Robotic Arm and Rover Actuator Systems for Mars Exploration

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Abstract

Missions such as the Sojourner Rover, the Robotic Arm for Mars Polar Lander, and the 2003 Mars Rover, Athena, use numerous actuators that must operate reliably in extreme environments for long periods of time. Financial and time constraints of these Mars missions require the systems to be developed under low budgets and on short schedules. For the actuator systems, this led to a design using DC brush motors. These motors are lightweight, with simple mechanical commutation that requires no extra sensing and control for proper functioning. They are extremely efficient in converting electrical energy to mechanical energy, resulting in high power to weight ratios. These traits make DC brush motors more desirable for use in Mars rovers and robotic arms than the complex DC brushless motors or inefficient stepper motors traditionally used for space flight applications. However, there are certain characteristics of DC brush motors that need enhancement to make them reliable, long-life actuators for operations in Mars' low-temperature, low-pressure, CO_2 environment. This paper will discuss the development of motors and actuator systems for the Sojourner Rover, the Robotic Arm for Mars Polar Lander, and the 2003 Mars Rover.

Introduction

Background

Brushless motors are traditionally used for space flight missions. Several past JPL missions where brushless motors have been used include Galileo, Spaceborne Imaging Radar-B (SIR-B), and SIR-C. A current mission using brushless motors is Cassini, and two future missions include MUSES-CN Asteroid Rover and Galaxy Evolution Explorer.

The performance history of brushless motors for space flight missions has been excellent. There are several characteristics of brushless motors that make them operate better than brush motors in vacuum applications. Brushless motors provide excellent heat dissipation because the windings are on the stator, which has a direct conductive heat path to the exterior. Conversely, brush motors must dissipate their heat from the rotor to the case primarily by convection, or by radiation if it is operating in a vacuum. This severely limits the power handling capability, and increases the danger of catastrophic failure due to overheating. Also, brushless motors do not have the problem of brush wear, which is the limiting factor of brush motor life. The brushless motors have been especially successful for vacuum environment applications requiring long life. The long lifetime requirement is one of the reasons that MUSES-CN has chosen to

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use brushless motors; the mission requires over 200 million motor revolutions. Vacuum operation of brush motors demands special compounds and processes, as well as rigorous testing. The Shuttle Radar Topography Mission (SRTM) wanted to use an already qualified brush motor, which was qualified for a Mars atmosphere, but SRTM needed to bypass the time-consuming modifications and testing of the brush motor to meet their schedule deadlines. So the brush motor was sealed in an atmosphere where it had already been qualified. This containment adds extra mass and complexity to the use of a brush motor and the life is still limited to amount of atmosphere that can be provided to the motor. Therefor, DC brushless motors the best choice for missions in vacuum where long life and the highest reliability are required.

NASA's Discovery series of "faster, better, cheaper" missions started with Mars Pathfinder[1]. This meant that the highly ambitious mission must be completed in a shorter schedule time with a lower budget than past missions. One way to minimize the time and money spent was to use as many commercial products as possible with minimal modifications. That was one of the reasons that DC brush motors were selected for use in the wheel and steering drives of Sojourner. Although DC brushless motors have had good performance records for space flight missions, they require extra electronics, which adds much development time and cost to a mission. DC brush motors do not need the extra electronics, thus simplifying the electronics system and resulting in savings in mass and development time. For missions where mass is limited, this savings is beneficial to the success of the mission. Also the Sojourner rover was considered a mission with a short lifetime (motor revolutions less than 10 million) and one motor failure would not be mission threatening. Table 1 lists several missions in vacuum or on Mars with the motor type selections.

Table 1. Missions, Environments, and Motor Types for several JPL missions

Mission	Environment	Motor Type
Galileo	Vacuum	DC brushless motor
Mars Pathfinder Sojourner Rover	Low temperature, low pressure, CO_2 atmosphere	DC brush motor, with precious metal brushes
Cassini	Vacuum	DC brushless motor
Robotic Arm for Mars Polar Lander	Low temperature, low pressure, CO_2 atmosphere	DC brush motor, with silver graphite brushes
Muses-CN	Vacuum	DC brushless motor
2003 Mars Rover, Athena	Low temperature, low pressure, CO_2 atmosphere	DC brush motor, with silver graphite or copper graphite brushes

Mission Overviews

Mars missions require that the spacecraft be tested and operated in several different environments[2]. While performing clean room function checks they must operate in ambient air with up to 55% relative humidity. Then during the system level testing, it is very beneficial if they operate in 1.0 kPa N_2 from -80 C to -10 C. During the flight and cruise phase of the mission, the actuators must survive, non-operating at least, in vacuum. Finally, they must operate on Mars in 1.0 kPa CO_2 from -80 C to -10 C, and survive temperatures as low as –125 C.

