The Challenges in Applying Magnetoresistive Sensors on the "Curiosity" Rover

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Abstract: Magnetoresistive Sensors were selected for use on the motor encoders throughout the Curiosity Rover for motor position feedback devices. The rover contains 28 actuators with a corresponding number of encoder assemblies. The environment on Mars provides opportunities for challenges to any hardware design. The encoder assemblies presented several barriers that had to be vaulted in order to say the rover was ready to fly. The environment and encoder specific design features provided challenges that had to be solved in time to fly.

1. Introduction

The Curiosity Rover uses three-phase brushless dc motors as the motive force in its actuators. Successful use of the brushless dc motors requires rotor position feedback sensors in order to commutate the motors as well as control their position during operation. Magnetoresistive (MR) Sensors were selected for use on the motor encoders throughout the Curiosity Rover. Figure 1 shows the locations of the actuators on the rover and the position of the Radioisotope Thermoelectric Generator (RTG). While most of the rover actuators are required to operate in the very cold temperatures on Mars, the RTG provides a source of heat that increases the thermal environment for the nearby High Gain Antenna actuator encoders.

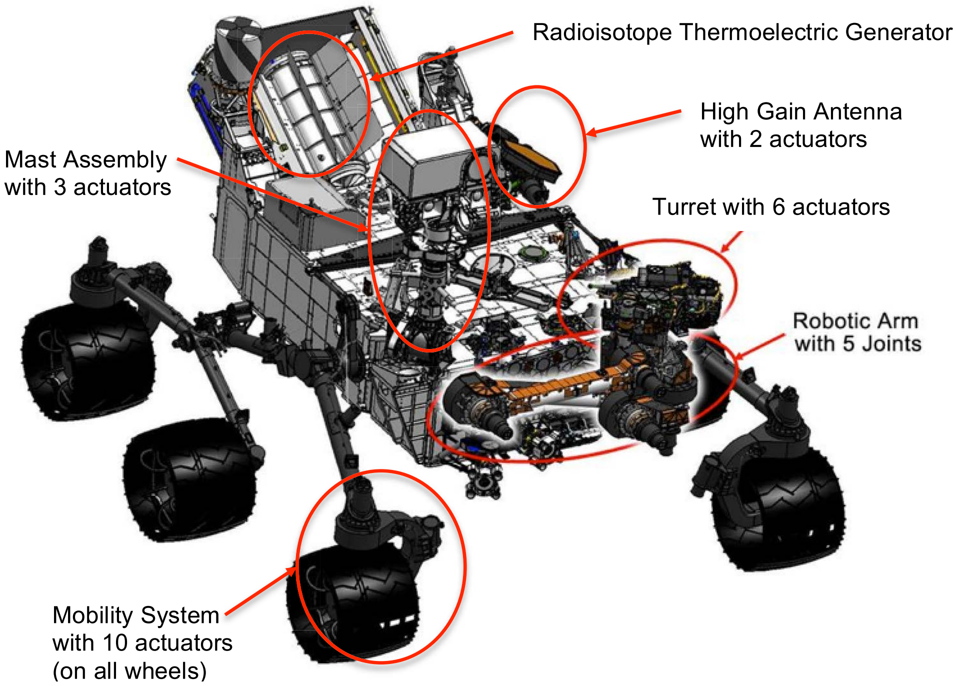

Figure 1. Locations of Actuators on the Rover and the Position of the Radioisotope Thermoelectric Generator (RTG). The locations of the Sample Inlet Cover Actuators on the top of the rover body are not visible in this view

Each actuator is composed of a brushless dc motor, a brake assembly, a gearbox, and an encoder assembly. Figure 2 shows the basic configuration of a typical motor without the attached gearbox.

