Until now, planetary exploration has largely been done by wheeled ground vehicles, which show limited mobility when it comes to unstructured terrain and sloped areas. Besides challenging surface conditions, the environment of low-gravity celestial bodies involve a unique set of unknowns, which an exploration robot has to handle. In order to overcome limitations of existing vehicles, research groups around the globe have started to exploit the possibility of applying legged systems for space exploration. However, these systems have not yet been able to take the full potential of the technology, considering the rapid development that can be observed in terrestrial legged locomotion over the last decade. The current generation of legged robots uses advanced actuation and new control algorithms allowing them to dynamically traverse and interact with complex environments. They feature locomotion skills that potentially revolutionises the way robots move in low-gravity environments. This paper analyses the use of legged robots for space exploration. We compare the underlying technologies of legged robots to existing space hardware to identify technology gaps and propose locomotion gaits for celestial bodies.

1 Introduction

Celestial bodies present a highly unstructured terrain and scientifically interesting places are outstandingly hard to reach. This makes versatile locomotion essential for exploration. For instance, permanently dark craters of the Moon are interesting sites to study, due to the existence of water ice [1]. Similar geological features like volcanoes and mountains are also of interest [2], and hard to explore because of complex terrain and steep slopes. The rover designs used so far were greatly restricted in this regards.

Today’s state of the art systems have reached a maturity, where they are, besides dynamic and efficient locomotion, capable of traversing complex terrain, overcoming obstacles and navigating autonomously. As the technology advances, the concept of legged locomotion becomes suitable for space explorations. With legged locomotion, yet unreachable areas and environments can become accessible. However, it is still unsure when the technology of legged robots will be readily available for use in space and how such systems will look like.

In the following section we first present a comparison between wheeled and legged locomotion, and a set of general requirements derived from literature. We then present an overview of the legged space prototypes developed so far and state of the art terrestrial legged robots. We identify key technologies of the most advanced legged robots and evaluate their technology readiness level (TRL). Lastly, we analyse locomotion gaits and their suitability for celestial bodies.

2 Legged vs wheeled locomotion

Wheeled locomotion is very well understood and has been used extensively on planetary exploration missions to the Moon and Mars. The energy efficiency, the mature technology, the relatively low complexity and redundancy are the main advantages of wheeled rovers [3].
A system with only three functioning wheels is still able to navigate [3].

Legged systems on the other hand are mechanically complex and planning the walking motion online can be computationally expensive [2, 3, 4, 5]. At this point, there is less experience in legged locomotion compared to the conventional wheeled locomotion.

However, depending on the mission, the capability of legged locomotion to maneuver steep and rough terrain can outbalance its shortcomings [5].

Due to wheel slippage, rovers got stuck in sand dunes [7] and rocky terrain has simply been inaccessible. Avoiding large obstacles or unsuitable terrain requires complex and slow path planning and also restricts the potential landing sites of rovers.

Legged systems can freely place their feet and with that minimize slip and maximize stability [8]. They are able to walk omnidirectionally and turn on the spot [1]. Overcoming obstacles of up to 35 cm and at least the robot’s height is possible [3, 4]. Redundancy of a legged robot can be achieved depending on the design [3] and has been successfully demonstrated by the DLR’s legged robot CRAWLER [9].

The comparability of the evaluated systems is limited, as we are comparing rovers that are already in space with prototypes only used in laboratory environments, while the objectives and scale of the missions differ greatly. We will hereby focus on a mission to explore a permanently dark crater on the Moon, where a potential locomotion system of a space robot has to meet the following basic requirements suggested by Bartsch [1]. We extended the list by adding specific values for the payload to weight ratio and the energy efficiency (COT). The list is not intended to be exhaustive.

- Climbing slopes of up to 40°
- Traverse on regolith, a loose, fine-grained, sharp-edged sediment
- Overcome obstacles of at least 0.4 m
- Be able to move payloads of at least the weight of 1.5 kg which is the mass of a geochemistry instrument suggested in [10]
- Payload to weight ratio of at least 10 %, which corresponds to the mean value of wheeled rovers (see table 1)
- Cost of transport (eqn. 1) of maximum 1.3, which corresponds to the value reached by the OPPORTUNITY Mars rover (referenced to earth for comparability reasons)
- Provide mobility in dark areas

The cost of transport (COT) is generally used to compare the energy efficiency of systems which use dissimilar forms of locomotion. It is calculated as:

\[
COT = \frac{P}{mgv}
\]

where \( P \) = power input of the system
\( m \) = mass of the system
\( g \) = gravity constant
\( v \) = velocity of the system

Based on the requirements above, a legged system provides a valid solution.

3 Legged robots

Legged robots can generally be divided into the categories bipedal and multi-legged robots. State of the art bipedal robots are still far behind the natural counterparts. The systems relatively slow, and can only negotiate small terrain obstacles [11]. Better locomotion performance in terms of speed, energetic efficiency, and obstacle negotiation skills, is achieved with multi-legged systems [11]. Hence, we focus on our analysis on multi-legged systems. Legged robots make use of gaits which can be static and/or dynamic. During static locomotion, the body-weight is supported during all times by at least three legs. This makes the system inherently stable. In dynamic locomotion, the system can be in contact with less than three legs allowing the system to move much faster and more efficiently. But inherent stability is sacrificed and higher demands are placed on actuation and control.