The Sojourner rover of the Mars Pathfinder Mission, as shown in Figure 1, was a small lightweight rover that traveled about 100 m on the surface of Mars, performing various scientific experiments and returning the data to Earth. The spacecraft landed on the surface of Mars on July 4, 1997, and both the lander and rover operated for 83 sols (Mars days) before the last transmission from the lander was received.

Several characteristics of the Sojourner rover affected the design and selection of the motors for the wheel drive and steering actuators. The 11 kg rover was designed to travel distances from 100-1000 meters at a top speed of .67 cm/sec. It actually traveled 100 m on Earth for testing before it was sent and then 100 m on Mars during the mission. The 100 m of testing on Earth and 100 m of driving on Mars amounts to approximately 1 million motor revolutions. But the motors selected for the rover must have enough margin in their lifetime for the "extended" mission of up to 1000 m of driving, approximately 5.4 million motor revolutions. The rover had limited computing capability with the 80C85 computer, which required the motor electronics to be simple. Also the thermal design of the rover minimized the wire interface for the actuator to reduce the heat loss from conduction through the copper wires.

Mars Polar Lander will arrive on the surface of Mars in December 1999 and begin operating the Robotic Arm, shown in Figure 2, to sample and dig a trench .5 m deep. The 2 m long, semi-autonomous, 4 degrees of freedom arm is designed to dig in hard soil. DC brush motors were selected for the joint actuators because of the success with Sojourner's motors. By looking at the scoop volume and how many movements required to dig a trench to the desired depth, the life requirement of the joint motors was found to be 80 hours. The equivalent life requirement of motor revolutions was calculated to be 10 million motor revolutions. In order to have a comfortable margin, the motor life should be in the range of 30 to 100 million revolutions.

The 2003 Mars Rover, Athena, is currently being designed at JPL, and the mission is set to launch in 2003. Figure 3 shows the current CAD configuration of the Athena rover with the instrument arm deployed and the mast stowed. This rover will use actuators for the wheel drive and steering mechanisms much like Sojourner. In addition, there will be actuators for an instrument arm, a mini coring device, sample cache mechanism, and camera mast. A total of 30 DC brush-type motors of all various sizes will be used[3]. The 75 kg rover will travel up to 10 km at a maximum speed of 6 cm/sec. That is ten times farther, ten times the speed, and almost seven times the weight of Sojourner. The drill motor of the mini coring device must operate at 20 W continuously for at least 100 million revolutions. These two examples of motor use for the Athena rover show that the life requirements of its motors have greatly increased from Sojourner.

Mechanism Development

Sojourner

The Sojourner rover used Maxon RE016 motors in the wheel drive and steering actuators. The 38 g motor is an ironless core, brush-type DC with precious metal brushes, neodymium iron boron magnets, oil-impregnated bronze bushings, and rotor mounted capacitor for arc suppression and long brush life. Its unique capacitor commutator reduced the wear on the brushes and commutator by suppressing the arcing. The motor is only a two-wire device, and there were no temperature-sensitive electronic components such as Hall Effect sensors needed. The reduced wire count benefited the thermal design of the rover.

The stock motors did not meet all the environmental requirements of the missions. The motors from Maxon are designed to operate in a minimum temperature of –20 C, which is far less then the required –80 C operating temperature on the surface of Mars. Modifications were made to the motor to achieve the low temperature operation. For example, the grease normally applied to the commutator was deleted. It was found that at temperatures below –60 C the commutator grease would bond the commutator to the brushes. This would result in a permanent failure of the motor due to bent brushes. Another feature of the motor affected by temperature was the bushing oil, which lost its effectiveness below -40 C, increasing the wear on the bushings. However, the increased wear was determined to be acceptable for the lifetime requirements of the Sojourner motors, so no modifications were made.

