Figure 2. SMS Actuators - Left: Carousel; Right: Elevator

2.2 Elevator Actuator

The linear Elevator actuator consists of a Hall commutated brushless DC motor, 80:1 planetary gearbox, 2.4:1 spur gear arrangement, and a pair of 5/16-12 ACME lead screws, resulting in resolution of 1088 Hall counts per millimeter. The two lead screws are mechanically coupled via Custom 455 H1000 Stainless Steel spur gearing in the bottom of the Elevator Assembly. The two lead screws are Nitronic 60, 50% Cold Worked Stainless Steel and the ACME nuts are 15-5PH H1025 Stainless Steel. The ACME screw is non-backdriveable. A magnetic detent brake on the motor rotor is sufficient to hold the elevator preloaded in the event there is no friction in the leadscrew nut. The lead screws rotate in Nitronic 60, 20% Cold Worked Stainless Steel journal bearings and 440C needle roller thrust bearings. The screws, nuts, bearings and gears are grease plated with Braycote 600 EF Micronic. Reservoirs in the journal bearings and the root of the ACME screws are grease packed.

The elevator actuator delivers 1350 Newtons to a sample cup within +/- 10% of the commanded force. A load cell could not be found that could withstand the temperature range (-55 to 110°C) and package within the mechanism constraints. A desire to reduce the burden on the control electronics and the added cost of development and qualification of a load cell led to an alternate solution custom tailored to the SMS design.

The load path for the seal force is transmitted through the lead screws and thrust bearings to a compliant flexure arm. At the end of the flexure arm is a spring-loaded electromechanical switch. With no load applied, the switch is an open circuit. Once a load is applied to the lift, the switch begins to close. Once the load reaches 450 Newtons, the switch closes. A short stroke wave spring provides the repeatable contact force for the switch assembly. Once the switch closes, the elevator structure becomes a stiff spring. The stiffness of the structure, in units of motor counts per Newton, is determined during mechanism calibration. Therefore, once the switch closes at a known force, all backlash in the load path and drivetrain has been eliminated. Commanding the motor to run a specific number of Hall counts past the switch transition will result in the desired seal force applied to the sample cup. A bellows assembly keeps the switch contact area free of particulate and Martian dust.

3. CONTROL ARCHITECTURE

A high degree of fault detection and correction capability is necessary to ensure tight control of the solid samples during experiment sequences. The large number, and relatively fragile nature, of the non-metallic sample cups drove the desire to implement a redundant feedback control architecture. The redundant components did not come at a high cost with respect to the common spacecraft constraints of mass, volume, and power though it must be noted that considerable design time was dedicated to providing this level of redundancy.

The redundant control architecture serves multiple purposes, chief among which is the ability to implement a voting scheme to ensure the state of the SMS is known with high confidence at all times. A second purpose is the ability to operate in several off-nominal modes should components fail during the nominal or extended mission. These off-nominal modes include: (1) Failure of 1, 2, or all 3 Hall sensors on either Brushless DC Actuator; (2) Failure of any of the 6 indicator switches. The resulting system is 3-fault tolerant with respect to feedback components.

At the core of the fault tolerant system is the finite state machine. A finite state machine, as its name implies, has only a finite number of states in which it can be oriented. For each commanded motion a singular event terminates the command nominally. Any other event which occurs during the motion is detected and the command is terminated in a fault state. The state machine architecture allows operators to ensure the SMS mechanisms and sample cups are safe at all times.

3.1 Command and Data Handling System

SAM operates under the control of a command and data handling (CDH) subsystem. The CDH and its linkage to the SMS are depicted in Figure 3.

