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ANALYSIS OF THREE-DIMENSIONAL ROLLER PERFORMANCE IN A MICRO-g ENVIRONMENT

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ABSTRACT

Approximately 960 hours of extravehicular activity (EVA), or spacewalks, are planned for the construction of the International Space Station over the next six years. This is over two-and-a-half times the total number of EVA hours accumulated by the National Aeronautics and Space Administration (NASA) in the past 35 years of U.S. spaceflight. Therefore, it is advantageous to explore ways to assist astronauts in being more efficient while working in space. The Space Systems Laboratory at the University of Maryland is investigating ways of improving conventional ratcheting tools that do not work effectively in confined spaces and have been seen to exhibit other limitations that restrict their use during EVA. By replacing the traditional ratchet mechanism with a NASA/Goddard Space Flight Center-developed three-dimensional (3-D) sprag and roller mechanism, ratcheting tools can be made more efficient. In October of 1998, a 3-D roller mechanism was flown on space shuttle mission STS-95 as part of the Space Experiment Module program. The goal of the experiment was to quantify the roller's performance when operating for an extended period in a micro-g environment. This paper discusses the design of the experiment, as well as the results obtained.

INTRODUCTION

As space exploration continues, more and more extravehicular activity (EVA) will be needed to expand and strengthen the foothold we have established in space, both in orbit and beyond. Starting in December 1998 with the first spacewalk of the International Space Station (ISS) era and continuing through the completion of the ISS in 2004, approximately 960 hours of EVA will be performed to assemble the station (ref. 1). This is over two-and-a-half times the 377 hours of spacewalks that the National Aeronautics and Space Administration (NASA) has conducted since 1965 (ref. 2). This increased need has led both engineers and designers to try to improve the efficiency of the tools and systems that astronauts use for EVA in space. In doing so, it is hoped that astronauts can get the most out of the limited time and currently available resources while working in space. Turning this interest toward tools, it can be seen that simply adapting tools designed for 1-g environments will not be sufficient for an intensive EVA program, such as that planned for ISS construction. By researching improvements to tools commonly used in a micro-g environment, it should be possible to limit astronaut fatigue and improve overall efficiency.

The Space Systems Laboratory (SSL) has been investigating a new type of wrench for use in space. This was done by incorporating the three-dimensional (3-D) sprag and roller technology developed by NASA/Goddard Space Flight Center (GSFC) in place of the ratchet mechanism found in existing wrenches. To further this research, a group of graduate and undergraduate students at the University of Maryland designed an experiment to evaluate the 3-D sprag and roller mechanism. This paper will discuss the on-orbit testing of the mechanism, flown on space shuttle mission STS-95 as part of the Space Experiment Module (SEM) program.

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BACKGROUND

Space Systems Laboratory

The SSL was founded in 1975 at the Massachusetts Institute of Technology. It then moved in 1990 to the University of Maryland, where its Neutral Buoyancy Research Facility, the only neutral buoyancy facility in the world located on a college campus, was completed in 1992. Over the past 24 years, the SSL has conducted research into ways to make human beings more productive while working in space and developed advanced techniques for neutral buoyancy simulation of space activities. This research has included studies of the ways the human body works in space, quantification of human abilities in orbit, and the design of tools and telerobotic systems to help astronauts work in space. The SSL currently has three faculty members, 12 full-time staff members, 20 graduate students, and approximately 30 undergraduate students.

Overrunning Clutches

Overrunning, or one-way, clutches are used in rotating mechanical systems when torque must be transmitted in only one direction or when the driven member is to be permitted to "overrun" the driver. Ratchet, roller, and sprag clutches are three types of overrunning clutches that automatically engage to transmit torque by relative rotation in one direction and automatically disengage for overrunning by relative rotation in the other direction.

The first type of overrunning clutch developed was the simple ratchet and pawl mechanism, originally used in clocks, dating back to 1162. Unfortunately, the geometry of this type of clutch constrains it to stopping at a limited number of positions and limits the torque that can be applied.

The next step in one-way clutch evolution was the roller clutch, referred to as a two-dimensional (2-D) roller clutch and shown in Figure 1. It has one race that provides a cylindrical race surface and another race that has a series of wedge-shaped friction surfaces spaced about its circumference. The rollers are installed between these concentric races at the wedge-shaped friction surfaces. Engagement and disengagement are determined by the direction of relative rotation. Relative rotation in one direction causes the rollers to roll up the wedge surface and wedge between the races, engaging the clutch and providing a solid link for the transmission of torque. Rotation in the other direction causes the rollers to roll down the wedge surface, disengaging the clutch for overrunning. This increases the amount of torque the clutch can transmit over that of a ratchet clutch and gives the clutch a nearly infinite number of stop positions.