A few legged robot prototypes for space exploration have been developed up to today, most notably DFKI’s SpaceClimber [4, 5], CREX [12], SCORPION [13], ETHZ’s ALOF [14] and NASA’s ATHLETE [15]. However, one has to note that all those prototypes are purely statically stable walkers while state of the art legged systems, such as ETHZ’s ANYmal [11], Boston Dynamics’ SpotMini [16], MIT’s CHEETAH [17] or IIT’s HyQ2max [18], make use of dynamic locomotion. A compact comparison of the electrically actuated systems, also including space robots, can be found in table 1.

3.1 Space legged robot prototypes

With SpaceClimber (2012) [4, 5] (see fig. 2) and predecessors CREX (2012) [12] and SCORPION (2007) [13], the DFKI showed, that the development of a statically stable walking legged robot meeting almost all the requirements for an intended space exploration mission is already possible.
SpaceClimber is specifically designed for a space exploration mission on the Moon and has space qualified actuators and electronics in combination with a low energy consumption and a low computational cost. The robot is walking statically stable and has six legs. The non-compliant actuation is conducted by brushless DC motors from RoboDrive in combination with Harmonic Drive gears. SpaceClimber has a sensor setup consisting of tactile feet sensors, cameras, IMUs and absolute position sensors in the joints, and is powered by a Lithium Polymer battery. For computational tasks, the hexapedal robot has a MicroBlaze soft processor with a very low processing power of about 1/6 of the processing power of the CURIOSITY Mars Rover. SpaceClimber has been extensively tested under varying slope angles on a lunar slope test track, which is covered by crushed loose basalt of granulation <1 mm.

ALOF (see fig. 3) was developed by ETH Zurich and initially tested in the ESA Lunar Robotics Challenge 2008 [14]. The robot has four legs and three degrees of freedom per leg. Non-compliant DC motors are used in combination with a high reduction gear. The motor and the gearboxes are dust protected. The robot’s design allows a wide range of motions. This enables special manoeuvres and different gaits which allow ALOF to both walk and crawl. It has been shown that crawling is especially useful, as it allows the robot to climb steep slopes with loose soil, while increasing the support surface and reducing sinkage. ALOF is able to recover itself from rollover after falling. Using haptic feedback collected from performing a special scratching movement with a foot on the soil, the robot is able to classify terrain shapes and soil. The system also has an IMU, stereo cameras and a structured light sensor.

ROBONAUT 2 (see fig. 4) is not a system for planetary exploration but worthwhile to mention, since it is the first humanoid space robot which successfully uses series elastic actuation (SEA) on-board the ISS [19]. The torso of the humanoid robot was sent to the ISS in February 2011. The legs have been transported later and were attached to the torso in 2015 [20, 21].

3.2 State of the art legged robots

Dynamically walking legged robots present a growing field of research. To give an overview of the those robots developed for applications on earth we present some of the most recent and advanced systems.

Starting from Raibert’s simple 2D hopper in 1986 [22], advancing to more complex systems such as Boston Dynamics’ quadrupedal BigDog in 2008 [23], Boston Dynamics has introduced the more advanced and much smaller, all-electric, quadrupedal SpotMini in 2016 (see fig. 5). Unfortunately, there is not much information on SpotMini available. After falling, the robot is able to get up again by itself with help of an attached robotic arm.

The MIT CHEETAH [17] (see fig. 6) is a quadruped running robot which was introduced in 2013 and accomplishes a very high efficiency with its pseudo-direct-drive system. It uses a custom large gap radius electric motor with a high torque density combined with a single stage planetary gear. The motor driver is capable of regenerating 63% of the impact energy by using a custom switch converter for the motor driver.
The robot’s control structure emulates passive springs and dampers. To explore energetic benefits in high speed running, a flexible spine, actuated by the rear legs, has been used. Elastic energy can be stored and returned by polyurethane rubber rings of the spine.

ANYmal is a dynamically walking quadrupedal which was introduced in 2016 by ETHZ (see fig. [1]). Its key technologies include the custom joint units called ANYdrive. The ANYdrive is a fully integrated SEA which includes the electric motor, spring, high-reduction gear, absolute position sensors and custom motor control electronics. The joint units are sealed, compact and are used in all the three joints of each leg. No additional equipment is needed since the sensors and drive electronics are integrated and the torque, position and impedance are directly regulated. In minimal configuration, the robot makes use of a rotating LiDAR, IMU, and custom force sensors in the feet.

3.3 Alternative forms of legged locomotion

Alternative forms of legged locomotion include jumping and wheel-legged hybrids. Jumping gaits are characterized by long flight phases and allow robots to reach several times their body height [24]. Jumping robots are especially suited for low-gravity environments [3].

Hybrid robots, such as NASA’s ATHLETE [15], are combining the advantages of wheels with the flexibility of legged locomotion. ATHLETE is a wheel-on-limbs robot which was introduced in 2007. Normally, the wheels are used for driving. Meeting difficult conditions, like sand, steep slopes or large obstacles the robot is able to switch to a statically stable walking gait using the limbs, allowing it to continue its mission. It has been proposed to use the ATHLETE as the lander module for a mission [15].

4 Scalability analysis

The recent development of dynamically walking robots has lead to increased researched activity on the underlying technologies. In the following chapter we would like to give an overview of those technologies and their current status in a terms of Technology Readiness Level (TRL).