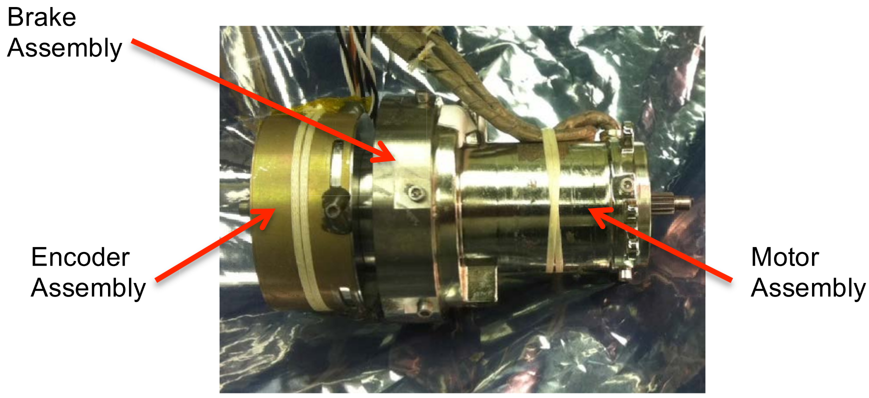

Figure 2. Motor Assembly with Brake and Encoder Assembly Attached

The brake assembly is a disc style friction brake that uses an electromagnet to move the friction disc against a set of springs, releasing the motor rotor so it can rotate freely. Removal of the current from the electromagnet will allow the friction pad to clamp the disc connected to the motor rotor, stopping rotation of the motor. The magnetic flux path for the electromagnet is closed when the magnetic brake disc has moved against the pole piece of the electromagnet and mechanically released the motor rotor.

The encoder assembly has two groups of paired MR sensors within the reading circuitry. The configuration of the sensor is shown in Figure 3. One of the sensor pairs reads the equally spaced poles of the magnetized wheel as it rotates. The second sensor pair reads the single pole of a "Home" position feature on a magnetized wheel. This allows the encoder assembly to provide the typical A-B quadrature outputs with a Z home output, the same as standard industrial encoders provide. The Home signal is compared with the number of quadrature signals between home pulses to maintain proper alignment of the electrical drive signals to the motor coils. The magnetized wheel and sensor combination are a matched set of hardware from Sensitec GmbH and maxon motor ag.

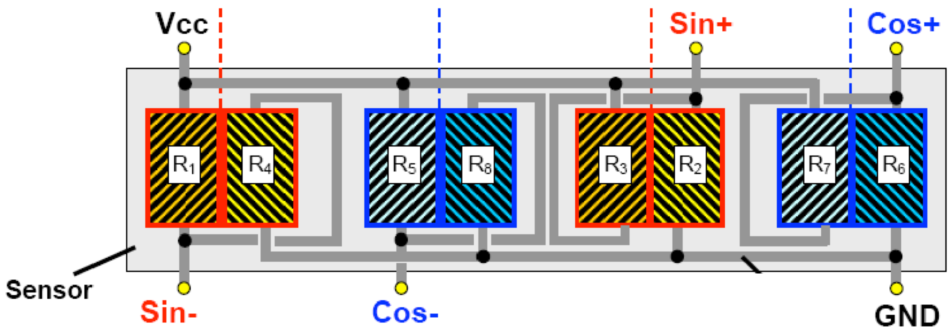

Figure 3. MR Sensor internal configuration showing the Sine and Cosine elements wired together as an H-Bridge. For the Home Sensor, only one of the two H-Bridges was used to provide the output signal to the reading electronics. Each independent H-Bridge is made up of four magnetoresistive sensors.

2. Mission and Environment Description

The Curiosity Rover mission is to search for organic compounds using the instrument and tool suite provided. The mission life is one Martian year, or 690 Martian days. Each day, the hardware on the rover must survive a 190°C temperature swing throughout the day and night. The mean temperature varies with the season, so the temperature extreme values change as the year progresses. The hardware had to be designed to handle the 190°C temperature swing every day of the mission with the lowest temperature in the winter being -130°C and the highest temperature in the summer being +85°C. In order to demonstrate margin in the design of the hardware, test cycle numbers were greater than the mission life totals. The summer period was deemed to be harder on the hardware, so more summer cycles were done in testing than winter cycles. Table 1 shows the temperature values and the number of cycles the hardware had to survive for testing.