The final step in perfecting the one-way clutch was the development of the sprag clutch, referred to as a 2-D sprag clutch and shown in Figure 2. It has a cylindrical outer and inner race and a series of specially contoured and processed sprags installed in the annular space between the concentric races.

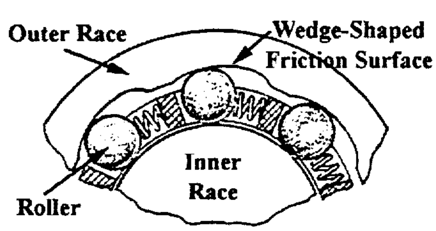

Figure 1: Two-Dimensional Roller Clutch

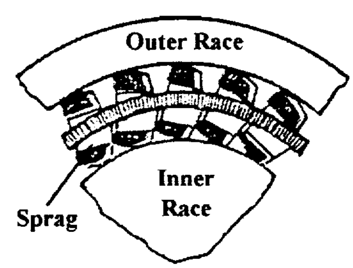

Figure 2: Two-Dimensional Sprag Clutch

Each sprag is designed with a geometry that makes its two diagonals of different length, as shown in Figure 3. One direction of relative rotation between the races causes the sprags to rotate so that the longest diagonal is in contact with the two races. The length of this diagonal is greater than the annular distance between the races, so the sprags are wedged between the races, providing a solid connection for the transmission of torque. Relative rotation between the races in the opposite direction causes the sprags to rotate so that the shortest diagonal is in contact with the two races. Its effective length is such that the clutch is disengaged and free to overrun.

NASA/GSFC was having problems with traditional 2-D sprags while using them in joint brakes for robots. They were attempting to use sprags with large contact angles to increase the frictional holding force, but the sprags kept slipping. In addition, lubricants required to get the 2-D sprags to unlock were off-gassing in a vacuum environment. The solution was to replace the concentric, cylindrical surfaces of the inner and outer races with grooves, into which the tapered periphery of a 3-D sprag (ref. 3) fits, as shown in Figure 4. Locking occurs as a result of the wedging action between the tapered periphery of the 3-D sprag and the grooved race.

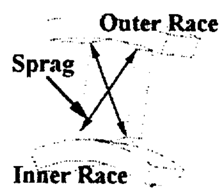

Figure 3: Two-Dimensional Sprag and Races

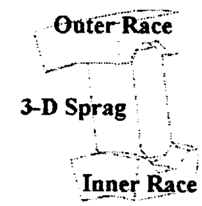

Figure 4: GSFC Three-Dimensional Sprag and Races

The benefits of 3-D sprags over their 2-D counterparts are that they:

- require no lubricants, thus preventing possible slipping in thermal vacuum
- create four point contacts (two between the outer taper of the 3-D sprag and the outer grooved race and two between the inner taper of the 3-D sprag and the inner grooved race) instead of the two line contacts of the 2-D sprag, thus:
    - allowing loose tolerances
    - doubling the number of contact points
    - increasing the locking efficiency
    - allowing larger contact angles, which reduce the level of sprag-to-race contact stress.

Ratchet Wrenches

Ratchet mechanisms have been in use in hand tools since 1847 (ref. 4), and the design has changed very little in the subsequent 150 years. Although the design functions well for use on Earth, as demonstrated by its longevity, it is not ideally suited for use by a space-suited astronaut. Typical problems encountered with traditional ratchet wrenches in space are:

- limited functionality in confined spaces
- high backdrive torque resulting in loosening when tightening is desired
- inability to control high-inertia interfaces
- lubricant evaporation
- user fatigue during repetitive throws of the wrench.

"Ratchetless" Wrench

Based on the previous discussion of the limitations of ratchet wrenches and the evolution of one-way clutches, it seems logical that wrenches should follow the same progression. Attempts have been made to create a "ratchetless" wrench using rollers or sprags (ref. 5), but all have failed due to high contact stresses. During the development of 3-D sprag and roller prototypes, the idea evolved to replace the traditional ratchet mechanism with 3-D sprags and rollers (ref. 6) because they have a lower contact stress than their 2-D counterparts.