4.1 Identification of key technologies

4.1.1 Actuation

As opposed to static locomotion, dynamic locomotion imposes three major requirements on the actuators, as listed in [11]. Namely high impact robustness, fast motion tracking and low impedance force controllability. Two technologies stand out which fulfill these requirements and provide compliant actuation.

Pseudo-direct-drive systems: In a pseudo-direct drive, a low reduction gear is used to provide high bandwidth controllability ("torque transparency") and backdrivability which leads to impact robustness. Controlling the motor current in pseudo-direct-drive systems is equivalent to regulating the output force, and can be done at very high frequency. Presently the torque is limited, direct actuation without any gears is not possible and high torques can only be produced by relatively large motors. The quadruped MIT CHEETAH [17] and many systems for applications in rehabilitation are using pseudo-direct-drive systems.

Series elastic actuation (SEA): Series elastic actuators consist of an inserted mechanical compliance between the output of a motor with high gear reduction and the joint. The major advantages of SEA are the possibility of an increased energy efficiency by temporarily storing energy during locomotion, the precise output force regulation and its shock tolerance.
4.1.2 Sensors

Robots are using a vast number of sensors for perceiving their own state (proprioceptive sensing) and their environment (exteroceptive sensing). Most legged robots are using some form of tactile sensors in the feet in combination with an IMU and LiDAR integrated in a head console, as well as vast number of cameras for hazard detection and navigation.

Tactile feet sensors: It is necessary for legged systems to know the contact state of the feet. Tactile feet sensors include ground contact and force sensors. Together with the IMU and leg kinematics, the terrain inclination can be estimated through the contact surface normal of each foot. This is a key sensing element, as the inclination is required to design a controller that minimises the robot’s risk of slippage. Feet sensors are vulnerable, as due to their placement, they are exposed to high and cyclic stress at every impact of the feet. The sensors need to work reliably on different types of surface material such as on hard rocks but also on soft loose soil.

Strain gauge based feet sensors are used by ANYmal [11] and pressure based sensors have been investigated for the MIT CHEETAH [36]. ETHZ’s Starlet ETH is using optical force sensors in the feet as tactile sensors [37].

On the other hand, the SEA limits the control bandwidth and therefore requires complex control design. SEA is successfully used in several state of the art legged robots like ANYmal [11], ROBO-NAUT 2 [10] or VALKYRIE [55].

Table 1: Specification of terrestrial and extraterrestrial robots. (Data from [4, 8, 11, 12, 13, 14, 16, 17]

<table>
<thead>
<tr>
<th>Robot</th>
<th>Year of Introduction</th>
<th>Target</th>
<th>Weight (kg)</th>
<th>Payload (kg)</th>
<th>End effector to Body Weight fraction</th>
<th>Maximum Speed (m/s)</th>
<th>Maximum slope at free end</th>
<th>Power supply</th>
<th>Nominal power consumption (W)</th>
<th>Maximum electrical power (W)</th>
<th>COT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFT</td>
<td>2014</td>
<td>220 300 500</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>NEDOS</td>
<td>2014</td>
<td>500 700 900</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>ANYmal</td>
<td>2015</td>
<td>200 300 400</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>MINERVA</td>
<td>2016</td>
<td>200 300 400</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>MAMON</td>
<td>2016</td>
<td>200 300 400</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>LUNAR ROVING VEHICLE</td>
<td>2017</td>
<td>100 200 300</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>CHANCE</td>
<td>2018</td>
<td>100 200 300</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>LUNARROVER</td>
<td>2019</td>
<td>100 200 300</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
<tr>
<td>LUNAR EXPLORATION</td>
<td>2020</td>
<td>100 200 300</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Solar panel</td>
<td>N/A</td>
<td>0.4</td>
<td>N/A</td>
</tr>
</tbody>
</table>

LiDARs: Both ANYmal [11] as well as MIT CHEETAH [36] have a range-finding LiDAR. They are used for active 3D sensing of the environment. LiDARs produce very accurate 3D representation of the world with relatively long range. They are light and scene texture insensitive. Downsides of LiDARs include relatively slow update rate for capturing a whole scene and high energy consumption.

Time-of-Flight (TOF) cameras: TOF cameras are not used by any terrestrial system we have reviewed so far. As opposed to a LiDAR sensor, a TOF camera can capture an entire scene instead of single points and provides high-speed imaging. Although TOF cameras have a lower accuracy, limited range and limited field-of-view compared to LiDARs at time of writing [31].

4.1.3 Computation power

Terrestrial legged systems are using powerful commercial off-the-shelf processors, since the software used for dynamic locomotion is computationally intensive. Especially state estimation and navigation is computationally demanding. ANYmal uses three Intel i7 FfPCs [11]. The workload is divided into locomotion, navigation and application-specific tasks. Each PC is responsible for one of these tasks. Within the locomotion PC, state estimation is responsible for the majority of the workload of about 80%. The Navigation PC is generally working at full utilization.

MIT’s CHEETAH used to have a NI cRIO-9082, housing both a Real-Time controller and FPGA Layer [17]. The Real-Time controller consists of a i7 dual core processor with 1.33GHz [17].
One core receives data from the FPGA and sends commands while the other core computes the forward kinematics and generates the trajectory and the force profile.

