THE NANOKHOD MICROROVER – USING STATE OF THE ART TECHNOLOGY FOR ACCESSING PRISTINE SITES OF SCIENTIFIC INTEREST ON THE MOON

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1. ABSTRACT

Further exploration of the Lunar surface and accessing extreme environments like polar regions, crater slopes, or even lava tubes state one of the most recent international activities and scientific investigations for planetary robotics. Technological advances, limited resources and a high degree of complexity reasons the efforts in the application field of robotic micro systems and advanced mobility concepts in particular. Since 2015, the University of Stuttgart`s Institute of Space Systems and the company von Hoerner & Sulger GmbH (vH&S) are focussing on various development aspects for a future application of the Nanokhod Microrover for versatile Lunar surface mission scenarios, thus continuing previous development phases of the Nanokhod Microrover within ESA`s BepiColombo mission to Mercury (MRP). As designed for the MRP Mission, the Nanokhod Microrover provides a constant Tether connection towards another surface element for payload data exchange and power supply of the rover. Since a long term application of the Nanokhod for a future Lunar mission is anticipated, several investigations and subsystem developments have been performed. This paper presents the recent development activities of the University of Stuttgart (US) and vH&S, pointing out technological developments and describing the benefits from connecting space industry, research and education. For a new development phase of the Nanokhod Microrover, five major development activities shall be covered in this paper (sketched in Fig. 1): the new design of the four similar, sealed, high-performance micro drives unit of the rover (chapter 3), the development of a new Tether Recoil Mechanism with a contactless power and data transfer (chapter 4), the implementation of a 100 m long ECSS qualified coaxial Tether for power and data transfer with the respective rover- and lander-sided transformation and interface modules (chapter 5), the development of a multi-mission deployment and operation bay for first analogue missions and the implementation and testing of commercial of the shelf sensory components within a new laboratory model of the rover (chapter 6). Also, capabilities of the Nanokhod rover and possible mission scenarios shall be presented.

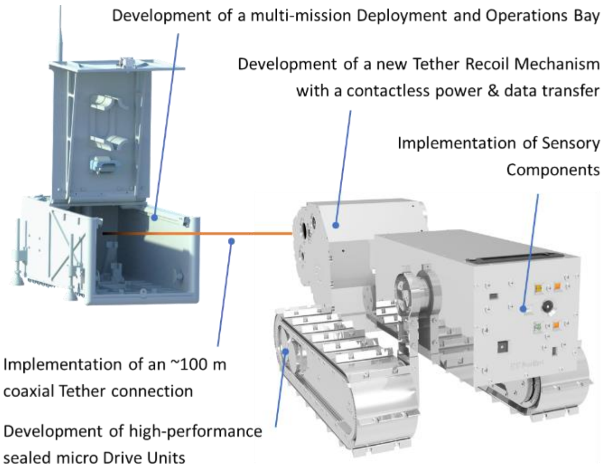

Figure 1: Recent development activities on the Nanokhod Microrover (sketched)

2. NANOKHOD MICROROVER

The Nanokhod Microrover mission scenario foresees a tethered connection between the rover and another surface element. Via the tether the power supply of the rover as well as command and data transfer are realised. Using these synergies, a high payload fraction can be obtained, making the Nanokhod a very versatile mobile complement to almost every surface exploration mission [1]. The Nanokhod Microrover (Fig. 2) consists out of five major subsystems: the central Payload Cabin (PLC) housing the scientific payload instruments (1), two individually driven track drive units (Locomotion Units) for surface mobility (2,3), the Tether Unit (TU), which provides the interface for power supply and data exchange (4), as well as the lever systems (5), one for active positioning of the PLC, one passively connected to allow harness routing between PLC and the Tether Unit. The MRP system had with a total mass of ~3,2 kg, including 1 kg of possible payload mass. The peak power consumption of the system reached roughly 6 W. The Rover was initially designed fulfilling the harsh environmenal requirements on the surface of Mercury for a mission duration of around 14 days. For this, a passivley deployed 50 m long Tether connection with slip ring interfaces between the Tether spool and the electronics interface was selected as a suitable solution.

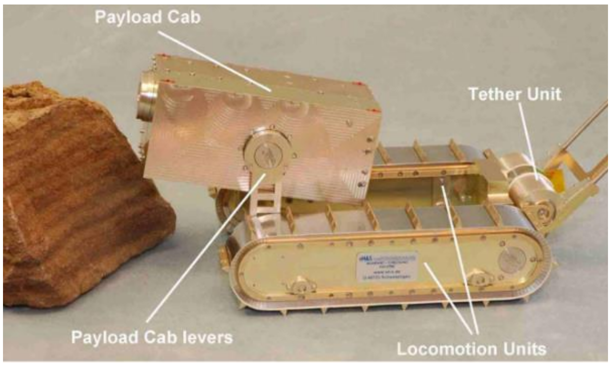

Figure 2: Nanokhod Microrover Design for MRP (Image by vH&S)

For a future longterm Lunar surface application the synergies of the tethered rover configuration were analysed, in order to investigate in key capabilities like the access of pristine locations within challenging environments.

