Remote Diagnosis and Operational Response to an In-Flight Failure of the Drill Feed Mechanism Onboard the Mars Science Laboratory Rover

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Abstract

On November 30, 2016 (Sol 1536 of the mission), the Mars Science Laboratory (MSL) flight operations team commanded the Curiosity rover to drill into a Martian rock to acquire the mission's 16th rock powder sample. The drilling operation was halted when the drill feed mechanism unexpectedly stalled shortly after disengaging its magnetically-actuated friction brake at the start of a long move to extend the drill bit into contact with the target rock. The drilling campaign was put on hold and later abandoned as diagnostic data revealed a tendency for the actuator to transition in and out of a high-drag state in which the mechanism could not actuate. In the subsequent months, the team conducted a variety of in-flight and ground-based investigations to determine root cause and identify mitigation strategies for continued operation. Mechanism reliability continued to degrade and, by June 2017, it became clear that the mechanism could not be relied upon to support drilling operations. The team identified a workaround that enabled collecting samples without the mechanism. This workaround utilized the drill feed in an extended configuration. The first feed-extended drilling sample was successfully collected on Sol 2057, 521 sols after the initial feed stall. This paper discusses the anomaly investigation process, failure analysis, and feed mechanism operation mitigation strategies. It concludes with key lessons learned about mechanism design, mission architecture, and operational best practices.

Background

The Mars Science Laboratory mission seeks to understand the past climatological and geophysical history of Mars in order to determine whether Mars might once have been habitable[1]. Of prime importance to this objective is the rover's subsurface sampling capability afforded by its rotary-percussive drill system. The drill system is an integral part of the rover's turret at the end of its robotic arm.

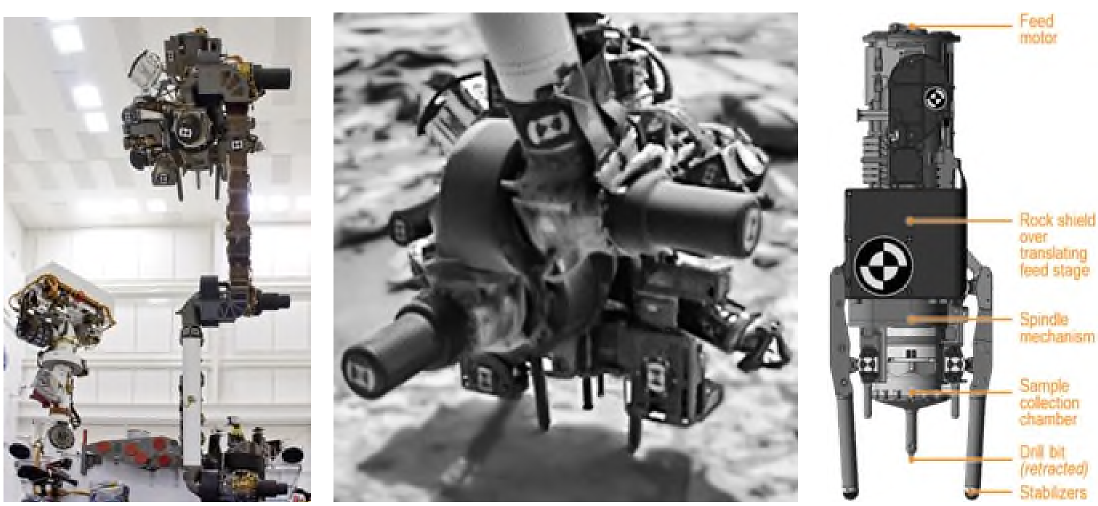

Figure 1. Left: MSL robotic arm and turret extended during pre-launch robotic arm deployment testing. Center: drill deployed against a Martian rock with stabilizers preloaded in the original drilling configuration and bit retracted prior to the start of drilling on mission Sol 170. Right: MSL drill system overview.

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The MSL Rover Drill System

The drill system design includes a pair of cross-linked stabilizers which, when preloaded against a rock by the robotic arm, serve to maintain axial orientation and position of the drill while drilling (see Figure 1). The tungsten carbide masonry drill bit penetrates rocks by simultaneously rotating and percussing while a linear feed mechanism maintains pressure and advances the bit. The drill's rotary motion draws pulverized rock powder into a collection chamber in the drill bit assembly via a set of spiral channels along the shaft of the drill bit. After drilling, the drill feed retracts to a stowed position which aligns an output port from the drill bit sample collection chamber with an inlet port to the CHIMRA (Collection and Handling for *In situ* Martian Rock Analysis) system for further processing and distribution to science instruments inside the rover[2,3,4].

A linear feed stage provides 110 mm of travel of the drill bit relative to the drill housing and stabilizers. This feed stage consists of a rotary actuator coupled to a 625:1 planetary gear set which drives a ball screw linear translation carriage. The feed carriage translates a percussion mechanism, a spindle mechanism, a ball-lock chuck mechanism, and a drill bit assembly. A toroidal force sensor measures axial force transmitted from the drill bit, through the chuck, spindle, and percussion mechanisms. During drilling operations, a control algorithm maintains roughly constant bit pressure by gradually feeding forward while sensing pressure against the drill bit.

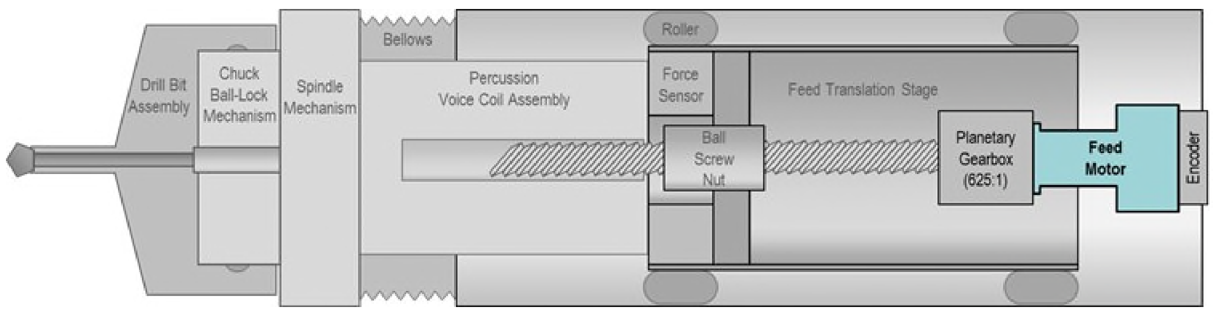

Figure 2. MSL drill system internal functional overview (not to scale)

The drill feed motor consists of a brushless DC motor fitted with a magnetic encoder and an electromagnetically-actuated disk brake. When the brake solenoid is unpowered, a set of springs preload an annular ferrous brake disk against a brake rotor that is attached to the motor shaft. To disengage the brake, the rover's motor control system drives current through one or both of the actuator's redundant brake solenoids, pulling the ferrous disk out of contact with the brake rotor. The brake plate translates axially along a set of guide pins (not shown in Figure 3). A magnetic encoder indicates the motor shaft angle to the motor controller for commutation.