4.1.4 Power supply
To achieve a high autonomy rechargeable Li-Ion batteries are the most used power storage. MIT’s CHEETAH, ETHZ’s ANYmal as well as Boston Dynamics’ SpotMini make use of them. ANYmal’s 650 Wh on-board battery provide the system with more than 2 h of autonomous operation [11]. SpotMini’s battery allow for up to 90 min of operation [10]. Terrestrial legged system do not generate power on-board and therefore depend on frequent recharging or changing of the batteries. Autonomous docking for recharging legged robots has been presented recently [35].

4.1.5 Thermal control
There is no special need for a highly elaborate thermal control on Earth as there is an atmosphere, and temperature changes are moderate compared to space missions. The main challenge on earth is to properly dissipate heat generated from motors and electronics through convection. An experiment on MIT’s CHEETAH energy efficiency came to the conclusion that 76% of the motors’ current is lost to Joule heating of the motor and dissipation in the electronics while the rest of the energy is converted to mechanical power [29]. ANYmal uses structural components surrounding the motor as heat sinks [11]. Heat generated by the on-board electronics is conducted via heat-pipes to an active cooling element attached to the main body.

4.2 TRL of key technologies
4.2.1 Actuation
So far, robotic systems in space and legged space prototypes use mostly non-compliant actuation, with the exception of the micro-gravity robot ROBONAUT 2. We therefore continue our analysis on the compliant actuators used on ROBONAUT 2 and actuator components.

Compliant actuation: Actuation with compliance is not widely used technology in space exploration. Nevertheless, compliant actuation has been successfully used and tested on-board the ISS by ROBONAUT 2 in form of force controlled series elastic actuators in combination with absolute position encoders [21]. Although the robot has so far only been used for Intra-Vehicular Activity (IVA), it is planned to develop the robot into a system for Extra-Vehicular Activities (EVA). ROBONAUT 2’s legs each consist of seven SEAs and have been specifically developed for Extra-Vehicular Activities.

Only EVA suitable materials have been used. Thermal vacuum testing has been conducted on the actuators and motor drivers and all electrical components have been radiation tested [21]. To our knowledge, the TRL of those series elastic actuators has not been officially stated. We can conclude by evidence of the so far successfully tested ROBONAUT 2, that the TRL of series elastic actuation are at least on level 5 when the final purpose is the usage in outer space. State of the art terrestrial legged robots are mostly using force/torque controlled actuation. With DLR’s ROKVISS space verification experiment torque-controlled joints have been tested successfully in space. Notably, torque-control was not used in combination with a compliant actuator such as SEA.

Motors: Brushed as well as brushless motors have been used in space. Specifically brushless motors are a standard component for reaction wheels. Brushed motors can be used when a pressurized housing is present to mitigate the risk of brush arching, which leads to accelerated wear [40]. The TRL of brushed as well as brushless motors is at the maximum level of 9.

Gears: Harmonic drive gears are used by all reviewed actuators in terrestrial and extraterrestrial legged robots, with exception of MIT’s CHEETAH, where a single stage planetary gear is used. Challenges of space qualified gearing include temperature range and contamination of other parts with lubricant. Therefore, dry lubricants are used in space rated gears. Harmonic Drive (HD) gears have been successfully space qualified before [3]. They have a history of more than 40 years in space exploration and have been used in many space applications such as in satellites or in the Lunar Roving Vehicle [11]. Additionally they have been successfully used in verification of the ROBODRIVE on-board the ROKVISS space verification experiment [12] and on-board the ISS by ROBONAUT 2 [19]. Beside HD gears, planetary, spur and worm gears are also frequently used [10]. Therefore, we estimate the TRL of gears to be at the maximum level of 9.

4.2.2 Sensors
Cameras, IMUs, LiDARs and tactile feet sensors are the key sensors in legged systems. Most of the sensors used in state of the art terrestrial legged robots are also used by the prototype systems designed for space exploration, and have been previously used in space exploration rovers.

Inertial Measurement Units (IMUs), cameras: IMUs and cameras have been successfully used by NASA’s Mars rovers [3, 17]. Therefore they all have an estimated TRL of 9. NASA’s CURiosity rover remarkably has a total of 17 camera sensors.
IMUs and cameras have been used in all space exploration rovers up date [31] and are thus a very reliable and well tested technology. Next steps to decrease the mass and power footprint of IMUs are underway and being developed in part of the envisioned ESA Mars Sample Fetching Rover (SFR) mission [31].

**Tactile feet sensors:** At this point, tactile sensors are not yet widely used in space exploration robots. Exceptions include the SOJOURNER rover, which had a contact sensor to detect objects, as well as DLR’s RObot Technology EXperiment (ROTEX) which also had tactile sensors [31]. The Apollo lunar module had a very basic touch sensor on the landing gear’s foot pad [13]. Touchdown of the lander completes a circuit, and with that informs the astronauts via a lamp to shut down the engines. The comet lander PHILAE did not have any touch-down sensors, rather it sensed the final touchdown on the comet in form of acoustic sound with its acoustic surface sounding experiment [44]. Other space craft landers may have had tactile feet sensors. However, we expect them to be binary or of a very low resolution. The CURIOSITY Mars rover uses load cells on its robotic arm, which leads to the conclusion that strain gauges based force and torque sensing should be at TRL 9.