The roller mechanism in the wrench uses three pairs of 3-D rollers installed between concentric races, as shown in Figure 5. Each pair is made up of two rollers (labeled A and B), that are connected by a spring. The spring pushes the A and B rollers apart, wedging them between the races, engaging both rollers. A moveable pin is placed between each A/B roller pair. When a pin contacts a roller, it pushes that roller out of the wedged position between the races, thus disengaging that roller. These three pins, which are constrained to move together, can be locked in one of three positions: center, rotated clockwise (CW), or rotated counterclockwise (CCW). When the pins are in the center position, they do not contact either the A or B rollers; all of the rollers remain engaged, allowing the mechanism to apply torque in both directions. Moving the pins from the center position in the CW direction disengages the A rollers of all three pairs. This allows torque to be transmitted in the CCW direction. When the pins are moved in the CCW direction, all of the B rollers are disengaged, and torque can now be transmitted in the CW direction.

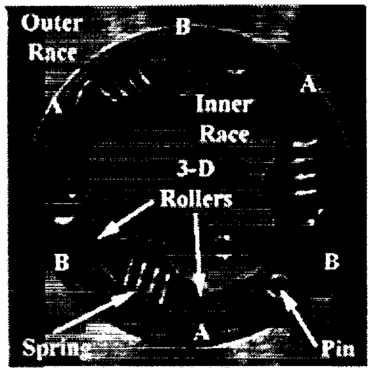

Figure 5: Three-Dimensional Roller Mechanism (pre-flight)

When used in place of the traditional ratchet mechanism, 3-D sprags and rollers result in a wrench that has the following advantages over the traditional ratchet wrench:

- ability to operate down to arbitrarily short backthrows
- low backdrive torque
- ability to apply torque in the clockwise or counterclockwise direction, or to lock out all motion and transmit torque in both directions
- no lubrication requirement, thereby extending on-orbit lifetime
- a compact, simple design
- a higher maximum torque than the equivalently sized ratchet wrench
- a lower perceived mental workload for the EVA subject using the wrench.

SPACE EXPERIMENT MODULE FLIGHT EXPERIMENT

Experiment Design

A 3-D roller mechanism was flown as part of the SEM program in the cargo bay of space shuttle mission STS-95 from October 29 until November 7, 1998. Twenty-one seconds of backdrive and applied torque data were collected every 2 hours. The objective of the experiment was to see how the mechanism operated during seven days in a micro-g environment. The inner and outer races of the mechanism were made of 455 stainless steel. The rollers were made of D7 tool steel and coated with a 0.0001" thick layer of titanium nitride to prevent galling.

At the beginning of a data run, a motor first turned the 3-D roller mechanism in the backdrive direction, free-spinning the mechanism. The motor then reversed, causing the rollers to lock, the motor to stall, and torque to be applied. It then reversed again and continued to free-spin the mechanism. Torque data were collected as the mechanism moved in both the backdrive and applied torque directions. A potentiometer was used to verify that the motor was turning during the backdrive portion and that the roller mechanism did not slip when locked in the applied torque direction. Two thermistors were located inside the module—one on the torque sensor to determine the temperature of the environment inside the module and one on the motor to determine its temperature. The experiment mounting plate onto which these parts were mounted is shown in Figure 6.

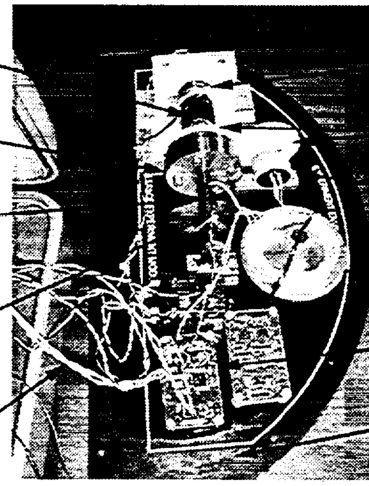

Figure 6: Three-Dimensional Roller Experiment Mounting Plate

Experiment Operation

The experiment operated as follows. The motor turned the 3-D roller mechanism in the backdrive direction for 2 minutes and 49 seconds. Then, for 1 second, it reversed, causing the rollers to lock and the motor to stall, applying 30 inch-pound-force (in-lbf) of torque. It reversed again and continued to free-spin the mechanism for 10 seconds. Twenty-one seconds of backdrive and applied torque data were collected every 2 hours. This consisted of 10 seconds of backdrive torque data before the motor stalled, 1 second of applied torque data while the motor was stalled, and 10 seconds of backdrive torque data after the motor reversed. Position data from the potentiometer and temperature data from both of the thermistors were collected the entire time that torque data were being collected. A sample data run, typical of those that occurred every 2 hours, 10 minutes, and 54 seconds, is summarized in Table 1. A total of 70 data runs were recorded, with all data collected at 5 Hz.