Remote Drill Operation

Drilling campaigns span many sols from target selection and triage to sample delivery to the analytical instruments. The target selection process begins with the science team identifying rock(s) of interest and specific parts of a rock to be sampled. Candidate targets are first studied by turret-mounted instruments prior to contact. Rover Planners then perform various triage techniques to evaluate stability before committing to full-depth drilling.

The drilling process as designed consisted of setting the drill stabilizers against a rock target and pressing against the target with 300 N generated by the weight of the turret and torque from the robotic arm. Once stable, the drill feed mechanism began translating the bit forward until the drill force sensor detected contact against the rock. The drilling sequence then performed a hole-start routine and proceeded to continuous rotary-percussive drilling, progressively ramping up and backing off percussion levels as needed to maintain steady rate of progress. The sequence nominally concluded when the drill bit reached the target depth (65 mm) or the algorithm detected that progress had slowed below a threshold level.

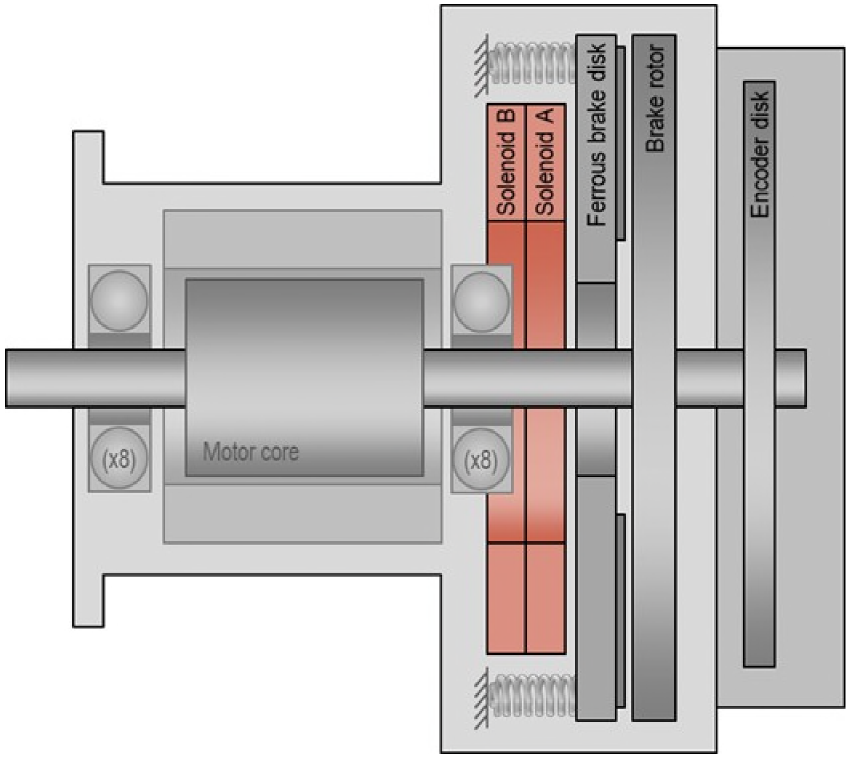

Figure 3. Drill Feed motor, brake, and encoder schematic (not to scale)

Rover Engineering Telemetry

The rover autonomously curates and prioritizes telemetry according to onboard selection rules and autonomous fault responses. Rover activities are generally optimized to generate just enough telemetry for the downlink team to declare success or investigate failures. Command sequences and autonomous fault responses can trigger creation of more detailed telemetry for planned critical events and autopsy data leading up to detected faults.

Engineering data for rover mechanisms is typically recorded with an 8-Hz sampling frequency, while parts of the drilling operation record specific events at 32 Hz and 64 Hz. Additionally, the rover's motor control system maintains a limited history buffer of detailed motor control telemetry sampled at 512 Hz. This history buffer is not normally downlinked to preserve data volume for science. However, the rover autonomously dumps this buffer to a data product following any motor fault. The high-rate motor control telemetry buffer has proven invaluable throughout the mission, most notably during the first drill percussion short event on Sol 911 [3], as well as during the drill feed fault described herein.

Upon indication of activity failures or motor faults, the downlink team performs an initial assessment to gauge the scope and severity of the problem. If there is any chance that the fault poses risk to the next sol's plan, the downlink team alerts the tactical planning team of the situation and may opt to introduce planning constraints. Anomaly records are written for new, emergent issues, and for major issues, an Anomaly Response Team is formed. This team is headed by the Engineering Operations team and draws on expertise from other parts of the mission team as well as relevant subject matter experts. Some anomalies can be solved rather quickly, restoring full rover capability within hours or days. Other investigations can persist for months, as iterations of ground and flight diagnostics are performed to better understand the behavior and if necessary, alternative capabilities are developed.

Drill Feed Anomaly Investigation Overview

On November 30, 2016, the MSL tactical planning team assembled a plan for the main drilling sol for the drilling campaign on a target named Precipice within the Murray Formation on the lower slopes of Mount Sharp. The following morning, the downlink team received telemetry indicating the drilling sequence had terminated prematurely due to the drill feed motor stalling.

The Sol 1536 drill feed stall anomaly presented an immense challenge to the engineering team. It imminently prevented drill sampling and posed a serious long term threat to sampling operations. The investigation unfolded and evolved over several months. Table 1 provides a high level overview of the phases and key events associated with the drill feed anomaly investigation.