Another modification to the stock Maxon motor was the addition of a magnetic detent encoder assembly. A motor with an ironless core rotor has no inherent detent torque, so external magnetic detents were added to the motors to hold them in position when the rover was unpowered to prevent the rover from accidentally rolling down a hill. These magnetic detent assemblies also included a LED/phototransistor pair with a rotating mask to create a one-bit relative encoder for motor odometry.

Two motors were tested at no-load in a +20 C, low-pressure air environment to 40 million revolutions without failure. Two complete actuators were tested under load and start-stop conditions, with part of the test conducted at –70 C in low pressure CO_2. These were run to failure at 30 to 40 million revolutions. These test results showed an adequate margin for Sojourner's mission requirement of 1 million motor revolutions.

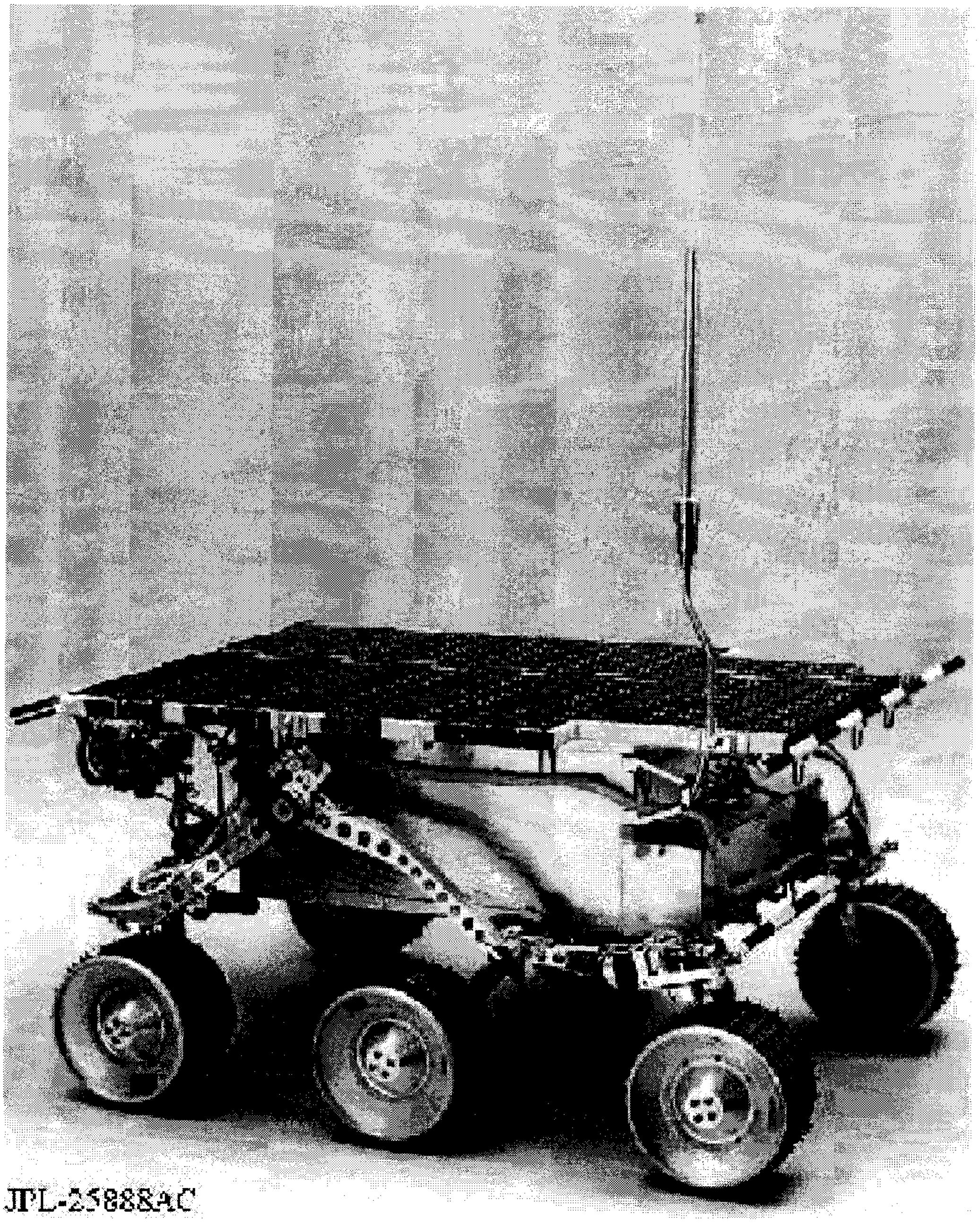

Figure 1. Mars Pathfinder Sojourner Rover

The entire Pathfinder mission lasted 83 sols on Mars. The rover traveled about 100 m, and the wheel actuators logged an average distance of 150 m, including the distance traveled when turning, with no failure of the wheel drive or steering actuators. There was only one wheel stall, believed to be from a pebble that got stuck in the rover wheel cleats. This was automatically remedied by the rover driving backwards to release the pebble. Afterwards, the actuator operated normally showing no signs of damage.

Sojourner's performance proved to be a great success in the use of DC brush motors for Mars exploration.

Robotic Arm for Mars Polar Lander

The project management decision for the motor selection process for the Robotic Arm started by using the same motors as Sojourner, the Maxon RE016. The differences in the design and operating conditions made additional testing necessary. The main differences were a higher voltage and a longer life requirement. The Robotic Arm motors had to operate at 30 V rather then the 15.5 V of Sojourner's motors. There had also been design changes to the Maxon RE016 since the two years that they had been used on Sojourner. They now came with ball bearings and a double-ended shaft. The ball bearings, lubricated with Braycote 604 for low-temperature operation, greatly improved motor performance below –40 C. The double-ended shaft simplified integration of the magnetic detent and encoder assembly.