Table 1: Three-Dimensional Roller Experiment Sample Data Run

Time	Event
T = 0m : 0s	Turn on the electronics
T = + 0m : 1s	Turn on the motor
T = + 2m : 40s	Collect torque data
T = + 2m : 50s	Reverse motor
T = + 2m : 51s	Reverse motor again (toward the original direction)
T = + 3m : 1s	Stop collecting data
T = + 3m : 2s	Turn off motor and electronics

Just as with every SEM experiment, the roller experiment had an integrated programmable control circuit board, or module electronics unit (MEU), that provided power, preprogrammed sequencing of the experiment operation, data acquisition, and storage of experiment data. A timeline based on the 70 data runs was generated using a C computer program and stored on the MEU.

Integration, Launch, and On-Orbit Operation

After installation of the experiment's equipment in SEM position 8, the 3-D roller SEM (which was designated experiment 0051), along with seven others, was integrated into the SEM carrier system, as shown in Figure 7. This was then placed into a Get Away Special (GAS) canister, shown in Figure 8. After integration into the GAS canister, the experiment was shipped the Kennedy Space Center, installed on the Spartan flight support structure, and loaded into the cargo bay of *Discovery* (see Figure 9).

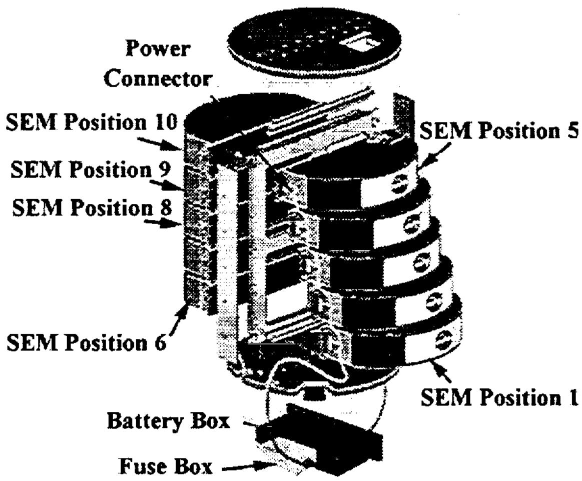

Figure 7: SEM Carrier System (adapted from ref. 7)

Figure 8: Integration of SEM-04 into a GAS Canister (NASA Photo)

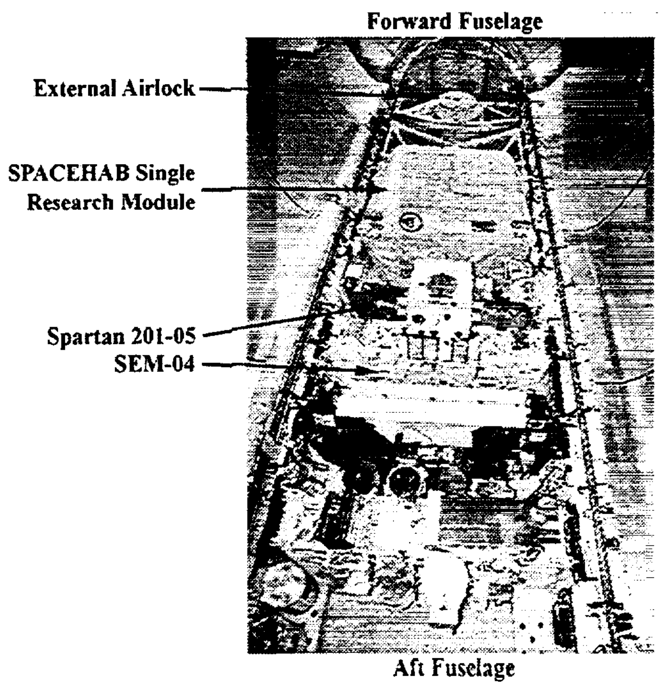

Figure 9: Photo of STS-95 Cargo Bay Layout (NASA Photo)

Launch of STS-95 occurred on October 29, 1998, at 2:19 p.m. EST. SEM-04 was activated at 6 hours, 25 minutes, and 40 seconds after launch (at 8:45 p.m. EST). The timeline ran for 6 days, 6 hours, 45 minutes, and 5 seconds. The experiment stopped running and data collection ceased on November 5 at 3:30 a.m. EST. SEM-04 was deactivated on November 5 at 4:03 p.m. EST (7 days, 1 hour, 43 minutes, and 50 seconds after launch). STS-95 landed on November 7, 1998, at 12:04 p.m. EST, and the experiment was returned to the SSL on December 16, 1998.

