DEVELOPMENT AND QUALIFICATION OF A MODULAR DRIVETRAIN UNIT

18th Space Mechanisms and Tribology Symposium 2019

Wieland Bertleff, Dr. Armin Wedler, Dr. Josef Reill

DLR RMC, Wieland Bertleff (Germany), Email: wieland.bertleff@dlr.de; www.dlr.de/rm/en
DLR RMC, Dr. Armin Wedler (Germany), Email: armin.wedler@dlr.de
DLR, Dr. Josef Reill (Germany), Email: josef.reill@dlr.de

Abstract

This paper presents the development and qualification process of DLR's permanent magnet synchronous motor/gear DriveTrain unit (DT38). Based on a plurality of laboratory tests and experiences in space missions like ROKVISS, SPACEHAND [4] or MASCOT, the unit was further developed and tested for upcoming space missions [1]. The robust and reliable DT38 unit has to cope with extreme environmental conditions like dusty or sandy terrain, large temperature differences and radiation.

For the qualification the drivetrain unit went through a radiation and shaker test as well as a thermal-vacuum analysis. The paper gives an overview on the results.

Motivation

With the rising interest in lunar and mars robotic exploration or on orbit servicing [7] the need for modular drive units that can be used in a very versatile way for rover locomotion and pan-tilt mechanisms is increasing. A common mission goal is to investigate on the soil of celestial bodies in-situ or sending a sample back home to earth. Therefore multiple mechatronic solutions like robotic arms, positioning devices for scientific instruments, soil crushing tools or dexterous manipulators need to be realized.

In exploration missions the pre-arrival information about the surface structure of planets, moons or asteroids is often very limited. The spectrum varies from rocky to sandy ground conditions. Especially regolith is known for its abrasive particles that may pose a threat for seals and moving parts.

Considering these facts, robotic exploration systems demand for multiple actuator units. NASA's MSL rover is a very good example for this as it contains different sized actuators for numerous applications.

DLR's Robotic and Mechatronic Institute (RMC) developed the Light Weight Rover Unit (LRU) as a platform for autonomous exploration. This robotic platform was used during Spacebot-Camp operation [5] and ROBEX analogue mission campaign [6].

Fig. 1 shows the LRU during the ROBEX demo mission campaign on Mount Etna, Sicily.

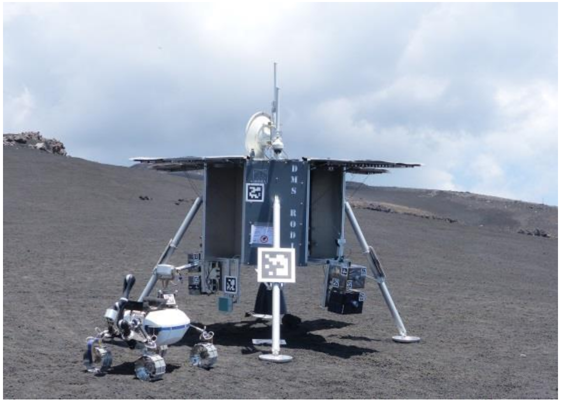

Figure 1: Demo Mission Space (DMS) on Mount Etna, Sicily

Wide Range of Applications

To cope with harsh environmental conditions a drivetrain unit was developed in a modular, sophisticated functional unit.

The concept may be scaled to half or double the mechanical power output, satisfying most of the mission needs in robotic exploration.

Ten drivetrain units are installed in the LRU. *Fig. 2* shows the use case as locomotion, steering and body orientation drive units.

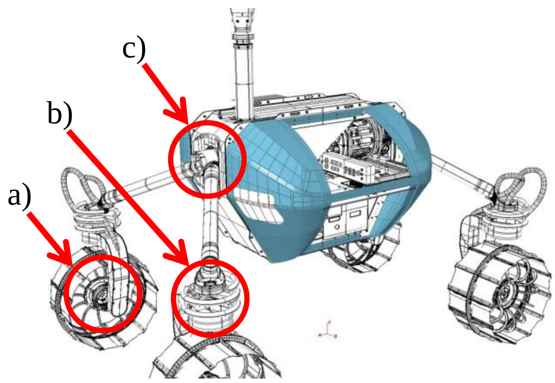

Figure 2: Applications of the DT38 Units

a) Driving units
b) Steering units
c) Spring/damper units for body control

Due to its very compact design the DT38 can be used as a hub drive designed to enable rover speeds of 1 m/sec. The size of the unit is about 80 mm x 70 mm x 65 mm with a weight of only 350 grams. At the same time the drivetrain unit can generate a torque up to 11 Nm.