Table 1. Timeline of Drill Feed anomaly investigation

Date	Sol	Event
Dec 2016	1536	Initial feed stall
Dec 2016 - Mar 2017	1537-1650	Early flight diagnostics focused on root cause investigation and understanding motion reliability with respect to various factors
Mar 2017	1627	Discovered similar failure signatures on the drill's chuck mechanism actuator
Apr 2017	1651	Regolith sample acquisition including significant amounts of turret dynamic activities
Apr 2017 - Jul 2017	1653-1753	Late flight diagnostics focused on mitigation techniques and achieving reliable motion. Observed accelerating degradation of performance. Began developing contingency feed-extended drilling technique.
Jul 2017	1754-1780	Permanent feed extension to enable potential development of feed-extended drilling
May 2018	2057	First feed-extended drilling on Mars

Sol 1536 Drill Feed Stall Fault

Telemetry from the rover indicated that the robotic arm had successfully deployed the drill against the rock and preloaded the stabilizers, but the motor controller detected that the drill feed motor stalled at the start of a long move to extend the drill bit into contact with the rock. Rover flight software autonomously terminated the drilling operation and dumped a high-rate (512 Hz) motor control history buffer to a high-priority data product. The robotic arm unloaded the stabilizers and lifted the drill away from the rock.

Upon receipt of initial telemetry from the Sol 1536 drill feed anomaly, it was immediately clear that this incident was not a simple commanding error or other easily recoverable fault. Engineers had not previously experienced a feed stall fault during normal operations in testbeds or in flight. The drilling campaign was suspended and an Anomaly Response Team consisting of subject matter experts and the operations engineers was formed to direct the anomaly investigation.

Early Diagnostics

Within the Sol 1536 high-rate motor telemetry, downlink engineers observed that the feed motor encoder indicated no change whatsoever in the motor shaft position. The closed-loop rate controller ramped up current through the motor in an effort to recover nominal rate, but quickly reached the motor's current limit without any indication of motor shaft motion from the encoder, thus triggering the stall declaration.

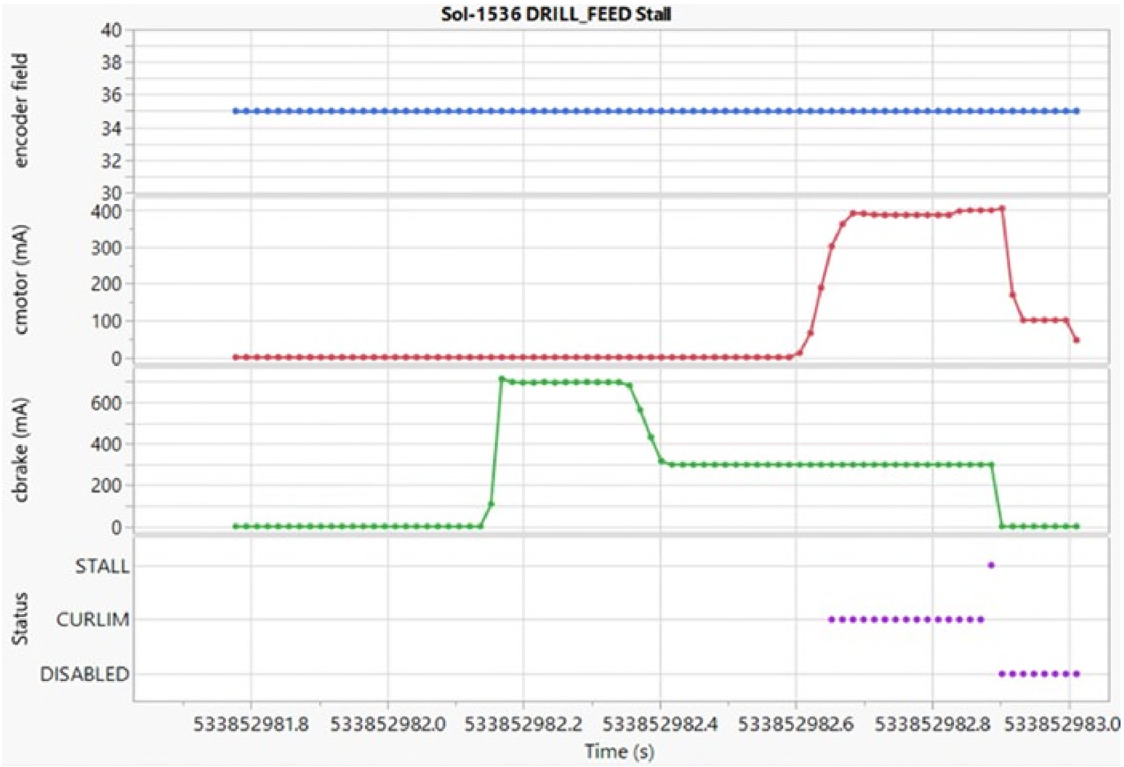

Figure 4. Sol 1536 drill feed stall motor telemetry. From top to bottom: encoder field number (between 0 and 144 DN); sensed motor current, brake current; control state. Brake current tracked the standard profile which started with a 0.2-second "pull-in" period then reduced to 300 mA during motor commutation. The closed-loop rate controller began commutating at time 533852982.6. Sensing no change in motor shaft position, the controller ramped up motor current, reached current limit, and declared stall.

The motor windings appeared to be healthy, indicated by a routine conductance check performed prior to first feed motion and corroborated by voltage and current telemetry during the attempted feed motion. This observation effectively ruled out potential problems with the motor windings and harness.

Several initial hypotheses were formed to explain the apparent lack of motor shaft rotation, including:

- encoder electrical or mechanical failure, or harness failure
- mechanical obstruction in the motor assembly
- gearbox failure
- brake disengagement failure
- control system electrical or logical failure

These initial hypotheses informed a first round of follow-up diagnostics designed to incrementally bifurcate the problem space. While these diagnostics were executed, the anomaly response team placed operational constraints against changing the drill's orientation or performing any activities that would vibrate the turret. The team wanted to perform initial diagnostics in the exact same configuration as the initial fault so that results would be less ambiguous if changes were observed.