Results

The first data run (data run 1) and the final data run (data run 70) are shown in Figures 10 and 11, respectively. The data from the torque sensor are shown as voltages. Backdrive torque is the lower data and applied torque is the data at 5 volts that was chopped off by the electronics. Zero applied torque occurs somewhere in between these two rages.

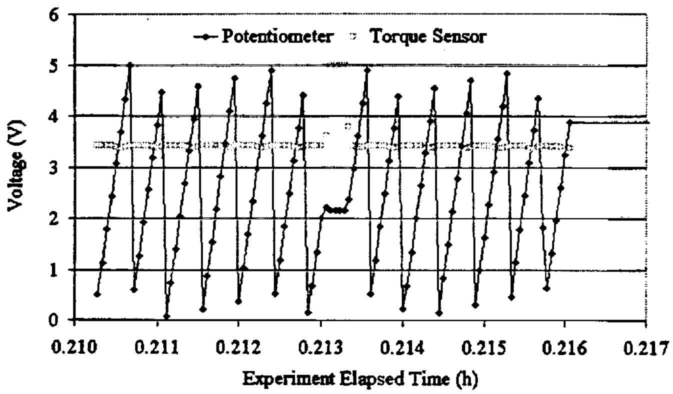

Figure 10: Data Run 1
(started at 12 minutes, 37 seconds)

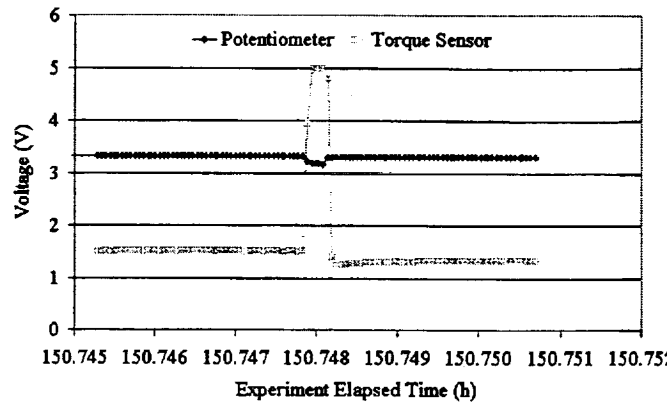

Figure 11: Data Run 70
(started at 6 days, 6 hours, 44 minutes, 43 seconds)

It appears from these plots and an analysis of the rest of the data that the backdrive torque, both during the 10 seconds prior to the mechanism locking and during the 10 seconds following, is relatively consistent over a given data run. As can be seen from Figure 11, the mechanism seized in the backdrive direction toward the end of the mission, as is evident from the flat potentiometer data. In reviewing the torque and potentiometer data over the entire experiment (Figure 12), it can be seen that the mechanism stopped working in the backdrive direction during the 33rd data run (Figure 13). This data run began at 2 days, 21 hours, 58 minutes, and 44 seconds. In data run 33, the potentiometer data show that the mechanism appears to have seized at 2 days, 22 hours, 1 minute, and 32 seconds, during the first backdrive portion. After this event, the potentiometer data flatten out, since the mechanism can no longer move in the backdrive direction. When the motor reverses 2.3 seconds later, the mechanism can be seen to operate correctly in the applied torque direction. The motor reverses again, and the backdrive direction is still shown to be seized. An oscillation in the backdrive torque can be seen in data run 33 prior to the mechanism seizing. The same oscillation can also be seen slightly in data run 1 (Figure 10) and the amplitude of this oscillation increased when the rest of the data runs prior to data run 33 were analyzed. The 34th through 70th data runs show that the mechanism still operated properly in the applied torque direction.