3. NANOKHOD DRIVE UNIT DESIGN

Planetary robotics face the inhospitable presence of sharp edged, abrasive and microscopic regolith particles. Therefore, dust-mitigation was one of the major development topics for the Nanokhod locomotion system redesign. The two independently driven track drives of the Nanokhod provide excellent tractive performance for especially small sized rover systems, thus facing a higher complexity and criticality in terms of blockage. The rover features four drive units in total, two for control of the two track drives (allowing skid-steering and point-turn movements), one for elevation control of the lever, and one for a 360° rotation inside of the PLC. The two drive units for operating the PLC and the Lever shall allow a positioning accuracy of below 1°, and provide a possible surface pressure contact of at least 1 N (Fig. 3).

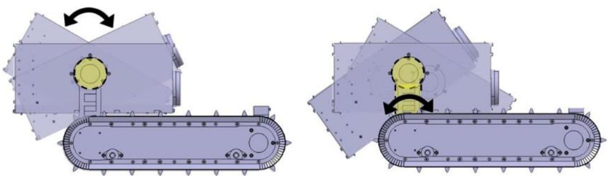

Figure 3: Drive Unit functionalities for PLC and Lever movement (sketched)

In order to reduce the system complexity and efforts in verification, all four drive units are designed in a similar configuration and shall feature commercially available components wherever applicable. For a long-term operation of the rover, a new, sealed, miniaturised drive-unit design was developed and tested. The new drive units combine multiple transmission stages and state-of-the-art technologies (e.g. small sized Harmonic Drive gears, dry operated hybrid ball bearings, as well as the possibility of implementing space modified brushless DC actuators). A new structure design allows both, a secondary sealing stage and an effective modular integration within the highly integrated locomotion units (Fig. 4). Amongst others, five main drivers for the drive unit design within the locomotion units are to be mentioned: very high volume restrictions (below 25 x 40 mm in width and height), demanding output torque performance requirement (above 3 Nm), increased output speed (over 3 m/h rover speed), low power consumption (below 6 W), as well as the possible space modification and utilisation (materials, lubrication, etc.) for a long term application.

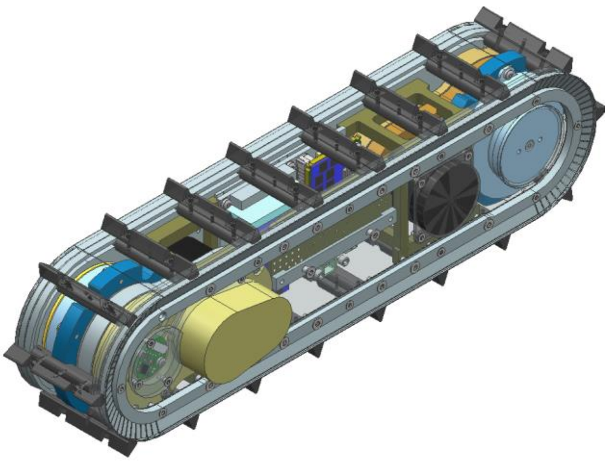

Figure 4: Exposed left-side Locomotion Unit (sketched), featuring the two drive units, Track Drive Unit and Lever Drive Unit and the spring-driven sealing membrane

Fig. 4 shows the exposed left side Locomotion Unit, featuring the two highly integrated drive units (Track Drive Unit and Lever Drive Unit), as well as structural components and required control electronics. The MRP activities showed, that a demanding sealing capability is required, in order to prevent critical regolith contamination of components located on the inside of the locomotion unit. Therefore, an optimised two-stage sealing concept was elaborated: a circumferential spring-enforced PTFE Sealing membrane (MRP heritage), and a secondary full-sized encapsulation and sealing of the drive units. The thin copper-beryllium springs are constantly pushing the custom-designed PTFE membrane against the track foil, thus providing constant tension on the tracks and a low-friction sealing against larger particle blockage.