Sol 1537 Diagnostics: Blind Commutation

The anomaly response team recommended attempting a short, standalone feed motion command to check if the problem was persistent across thermal cycles and power states, followed by a second motion using a blind commutation mode which could potentially differentiate between an encoder signal problem vs mechanical. Engineers devised and tested a sequence to command the prescribed diagnostic feed moves and incorporated this sequence into the next sol (1537) plan. The following day, the downlink team reported that the feed motor had stalled again, both during the initial feed motion command with normal commutation, and during the later command using blind commutation. This result reduced the likelihood that the problem originated from the encoder.

Sol 1541 Diagnostics: Increasing Brake Hold Current

The standard brake control profile starts with a brief pulse of "pull-in" current prior to the start of active motor commutation, then drops the brake current to a more thermally sustainable "hold" current level for the duration of motor motion. The next experiment raised the hold current to match pull-in current to check if the brake might be reengaging during the transition from pull-in to hold. This diagnostic sequence started by repeating the blind commutation method, first with nominal 2-step brake pull-in and hold current values, then with hold current increased to match pull-in current. Both operations failed. The encoder signal appeared to deflect by three counts opposite the commanded direction, but these signal deflections could not be definitively attributed to physical motion.

Sol 1543 Diagnostics: Combinations of Primary and Redundant Brake Solenoids

Similar to the previous plan, the plan on Sol 1543 started with another attempt to move the motor using standard brake current settings and blind commutation to confirm the problem had not spontaneously cleared since the previous attempt. Unsurprisingly, this first move stalled as before. Next, the sequence reconfigured controller settings to energize the backup brake solenoid rather than the primary. This yielded another motor stall result. This helpfully reduced the likelihood of a possible open-circuit condition local to the primary brake control circuit. The same move was retried, using the backup solenoid, but increasing hold current to match pull-in current. This again resulted in a stall.

The Sol 1543 diagnostic sequence then enabled both the primary and redundant brakes simultaneously, effectively doubling the force used to disengage the brake. The anomaly response team was pleasantly surprised to find that this worked. After reading a home pulse on the encoder, the motor controller exited the blind commutation mode (denoted as STARTUP status in Figure 5), and the feed motor appeared to operate nominally with no obvious signs of physical resistance or other anomalous behavior.

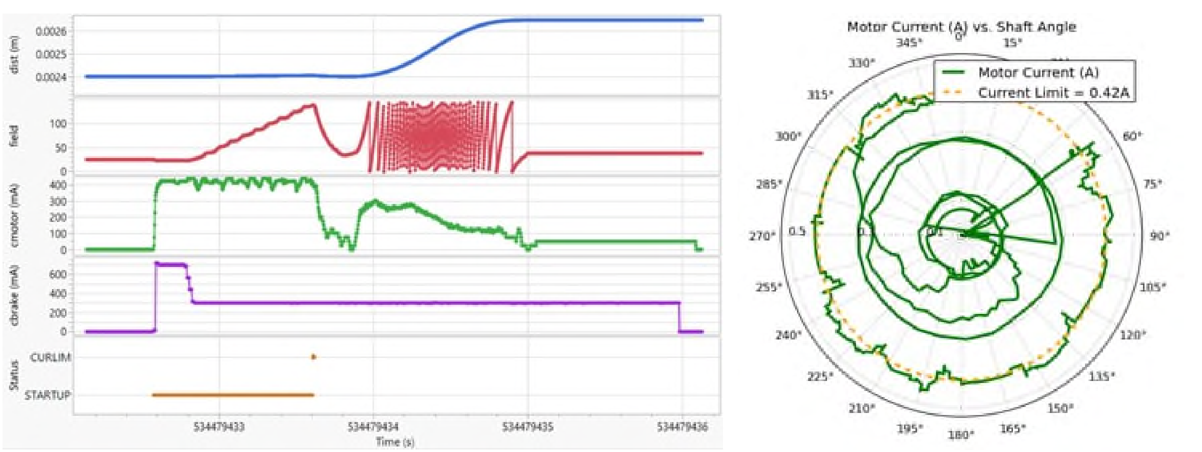

Figure 5. Sol 1543 drill feed diagnostic motion with primary and redundant brake solenoids energized. Brake current (per-coil "cbrake", violet) tracked the standard 2-step profile. Motor control started in blind commutation ("STARTUP") mode, then transitioned to normal closed-loop rate control just before time 534479434. Motor current ("cmotor", green) appeared normal. Right: motor current vs shaft angle.

Sols 1544 - 1573 Diagnostics: Early Exploration of Dynamic Sensitivities

Following the first successful post-anomaly motion on Sol 1543 with both brakes energized, the team attempted 7 feed motions, all using the primary brake solenoid with standard current settings. All 7 moves completed successfully with no signs of resistance.

The anomaly response team and project management then lifted operational constraints against activities, allowing robotic arm motion, driving, and CHIMRA sample processing operations. The anomaly response team requested that planning teams execute short forward and back drill feed motions following the first instance of each of these physically dynamic activity types to gauge sensitivity to turret dynamics.

A sample processing activity on Sol 1545 utilized CHIMRA vibration and was followed by the drill feed diagnostic sequence containing commands to drive the feed a short distance forward and then back. In this experiment, the feed motor stalled after nearly reaching its goal. Telemetry inspection revealed a new signature and new insight into the behavior inside the feed actuator. Distinct, repeating current spikes were observed with frequency equal to the rotation rate of the motor (one spike per motor revolution).