The currently used technologies in tactile sensing of space robots are not comparable to the intended use of tactile sensors in the feet of legged space robots. Legged space prototypes such as MANTIS and SpaceClimber are using custom developed sensors. SpaceClimber’s feet sensors for example consist of multiple pressure sensors, accelerometers and optional strain gauges which are interfaced by an Spartan 3A FPGA taken care of contact detection and slip estimation [3].

To conclude, tactile feet sensors as such have not yet been used in space exploration, but the underlying technologies have been successfully implemented in terrestrial and extraterrestrial systems. Thus we estimate to the best of our knowledge the TRL of tactile feet sensors to be at minimum 4.

Future work in developing space qualified tactile feet sensors is necessary. Although legged planetary space exploration robots without feet sensors may be possible, all space prototypes and terrestrial legged robots are using them.

**LiDARs:** Active 3D scanning with LiDARs is very prominently present in terrestrial legged robots and is also used by the space prototype MANTIS. Nevertheless, so far only NASA’s SOJOURNER Mars rover has used an active ranging sensor in form of a custom laser-line projection system, which was used for obstacle detection [31]. LiDARs are also regularly used in the rendezvous and docking sequence of Space Shuttles and the CYGNUS spacecraft with the International Space Station [31]. Apart from those applications there is no use of LiDAR in space robotics due to its bulky footprint with respect to power, weight and size. This problem has been tackled recently by both ESA and NASA with their initiatives in miniaturization and space hardening of LiDARs. NASA has released a Request For Information for a low footprint LiDAR to be used as soon as 2019 in an anticipated lunar rover mission [31]. Further, two low footprint LiDAR breadboard prototypes have recently been developed [45, 46].

Concluding from those findings we estimate the TRL of LiDARs for legged planetary space exploration robots to be at level 4. Future work in LiDAR sensors for space exploration robots needs to be done and is currently ongoing.

**Time-of-Flight (TOF) cameras:** To our knowledge, TOF cameras have not yet been used on a space mission. However, projects have been initiated by NASA to develop a 3-D imaging flash lidar to enhance hazard avoidance capabilities for landing missions and enable autonomous rendezvous and docking in space [17]. A successfully tested prototype has been developed by NASA Langley Research Centre and further developments are on their way [17]. We estimate the TRL to be level 4.

**Stereo Cameras:** Stereo cameras have drawbacks compared to other 3D scanning technologies. Stereo cameras have a poor resolution, depend on adequate scene lighting and on texture. Nevertheless, the technology is very well understood and has been used in space exploration before, for instance by the Mars rover SOJOURNER and OPPORTUNITY [31]. Hence, the TRL of the technology is at level 9.

### 4.2.3 Computation power

Complex navigation and path planning of legged systems lead to an increased requirement in computational power. Capabilities of current space processors are limited in term of performance and power consumption.

Space processors come in great variety. The most common and most flexible option are General-purpose processors (GPP). Other options include the use of Field-Programmable Gate Array (FPGA) or dedicated processors such as Digital Signal Processors (DSPs) and Graphical Processing Units (GPUs).

**General-purpose processor (GPP):** The CURIOSITY rover is using the commonly used RAD750 space processor, which can process more than 266 million instructions per second (MIPS), whereas EXOMARS will be using a 96MHz LEON2 processor with 75 MIPS [4, 31].
The RAD750 is a radiation hardened version of the 200MHz PowerPC processor used in the original Apple iMacs. Today’s space processors falls short of the need of state of the art terrestrial legged robots, which currently use the much higher processing power of commercial-off-the-shelf (COTS) processors exceeding vastly the capabilities of the existing all purpose space-processors. We estimate the TRL of the corresponding computation system to be on level 4.

Work is underway at ESA and NASA to improve the processing power of general purpose space processors. The goal of a NASA and Air Force Research Laboratory joint project is to develop a space processor with 100 times the processing power than that of the RAD750 processor by 2025 [31, 48]. They concluded that a multi-core processor will be the best option in term of flexibility and wide support of applications. In a comparative analysis of the NSF Center for High Performance Reconfigurable Computing of the University of Florida [49] all major current and future space processors and their COTS counterparts, and are listed with their specification, are compared and evaluated. The analysis concluded that the Core i7-4610Y and Exynos 5433 are the best future space processor for most applications.

1. Digital signal processor (DSP): DSPs are parallel processors and are optimized for performing signal processing. Radiation hardened DSPs have been developed but have not been used for navigation tasks [31].

2. Graphics processing unit (GPU): GPUs are optimized to perform calculations on a video frames. No radiation hardened GPU are available at time of writing [31].

3. Field-programmable gate array (FPGA): Radiation hardened FPGAs are widely available and have reached a powerful stage. For instance, the in space successfully tested SpaceCube 2.0 [50, 51] consists of a hybrid system of FPGAs and integrated DSPs. This setup has the major advantage of reconfigurable FPGAs, flexible interface options combined with a modular architecture. It consists of two Xilinx Virtex-5 FPGAs and eight memory modules (2GB DDR, 8GB NAND Flash). SpaceCube 2.0 reaches more than 16 times the computational power of RAD750 with 5000 MIPS and is highly energy efficient with 500 MIPS/W [51]. The system has been tested on-board the ISS and has reached a TRL of 6.