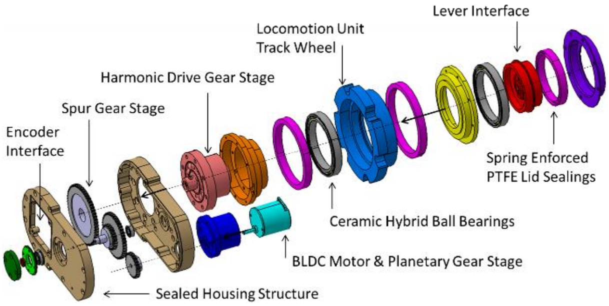

Figure 5: Lever Drive Unit schematics and integration principle sketched

For the secondary stage, a new redesign of the drive unit mechanism was elaborated. Besides preventing particle contamination of the highly sensitive components like the Harmonic Drive, spur gear and deep groove ball bearings, a modular integration of the complete drive unit assembly is possible, allowing advances in testing and inspection possibilities prior to a final integration into the locomotion units. To seal all outlying rotary output shafts connected to the actuated components (Track Wheel or Lever Interface), stainless steel spring-enforced micro Lid-Sealings were elaborated together with BalSeal Engineering. The chosen materials shall allow high-vacuum as well as deep-temperature applications. A sketch of the miniaturised multi-stage drive unit assembly is shown in Fig. 5. For breadboard modelling of the first Nanokhod Laboratory Model, commercially available components without specific space product documentation (e.g. for the Harmonic Drive Gears and the Actuators) were chosen.

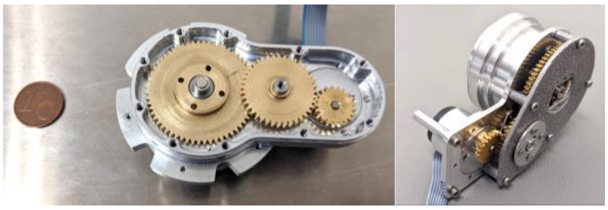

Figure 6: Development of a new type of sealed high-performance micro drive units

For the initial design, a commercially available brushless micro-motor from Faulhaber was implemented. Along with the development of the Nanokhod Tether Mechanism (see chapter 4), a new, fifth, actuator is implemented into the Nanokhod Microrover system. In order to meet the requirements and follow the “design philosophy”, together with Maxon Motor a suitable micro actuator solution was elaborated for future applications, which was derived from the successful heritage of the Mars 2020 actuator developments from Maxon Motor and NASA [2]. The analytical performance characteristic for a final Nanokhod Drive Unit Actuator can be summarized in Tab. 1, thus featuring high margins regarding output-torque performance and the feasible overall rover locomotion speed (values for nominal operation). For the components, a full sealing concept as well as a future space-suitable modification possibility could be achieved.

Table 1: Estimated Drive Unit Performance Characteristics

	BLDC Actuator & Gear Head	Spur Gear Transmission	Harmonic Drive HFUC-8-100	Track Wheel Output
Ratio	1 : 12	1 : 4,68	1 : 100	-
Efficiency	0,59	0,85	0,5	-
Velocity	667 rpm	142 rpm	1,42 rpm	13,42 m/h
Torque	26,76 mNm	106,46 mNm	5323 mNm	5323 mNm

For functional tests the initial COTS drive unit version (Fig. 6) were integrated into the new Nanokhod Laboratory Model (Fig. 7), while motor currents and turning speeds where measured. First locomotion system tests (operation of two synchronized track drive motors) showed a low average power consumption of ~0,95 W for a nominal motor turning speed of 5000 rpm (solid flat surface in laboratory environment under Earth gravity).

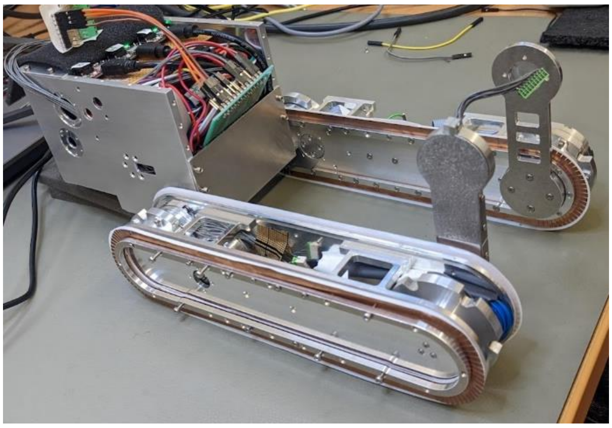

Figure 7: Integration setup of first Nanokhod Laboratory Breadboard model

Ongoing investigations focus on a more advanced analytical model for the Nanokhod Rovers’ soft soil operation, thus respecting the drawbar pull performance characteristics. Future tests within the Institutes small-sized Lunar Analogue test environment (see [3]) are planned in order to investigate the sealing quality of the two-stage sealing solution

4. NANOKHOD TETHER MECHANISM

The Nanokhod Tether Mechanism (NTM) summarizes a recent technology development funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) via the German Space Agency (DLR). The mechanism shall allow a controlled recoil and deployment of the 100 m long Tether, thus allowing a significant increase of the exploration area and providing required capabilities for a long-term mission scenario [3].