The RE016 motors were tested in a variety of conditions. The environmental conditions included tests in air, vacuum, low-pressure CO_2, and low-pressure N_2. The test temperatures were between –70 C and –80 C. There were several methods of commutator lubrication, and a total of 29 motors were tested.

The test results found much lower lifetimes of the motors. The new lifetimes averaged fewer then 10 million revolutions, which is much less then the 30 to 40 million revolutions to which they were tested before Sojourner. Three failure modes were observed. Rotor shorting due to conductive debris in the commutator slots was the most common failure mode, which had also been observed in the original Sojourner motor tests. Another failure mode was caused from motor brush damage. The motor brushes and commutator would gall, or micro-weld together. This would either bend the delicate brushes out of contact with the commutator or break the brushes off entirely. The last motor failure mode was an open circuit in the rotor winding caused by contact between the rotor and motor casing. This was only observed one or two times. The motors were being operated well outside the limits specified by the manufacturer. Although the exact cause of this last failure mode was unknown, it could be due to the rotor warpage or differential expansion at the extreme temperature, or a simple out-of-tolerance fabrication error.

With the disappointing test results from the RE016, a decision was made to identify alternative motor designs and suppliers. The Cassini program developed a successful brush DC motor for the engine gimbal actuator. It operated in vacuum with silver-graphite motor brushes (SG54-27 from Superior Carbon) and a copper commutator. The size of the motor was not directly applicable to the Robotic Arm, but the successfully qualified brush material was directly used in the new motors for the Robotic Arm.