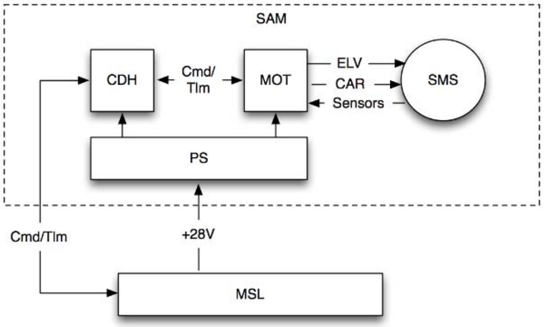


Figure 3. SAM Control Block Diagram

The CDH is a specialized single-board computer built around a radiation-hardened ColdFire processor with 2 MB of RAM and 1 MB of EEPROM for program storage. It receives scripted command sequences from the MSL Rover, prepared by the science operations team on the ground and uplinked to the rover. Once the CDH has received a command sequence, it is capable of autonomous operation. An experiment sequence may take several hours to complete, and the MSL Rover can be turned off during the SAM experiment sequence to conserve battery power. The CDH stores its science and housekeeping telemetry in a 64 MB flash memory, whose contents are preserved across SAM power cycles. The telemetry is later downloaded from the flash memory under control of the MSL Rover, formatted into data products, and transmitted back to the ground data system.

The CDH controls SAM's complex gas processing subsystem (GPS), consisting of more than 60 pipes and transfer lines, wrapped with individual heaters and interconnected at 15 manifolds with 52 microvalves. The heaters and microvalves are controlled through a microsequencer, which synchronizes their operations with the QMS science data acquisition. The GPS has two pressurized reservoirs of high-purity helium, as well as reservoirs of oxygen and calibration gas. The helium acts as an inert carrier gas to convey the gases for analysis through the system.

3.2 Motor Control Board

The CDH controls the six motors in the SAM instrument via a separate motor controller subsystem (MOT). The MOT drives the SMS carousel and elevator motor actuators, and reads the state of the SMS sensors. In addition, the MOT controls two wide-range pumps (WRPs), which evacuate the QMS and maintain the flow of gases through the instrument, and two motor-driven high-conductance valves, which are used to seal the high vacuum inside the QMS.

All six motors operate at a nominal voltage of 12V, delivered by the SAM regulated power supply (PS). The two HCVs and the SMS Carousel and Elevator motors are commutated by Hall-effect logic. They operate at a maximum speed of 24000 electrical rotations per minute and a nominal range of approximately 200-6000 electrical rpm. The MOT is designed to control one of the four Hall-effect motors at one time through a single multiplexed controller. The two WRPs have much different characteristics. They are commutated by back-EMF sensing logic, and they operate at a nominal rotation speed of 100K rpm. The MOT can operate both WRPs, separately or together, independently of the one Hall-effect channel.

A block diagram of the MOT subsystem is depicted in Figure 4. The MOT is constructed on a multi-layer printed circuit board using three FPGAs for its control logic, designated "A," "B," and "C." The "A" FPGA is the master controller. It contains the logic to communicate with the CDH and direct the operation of the other two FPGAs. The "B" FPGA is configured to act as a microprocessor core and memory manager. The microprocessor, known as a minimum instruction set computer (MISC), is a 24-bit computer with only 64 instructions, 32 of which are arithmetic and logic instructions, and the remainder of which are general-purpose I/O. The MISC software program is downloaded into the MOT static RAM by the CDH, and implements the high-level control algorithms. The "C" FPGA is the motor sequencer. Under control of the "A" and "B" FPGAs, it handles the motor drivers, commutation, and the finite state machine logic.

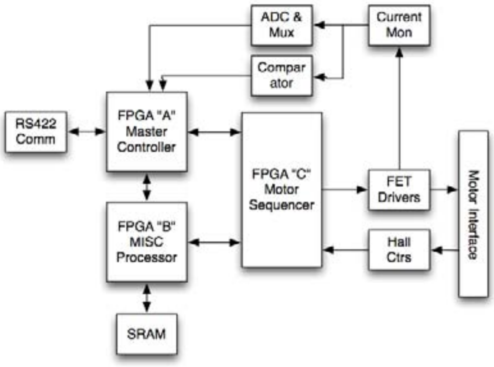


Figure 4. MOT Architecture

The MOT implements a simple command-and-response system for communication with the CDH. Each command is 32 bits (4 bytes) in length, consisting of an 8-bit opcode and 24-bit data. The 24-bit data width matches the 24-bit bus of the MISC processor. The MOT replies to each command word in the same format, 8 bits echoing the opcode and 24 bits of status or reply data. The MOT does not transmit any information except in response to a command. Upon reset, the MISC processor is inactive. The CDH retrieves the compiled MISC program from its own EEPROM and downloads it to the MOT one word at a time. This process takes approximately 10 seconds. Once the program code is in memory, the CDH allows the MISC processor to run, and it begins executing its code.