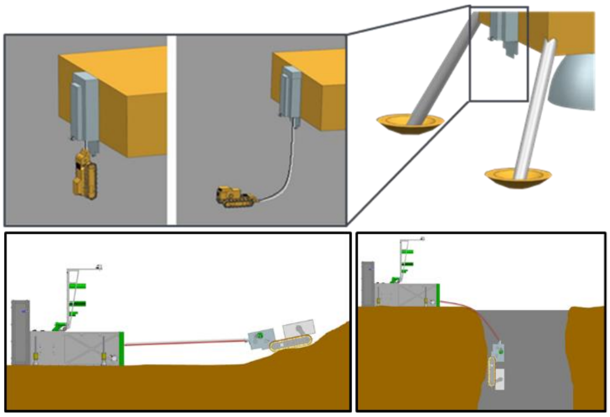

Figure 8: Additional operational scenarios provided by using a Tether spool mechanism (Studies at the University of Stuttgart)

In the cooperative development, vH&S and the University of Stuttgart elaborated an innovative solution covering technological miniaturisation, Tether tension-monitoring, mitigation of regolith particles on the Tether, as well as an efficient method of simultaneous power and data transfer via several transformation modules. Besides these technological advances, synergies for new operational modes of the Nanokhod Microrover were investigated, such as a Tether-sided assist in accessing steep crater slopes up to vertical deployment into skylights and collapsed lava tubes. Also, an independent deployment from another surface element is considered to be a suitable scenario, defining various design requirements for the NTM (sketched in Fig. 8). The development of the NTM lead to an in-depth impact investigation on the Nanokhod Microrover system, affecting both, the overall rover configuration and subsystem interfaces, as well as the impact towards new operational concepts of the rover. For the development, an iterative design process starting with concept studies, a detailed design layout, as well as manufacturing, integration and testing activities of the new mechanism were undertaken (shown in Fig 9). For this development, existing design solutions of the new Nanokhod Microrover Laboratory Model, defined components, materials etc. were adapted wherever possible, and best-practice solutions applied. Also, specifically space suitable components were taken into account.

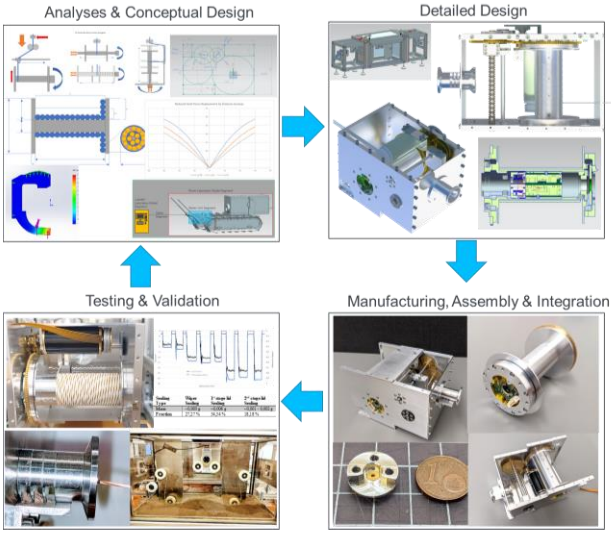

Figure 9: Development and testing of a miniaturised Tether-Recoil Mechanism (NTM) for the Nanokhod Microrover

The NTM features five major subsystems: the Sealing Unit, the Spool Module, the Tether Tension Module, as well as the Level Wind Module and the Actuation & Transmission Module [2]. High efforts were put into the realisation of a high degree of miniaturisation and in order to allow a controlled orthocyclic layering of the over 900 windings, also whilst enabling a sealing solution against regolith particles adheased to the Tether. Fig. 10 shows the functional principle of the NTM in a sketched configuration.

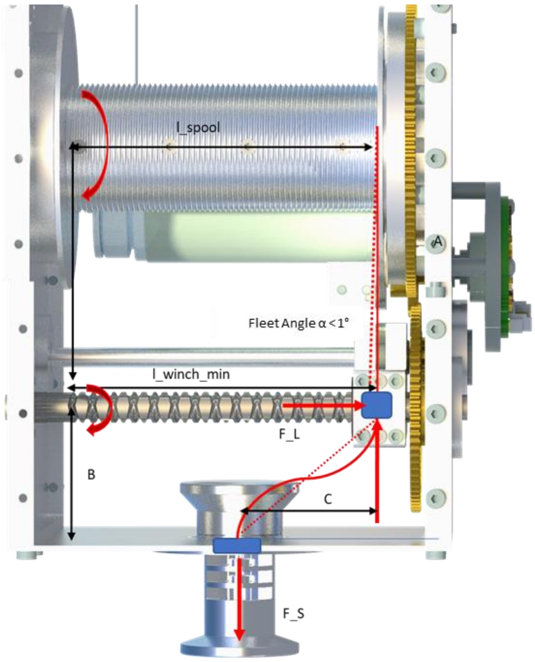

Figure 10: Functional principle of the Nanokhod Tether Mechanism

A key capability of active tether recoil and deployment during a nominal operation of the Rover or during access from and into extreme environments is the tether tension monitoring. Therefore, the NTM features the Tether Tension Module (Fig. 11). The miniaturised spring-clutch is implemented on the interface between the spool and actuation module. A deflection of the micro springs is measured by a high-performance encoder, thus allowing to characterise applied tension in a go/no-go characteristic.