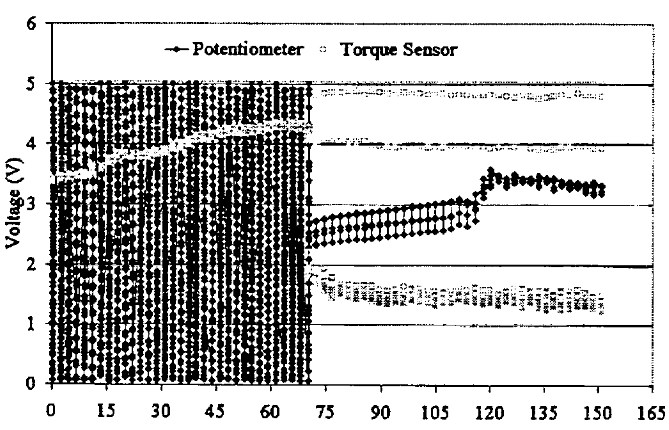

Figure 12: Three-Dimensional Roller Experiment Data

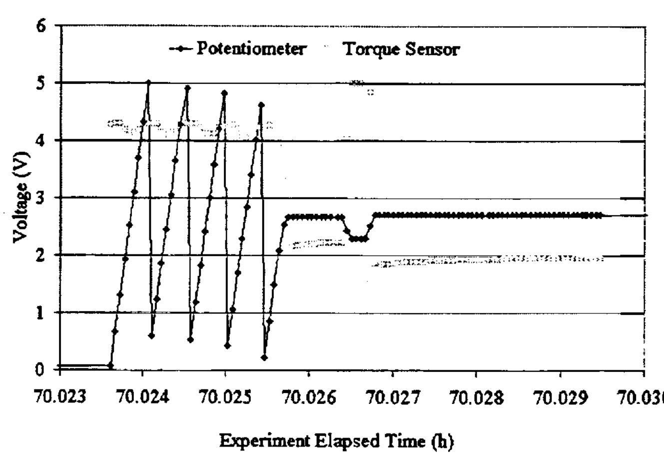

Figure 13: Data Run 33
(started at 2 days, 22 hours, 1 minute, 25 seconds)

After opening up the mechanism, it appears as if one of the rollers came out of the groove and got wedged between the outer race and the side of the inner race, as shown in Figure 14. This is exactly the type of behavior that was observed during preflight tests.

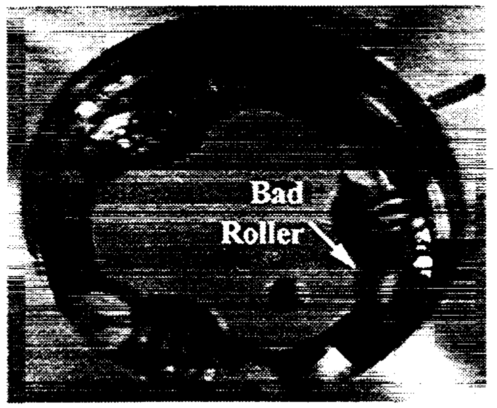

Figure 14: Three-Dimensional Roller Mechanism (postflight)

The temperature data collected on the surface of the motor, when compared with the temperature in the rest of the 3-D roller SEM and other SEMs, indicate that the motor began heating after the 33rd data run. This can be seen in Figure 15, suggesting a stalled motor and/or a seized mechanism. The temperature measurements collected by NASA (ref. 8) were done inside another SEM at position 9 and on the outside of the SEMs in positions 5 and 6.