When no motor is operating, the MOT processor is in an idle loop. When a motor is selected and a speed is commanded, the MOT processor begins executing a PID control loop to control the motor speed. There is no special startup control required. On the first iteration, the sensed speed will be 0 rpm and the error (i.e., difference between commanded speed and sensed speed) will be large. The error is multiplied by a proportional gain, and the result is scaled to the range 0-255 and sent to the motor sequencer FPGA. The motor sequencer sets the corresponding voltage applied to the motor windings via pulse-width modulation, and handles the motor commutation via the Hall sensors. On subsequent iterations, the PID control loop adjusts the voltage command, and the desired speed is achieved within a fraction of a second. The PID iteration rate is 500 Hz.

In the nominal case, the MOT motor sequencer requires that the three Hall sensors transition in the correct sequence for the desired rotational direction for motor commutation. It senses the motor speed by counting the number of pulses in a fixed 10 MHz oscillator between correctly sequenced Hall transitions. The MOT processor converts this to rotations per minute by arithmetic division.

Even though the Hall-effect sensors are at the core of the MOT control logic, it is possible to operate the SMS with a degraded set of Hall-effect sensors. Nominal closed-loop operation can only be accomplished with the full complement of 3 Hall sensors per motor, because the MOT motor sequencer requires Hall transitions to occur in the proper sequence to compute a motor speed. Nevertheless, through software counting methods, the motors can be controlled sufficiently accurately for SMS mechanism positioning with two, one, or even zero Hall sensors, as described in detail below.

The motor stopping criteria are of critical importance, to avoid damage to mechanisms and electronics. For all motors, the MOT implements a fast motor current comparator with a commandable threshold. If the motor current exceeds the programmed threshold, the motor is disabled within microseconds and a fault condition is raised. The MOT current comparator logic operates at a higher bandwidth than the SAM and MSL power supply regulators, so a motor current spike is detected and acted upon in the MOT before a current overload can cause a circuit breaker or fuse trip elsewhere in the system. The MOT has similar fast comparators to detect undervoltage situations on any of the power rails. The MOT also has temperature sensors on each of the motors, and the high and low temperature limits are programmable. A sensed temperature outside the programmed range will disable the corresponding motor.

3.3 Feedback Switches

For the state machine to operate effectively the system must be instrumented with a full complement of switches to determine the state of the SMS at all times. The SMS contains 6 binary state switches, 5 optical and one electromechanical. Each switch is located to identify significant SMS events.

Optical switches reside at the output of the Carousel actuator and consist of opposed LEDs and Phototransistors. A pair of LED/PT switches, together with the toothed profile on the fixed locking ring act as a custom incremental encoder located at the output of the mechanism, Figure 5. The "region of alignment" indicates the Carousel actuator is in a position where it is acceptable to actuate the carousel caging mechanism or raise and lower a cup.

Other switches identify home positions for each actuator. By integrating feedback to the output of the mechanism, motor Hall counts can be compared to switch state transitions to detect faults promptly before harm can be done to sample cups. Together with the hard-stops on the center hub, the SMS is capable of full recovery from an unexpected loss of power which would result in the loss of position information.

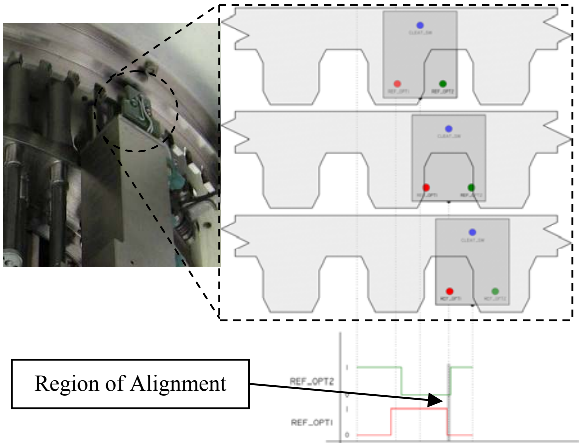


Figure 5. Custom Incremental Encoder

The electro-mechanical preload switch on the elevator mechanism initiates the motion to apply a specific sealing force on the sample cups. Once the switch closes the number of motor counts past the switch event is calculated based on a calibration curve, Figure 6.