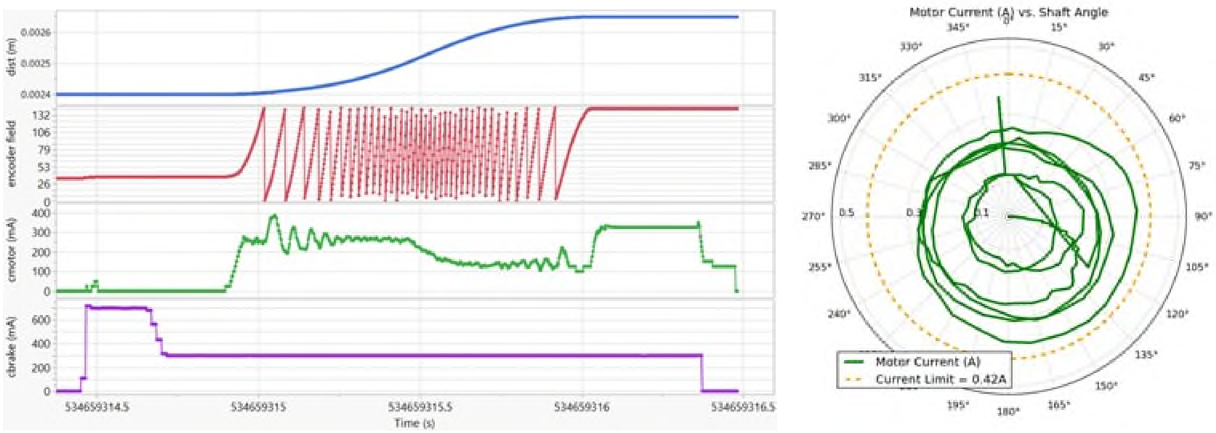

Figure 6. Sol 1545 drill feed diagnostic motion following turret vibration from a sample processing operation. Left: Oscillations in motor current ("cmotor", green) correlate to encoder-indicated motor shaft angle (red), indicating presence of a clocking-dependent disturbance. Right: motor current plotted versus motor shaft angle indicating asymmetric torque disturbance.

Motor current reflects the closed-loop rate controller's reaction to sensed torque disturbances. Plotting motor current vs shaft angle (as shown in Figure 6) provides a rough indication of mechanical resistance within the motor assembly, correlating to shaft position. Nominally, motor current should not significantly vary with motor shaft position during steady state control, in which case the motor current polar plot should appear roughly axially symmetric, as exemplified on Sol 1543 in Figure 5. Asymmetric skew depicted in Figure 6 indicates higher mechanical resistance within a limited fraction of the motor shaft's range of motion. This method of polar plotting motor current vs shaft angle proved invaluable throughout this investigation for tracking the evolution of an apparent "high friction zone".

The small forward and back motion was attempted again three days later, on Sol 1548. These instances completed successfully, but exhibited current spikes similar to those seen on Sol 1545.

A more advanced diagnostic activity was developed, involving several small forward and back motions at normal and slow speeds, and with one or both brake solenoids energized. In addition to gathering data to help identify root cause, these diagnostics were also intended to build confidence in (and experience with) feed stall recovery methods in anticipation of needing to redesign drilling algorithms to autonomously recover from intermittent feed stalls.

The new diagnostic sequence first executed on Sol 1552 with promising results. The first forward and back motions stalled; the first near the end of motion, and the second at the start of motion. A third motion reached its goal but exhibited worsening current spikes and nearly stalled toward the end. The next move energized both brake solenoids. Encouragingly, this move succeeded with no clear periodic current spikes. Further, the next pair of standard feed moves also executed cleanly, adding another data point suggesting that energizing both brakes simultaneously seemed to clear the periodic elevated mechanical resistance signature.

Failure Analysis

The anomaly response team divided and managed tasks to maintain steady progress toward understanding the nature of the persistent drill feed stall anomaly through flight diagnostic activities while also pursuing other lines of investigation. The team generated a fishbone failure diagram to organize hypotheses and evidence for and against each, shown in Figure 7.

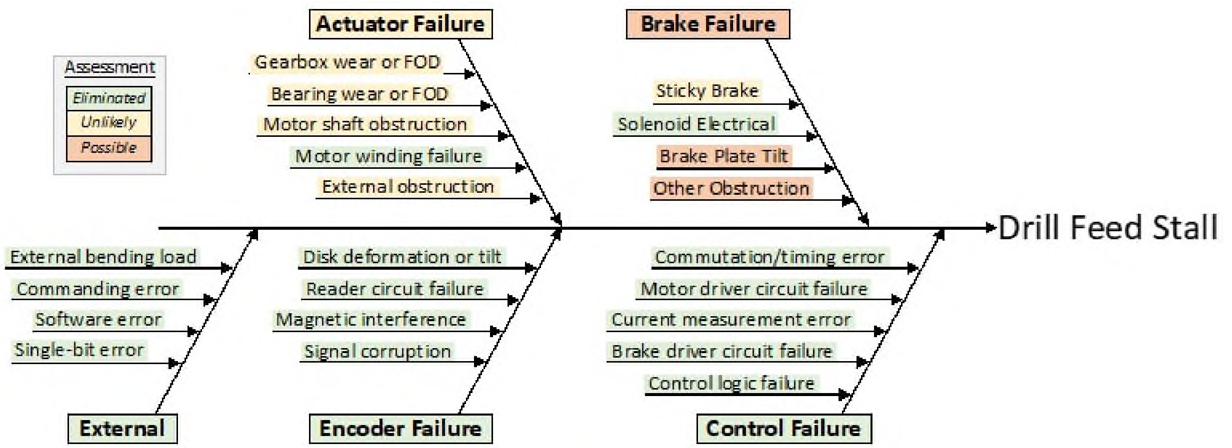

Figure 7. High-level anomaly fishbone failure diagram based on initial flight diagnostics

Telemetry and other observables from the rover were used to rule out whole branches of the fishbone. Once flight diagnostic activities regained motion of the actuator, the team quickly narrowed in on the brake being the most likely branch that caused the anomaly due to the telemetry collected. One key observation ruled out a significant number of potential root causes. Specifically, the impediment to the feed actuating was observed as a "high friction zone" that occurred at a consistent clocking angle with respect to the motor output, and was roughly one third of a motor revolution wide. This meant that obstructions within the gearbox, bearings, or external to the actuator, were highly unlikely. In addition, all other actuator telemetry from the encoder, PRTs, and motor controllers appeared to be otherwise nominal. This telemetry ruled out root cause options related to avionics and control software. Additionally, it was discovered that applying higher brake disengagement force by energizing both brake solenoids simultaneously reduced the magnitude of the drag on the motor through this zone. Repeatedly "clapping" the brake open several dozen times in between motor rotations could achieve a similar effect.