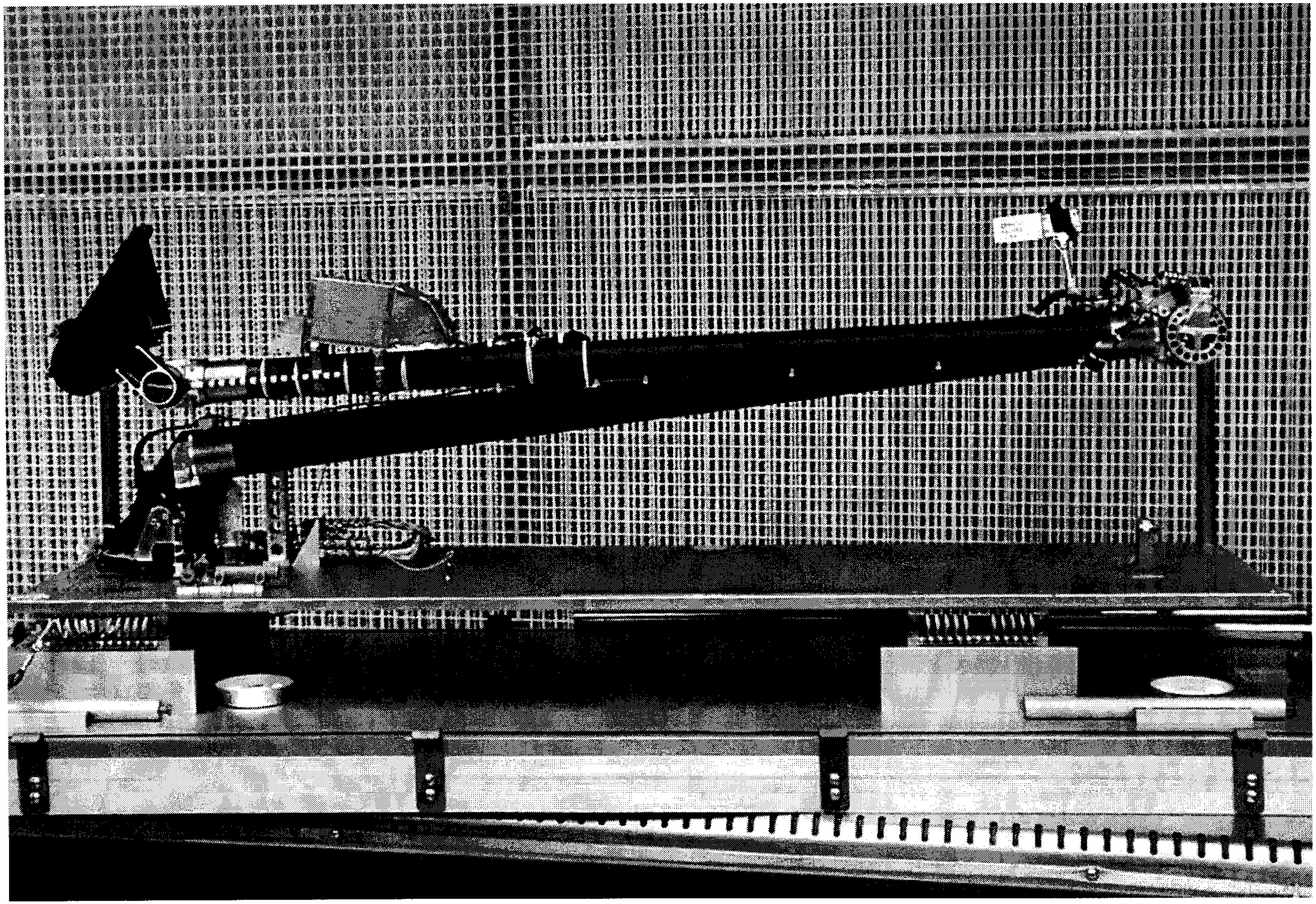

Figure 2. 1998 Mars Surveyor Program Robotic Arm

It was decided that a larger motor would provide several advantages. Higher torque would decrease the gear ratio and reduce the number of motor revolutions. Higher power would enable the mission to be completed in a shorter period of time. The lander was capable of supplying more power then the RE016 motors could use.

The one major drawback of using a larger motor was the increase in mass. The small increase in mass was not originally allocated in the mass budget. So the project evaluated the reliability and lifetime issues for the Robotic Arm. The long life requirements of the motors and the fact that they were single-point failures for the Robotic Arm led to an increase of .3 kg in the mass budget to allow for the larger motors. The larger motor design allowed the gear ratio to be decreased by a factor of 5 by removing one stage of the planetary gearbox and shortening the gearcase.

Because of the change in motors, there only remained the relatively short time of 3 to 4 months before the new motors were needed for the Robotic Arm. A new baseline approach was taken with a motor developed by the American Technology Consortium (ATC). They proposed to design 100 g motors with a conventional iron-core rotor. The iron-core rotor with squewed magnets would provide the inherent magnetic detent torque needed for the actuator design. ATC also had a good record with developing a Mars Pathfinder actuator in a short period of time. A back-up option of using stock Maxon RE025 graphite brush motors with an ironless rotor was also designed at the same time. The Maxon motors would need to be retrofitted with the SG54-27 brushes, re-lubricated bearings, and external magnetic detent assemblies. The stock RE025 motor weighs 130 g, and compared to the ATC motor, would have added about 160 g to the complete Robotic Arm assembly.