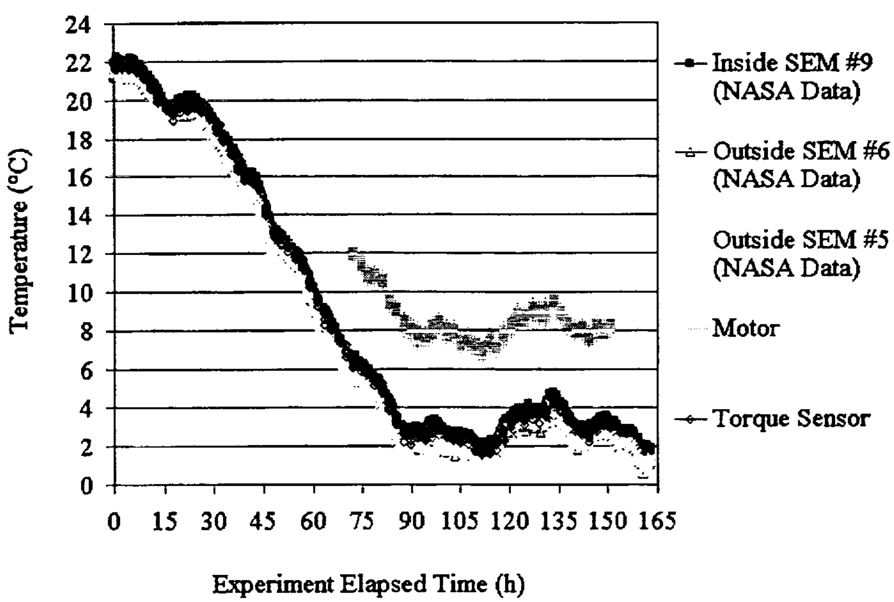

Figure 15: SEM-04 Temperature Data

The battery usage profile collected by NASA for SEM-04, as shown in Figure 16, indicates discharge spikes corresponding to the motor turning on. Not every cycle was captured by NASA's MEU, because battery data were only collected every 5 minutes. Therefore, the timing was sometimes out of phase with the data runs. Comparing the battery discharage voltage over the entire mission further corroborates the conclusion that the motor stalled in the backdrive direction. This is indicated by the increased discharge voltages that occur after the 33rd data run, as compared with those before that run.

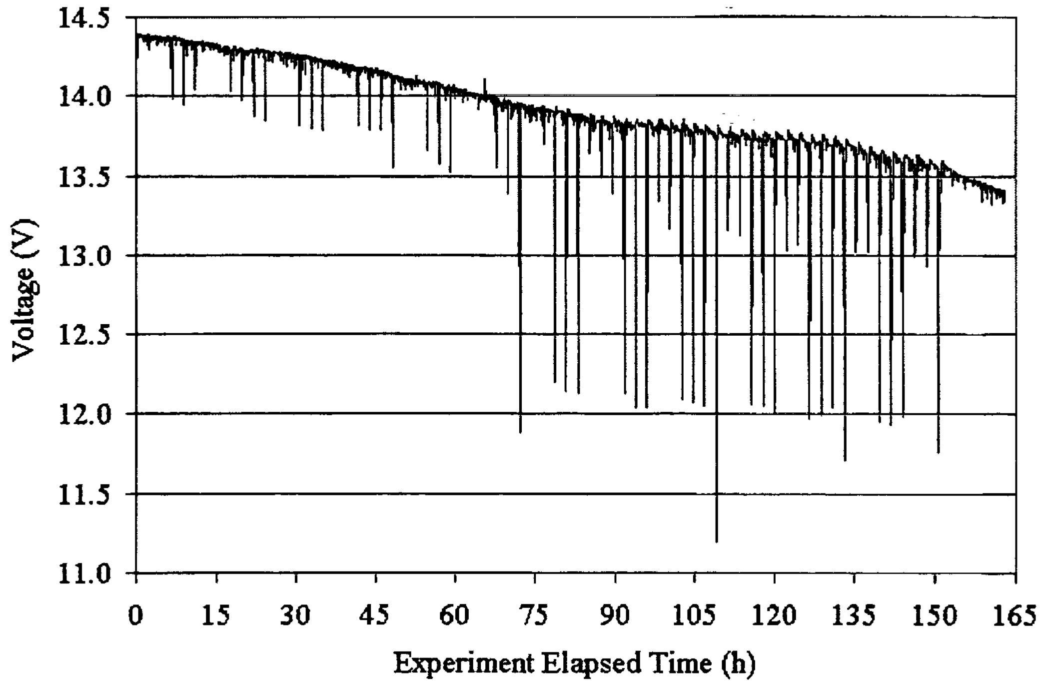

Figure 16: SEM-04 Battery Data

Before the mechanism seized in data run 33, the backdrive torque decreased (high voltage corresponds to lower backdrive torque). This can be seen in Figure 17, which plots the average backdrive torque for each of the 70 data runs.