Table 1. Hardware Design Temperatures

Season	Low Temperature	High Temperature	Temperature Range	Number of Test Cycles
Winter	-130°C	+60°C	190°C	600
Summer	-105°C	+85°C	190°C	1400

3. Martian Hurdle #1:
Packaging of Encoder and Sensor to Survive the Temperatures

The motor encoder assembly needed to be as small as possible and it had to incorporate the sensor reading electronics fully in the local assembly. This is because the cabling from the motor encoders to the reading electronics in the body of the rover could be as long as nine meters. The motor current is running along with the encoder signals in the same cabling. To eliminate interference issues, the conditioning electronics in the encoder assembly produce strong low-noise signals that are not compromised by the long cable length to the motor controller. The electronic packaging technology with the best chance of surviving the large thermal cycles without failure was deemed, at the start of the effort, to be chip-on-board packaging.

The encoder design approach for Curiosity was based on the successful use of maxon motor ag (Maxon) encoders that were purchased with the motors directly from Maxon. The sensors on the encoder assembly from Maxon were provided by Sensitec GmbH to Maxon where they were incorporated onto a circuit board designed by Maxon. The electronic circuit boards were populated at the Jet Propulsion Laboratory with Established Reliability electronic parts and then returned to Maxon for final assembly into the motor/encoder assemblies. Figure 4 shows three photos of the sensor installation that was used for the flight encoder assemblies on the Spirit and Opportunity rovers. The sensors were mounted using chip-on-board with a covering of epoxy to protect the wirebonds.

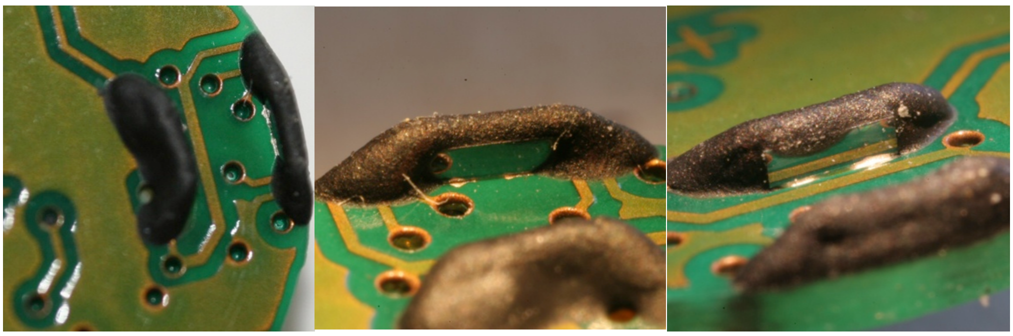

Figure 4. Photos of the Magnetoresistive Sensor Installation on the maxon motor ag Encoder Assembly that Flew on the Spirit and Opportunity Rovers.

The mission for the Spirit and Opportunity rovers was 90 days, substantially less than what Curiosity would be expected to survive. To maximize the probability of success, the same mounting method of chip-on-board was used on a new circuit board design, but without the epoxy covering. This meant the wirebonds would be exposed and could be easily damaged during handling. Test fixtures and specialized assembly tooling that covered the wirebond areas were used and every encoder assembly had a shipping fixture that provided protection for the wirebonds during any handling other than direct testing or installation into the encoder assembly. The only protection that the wirebonds have against electrical shorting is a thin coating of parylene, which also provides a moisture seal for the board assembly.

Figures 5 and 6 show photos of the sensor installation on the circuit board as it was used on the Curiosity rover and Figure 7 shows the assembly with the magnetized wheel installed.