Once the ATC motors were completed, screening tests were conducted to check for early failures or defects. They were tested in two cycles between +80 C and –125 C with the motors not operating. Then the motors were run at various speeds at temperatures between +80 C and -90 C. After the screening tests, the motors were characterized to select the best ones for flight with additional tests done at ATC and JPL. The characteristics examined included the magnetic detent torque, no-load speed, minimum running voltage, and estimated friction torque from measurements. After the selection of flight motors and spare motors, dynamometer tests were conducted to get plots of current vs. torque and speed vs. torque.

The no-load life tests of the ATC motors in air and 1.0 kPa CO_2 showed excellent life and reliability. The motors ran for more then 100 million revolutions without failure. Extrapolating data from the measured brush wear, it was estimated that the motors would survive between 300 to 500 million motor revolutions in a no-load condition. Complete mechanisms with the ATC motors were cycled under high load conditions. The resulting lifetimes, before the motor brushes wore out, were 102 million at –70 C in 1.0 kPa CO_2, 36 million at –70 C in 1.0 kPa N_2, and 62 million in ambient air. The difference of the results in CO_2 and N_2 could only be attributed to the differences in the gases, but no conclusions were made based on the single test.

Tests of the ATC motors performed in vacuum were less then satisfactory. These were conducted for the Shuttle Radar Topography Mission (SRTM) and their results were not critical to the Robotic Arm. The tests were no-load only, and the motors would last for several minutes to hours with smooth operation and then there a high and variable current draw would occur. The motor brushes would wear out in as few as 3 million revolutions. Another brush material, Superior Carbon SG59, performed better with 5 million revolutions of smooth operation before the high current phase, and 20 million revolutions before brush wear-out. Three completely stock RE025 motors with lubricated precious metal brushes were run for 21 million revolutions in vacuum at +20 C without any problems, but this option was only kept as a back-up. SRTM's limited funding and schedule time along with their requirement for a highly reliable motor, dictated a pressure vessel solution for using a DC brush motor.

2003 Mars Rover, Athena

The Athena rover project has begun its design phase and started testing various motors and brush materials in order to choose the best candidates to use in the many different actuators. In the brush material tests, the Maxon RE025 motors were used. They are rated for 48 V, but for the tests they were operated at 30 V. They are .13 kg motors with neodymium iron boron magnets.