For the application as steering unit an external end stop is attached to avoid a wind up of the motor cables. The unit itself is rotatable and therefore versatile in use.

The same unit is also used for orienting the rover body in rough terrain to optimize driving performance when traversing obstacles or driving a slope. To prevent shock loads from the body the DT38 is combined with a spring damper combination, the so called Serial Elastic Actuator (SEA) unit, which allows to control the rover body in a range of 30°.

The LRU makes use of a stereo camera system as a perception unit that takes care of path planning and obstacle avoidance. This is mounted to a pan-tilt device (see *Fig. 3*) with actuators in small scaled version (DT25 unit).

Figure 3: Pan/Tilt Unit of the LRU

For the pan-tilt application only reduced actuation power is needed and therefore a smaller unit can be used. Nevertheless the concept of the unit is similar and actually flight proven. MASCOT [2] and [3] a small (28 x 29 x 21 cm and 9.8 kg) asteroid lander was equipped with one of these small actuators to enable relocation on asteroid surface at very low gravity. The lander was a DLR contribution to JAXA's Hayabusa2 mission to asteroid Ryugu. It was launched on 3rd of December 2014 and reached the asteroid in summer 2018. The MASCOT landing took place on 3rd of October 2018. In about 17 hours of operation on asteroid surface the lander did relocate and upright to nominal orientation to position the scientific instruments properly. The actuator showed excellent behavior and proves that the concept of the design is appropriate for space applications.

Drivetrain Unit – Interior

The DT38 makes use of a permanent synchronous brushless DC motor (BLDC) as this is a robust and reliable actuator principle. The attached Harmonic Drive® (HD) gearing shows low backlash and makes up a powerful, precise and robust overall system.

Fig. 4 depicts the main parts of the unit. These are: an output position sensor (e.g. potentiometer), a Harmonic Drive gear, a space qualified permanent magnet synchronous brushless DC motor and a commutation sensor PCB based on digital hall sensors.

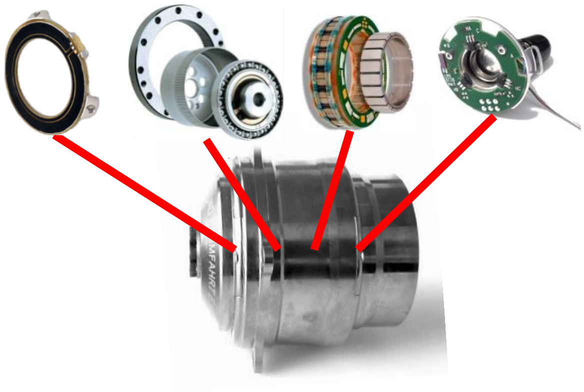

Figure 4: DT38 Unit - Interior

Due to the reduced number of moving parts compared to DC motors the actuator shows increased reliability. Additionally the motor principle offers great ability to overload the motor for short time. Considering friction stick-slip effects this is a remarkable advantage. The motor stator windings are connected thermally to the motor housing. This is beneficial for cooling the unit.

On the MASCOT mission the lubrication of the output shaft ball bearing is achieved by a combination of stainless steel rings, peek bearing cages and ceramic balls. This solution complies with a non-metallic/metallic combination that prevents cold welding. For the gearing bearing no hybrid ball-bearing could be found in the appropriate size. Therefore MoS2 lubrication was used there and on the gear teeth. Finally a DICRONITE® DL-5 coating was applied to the Harmonic Drive® wave generator bearing. It is of strong importance that mobility in MASCOT is no continuously running application. This is why DT38 is lubricated with Braycote® without DICRONITE® coating applied.

Performed Qualification Steps

After running the units on many laboratory test sites and performing the Etna Demo Mission, next step was to increase the TRL 3 up to TRL 6 by starting a qualification campaign.