So far FPGAs have not been used for navigation tasks, but NASA plans to use an FPGA for stereo vision and visual odometry in the upcoming Mars 2020 rover [31]. Notably SpaceClimber uses a FPGA and it has been shown that the setup of the SpaceCube 2.0 FPGA can be adapted with modest work for a wide range of applications including robotics [50].

4.2.4 Power supply

So far, only rechargeable batteries have been used in both terrestrial as well as extraterrestrial prototypes of legged robots, and power generation has not been researched. But in planetary space missions, power generation has to be taken into account as well. To generate power during space missions, systems use either solar panels or Radioisotope Thermoelectric Generators (RTGs) (see table 1). On-board power generation has not been investigated for any legged prototypes, but the technologies of both commonly used methods of power generation in space exploration have been used extensively in past missions. Additionally, we are proposing the idea of a charging station at the spacecraft’s lander or, if a scout approach is used where the legged robot is uncoupling from a main rover, power generation on-board a main rover could be a valid solution. A scout approach has been suggested by Bartsch in development of the SpaceClimber prototype [4].

Solar Panels: The advantages of solar panels are their mature technology and their low weight (150 W/kg at 1 AU). On the other hand they are dependent on environment conditions (shadow, dust accumulation, etc.), and power production is discontinuous because it is depending on the solar cycle [31]. Solar irradiation limits the use of solar panels to the inner planets. Beyond Mars solar panels become too large [31]. Estimations on the efficiency of solar panels by the end of 2017 are projecting an efficiency of 33% to 36% [31]. Data collected from the Mars Exploration Rover OPPORTUNITY and SPIRIT suggest a loss due to dust accumulation of maximum 30% [52]. From time to time the accumulated dust removes itself, due to unknown reasons called cleaning events [31]. Solar Panel cleaning techniques such as mechanical brushes, vibration of the panels, blowing by compressed gas and electrodynamic screens have been tested [31]. To satisfy the energy consumption of a given system, the required area of solar panels is varies depending on the solar irradiation of the target planet. To start examining the needed area, we use a rather simple approach by estimating the solar panel area with eq. 2.

To validate the approach further, we tested it on the data of the OPPORTUNITY Mars rover and calculated the solar panel area for an employment on Mars with a solar irradiation of 588.6 W/m², a power consumption for driving of 100 W [53], dust loss factor of 0.7 [52] and a solar panel efficiency of 27.5% [52]. The simple approach resulted in a required solar cell area of 0.88 m².
The results can be found in table 2. Power consumption of the systems we used the average power needed while walking or driving. The power consumption of the systems we used the average power needed while walking or driving.

To shrink the panel size further a dust removal strategy is suggested. To solve power generation beyond lunar distance, we suggest suitable energy saving strategies. To solve power generation beyond lunar distance, we suggest suitable energy saving strategies.

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This falls short compared to the actual used solar panel area of 1.3 m² (see table 1). This deviation is not surprising, as our approach was very simplistic. The deviation can be explained by the many missing factors, such as a needed over capacity, redundancy, uncertainty factor, atmosphere etc. Further improving our approach, we suggest a safety factor, which collects all unknown factors and a safety margin. This factor can be calculated from the results of the OPPORTUNITY rover resulting in a safety factor of 1.5. We used eq. (2) to estimate the required solar panel area of legged systems in an intended space exploration mission. We assume a solar panel efficiency of 33 % [31], robot power consumption from [4, 11, 17, 33] and a safety factor of 1.5 (see above). For the power consumption of the systems we used the average power needed while walking or driving. The results can be found in table 2.

\[
A = \frac{P}{\eta \lambda R} S
\]

where \(A\) = Solar panel area \([m^2]\), \(P\) = Required Power \([W]\), \(S\) = Safety factor (1.5), \(\eta\) = Efficiency (33 %), \(\lambda\) = Dust loss factor (0.7), \(R\) = Solar irradiation \([W/m^2]\).

The goal of this approach is to give a first overview of where solar panels might provide a valid solution. The needed solar panel area of the legged systems at lunar distance is 1 m² to 1.79 m² (see table 2). Comparing this with the actual solar panel area of the OPPORTUNITY Mars rover at Martian distance of 1.32 m² (see table 1), the required area for legged systems and with that the usage of solar panels for legged systems, might be feasible up to lunar distance. To solve power generation beyond the Moon, we suggest suitable energy saving strategies. To shrink the panel size further a dust removal technique could be used. As an energy strategy we suggest frequent recharging events, which can last for long timespans. The main advantage of solar panels is their low specific power and their maturity. They have been frequently used in past space mission and their TRL is 9. Nevertheless, the implementation of solar panels with legged systems has not been shown yet.

Radioisotope thermoelectric generator (RTG): The alternative to solar panels is the use of RTGs. They generate power by converting heat of a nuclear heat source, for instance plutonium-238 dioxide, to electricity. RTGs become inevitable for destinations in outer planets and permanently dark areas. The main advantages are continuous power generation and independence from environmental conditions. While the disadvantages include high mass, low availability, safety and difficulty to dissipate the continuously generated heat during night. Availability is a problem as there is only a very low production of the required radioactive material. In Europe, RTGs are in fact unavailable. Estimations on future RTGs are projecting a specific power of 6.4 W/kg [31], this falls short behind the specific power of solar panels of 150 W/kg at 1 AU. More mass is needed to produce the same energy compared to solar panels, this becomes a problem for small robots. We therefore estimate that RTGs are unfeasible for legged robots, due to the heavy weight of RTGs in combination with a potentially small legged systems. However, RTGs are a mature technology and have been used frequently in past missions, such as in the CURiosity Mars rover, and therefore have a TRL of 9.