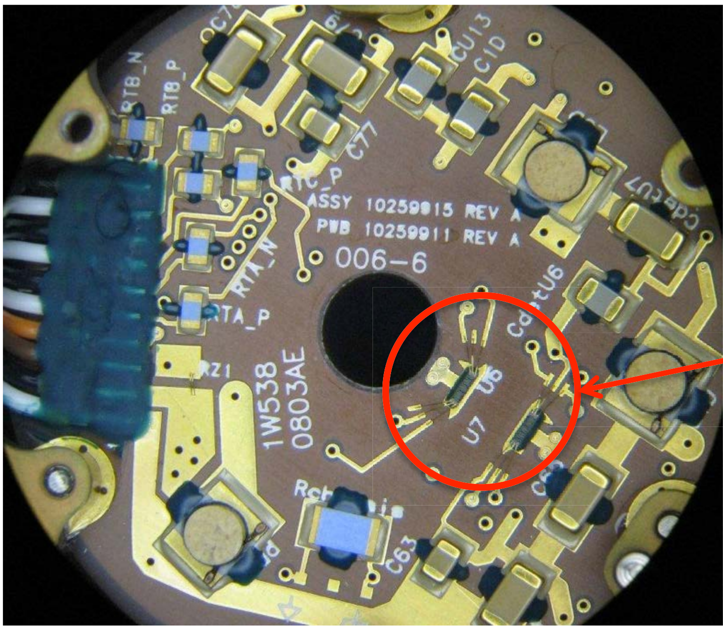

Figure 5. View of Curiosity Encoder Circuit Board Assembly showing MR Sensors.

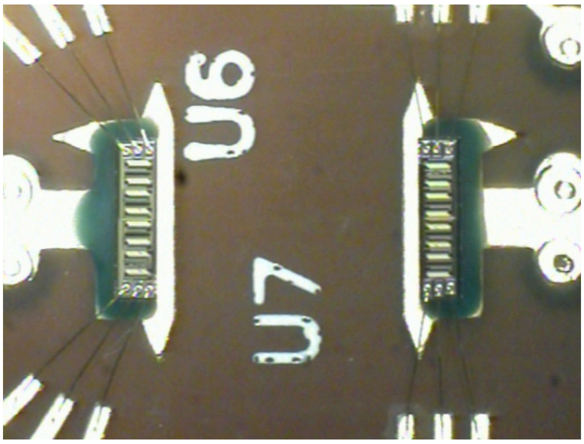

Figure 6. Close-up view of MR Sensors on the Curiosity Encoder Circuit Board. U6 is the home sensor and the two MR sensors on U6 are wired to add together their signal output. U7 is the Quadrature MR sensor and the two sensors on U6 are wired independently to provide two separate outputs shifted 90 degrees. The pointed traces on the circuit board were used to align the sensors mechanically to be in the proper location with the planned clearance to the magnetized wheel.

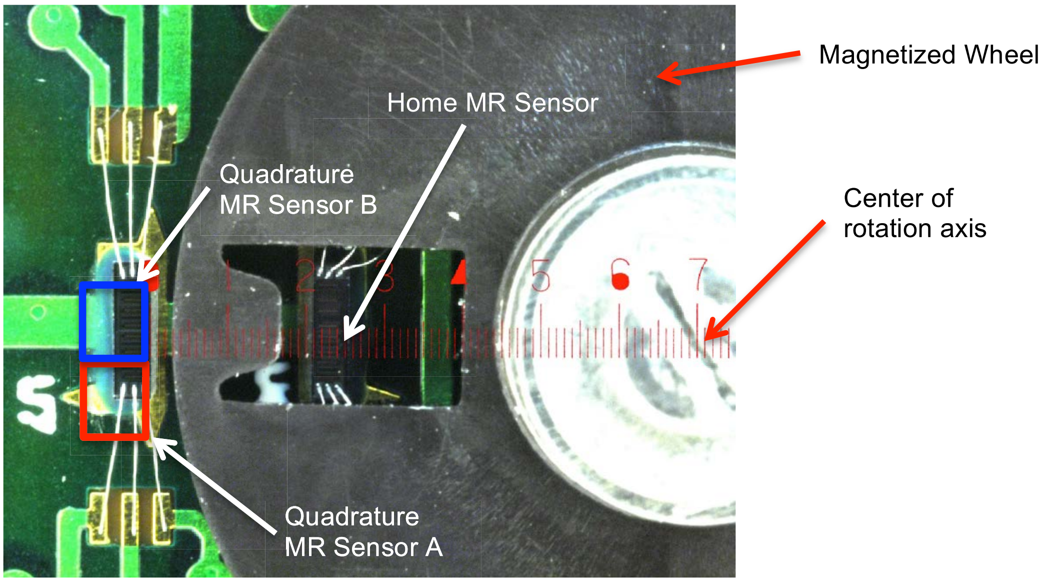

Figure 7. Back side of Encoder Assembly installed on a motor showing the relative positions of the MR sensors and the magnetized wheel.