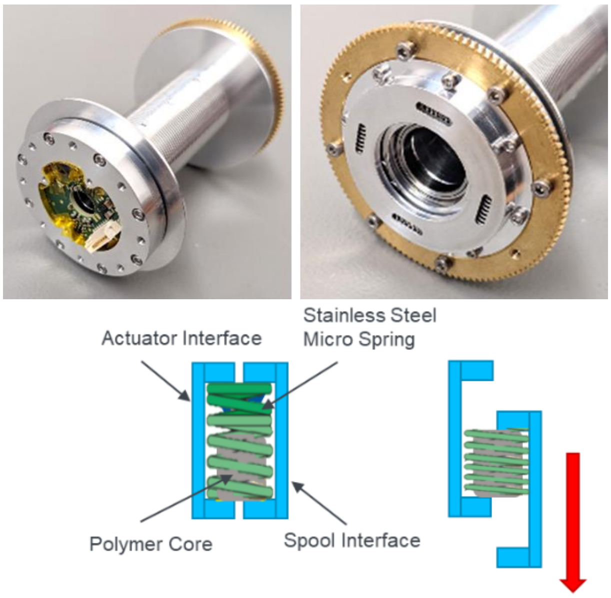

Figure 11: Tether Tension Module (TTM) Interface attached to spool drum (top) and functional principle of micro spring clutch (bottom)

As the unexpected high bending stiffness of the Tether could result in tension load peaks or even abrasion effects while guiding the Tether through the miniaturised mechanism assembly, ongoing investigations focus on a further reduction of the surface contact friction while by using of small-sized rotational bushings.

Table 2: Estimated NTM Drive Unit Performance Characteristics

Parameter	**Requirement incl. Margins**	**NTM Actuator Output**
Deployment Speed	0,1 – 15 m/h	
Rover Mass	3,2 – 4,2 kg	
Spool Tether Layer Diameter	24 – 55 mm	
Max. rotational spool deployment velocity	3,32 rpm	3,60 rpm
Max. spool torque (Earth / Moon)	2,3936 Nm (E) 0,3983 Nm (M)	1,99 Nm (nom) 3,93 Nm (max)

The selected brushless DC Motor with 20 mm diameter for operation of the NTM was defined together with Maxon Motor within an iterative development to also fit the Nanokhod drive unit actuator requirements. In combination with the actuator-mounted high-power planetary gearhead, even spool-torque requirements from a vertical-deployment scenario of the Nanokhod Microrover under Earth gravitation could be realised. Exemplary requirements and output data for the NTM Actuator design are shown in Tab. 2.

5. TETHER POWER AND DATA TRANSFER

The main focus on the tether study was on established qualified cables. The previous design did implement two tethers and two corresponding tether mechanics. The main reason was to ease power and data transmission. For reliability considerations this double design makes no sense in view of that there is not any redundancy. Additionally, due to the dramatically increased goal for the tether length this concept was discarded. As a result of this trade-off, we selected a coaxial design against a multi-wire cable. This primarily is due to the lower isolation voltage which can be achieved in a multi-wire design compared to a coax-design. Further benefits of the coax-design are a perfect rotationally symmetrical cross section, which is an important characteristic for mechanical sealing, when the tether is entering the tether housing. Further benefits are defined line impedance for data transmission and the best relation of copper cross-section to tether cross-section. The drawback is a much more complicated way to transfer power, commands and science data over one single line. A first candidate is a shielded wire cable according to ESCC 3901 002 64 with a diameter of 1,07 mm. This cable has a high isolation voltage of 600 V and quite low resistances compared to other cables of this diameter: 100 Meters do result in 13 Ω for shield and 18 Ω for the inner wire. Among the examined 1,0 mm cables these values are the best. It is quite high capacitive with 358 pF/m, which results in a low characteristic line impedance of 18 Ω. A drawback is a surprisingly high stiffness. A further topic was custom specific cable design. Two suppliers had been contacted. As result of this activity it turned out, that it is quite difficult to establish a design, which outperforms the established standard candidates. All design proposals of the suppliers underachieved the expectations. If a custom design will be an issue, then a very expensive design process has to be accepted, for which at the end a reliable result is not guaranteed, and multiple design iterations may occur.