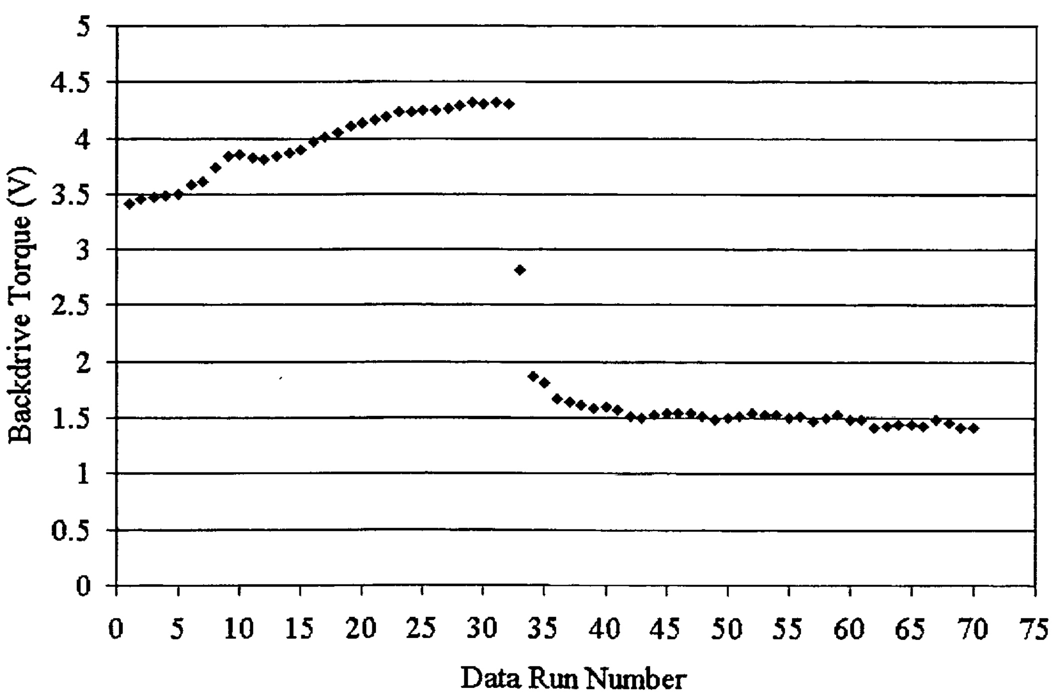

Figure 17: 3-D Roller Experiment Backdrive Torque for Each Data Run

LESSONS LEARNED AND FUTURE PLANS

One set of data that would have been helpful in the analysis is torque collected when nothing was moving. The motor spun the mechanism in the backdrive direction for 2 minutes and 39 seconds before torque data were collected. Before the motor was activated, an entry should have been made in the timeline to collect zero torque data during each data run. In addition, the required delivery date of the experiment was moved up by one month, which prevented an intensive series of ground tests of the mechanism. If the experiment is flown again, a series of ground tests should be run to collect baseline data and to catch potential problems with the operation of the mechanism early enough to make modifications. Because of the problem with the roller coming out of the groove, the inner hub has been redesigned with deeper grooves, which provide more metal above and below the rollers, helping to prevent them from coming out of the inner race. It is the hope of the team that the redesigned 3-D roller mechanism will refly on a future shuttle flight.

Using the technology discussed in this paper, an EVA wrench has been built using 3-D rollers in place of the ratchet. This wrench has been verified in two different simulations of the weightless environment of space—the KC-135A Reduced-Gravity Flying Laboratory and the NASA/Johnson Space Center's Neutral Buoyancy Laboratory (NBL). However, both of these simulations have limitations. Although the KC-135A is a good simulation of the "free-fall" feeling of spaceflight, it is limited in duration to around 25 seconds at a time. The NBL provides a good long-duration simulation of the weightlessness that an astronaut will feel, but because the wrench is not neutrally buoyant, its true performance in a weightless environment cannot be measured. The SEM experiment quantified the roller mechanism's performance when operating for an extended period in a micro-g environment. By using a combination of these results, it is hoped to further prepare the 3-D sprag and roller technology for extensive use in aerospace mechanisms and EVA tools by space-qualifying its geometry.

For a complete summary of the development and evaluation of the roller wrench, see reference 9 or visit http://wrench.ssl.umd.edu

SYMBOLS AND ABBREVIATIONS

2-D	two-dimensional	ISS	International Space Station
3-D	three-dimensional	MEU	module electronics unit
CCW	counterclockwise	NASA	National Aeronautics and Space Administration
CW	clockwise	NBL	Neutral Buoyancy Laboratory
EVA	extravehicular activity	SEM	Shuttle Experiment Module
GAS	Get Away Special	SSL	Space Systems Laboratory
GSFC	Goddard Space Flight Center	STS	Space Transportation System
in-lbf	inch-pound-force		

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