Thermal cycle testing of this electronic packaging method demonstrated no visible damage at the end of the cycle testing shown in Table 1, making it acceptable to send to Mars onboard Curiosity. But . . .

4. Martian Hurdle #2: Making the Sensor and Reading Electronics Work Together

The reading electronic circuit for the sensor assembly is a complex version of an electronic comparator. The sensor output is compared to a reference voltage and the output is toggled high or low depending on where the sensor output voltage is relative to the reference. A North polarity field produces a high and a South polarity produces a low output signal from the comparator. The voltage output of the sensors is shown in Figure 8.

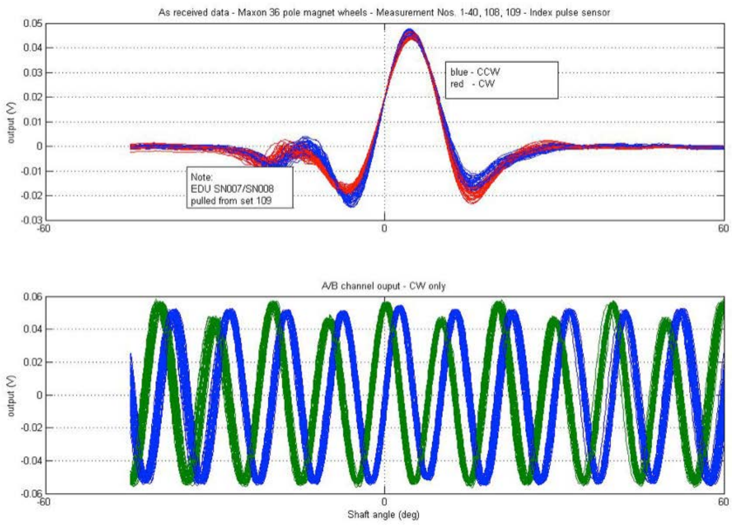

Figure 8. Waveforms from the magnetized wheel and MR sensor combination. Top trace is the home sensor output as the home pole passes by the MR sensor. Bottom trace is the quadrature MR sensor output with the A and B waveforms shifted by 90 electrical degrees. Waveforms shown are multiple measurements in both directions for several sensors. Outputs shown are at 25°C.

The voltage magnitude and separation along with the background noise levels, indicated that the basic comparator approach was a viable solution to get quadrature square waves and a square home signal output from this type of MR sensor. Note that the home index MR sensor output signal is different from the smooth quadrature signals because it has low voltage lobes on each side of the main pulse. These undesirable signal lobes are well below the magnitude of the main signal peak, so a threshold voltage value could be found that triggered only on the main pulse and not the side lobes.

However, as the MR sensor gets cold, the strength of the MR sensor output signal increases, providing more signal to detect. Additionally, the operational amplifiers that were used for the encoder assembly have a gain that drops as the temperature drops (faster than the output of the MR sensor increases), opposing all of the change in the output signal from the sensor. The MR sensor impedance also changes with temperature, causing the bias of the output signal to move as the temperature is reduced. Finally, the height of the side lobes increases relative to the main pulse making the area for triggering margin smaller. The combination of these several effects on the waveforms produced traces as shown in Figure 9.