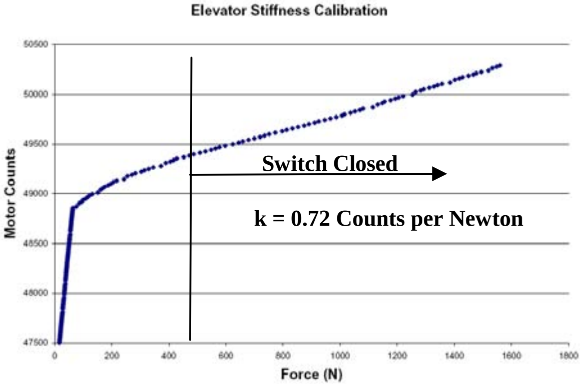


Figure 6. Elevator calibration curve specifies motor counts for a given seal force

3.4 Software

For SMS operations, the software is organized hierarchically as shown in Figure 7.

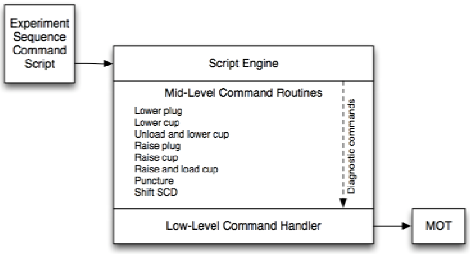
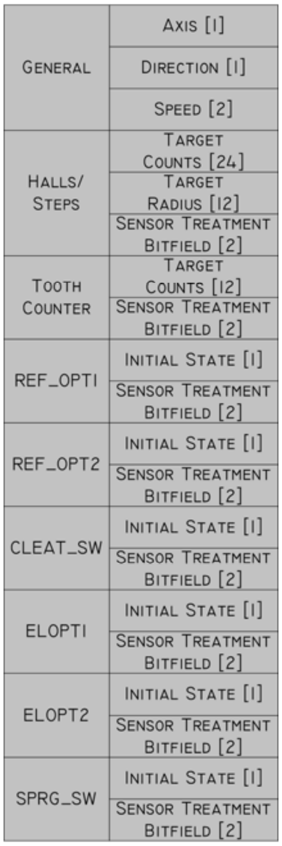


Figure 7. Command Architecture

The MOT has direct access to the six switches that are used to sense the positions of the various mechanisms. The MOT implements commands to specify the treatment of all six switches during any motor motion.

At the bottom are the SMS low-level commands. Each of these commands performs a single, context-dependent motor actuation. The initial conditions, motor speed and direction, and stopping conditions for each low-level command are placed in a data structure (figure at left) and passed to the low-level command handler in the SAM CDH. The command handler programs the MOT registers, starts the motion, and polls the MOT for the motion termination. The low-level commands are primarily invoked by the SAM CDH flight software, but there is a scripted access to low-level operations as well.



General	Axis [1]
	Direction [1]
	Speed [2]
Halls/ Steps	Target Counts [24]
	Target Radius [12]
	Sensor Treatment Bitfield [2]
Tooth Counter	Target Counts [12]
	Sensor Treatment Bitfield [2]
REF_OPT1	Initial State [1]
	Sensor Treatment Bitfield [2]
REF_OPT2	Initial State [1]
	Sensor Treatment Bitfield [2]
CLEAT_SW	Initial State [1]
	Sensor Treatment Bitfield [2]
ELOPT1	Initial State [1]
	Sensor Treatment Bitfield [2]
ELOPT2	Initial State [1]
	Sensor Treatment Bitfield [2]
SPRG_SW	Initial State [1]
	Sensor Treatment Bitfield [2]

Next higher in the hierarchy are the mid-level commands. The mid-level commands are composed of sequences of low-level commands. There are only 8 distinct mid-level commands that form the building blocks for all nominal SMS operations. The mid-level commands are coded and compiled into the SAM CDH flight software. All the mid-level commands check the completion status of every low-level motion and exit if an error occurs. The mid-level commands are invoked by SAM script commands.