To prepare hardware for an extraterrestrial mission the following tests have to be fulfilled.

- Performance tests
- Thermal-Vacuum tests
- Vibration tests
- Radiation tests

The results of these tests were already described in [8]. In the following some investigations, regarding the temperature behavior are described.

Most Relevant Test Results for Space Applications

Thermal-Vacuum test for lubricant investigation

As already mentioned in the first chapter, temperature plays a significant role during rover missions on celestial bodies. Significant variations in temperature can affect electronical parts, forces mechanical stress or change for instance the chemical characteristic of lubrication.

Therefore the two drivetrain units went through several thermal-vacuum tests. One of these units was lubricated with Braycote® and Fomblin oil and the other to industrial specification with Flexolub A1®. Of course for the Braycote® a minimal quantity lubrication was used as recommended by the manufacturer, the Harmonic Drive® company.

This test shall demonstrate the differences of the lubricants. Both drivetrain units were installed in the same way to the TV chamber thermal plate and a vacuum of 10^{-4} bar was generated.

With a step size of 10 degree, the temperature then was changed from -20°C up to +50°C whereby at each step a unit functional test was performed by recording the current as a function of the motor-revolution.

Fig. 5 shows the results of the lubrication test. As expected, both lubricants become more viscous at low temperatures characterized by a higher current consumption.

Both graphs also show the typical increasing of the current with the revolution. However, at low temperature this current value decreases with a rising motor revolution, which may indicate a heating effect in the gear and therefore in the lubrication.

In conclusion the Braycote® unit consume 1 ampere more current for the same revolution of the unit.

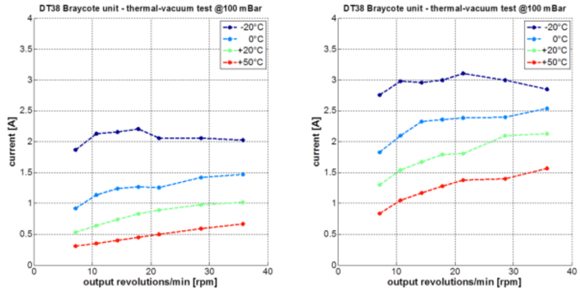

Figure 5: TV Test Results for Lubrication

Low Temperature Test for Commutation Sensor

Another important question is the behavior of the commutation sensor at very low temperatures. With the upcoming mission Martian Moon Exploration (MMX), the requirements for a drivetrain started to become even more critical.

Due to the lack of missing requirements regarding the temperature for the mission to the martian moon, a value of -120°C must be considered as a worst case. As the rover cannot be operating during such deep temperatures, the hardware at least has to survive such environmental conditions.

The most critical electronic part inside the motor unit was the commutation sensor which is build up with digital hall sensors.

The data sheet of these hall sensors guarantee their functioning down to -40°C. So the next measurement took place in a thermal chamber were a temperature of -75°C could be reached to bring the electronic to its limit.

Since a vacuum would not probably show any influence on this test, it was decided to use the thermal chamber instead of the thermal vacuum test site. Therefore a DT38 unit was installed to the thermal test facility seen in *Fig. 6*.

Figure 6: Low Temperature Test

The drivetrain unit was under power during the entire test. The sensors worked as described by the manufacturer, at -40 degree so it was decided to go on and decrease the temperature.

It turned out, that when reaching a temperature in the range of -60 degree, all hall sensors shown a faulty behavior. After rising the temperature above the -55 degree level, the hall sensors returned to their original state and functionality.

Further tests confirmed these results, so this process obviously is reversible. *Fig. 7* depicts the switching of the sensors.

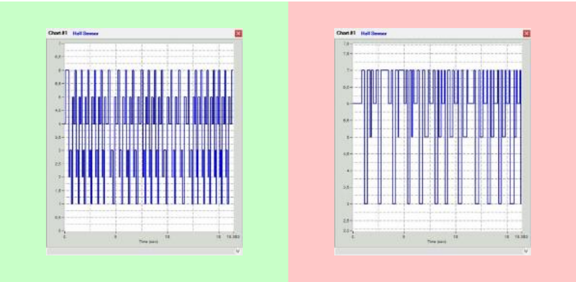

Figure 7: Switching behavior of the Hall Sensors

Next step is the investigation about the survivability of the sensors at even lower temperatures and under thermal cycling. For this test a number of 100 digital sensors have to run through 100 thermal cycles, reaching from -130°C to +60°C. During this test the parts are passive and under nitro atmosphere. At regular intervals some of the samples are removed for a functional test. The temperature rate is defined to a value of 1.6°C/min. This value is derived from the mars moon *Phobos* and its day/night cycle.