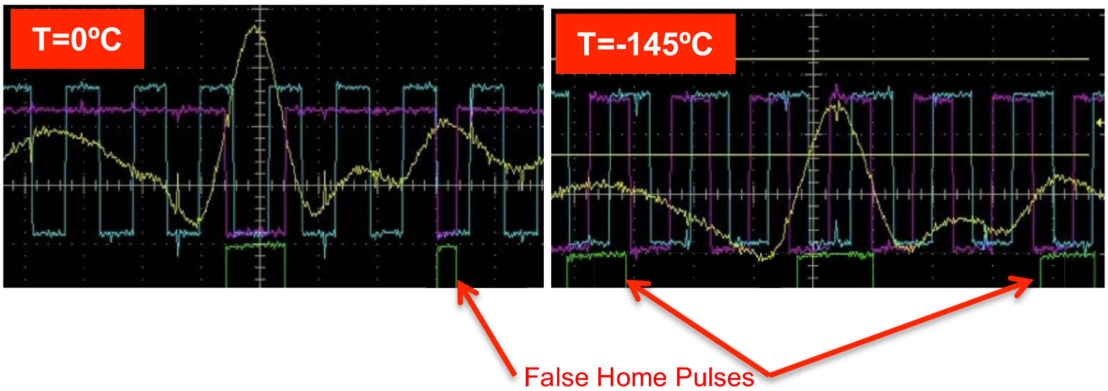

Figure 9. The output signals from the MR Home Sensor, the resulting home output signal, and the two quadrature output waveforms. The quadrature outputs are the blue and violet traces, the home MR sensor output is the yellow trace, and the home output waveform is the green trace. Note the “extra” home pulses triggering off of the side lobes around the main MR sensor home output signal.

The result of the temperature variation of these parameters is that a single threshold voltage value in the circuitry could not be made to work over the entire temperature range. When the threshold was set for room temperature and warm operation, several “extra” home pulses would show up as the temperature was lowered, as shown in Figure 9. The change of the side lobe magnitude relative to the main pulse seemed to be a feature of the sensor and magnetized wheel combination, not the sensor alone. Several circuit modifications were put into the reading electronics to eliminate the “extra” home pulses and logic was also put into the motor controllers to determine if the home pulse the controller received was valid.

Once these changes were put in place, all was well with the encoder design and it was ready to send to Mars. Then . . .

5. Martian Hurdle #3: Encoder Output during Electromagnet Brake Operation

This Martian Hurdle did not occur until very late in the project, after almost all of the hardware was built and being tested. The late arrival of this issue limited the possible solutions that could be pursued. The motor assembly that includes the encoder on the back also has an electromagnetic brake on its end. The brake assembly was designed using high permeability material to provide a closed loop for the magnetic flux when energized, in order to prevent the field from interacting with the sensitive MR sensor and magnetized wheel pair. The encoder is mounted on the back of the brake assembly with a shaft that extends through the brake assembly and into the encoder. This shaft rotates the magnetized wheel that then provides the signals used to commutate the motor and control its position. Figure 10 shows a motor, brake, and encoder assembly and a representation of the primary internal brake magnetic flux and the external magnetic field that leaks from the electromagnet. The image shows that the magnetic field follows the shaft into the encoder assembly, out the end of the encoder, and back toward the electromagnetic brake assembly. The housing of the encoder assembly was made from aluminum for low mass and good thermal conductivity, which also does not provide any magnetic path help for the leakage flux as the magnetic flux expands from the end of the encoder shaft.

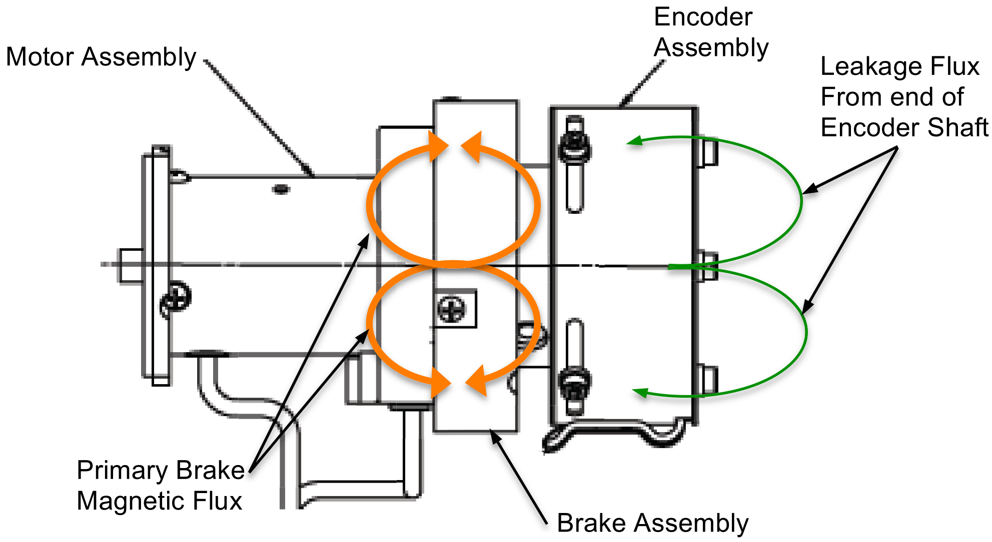

Figure 10. Motor, Brake, and Encoder Assembly showing the magnetic flux paths for the primary brake electromagnet and the leakage flux that exits the rear of the motor from the end of the encoder shaft.