At the top of the hierarchy are the SAM experiment sequences. The experiment sequences are scripted in a high-level scripting language with the built-in capability to actuate all of the SAM hardware functions, read the related feedback information, and take complex actions based on environmental and internal conditions. The SMS functions required for a given experiment sequence are invoked, when they are needed, through the mid-level script commands. The actual SMS command sequence in each case depends on the science goals and engineering requirements of the mission. During Mars surface operations, experiment sequences may be constructed on the ground and uploaded to the instrument, or they may be stored in nonvolatile memory

(EEPROM) on SAM and recalled, modified as necessary, and executed.

Any off-nominal SMS condition during SAM operations results in an immediate cessation of motor operations, a break in the scripted experiment sequence, and a diagnostic telemetry dump. The state of the SMS and the symptoms of the problem can be identified from the telemetry information. Analysis on the ground must determine the cause of the problem and the way forward. Because of the time delay in communications to Mars, real-time operation is not possible. However, the scripting languages makes it possible, from the ground, to program remedial sequences and take further action using any available combination of actuators and sensors.

3.5 Command Preconditions

For each switch, there are three initial conditions (on, off, or ignore) and three stopping conditions (nominal, fault, or don't care). These conditions constitute the initial state and sensor treatment bitfield in the command structure shown on the previous page. Before any motor motion is initiated, the sensor treatments specific to that motion are commanded by the CDH and programmed into the MOT registers. When the motor is commanded to operate, the MOT hardware first checks the initial conditions, and if they are not all met, raises a fault condition without starting the motor. Once the motor is started, the MOT continuously compares the current state of the sensors to the stopping conditions, and stops the motor, with a fault or nominal termination code as appropriate, when one or more programmed condition is met.

By setting a switch precondition to "ignore," the sequence will execute as if that switch did not exist. Thus, if a switch fails during the mission, full experiments can still be executed with a lower sensitivity of fault detection by ignoring the switch.

The MOT motor sequencer FPGA also implements Hall counting logic which can be factored into the motor stopping criteria. Hall counts are computed for both SMS motors. A range of Hall counts can be specified as stopping criteria on any motion, and are handled by the MOT logic in a manner similar to the other sensor treatments. If the nominal stop criterion is a switch state change, the MOT will verify that state change occurred within the acceptable range of Hall counts. If the acceptable range of Hall counts is exceeded prior to the expected switch state change, a fault will terminate the motion.

The nominal sequences assume that all sensors are working properly. In case of malfunctioning sensors, the SMS FSW has provisions for off-nominal operation, enabling continued functionality with little or no change to the software. The key to this functionality is the Global Sensor Mask, a CDH-side bitfield that specifies which (if any) sensors are unreliable and should not be used in SMS operations.

At the beginning of each experiment, the FSW applies a set of rules that sets various MOT-side state variables based on the Global Sensor Mask. Before sending each low-level motion command to MOT, FSW applies another set of rules, adjusting command parameters based on the Global Sensor Mask.

At the beginning of the experiment, the Global Sensor Mask bits corresponding to the current and temperature sensors are examined. If any of these sensors is faulty, FSW uses a state variable write command to set its counterpart mask on MOT, disabling the limit checking on that sensor.

If the Hall sensors for the carousel or elevator motors are faulty, FSW sets the MOT commutation mode accordingly, causing the compromised motor to operate in stepper mode. The speed value table for that axis is reduced to prevent the motor field moving faster than the rotor will respond.

Before sending each low-level motion command to MOT, FSW applies the following set of rules, adjusting command parameters based on the Global Sensor Mask. If a sensor is masked, the corresponding Sensor Treatment Bitfield is set to 00 (ignore sensor). If the sensor that provides the nominal stop condition for the motion (i.e., the sensor whose Sensor Treatment Bitfield is 10, nominal end-of-motion) is masked as faulty, then the Sensor Treatment Bitfield for the Hall/step counter is set to 10 (nominal end-of-motion), and the target radius is tightened to 0 to terminate on a Hall count rather than a switch transition.