Power Transmission

The power, the rover needs for locomotion and instrumentation, is transferred via tether so that the rover must not be equipped with energy supplies and batteries. Due to the very long and thin tether the electrical resistances are quite high so that for the transmission of electrical energy higher voltages must be used in order to keep current and power dissipation within the tether low. A typical value for the DC transmission voltage has been found to 100 V. On lander side a rover power supply unit generates a DC voltage of 100 V, on rover side a small converter transforms the voltage down to usable voltages as 24 V, 12 V etc. But on rover side there is a barrier which has to be get over: the tether arrives on a cable drum, which is rotating and therefore prevents a direct electrical connection to the rover chassis. In former studies collector rings were used for the transfer of power and data signals between cable drum and rover chassis but this solution of course let arise doubts on reliability. In the current study a contactless transfer method was developed, which replaces the collector rings. Hereby the tasks of converting down the 100 V DC tether voltage and the contactless power transfer within one single and very small conversion unit were combined.

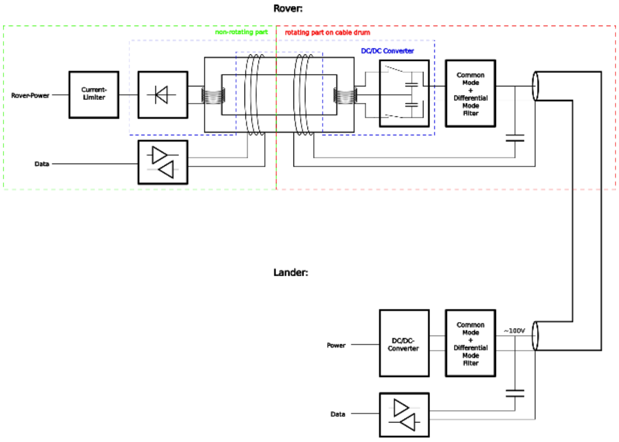

Figure 12: Block Diagram of the Power and Data Transmission System (sketch)

The central element of this conversion unit consists of a transformer. The transformer is fed with a 100 V AC voltage and on its secondary side a smaller AC voltage is rectified and filtered. The core of the transformer has a rotationally symmetrical shape and consists of two halves. One half is fixed to the rotating system of the cable drum, the second half is fixed to the rover chassis system. The core is placed on the drum axis. To generate the needed AC voltage a very small self-oscillating DC-to-AC-converter has been developed, which fits onto a small PCB of 26 mm x 20 mm size. This PCB can be accommodated within the axis tube of the cable drum. The actual realisation is with commercial parts, but the parts already has been selected so that all parts can be replaced by HiRel counterparts of the same size so that not more PCB size will be needed.

A complete transmission chain was realised, starting from an up-converter from 28 V to 100 V, the 100 m tether, the down-converter from 100 V to 32 V in a breadboard. Although the converter consists of very few electronic parts it performs with good efficiency. For the total chain an efficiency of 70,7 % for a transferred power of 9 Watts was achieved. Hereby, the up-converter achieved an efficiency of 87,8 % and the down-converter 82,1 %, 1,8 % are lost in the tether. In spite of its tiny size the down converter has a high power margin: up to 20 W output power can be permanently transferred with an efficiency of 85,2 %.

Command and Data Transmission

An essential point of the development is that the established power transmission system also can be used for the transmission of data signals in both directions: command data from lander to rover and science data from rover to the lander. The first iteration of the system which is currently under development uses half-duplex communication based on FSK-modulated UART. A full-duplex arrangement is considered for future versions. Again, as central element of the data transmission is the transformer, which already has been mentioned in the power section. Two additional windings were added in order to minimise the coupling between power and data windings and to achieve fairly separated magnetic transmission paths. Fig. 12 shows the block diagram of the complete power and data transmission system. A functional breadboard model of the power and data transmission module was realised as shown in Fig. 13.

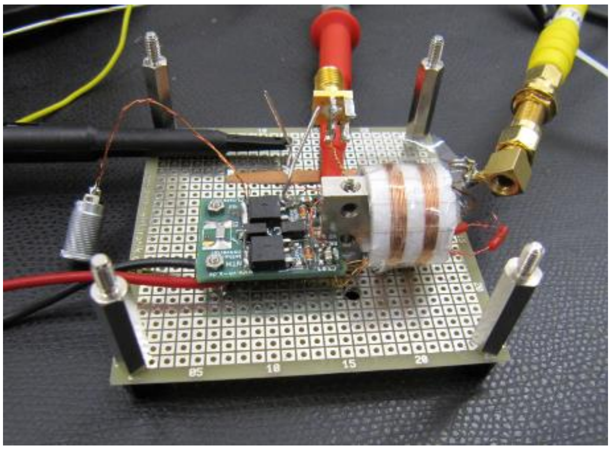

Figure 13: Breadboard of the Power- and Data Transmission Module

To transmit commands to the rover as well as science and housekeeping data to the lander, a data transfer system is designed and implemented. As mentioned above, the data transfer system uses the coaxial cable as well as data windings around the core of the power transformer. The signal attenuation through the data windings and the coaxial cable for the direction from rover to lander over a range of frequencies is shown in Fig 14. For the reverse direction, the attenuation is of similar magnitude. The attenuation is increasing with higher frequencies, which limits the achievable data rates at given transmission power.