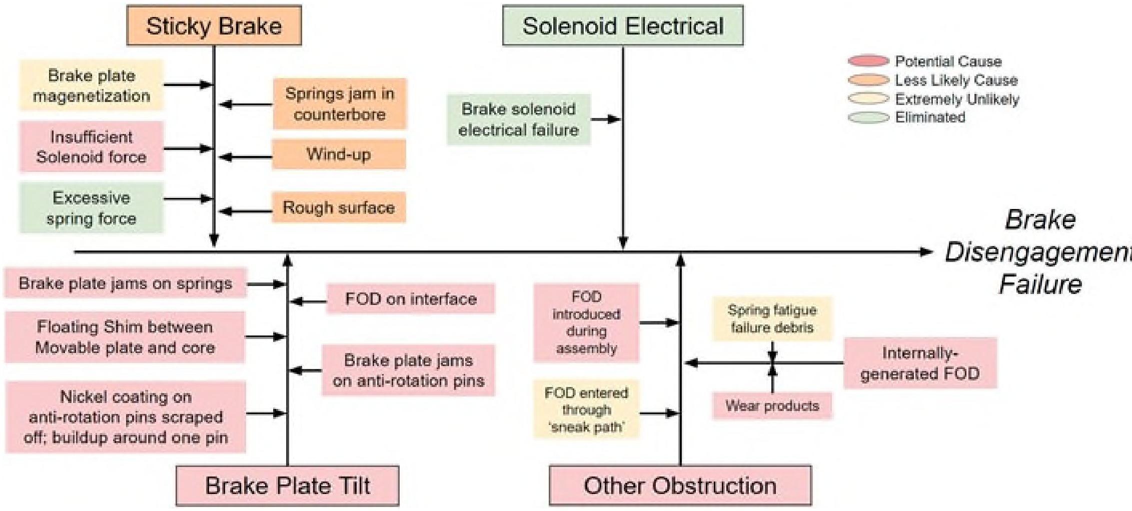

Figure 8. Detailed fishbone failure diagram focusing on potential brake-related problems

The anomaly response team was unable to rule out root causes related to the brake plate failing to disengage creating a high friction zone when the motor turned. Mechanically, this could be explained by the ferrous brake disk not being able to fully retract with a foreign object or piece of debris (FOD) or other obstacle preventing it. This would lead to the ferrous brake disk being tilted with respect to the brake rotor, which is also not perfectly perpendicular to the rotor axis due to assembly tolerances, resulting in a once per motor revolution interference. However, some signatures in the telemetry were not explained by this model. For example, the friction zone appeared to be more difficult to pass through moving in one direction than the other, and would increase in magnitude over time as it was driven through repeatedly, but could be reset by clapping the brake several times. A reduced fishbone diagram focusing on the Brake Failure branch is shown in Figure 8.

At the conclusion of this investigation, the leading theory was that the feed actuator brake was only partially disengaging in a titled state. This was supported by all telemetry from initial diagnostics conducted on the rover. The sub-branches of the anomaly fishbone detailed in Figure 8 show the family of root causes that could lead to a disengagement failure. The most likely causes were either related to parts within the motor shifting within their tolerances (Brake Plate Tilt), or debris building up behind the brake plate (Other Obstruction), or potentially a combination of these causes. The next sections of this paper summarize investigations that were done in parallel with the flight diagnostics in an attempt to narrow down the root cause further.

Review of Feed Actuator Life Qualification Testing and Flight Usage

During development, a qualification model unit of a similar motor type underwent qualification testing involving representative thermal cycling for the duration of the prime mission and rotary life testing with representative mechanical load and 2x total motor and brake cycles. Typical wear products were found inside the qualification model unit during inspection after the life test. No signs of functional or physical degradation were observed during the life test or post-test inspection.

Representative qualification model and flight units were also subjected to limited vibration and shock profiles primarily representing launch and landing dynamic loads. Some limited vibration exposure testing was conducted with representative turret vibration (4-g), but not in a high-fidelity flight-like configuration and not for prolonged periods representing anticipated 1x surface life exposure time. This is in part due to the fact that sample processing and handling routines were developed in parallel with or after the motor development program through systematic characterization of sample processing performance.

At the time of the Sol 1536 feed stall anomaly, the mission overall had surpassed the prime mission surface duration (669 sols) by a factor of 2.3 and had completed 15 successful drilling campaigns out of 27 in the reference mission description. Due to late development of target rock triage routines which added many full-length feed extension cycles, the feed actuator usage rate turned out to be higher than anticipated. Prior to Sol 1536, the flight unit had traversed 97% of its 1x life cumulative travel requirement. This alone was not overly concerning given that the actuator type had been qualified to 2x life. As will be explained in later sections of this report, this accelerated usage profile is not believed to have been a primary driver of the apparent premature failure of the drill feed mechanism.

<u>Investigation of Ground Spare Units</u>

An engineering model actuator from a development chuck mechanism was CT scanned, disassembled, and analyzed for potential signs of wear. No abnormalities were observed, though particle analysis showed signs that small amounts of debris was being generated from the brake plate and other hardware within the motor. None of the qualification model units that went through multiple life cycles, and are frequently used in ground-based testing far beyond 1x life requirements, have shown any anomalous behavior to date.

<u>Benchtop Recreation of Anomaly Signature</u>

In parallel with the on-going flight diagnostics, additional ground testing was executed to support the anomaly investigation. The objective was to re-create the anomalous behavior using an engineering model actuator to aid in determining potential mitigation steps beyond what had already been discovered. The tests were successful in recreating a once per motor revolution friction zone with approximately the correct torque by using stainless steel shims with different thicknesses, widths, and positions. This confirmed the viability of the brake tilt hypothesis as the probable root cause. It also demonstrated that either “clapping” (repetitively cycling) the brakes open and closed or increasing the brake solenoid current could reduce the drag even with an incompressible steel shim. Lastly, it was discovered that clapping the brake was producing axial displacement of the motor shaft within its slop which potentially explained why the benefit was only temporary.