4. Test Results

Tests were executed on the SMS Engineering Model for all operating modes. Nominal mode is straightforward and serves as the baseline for comparison. Off-nominal mode where 1 or 2 Hall effect sensors are disabled has been tested and shown to provide looser closed-loop speed control. Off-nominal mode where all three Hall sensors for a given actuator are not functioning has also been demonstrated. The open-loop mode with no Hall feedback required slight modification to some motion commands with nominal termination set to Hall counts. Off-nominal modes masking each of the 6 switches have also been successfully demonstrated.

4.1 Nominal Operation

Nominal operation of the SMS is the case where all switches and Hall effect sensors are functional. In this condition, no real-time modifications are necessary for low level command in mid-level and high-level sequences. The SMS will operate with the lowest power and energy possible, Figure 8 - Top.

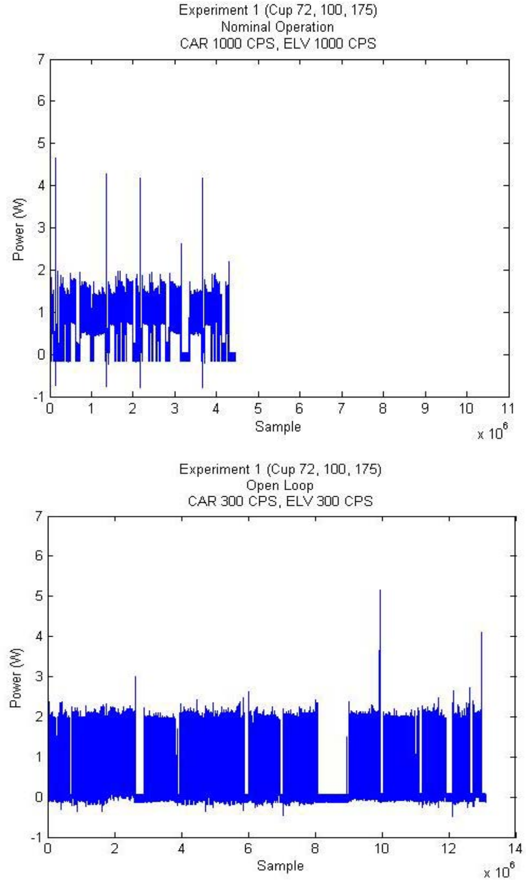


Figure 8 Power Comparison for Nominal (Top) and Off-Nominal (Bottom) SMS Operation

4.2 Off-Nominal Operation with at least 1 functional Hall sensor

If a Hall sensor fails, the MOT will commutate the actuator in stepper mode. However, with one or two operating Hall sensors, a rotating motor shaft still produces Hall sensor transitions that can be counted in software to obtain a speed. Thus, speed control can still be achieved at a lower control loop rate. The MOT MISC software queries the motor sequencer to obtain the current Hall sensor state. It then uses its 500 Hz clock to count the time between Hall state transitions. This algorithm is simplest with one sensor, when there are 2 state transitions per rotor rotation. A programmable bit mask identifies which Hall sensor is to be counted. By keeping a running average of the time between state transitions, the MISC processor can compute a rotational speed. The theoretical maximum speed that can be computed this way is 500 transitions per second, which corresponds to 250 rotations per second, or 15000 rpm. However, reliably detecting state transitions requires at least 2 counts per transition, for a maximum speed of 7500 rpm. The nominal SMS motor operating speed falls within this range.

Without the full complement of 3 Hall sensors, it is not possible to perform the sequence checking that determines whether a Hall state change corresponds to a motion in the forward direction. However, in an operating motor, there are always many spurious Hall transitions, and without some anti-flicker checks, the simple Hall state counting algorithm described above yields a computed speed much greater than the actual rotational speed due to these excess transitions. Accordingly, for a single Hall sensor, a timing threshold is used to distinguish “real” forward transitions from flicker or backwards transitions. If a second transition is detected within the timing window, it is ignored. The timing threshold is programmable, and is dependent on the target rotational speed. It was found that setting the timing threshold just below the expected transition period for a given rotational speed produces the best results.