This test is currently running and shall confirm the usability of the commutation sensor for upcoming challenging missions.

Radiation Tests

For motor commutation the DT38 unit includes three digital Hall sensors, which are identified as critical components concerning radiation. With respect to an envisaged lunar pole mission, a radiation dose of 700 Gy was defined for the qualification of the DT38 unit.

Figure 8: Radiation Test Facility, Berlin

According to ECSS standards for qualification a lot of nine Hall sensors have to pass a destructive test. The result is the radiation level. *Fig. 8* shows the radiation test facility at the Helmholtz Center Berlin Wannsee, were a radioactive Co60 source (gamma emission) is available. The radiation source is put in the center and the three test-boards are positioned radial in defined distance.

The interface board generates the trigger signals for the Hall sensors and monitors the supply current, see block diagram in *Fig. 9*. A triangular current with a one Hertz frequency is used as a trigger signal for the Hall sensors. This current stimulates coils which are located close to the Hall sensor and applies a magnetic field to the sensor see *Fig. 10*: blue graph: coil current; green graph: switch signal Hall sensor).

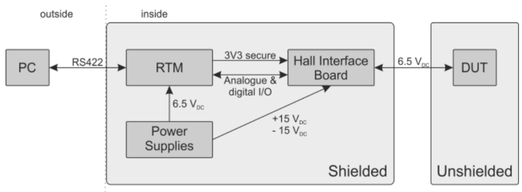

Figure 9: Radiation Test Setup

A damage of a Hall sensor can be recognized in an altered switching threshold.

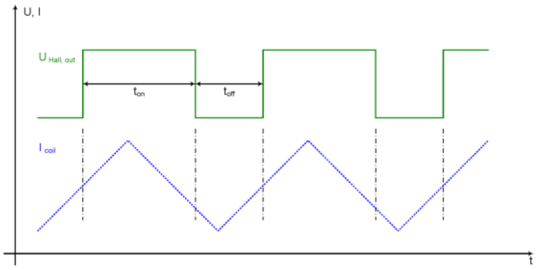

Figure 10: Hall sensor output signal (green) and exciting current of the magnetic coil (blue)

Conclusion

The DT38 unit was developed, tested and qualified at the DLR's RMC. It turned out, that the compact and powerful drivetrain unit is a robust and reliable component, suitable for a large number of applications in the field of planetary exploration rover.

A couple of DT38 units were prepared for space flight and went through a series of tests to prove its technical competence. Radiation tests, thermal-vacuum tests and vibration tests were conducted successfully. In parallel the design concept was successfully used in MASCOT mission.

Outlook

Future missions will focus on investigation on celestial bodies at several points of interest that may be spread over many square kilometers. Therefore a load- and duration test is currently ongoing to ensure the capability of a long-term rover mission. Considering a heavy rover with a weight of 30kg and full of scientific instruments, this test seems to be very important.

References

1. A. Wedler, M. Chalon, K. Landzettel, M. Görner, E. Krämer, R. Gruber, A. Beyer, H.-J. Sedlmayr, B. Willberg, W. Bertleff, J. Reill, M. Schedl, A. Albu-Schäffer, and G. Hirzinger, "DLRs dynamic actuator modules for robotic space applications," in Proc. of the 41st Aerospace Mechanisms Symposium (E. B. L. M. Space) and S. L. (NASA), eds.), no. 41 in Aerospace Mechanisms Symposium, Passadena – Hilton-JPL, USA, 2012