Batteries: Batteries have been used extensively in space exploration missions and therefore are a mature technology. Li-ion rechargeable batteries already reach a energy density of 190 Wh/kg and rechargeable Li-S batteries are expected to have a energy density over 350 Wh/kg [31]. We estimate that those batteries can be used without any large adaptation for legged systems, we estimate their TRL to be at level 9.

Table 2: Estimated required solar panel area across solar system with eq. (2) (irradiation data from [31], robot power consumption from [4, 11, 17, 33])

<table>
<thead>
<tr>
<th>Target</th>
<th>Distance (10⁸ m²)</th>
<th>Mean Solar Irradiation (W/m²)</th>
<th>SpaceClimber</th>
<th>ANYmal</th>
<th>MIT CHEETAH</th>
<th>OPPORTUNITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>57</td>
<td>9116.4</td>
<td>0.15</td>
<td>0.21</td>
<td>0.27</td>
<td>0.09</td>
</tr>
<tr>
<td>Venus</td>
<td>108</td>
<td>2661.0</td>
<td>0.51</td>
<td>0.71</td>
<td>0.92</td>
<td>0.29</td>
</tr>
<tr>
<td>Earth/Moon</td>
<td>150</td>
<td>1366.1</td>
<td>1</td>
<td>1.38</td>
<td>1.79</td>
<td>0.57</td>
</tr>
<tr>
<td>Mars</td>
<td>227</td>
<td>588.6</td>
<td>2.32</td>
<td>3.20</td>
<td>4.16</td>
<td>1.32</td>
</tr>
<tr>
<td>Jupiter</td>
<td>778</td>
<td>50.5</td>
<td>27</td>
<td>37.29</td>
<td>48.48</td>
<td>15.43</td>
</tr>
</tbody>
</table>

This deviation is not surprising, as our approach was very simplistic. The deviation can be explained by the many missing factors, such as a needed over capacity, redundancy, uncertainty factor, atmosphere etc. Further improving our approach, we suggest a safety factor, which collects all unknown factors and a safety margin. This factor can be calculated from the results of the OPPORTUNITY rover resulting in a safety factor of 1.5. We used eq. (2) to estimate the required solar panel area of legged systems in an intended space exploration mission. We assume a solar panel efficiency of 33 % [31] for the legged systems and 27.5 % [52] for the OPPORTUNITY rover. We keep the Martian dust loss factor of 0.7 [52] and a safety factor of 1.5 (see above). For the power consumption of the systems we used the average power needed while walking or driving. The results can be found in table 2.

\[
A = \frac{P}{\eta \lambda R} S
\]

where \(A\) = Solar panel area \([m^2]\), \(P\) = Required Power \([W]\), \(S\) = Safety factor (1.5), \(\eta\) = Efficiency (33 %), \(\lambda\) = Dust loss factor (0.7), \(R\) = Solar irradiation \([W/m^2]\).
4.2.5 Thermal control

In space missions heat can not be dissipated via convection and temperature changes are drastically. Therefore, depending on the destination, the robot has to withstand the conditions of vacuum. During the transfer to the final target the system can be connected to the external radiator of the transfer vehicle. Arriving at Mars, because of the thin atmosphere, convection is highly reduced but still possible. In addition to convection Mars rovers, such as CURIOSITY and EXOMARS, therefore typically use a large radiator setup for heat management.

In the Apollo missions the Lunar Roving Vehicle’s (LRV) batteries and electronics used passive thermal control via phase-change thermal capacitors and upwards facing radiating surfaces. To avoid dust accumulation, the radiators of the LRV have been covered in blankets while driving and were manually cleaned by the astronaut with hand brushes after driving. Heat generated by the motors was radiated to space through the casting. To support transmission of heat from the motors to the outer wall, Nitrogen was sealed inside each drive assembly.

Temperatures in a thin atmosphere drop very low during nighttime, and robots need to heat their internal systems to stay within the operating temperature of the components. This can be done by an electric heater, by using waste heat, or by a Radioisotopic Heater Unit (RHU). An other option is the usage of insulation to reduce the heat transfer to the environment.

Processors and electric motors are the main source of heat in legged system. We discuss the thermal control of them further.

Processors: Future space processors consume less energy per instruction and with that are more energy efficient, but will also be more powerful. The combination of those two factors leads to, in absolute terms, stagnating energy consumption of the processor. Taking the energy consumption as a metric of thermal dissipation, this also means a stagnating thermal dissipation of the processing unit. This can be further shown by comparing the much more powerful SpaceCube 2 with the RAD750 processor. Spacecube 2’s FPGA has the same absolute energy consumption as the RAD750 processor of the Mars rover CURIOSITY while having 16 times the computational power. We estimate that the thermal control of the processor of the CURIOSITY rover should be sufficient for the thermal control of the processor of a legged planetary space exploration robot. Thus we estimate the according TRL of thermal control of processors at level 9.