To control a motion in stepper mode, the CDH performs a primitive control algorithm. Initially, it outputs a fixed rotating voltage to the motor windings using the MOT stepper mode. It then periodically senses the motor speed, computed as described above by counting transitions of a single Hall sensor. If the measured speed is lower than the target speed, the voltage is incremented. This method quickly brings the motor up to its target speed, and allows it to overcome moderate frictional artifacts. However, it was found that decrementing the voltage correspondingly is not helpful. This is because lowering the voltage causes the shaft to slip occasionally as the rotating magnetic field passes over the poles, since there is insufficient torque to maintain the programmed speed. A slipping motor shaft tends to produce back-and-forth Hall transitions that are indistinguishable from forward transitions without the full 3-sensor sequence checking capability.

This algorithm can also be used to identify which Hall sensors are functional. When the MISC processor uses a non-functioning Hall sensor in the counting algorithm, the PWM increases rapidly because the speed remains zero. This causes a current limit fault within only a few cycles, thereby preventing the mechanism from running away to the stroke limit of the mechanism.

When operating without one or two Hall sensors in this manner, the MOT Hall counting capability is unavailable, which means, in turn, that the stopping criteria programmed into the MOT registers cannot include a Hall count. However, a substitute Hall count is available via the transition-counting logic described above, and this substitute Hall count is sufficiently accurate to be used in the standard SMS low-level commands, using modified software to perform the Hall count check.

4.3 Off-Nominal Operation with 0 Hall sensors

The SMS low-level commands primarily use the Hall count as a backup to the switch sensors. Therefore, it is even possible to operate the SMS without Hall sensors altogether. A PWM value was empirically determined at which the motor shaft will turn with the desired rotational speed given the anticipated load environment. Tests were performed to determine what PWM for a given speed was optimal to produce accurate motion where the field did not come out of phase with the motor rotor, Table 1.

Table 1 PWM Versus Speed for Carousel and Elevator Actuators

Carousel		Elevator	
Speed (cps)	PWM	Speed (cps)	PWM
100	40	200	60
200	60	250	60
300	90	300	80
400	110	400	100
500	140	500	120

Operating the motors in stepper mode is not an efficient means to turn a brushless dc motor. The motor windings are not designed to be operated in step mode. The stepper mode requires higher phase voltage applied over longer periods. The corresponding temperature rise in the winding must not exceed what is allowable. Tests were conducted to measure the temperature rise in each actuator winding for a given PWM value, Table 2.

Table 2 Temperature Rise Versus PWM

Carousel			
Speed (cps)	PWM	ΔR (ohms)	ΔT (°C)
300	90	0.226	58
500	140	0.435	111
Elevator			
Speed (cps)	PWM	ΔR (ohms)	ΔT (°C)
300	80	0.107	28
500	120	0.195	50

It was determined that operating both actuators at 300 counts per second would not overheat the winding for any commanded motion.

When the low-level Hall count stopping criteria are disabled in this mode, the switch sensors are the only criteria for stopping the motor at the desired location. The motor is then started in stepper mode, using open-loop speed control. The MOT stops the motor on the programmed switch configuration. For the few motor operations that rely solely on Hall counts, a time duration is empirically determined that will produce the desired number of rotations, and the motor is enabled and disabled based on that predetermined time interval. This zero-Hall sensor method of control has been demonstrated on MOT-SMS hardware. Figure 8 shows the comparison between the power and time required for nominal versus 0 Hall sensor operation.

5. CONCLUSION

Fault detection and correction was considered throughout the SMS design process. The system was designed from the beginning to enable operation in off-nominal modes while not sacrificing system functionality and safety. It is important to note that this endeavor manifested itself in all aspects of design, from mechanisms to electrical to software design and spanned across mechanical, electrical, software, and communication interfaces. Had the problem of fault detection and correction been left to later in the design process, the system would have been much more vulnerable to off-nominal conditions during mission operations. Early implementation of fault trees and system level logic diagrams enabled the team to identify points in the SMS experiment sequences where simple feedback would enable high reliability and complete system state information. Consequently, the SMS can be operated safely in multiple modes Behavior in each of the off-nominal modes is well understood and validated.

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