2. T.-M. Ho, V. Baturkin, R. Findlay, C. Grimm, J.-T. Grundmann, C. Hobbie, E. Kesnik, C. Lange, K. Sasaki, M. Schlotterer, M. Talapina, N. Termtanasombat, E. Wejmo, L. Witte, M. Wrasmann, G. Wübbels, J. Rößler, C. Ziach, J. Biele, C. Krause, S. Ulamec, M. Lange, O. Mierheim, R. Lichtenheldt, M. Maier, J. Reill, H.-J. Sedlmayr, P. Bousquet, A. Bellion, O. Bompis, C. Cenac-Morthef, M. Deleuze, S. Fredon, E. Jurado, E. Canalias, R. Jaumann, J.-P. Bibring, K. H. Glaßmeier, M. Grott, L. Celotti, F. Cordero, J. Hendrikse, T. Okada, "MASCOT - the mobile asteroid surface scout onboard the HAYABUSA2 mission" Space Science Reviews, volume 208, Springer, July 2017. https://link.springer.com/content/pdf/10.1007%2Fs11214-016-0251-6.pdf.
3. J. Reill, H.-J. Sedlmayr, P. Neugebauer, M. Maier, E. Krämer, R. Lichtenheldt, "MASCOT - Asteroid Lander with innovative Mobility Mechanism", 13th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), ESA/ESTEC, Noordwijk, Netherlands, May 2015. http://robotics.estec.esa.int/ASTRA/Astra2015/Papers/Session%202A/95807_Reill.pdf
4. M. Chalon, M. Maier, W. Bertleff, A. Beyer, R. Bayer, W. Friedl, P. Neugebauer, T. Obermeier, H.-J. Sedlmayr, N. Seitz, A. Stemmer, "SPACEHAND: a multi-fingered robotic hand for space", 13th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA), ESA/ESTEC, Noordwijk, Netherlands, May 2015. http://robotics.estec.esa.int/ASTRA/Astra2015/Papers/Session%206A/95690_Chalon.pdf
5. M. Schuster, S. Brunner, K. Bussmann, S. Büttner, A. Dömel, M. Hellerer, H. Lehner, P. Lehner, O. Porges, J. Reill, S. Riedel, M. Vayugundla, B. Vodermayer, T. Bodenmüller, C. Brand, W. Friedl, I. Grixa, H. Hirschmüller, M. Kaßecker, Z.-C. Marton, C. Nißler, F. Ruess, M. Suppa, A. Wedler, "Towards autonomous planetary exploration" Journal of Intelligent & Robotic Systems, November 2017. https://doi.org/10.1007/s10846-017-0680-9
6. Wedler, M. Vayugundla, H. Lehner, P. Lehner, M. Schuster, S. Brunner, W. Stürzl, A. Döml, H. Gmeiner, B. Vodermayer, B. Rebele, I. Grixa, K. Bussmann, J. Reill, B. Willberg, A. Maier, P. Meusel, F. Steidle, M. Smisek, M. Hellerer, M. Knapmeyer, F. Sohl, A. Heffels, L. Witte, C. Lange, R. Rosta, N. Toth, S. Völk, A. Kimpe, P. Kyr, and M. Wilde, "First results of the ROBEX analogue mission campaign: Robotic development of seismic networks for future lunar missions", 68th International Astronautical Congress (IAC), Adelaide, Australia, September 2017. paper no.: IAC-17-A3.IP.31.
7. R. Bayer, W. Bertleff, A. Beyer, B. Brunner, R. Burger, J. Butterfass, M. Grebenstein, R. Gruber, G. Grunwald, T. Gumpert, F. Hacker, M. Heumos, E. Kraemer, M. Maier, S. Moser, J. Reill, M. Schedl, H.-J. Sedlmayr, N. Seitz, M. Stelzer, A. Stemmer, G. T. Manteiga, T. Wimmer, A. Albu-Schaeffer, "CAESAR: Space Robotics Technology for Assembly, Maintenance, and Repair", 69th International Astronautical Congress (IAC), Bremen, Germany, October 2018. paper no.: IAC-18.D1.6.3x42634.
8. W. Bertleff, A. Wedler, J. Reill, A. Maier, B. Willberg, H.-J. Sedlmayr, P. Kyr, „Modular Mechatronic Component Development", 69th International Astronautical Congress (IAC), Bremen, Germany, October 2018. paper no.: IAC-18.C2.5.1x47290.