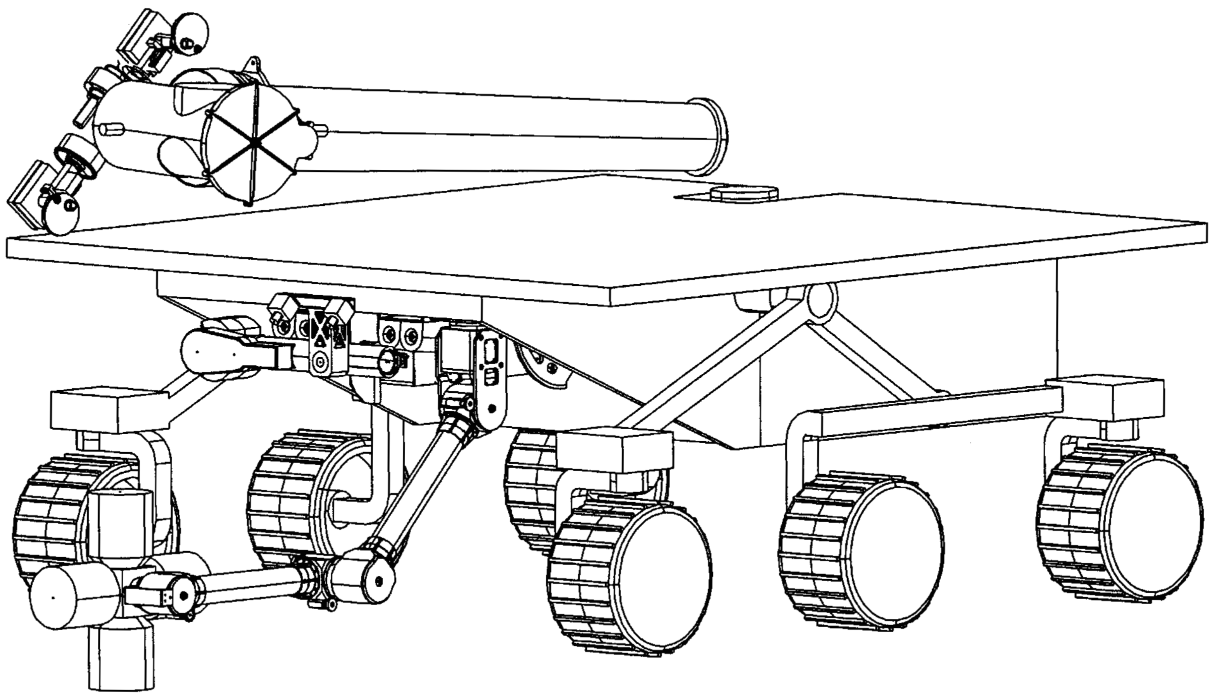

Figure 3. CAD configuration of the 2003 Mars Rover, Athena with Instrument Arm Deployed

The importance of brush wear on the lifetime and performance of brush motors has led to the testing of various brush materials to obtain more accurate data on brush material behavior in a Mars environment. The brush materials chosen for these tests were all easily obtainable commercial materials. There are other custom materials that could also provide good results, but they were not used in these tests because they were not easily obtainable. The focus of the test was to investigate brush performance vs. current density in a CO_2 environment to simulate Mars atmosphere. Tests were also performed in ambient Earth atmosphere, because missions require various system tests to be performed before launch. A vacuum test was also conducted just for the potential benefit for other space flight programs.

The selected brush materials were chosen for their potential to work well in high-altitude and vacuum applications. The brush materials tested included:

SG54-27, a silver-graphite from Superior Carbon;

SG54-27-V, the above material with a proprietary wet lubrication impregnation from Ball Aerospace;

SG59, a silver-graphite-MoS_2 from Superior Carbon;

BG91, a copper-sulfide graphite material from Superior Carbon;

BG91-V, the BG91 material with a Vac-Kote applied;

Copper-graphite, the stock material provided with the Maxon RE025 motors.

The tests performed included two no-load tests, one in Earth atmosphere and the other in .8 kPa CO_2, and three full-load tests, two performed in .8 kPa CO_2 and one in vacuum. From these tests, it was discovered that several important characteristics of motor brush materials need to be considered when deciding the suitability of a particular brush material for an application. These characteristics include the cohesiveness of the brush debris, the electrical properties of the debris, the contact resistance between the brush and commutator, and the wear rate, which is the linear brush wear divided by the distance traveled at the commutator surface.

There were several good performers in low-pressure CO_2. SG54-27 was the best choice overall for long life with good performance. The motors with this material went 40 million revolutions operating at an average of 0.53 W in a no-load condition. There was very little brush debris produced with the low average brush wear of 0.1 E-10 cm/cm for the motors in a loaded condition. The Maxon motors with the stock copper-graphite brushes had higher wear rates, an average of 5.0 E-10 cm/cm. This would make this stock motor a suitable alternative for a motor not requiring long life, such as deployment devices, when a mission schedule could not include major modifications to a motor. BG91 had low wear rates, high contact resistance, and a low no-load current, making it a good material to use in an application where no-load power should be maximized. The motors with this material operated at an average power of 0.14 W in a no-load condition. SG59 had low contact resistance, making it a good material to use when the power throughput should be minimized. Also it was found that applying wet lubrication to the commutator did not help the wear rates and only made the bush debris more cohesive, making it undesirable for use in a CO_2 environment. Tables 2 shows the average values for the motor revolutions, current densities, and brush wear rates for the various brush materials on the motors tested in CO_2.

Table 2. Motor Revolutions, Current Density, and Wear Rates for Loaded Motor Tests in .8 kPa CO_2

Brush Material	Motor Revs ($x10^6$)	Current Density (A/cm^2)	Wear Rate ($cm/cm \times 10^{-10}$)
SG54-27	40	6.7	0.1
SG54-27-V	40	7.7	0.1
BG91	40	6.9	0.2
BG91-V	40	6.8	0.3
SG59	40	7.3	2.0
Stock	40	7.6	5.0

The results in vacuum showed that only SG54-27-V, BG91, and SG59 performed approximately as well in vacuum as they did in CO_2. Table 3 shows the average values for the motor revolutions, current densities, and brush wear rates for the various brush materials on the motors tested in vacuum. All the other materials had excessive wear, which resulted in some motor failures, as shown in Table 3 for the motors that went less then 35.8 million revolutions. The failures all seemed to be caused by the debris getting into the commutator slots and forming a partial short. This short would increase the power draw and heat, causing the rotor temperature to rise until the winding insulation fails. This problem is especially serious in vacuum because of the heat dissipation from the rotor is poor.