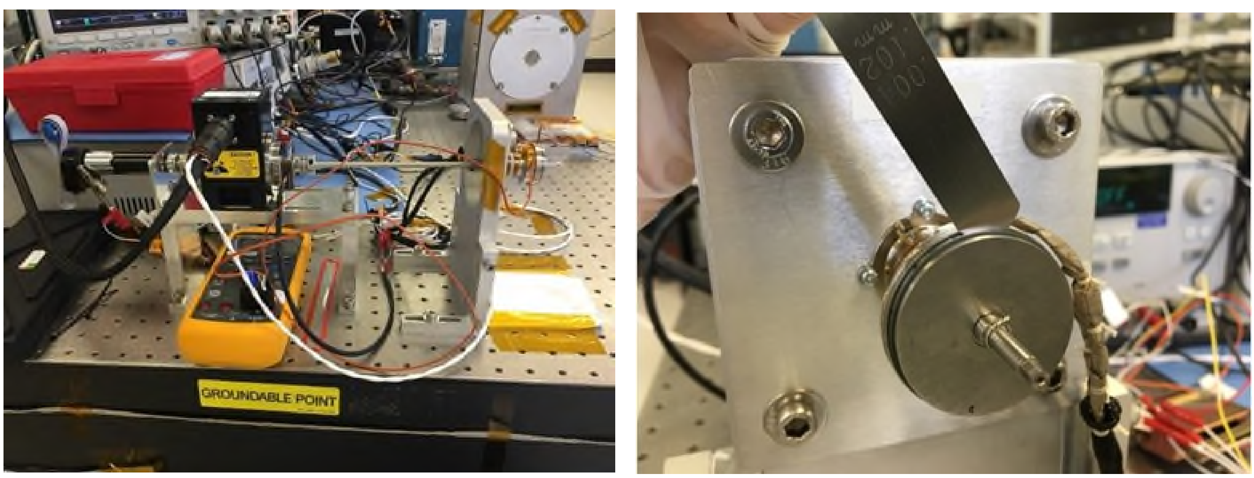

Figure 9. Test setup for benchtop motor investigation (left) with shim manually inserted behind ferrous brake disk to recreate anomaly conditions (right)

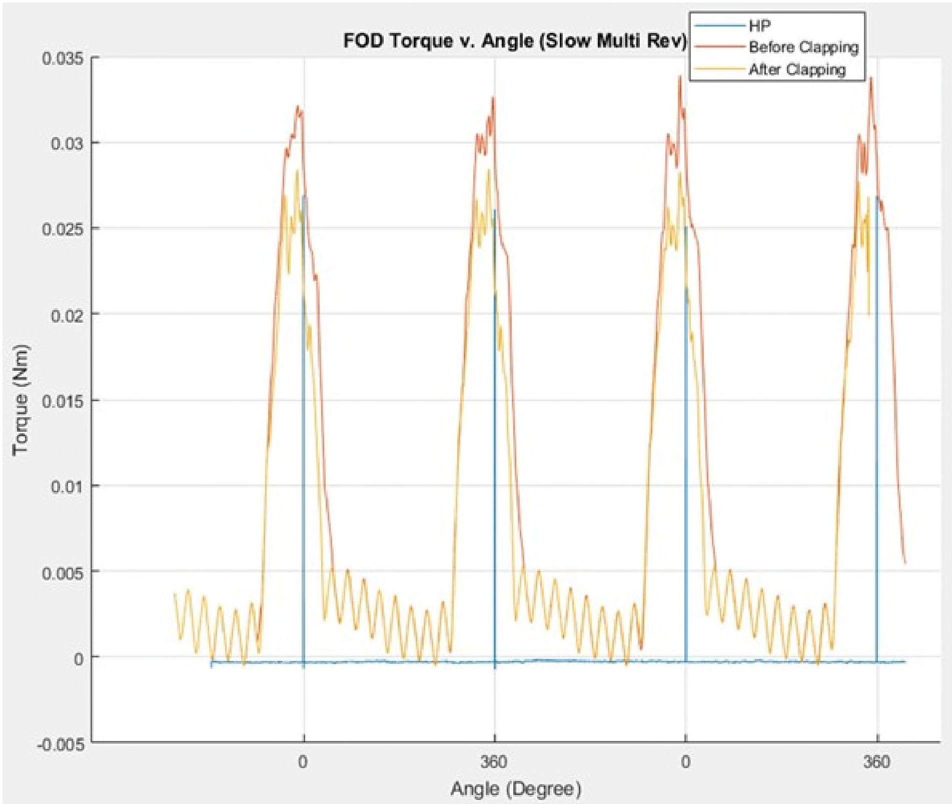

Figure 10. Benchtop motor test sample results. Inserting a shim behind the brake disk to prevent full disengagement yielded a 0.025 N-m torque disturbance spanning approximately one third of a motor revolution, roughly matching flight observations. Furthermore, "clapping" the brake reduced the torque disturbance (yellow).

Late Diagnostics

The Mars Science Laboratory mission continued its scientific investigation of Mars, albeit without a rock sampling capability, in parallel with the ongoing feed anomaly investigation. Over the subsequent months after the initial fault, the team executed a number of diagnostics investigating not only the root cause, but also exploring techniques to overcome the motor drag and conditions that impact mechanism operation reliability. In addition to the aforementioned mitigations, diagnostics explored techniques to begin commanding far from the friction zone, to generate inertia prior to entering the friction zone. The impact of mechanism orientation with respect to gravity, motion directionality, motor velocity, and mechanism heating were also explored, generally with marginal results or statistically insignificant improvement indicators. Repeatable diagnostics continued to be inserted before and after activities imparting turret dynamics. Lastly, increasing motor current limits, effectively allowing the motor controller to request more current, also improved reliability, however there were hardware safety implications with this mitigation. Maximum allowable stall torque limited the amount that motor current could be increased and thermal considerations limited the duration of elevated current operations.

In addition, the Project performed diagnostics on mechanisms similar to drill feed, some of which were used rarely in operations. Through the course of the investigation, it was discovered that the actuator for the drill chuck mechanism showed similar symptoms (but to a lesser severity), and a prior intermittent in-flight stall of the CHIMRA tunnel actuator is suspected to also have had the same root cause. The drill chuck actuator had never been used in flight, so the fact that it was symptomatic indicated the root cause was not related to lifetime usage of the actuators. This implicated other external factors such as turret dynamics, thermal cycles, and other environmental impacts.