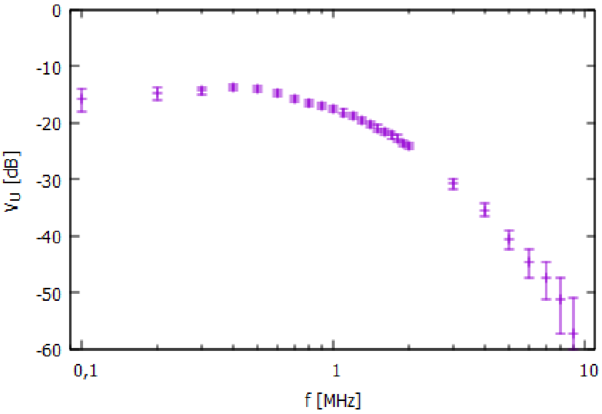

Figure 14: Signal attenuation in transmission line

Based on the measured attenuation, transceivers for lander and rover are designed. These consist of FPGAs for signal processing and amplifier circuits for transmission and reception (Fig. 15). The FPGAs receive data messages via RS485 bus from the lander CPU and the rover CPU, respectively. First, these UART-messages are repeated by the FPGA with a different baud rate, which is optimized for the transmission. Then the UART-stream is FSK-modulated, and the resulting square wave signal is sent to the transmission amplifier, which uses a low-footprint inverter circuit to increase the voltage level to 5 V and provide higher transmission power. When received on the other end of the transmission line, the square wave has been transformed to a sine-like signal due to the larger attenuation of its higher frequency components in the transmission line. The received signal level is approximately 0,5 Vpp (in the frequency range of 1-2 MHz). This sinusoidal signal needs to be re-converted to a square wave in the receiver. Therefore, an analog comparator is used to detect zero-crossings of the input signal and switch its output accordingly to create a 3,3 V TTL square wave signal, thereby also acting as amplifier. To prevent the transmitter from short-circuiting the receiver input, it is decoupled using antiparallel diodes. The TTL signal generated by the receiver is processed by the receiving FPGA. A demodulator measures the length of the signals' half-periods and thereby determines the frequency. The output of the demodulator shows the originally sent UART-signal. Its baud rate is then changed to the RS485 baud rate, and it is sent to the CPU. The UART-messages contain CRC check values to enable reliable data transmission.

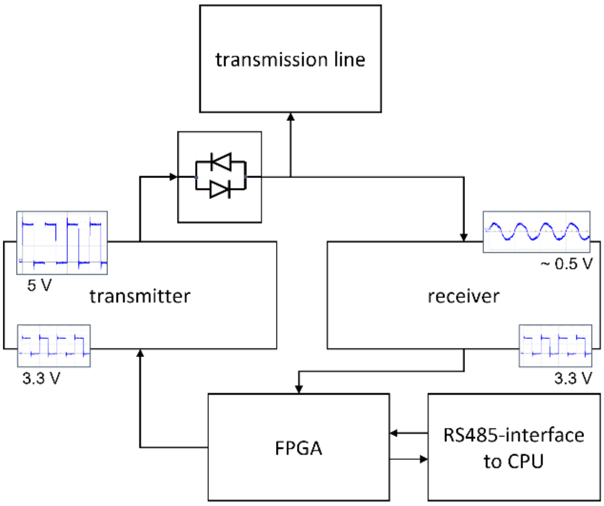

Figure 15: Transceiver block diagram

If a message is not received correctly, a re-send can be requested with the next message in opposite direction. Using the outlined system, a baud rate of 500 kBd is realized on the transmission line when using 1 MHz/2 MHz FSK-modulation without the need of an intermediate data repeater at the location between cable and transformer. Even without CRC the measured bit-error-ratio of a transmission without simultaneous power transmission is very low at 0.000 in the direction lander-rover and 0.035 in the direction rover-lander. Further topics are appropriate filter design to separate distortions of the power converter from the data signals. For simultaneous power transmission further tests and analyses will be conducted in the future.