Table 3. Motor Revolutions, Current Density, and Wear Rates for Loaded Motor Tests in Vacuum

Brush Material	Motor Revs ($x10^6$)	Current Density (A/cm^2)	Wear Rate ($cm/cm \times 10^{-10}$)
SG54-27	26.4	6.9	35.6
SG54-27-V	35.8	6.5	0.2
BG91	35.8	5.9	0.6
BG91-V	4.6	5.9	?
SG59	35.8	6.9	1.6
Stock	2.7	6.5	10.6

\Some additional tests performed for the Athena rover included preliminary qualification tests for two specific motor applications. The first test was with one Maxon RE025 motor with 24 V windings. The motor brush material was SG54-27, and it was tested in .8 kPa CO_2 for 47 million revolutions with no failure. Then with an increase in power, which in turn increased the brush current density and wear rate, the motor was run for an additional 60 million motor revolutions with still no failure. The second test was with three Micro Mo 1727-18 motors at 16 V with stock copper-graphite brushes. They were tested in .8 kPa CO_2 in a no-load start-stop condition with dynamic braking and direction reversal. There were no failures or anomalies during the whole test of 1.9 million start-stop cycles with 218 million motor revolutions. A similar test was conducted with two Maxon RE016 motors, two prototype Maxon RE020 motors, and two Micro Mo 2342 motors. All were equipped with stock copper-graphite brushes. The test was stopped at .5 million cycles, with about 100 million motor revolutions. There were no failures, and insignificant brush wear. One RE020 motor exhibited variable high current, but continued to function adequately. Disassembly and inspection yielded no clues to the source of the anomaly. The results of these tests show excellent progress for the actuator development of the Athena 2003 Mars Rover.

Conclusions and Lessons Learned

During the development of the motors for the Robotic Arm it was found that testing programs are often not long enough due to schedule and cost pressures. The engineers recommended testing earlier for future developments. This has led to the current testing procedures being done on the motors for the 2003 Mars Rover, Athena. From those tests is has been found that to reduce the risks in using brush motors, it is important to select the appropriate material and perform many representative tests in the expected environment. Monitoring current or temperature of the motors can avoid catastrophic failure due to overheating.

DC brush motors have been developed to be successful for Mars missions. The Sojourner rover showed extreme success with the Maxon RE016 motors used in the wheel drive and steering actuators with only slight modifications to the stock motor design. The Robotic Arm for Mars Polar Lander was able to develop another successful brush motor, by ATC, that is larger, higher power, and higher torque then the Sojourner motors. All of the life tests performed on the ATC motors show that they will easily survive that Robotic Arm's task of digging a .5 m deep trench. The Athena rover is also starting to test motors for use in its wheel drive actuators, drill mechanism, and instrument arms. The extensive testing of a variety of graphite brush motors in Mars atmosphere, has been completed so far with no failures and only one minor anomaly. There have been many failures in the tests conducted in vacuum, but with more careful attention to brush material and heat dissipation, a successful brush motor can be developed. Although some of the tests have shown that DC brush motors are not as reliable as DC brushless motors, it has been shown that brush motors are a viable solution when mass, power, funding, and schedule of a mission is limited.

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References

1. Howard Jay Eisen, Carl W. Buck, Greg R. Gillis-Smith, Jeffrey W. Umland, "Mechanical Design of the Mars Pathfinder Mission," 7th European Space Mechanisms & Tribology Symposium, ESA SP-410, October 1997

2. D. Braun, D. Noon, "Long Life DC Brush Motor for Use on the Mars Surveyor Program," 32nd Aerospace Mechanisms Symposium, May 1998

3. Don Noon, "Motor Brush Testing for Mars and Vacuum," 33rd Aerospace Mechanisms Symposium, May 1999