The consequence of the leakage flux at the rear of the encoder assembly intermittently produced spurious encoder counts and home pulses that were not representative of any shaft rotation. When the brake is energized (which releases the mechanical braking function), the motor is not turning. The resulting spurious counts clearly cannot be from the rotation of the motor shaft. The controller did not know the difference, however, and added or subtracted these counts from the motor position register. This led to motor position errors that were then responded to by the servo controller, resulting in sudden movement of the motor that was not appropriate.

The electromagnet in the brake assembly has two independent coils that can be separately energized for redundancy. The two brake coils are wound in opposite directions to prevent the permanent magnetization of any brake components, since the electromagnet does not depend on the direction of the magnetic flux. The brake is operated with a large current to release the brake mechanically when the electromagnet's air gap is largest. Once the brake has released, the flux path is closed and a much smaller holding current can be used to maintain the brake in the released position. This prevents the unnecessary dissipation of power and heat generation at the brake assembly.

After investigating this phenomenon with the intermittent spurious counts, it was determined that the false counts occurred when the current driven through the brake coils produced a magnetic North pole out of the rear of the motor. The counter-wound coils added an extra variable to the search for why the spurious signals were intermittent; increasing the time it took to find the root cause. It was also determined that the false encoder counts occurred only during the initial high current operation of the brake assembly, used to mechanically release it. Once the lower holding current was established, the encoder no longer produced the false counts. The final solution to this issue was handled on several fronts:

1. The brake assemblies were tested for magnetic polarity during operation using a magnetic compass. This guaranteed that the current through the brake coils was in the benign direction, in case the wire color coding for the brake had an error.
2. Both of the brake coils were wired into the harness so the current always ran in the same direction in the assembly. The possible magnetization of any brake components was deemed insignificant based on the materials selected for all of the individual brake components.
3. The lowest possible release current was determined in environmental testing of the brakes so the minimum acceptable margin was assured. Too much additional margin was not preferable in this case.
4. The brake release procedure was modified to energize the motor windings with the current level and commutation to produce a steady holding torque at the current position. The brake was then energized to release it mechanically and the length of this high current pulse was reduced to the minimum allowable margin operating time. The encoder output was ignored for the time period that the brake was energized with the high current pulse. When the high current pulse was dropped down to the holding current level, the encoder outputs were then applied to the position total normally and the motor started moving.

6. Conclusion

The use of the maxon motor ag encoder assemblies with high reliability electronic parts on the Spirit and Opportunity rovers demonstrated that magnetoresistive sensors could possibly provide the motor position sensing for a much longer life mission. The biggest difference between the applications was the length of the mission and the temperature range (the previous encoders were heated to keep from getting cold). This fact indicated that the most difficult issue that had to be solved was the electronic packaging of the sensors and related electronic assembly would need to survive the thermal cycling range and extreme temperatures. This issue was tackled early in the program and a solution using chip-on-board technology was selected well before the hardware had to be fabricated. The next issue related to the encoder performance over temperature showed up during development testing of the encoder hardware design and was dealt with before the encoders were needed for motor testing. The final issue happened much later, when modifying the electronic circuit or changing the mechanical configuration of the encoder/motor assembly was not possible. A viable solution was determined and implemented that did not compromise the reliability of the mission or its functionality. These types of issues are typical with the development of a new sensor application. What made the last one particularly stressful was that it appeared during the final build phases of the program. The solutions have demonstrated ample robustness and continue to return amazing data from our nearest planetary neighbor, Mars.

7. Acknowledgements

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