6. NANOKHOD DEPLOYMENT & OPERATION BAY AND PLC SENSORY SYSTEMS

To provide a modular interface for a variety of possible mission scenarios and the "full scale" of necessary subsystems for operating the rover, investigations in a modular Nanokhod surface element were taken. The Deployment and Operations Bay (sketched in Fig. 16) provides required subsystems to allow an independent operation of the rover. The multi-mission device is initially intended first to be used especially for terrestrial analogue and technology demonstration missions. Mechanically, Hold-Down and Release Mechanisms as well as spring driven deployment mechanisms are implemented. For power supply, an internal PCDU provides a 28 V interface towards another spacecraft. Internal electronics provide a control and command interface towards the FPGA sided communication to the rover and an interface to another surface element. Optionally, a LiPo Secondary Battery for an around 40 h operation of the rover can be connected.

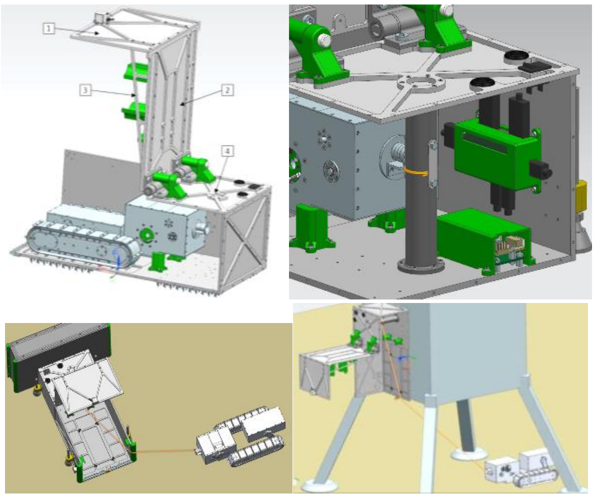

Figure 16: Development of a modular surface Deployment and Operation Bay for multiple operational scenarios (sketched)

Commercial of the shelf components were selected for all electronical components as well as the battery system. For the HDRM devices, a custom spring-driven design solution with micro-servo drives was elaborated, whereas the actuators provide substitute possibilities with small-sized space compatible Pin Puller actuators.

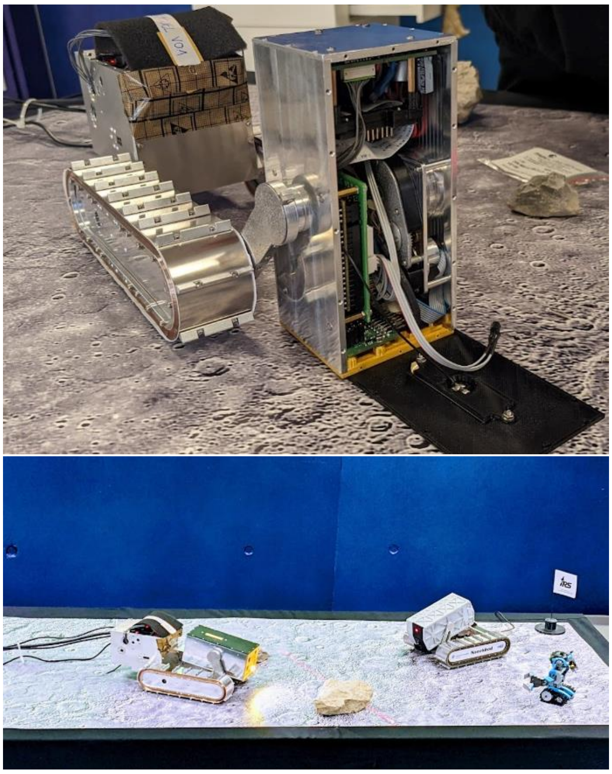

Figure 17: Integration of a customised Nanokhod PLC sensory and instrument suite for terrestrial analogue mission scenarios (top), Nanokhod Laboratory model operated within a demonstration setup (bottom)

For terrestrial application, command and data exchange with the Nanokhod Deployment and Operation Bay is intended to be realised with a small sized mobile surface element. Besides investigations towards suitable surface support systems, recent activities focussed on suitable Nanokhod sensor and payload components. For an initial terrestrial demonstration mission, a set of payload sensors and instruments for the Nanokhod PLC were developed within an interdisciplinary education program on space robotics and exploration rover systems [4] at the University of Stuttgart during the winter semester 2021/22. Hereby, two student teams developed solutions for a successful implementation of a variety of small-sized and commercially available sensory components such as thermal sensors, time-of-flight sensors, inertial measurement units, (UV) LEDs, camera systems, etc., as well as a compatible rover onboard computing unit (Fig. 17). Preparation of a complete test and demonstration procedure connecting all interfaces are part of the ongoing investigations.

7. CONCLUSION

This paper presents and summarises the most recent development activities on the Nanokhod Microrover undertaken by the University of Stuttgart and vH&S. Design solutions on a functional breadboard model level were elaborated in order to investigate the technological challenges of accessing environmental extremes and to consolidate a robust rover design for a future lunar surface application, thus advancing from the heritage of MRP. The authors would like to thank all project partners and colleagues involved for their valuable contributions.

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