Four months after the initial fault, the Project began a regolith sampling campaign at Bagnold Dunes. Regolith sampling did not use the drill and only required CHIMRA actuators to scoop sand, process the material, and deliver instrument portions[3]. This activity included 20 minutes of vibrating the CHIMRA mechanism while rocking the scooped sample back and forth across a 150 micron sieve to separate particles small enough for instrument delivery from the rest of the bulk material. This represented significantly longer duration dynamics than had been executed since the discovery of the feed anomaly. Given the scientific importance of sampling regolith at this site, and the uncertainty in the operation's likelihood to negatively impact the feed mechanism, the Project made the decision to continue with regolith sampling on Sol 1651. As had become routine, dynamic activities associated with regolith sampling were interleaved with feed diagnostics.

Feed diagnostics following the sieving operations yielded no feed motion. The anomaly response team used the subsequent week to re-attempt techniques that had previously been successful, failing to achieve any motion. Finally, the team began combining mitigations that were previously independently successful as well as strategies that anecdotally seemed to improve reliability without strong statistical evidence. On Sol 1659, the feed completed some successful motions, relying on elevated brake and motor currents, energizing both brake solenoids, increased commanded acceleration, and additional mechanism heating. This week completely changed the tone of the anomaly investigation, as the team shifted from root cause investigation and strategies for improving motion reliability to long term preservation of sampling capabilities.

Path Forward

As the team began to conclude that feed motor performance was not reliable enough to be utilized within the dynamic environment of a full drill campaign and normal rover operations risked a complete loss of functionality, efforts were diverted to sampling capability preservation. In the nominal feed stowed position, the drill bit is unable to contact most surfaces due to its positioning behind the contact stabilizer hardware. The stabilizers were designed to contact and preload against any surface in order to stabilize the arm in preparation for drilling activities. Despite all currently available drilling methods first depending on the use of the stabilizers prior to drill bit extension, the Project decided to fully extend the feed mechanism. This action would retain access to the drill bit, thus preserving the possibility of future sampling capability developments.

The process to extend the feed was carefully planned and executed. Long duration and repeated use of the feed motor had been shown to worsen the overall anomaly state. To reduce risk of irreversible binding, motions were conducted using an open-loop commutation mode with moderate brake and motor current limits to ensure that any worsening state of the actuator could be recovered using previously developed mitigation strategies. A thermal watchdog strategy was developed to avoid excessive self-heating due to non-standard, elevated, brake and motor currents that could result in motor heating not easily detectable by conventional thermal fault protection. Brake cycling was inserted after each attempt at extending the feed to reduce the magnitude of the friction zone. The full activity required 4 sols of motion to reach an extension of 58mm, about half way. At that point, Mars and Earth entered solar conjunction, halting communication with the vehicle for several weeks. During this period, the mechanism was placed in what the team believed to be the most beneficial gravity vector with the drill bit pointing up. Following conjunction, the remainder of the activity was performed in a single sol and was successful in moving the feed to its fully extended position of 110 mm. Figure 11 shows the drill bit location at its fully extended position. Without reliable use of the feed mechanism, the team needed to develop a new technique to preload directly on the drill bit and use the robotic arm's 5 degree of freedom capability to safely drill, retract, and deliver samples.

Figure 11. Left: Sol 1780 MastCam verification of the drill feed in its extended position, placing the drill bit beyond the drill stabilizers and preserving the possibility of later development of feed-extended drilling. Right: Sol 2057 drill bit placement at start of first feed-extended drilling operation. (Image Credit: NASA/JPL-Caltech/MSSS)

Conclusion

While MSL's drill feed anomaly investigation never yielded a clear root cause, a family of root causes related to the alignment or obstruction of the ferrous brake plate emerged as a likely source of the behavior. Causes impacting alignment and obstructing the brake were proven to potentially result in the observed behavior and such an issue arising late in MSL's extended missions was deemed credible. Additionally, most alternative suspects were eliminated or determined to be unlikely.

Reliable feed motion has not been achieved since fully extending the feed mechanism. Diagnostics after the feed extension confirmed the engineering team's fears; the mechanism had reached end of life. However, MSL was successful in developing feed extended drilling and sample transfer techniques. After over a year of being unable to sample, Curiosity collected the first feed extended sample on Sol 2057. Curiosity has now collected the majority of its samples using feed extended sampling techniques and continues to conduct a productive and fully capable scientific investigation on Mars.

This investigation exposed several valuable lessons. Paramount to all aspects of the investigation was mechanism performance visibility. The ability to record motor telemetry at a rate significantly higher than the motor turn rate was crucial to understanding the behavior and evaluating mitigation strategies. Additionally, the system's ability to autonomously write higher rate mechanism data in the event of a failure provided key visibility, and saved sols by eliminating the need for additional diagnostics. This lesson was carried forward to the Mars 2020 and Europa Clipper projects, among others. Additionally, several dimensional changes were made to actuators on the Mars 2020 rover to mitigate the most likely causes related to jamming of the brake plate.

An adaptable flight software command architecture coupled with flexible avionics also proved to be an invaluable diagnostic tool. The software preserved the capability to modify motor current limits, commanded brake currents, simultaneously command both brakes, and modify the motor controller commutation mode. All of this was within the existing avionics system's design capability. This exposed uncommonly used functionality that provided operators with an arsenal of diagnostic options, immediately available to the operations team.

This experience exemplified the need for routine mechanism health checks to detect behavioral changes and establish performance baselines for reference when anomalies occur. In the case of the MSL drill chuck mechanism, early detection allowed the team to put into place periodic monitoring and mitigations which are believed to have extended its life. The MSL Project has adopted routine trending activities that provide enhanced visibility into mechanism health beyond nominal use. The Mars 2020 Project intends to repeat critical mechanism health checkout activities performed after landing periodically to monitor system performance.

Lastly, engineers gained an appreciation for *planning for all potential outcomes*. The Project's decision to extend the feed while it was still semi-operable proved invaluable to restoring drilling capability at the heart of Curiosity's scientific mission and furthering humanity's understanding of the history of Mars[5].

Acknowledgements

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