Electric motors: Thermal control of the electric motors can become a challenge for both non-compliant and compliant actuation. DFKI’s SpaceClimber is using a ROBODRIVE motor, which has been space qualified and tested in the ROKVISS space verification experiment. The ROKVISS experiment has not reported any problems with thermal control of the motor. Therefore we estimate, that thermal problems with the motor might not be an issue for statically stable walking robots and their non-compliant actuators.

There has not yet been major research in the thermal control of compliant actuation, as used in dynamic locomotion, for space exploration. However, ROBONAUT 2’s SEAs must be constructed with thermal control in mind, as the legs and their actuation have been constructed specifically for Extra Vehicular Activities. Still, there is no particular information available about the thermal control of the legs and their actuation. Similarly, motors with Pseudo-direct drive systems produce a lot of heat due to Joule heating. Concluding from those finding we estimate the TRL of thermal control of the electric motors to be on level 7 for non-compliant actuators respectively on level 5 for compliant actuators.

There has not been any particular work for legged robots in heating or isolation of the internal compartment during night, nor has there been any research in dissipating waste heat of legged robots in space. Nevertheless it is expected that the technologies used so far can be adapted. Future work is especially needed in thermal control of compliant actuators.

5 Gait analysis

Animals can make use of different gaits depending on the situation and the desired walking velocity. This also holds true for legged robots. Depending on the environment, constraints and optimisation objectives, different gaits become suitable. Optimisation objectives include energy efficiency, desired velocity and risk minimization. Different gaits can be classified by using Hildebrand diagrams. An example of Hildebrand diagrams is provided in fig. A gait can be classified by the duration in which feet have ground contact, which is called Duty Factor, and by the Phase Difference the rear and the front legs have. Both variables are expressed by percentage of a total gait cycle. Gaits can further be classified as asymmetrical and symmetrical (fig. 8).
In symmetrical gaits, each foot of a pair have the footfall at the same time and have ground contact for the same duration \[2\]. Symmetrical gaits can be further classified into walking gaits, which have a duty factor of 50\% or more, and running gaits which have a duty factor of 50\% or less \[54\].

Fig. 8: Hildebrand gaits used in simulation with ANYmal

Ackermann et al. \[55\] optimised bipedal gaits under physiological constraints with realistic musculoskeletal models using predictive computational simulation. The study reveals that a skipping gait is the most efficient and least muscle fatiguing gait in micro-gravity, such as on the Moon \[55\]. Skipping performance is better in micro-gravity as both walking and running. On Mars gravity, all three gaits walking, running and skipping are coexisting with each minimizing a different objective. On Mars gravity, all three gaits walking, running and skipping are coexisting with each minimizing a different objective. On Mars, walking is best at 1.1 m/s and at 2 m/s running needs minimal energy, while hopping is least muscle fatiguing. Performance criteria, such as risk of trapping or stability, may lead to different outcome and by that to a different optimal gait \[55\].

A study conducted by ESA analysed different quadrupedal gaits by using Hildebrand gait diagrams \[2\]. The gaits were analysed under varying environment conditions such as gravity. An optimisation of the gaits based on important criteria of space missions such as motion speed, energy efficiency and payload capability was conducted, and the appropriate gaits chosen. Environment conditions such as gravity and soil property were included in the model. The study concluded from the optimisation the following:

- with increasing gravity the duty factor increased
- with increasing gravity the phase difference was decreased
- with increasing slope inclination the duty factor decreased
- with increasing leg stiffness the phase difference was decreased
- with increasing leg stiffness the phase difference was decreased
- with increasing body mass the duty factor increased
- with increasing desired forward velocity the duty factor decreased
- with increasing desired forward velocity phase difference was increased

Analysing the results of \[2, 55\] we estimate, that on small celestial bodies with gravity lower than that of Mars, jumping and running gaits are the most suitable gaits. With further decreasing gravity, running becomes less suitable and jumping becomes ultimately the most suitable gait in terms of energy efficiency and overall speed. We performed a simulation with our robot ANYmal and can confirm the tendency. With decreasing gravity on Mars and Moon, energy consumption reduces drastically for running gaits while it also reduces, less significantly, for walking gaits (fig. 9). The COT diagram reveals that gaits with flight phases ultimately start to become more energy efficient than walking gaits (fig. 10). For the sake of comparability, we used the gravity constant of each celestial body and fixed the robot’s forward velocity to a constant value, \(V_{des} = 0.62\) m/s, on all gaits. To optimise for energy efficiency one could find the optimal velocity for the respective gaits which might lead to higher efficiency on the running gaits as Ackermann suggests \[55\]. At bigger celestial bodies with a gravity stronger than that of Mars, walking is the most suitable gait for a slow desired speed and running for a fast desired speed. With increasing gravity, walking becomes more favorable also for higher speeds.

Fig. 9: Simulation results for average power consumption on Earth, Moon and Mars

IAC–17–17.D3.3.5
Fig. 10: Simulation results for COT on Earth, Moon and Mars

With our conclusion of the studies and the characteristics of possible destinations we suggest suitable locomotion approaches for space exploration robots in table 3. The suitability of the locomotion approach is based on our findings and gives a first direction. The choice of suitable locomotion approaches are based on energy efficiency, speed and the capability to traverse highly unstructured and steep terrain. Gravity was the main celestial body characteristic that was taken into account for estimating the locomotion suitability.

6 Conclusions

Firstly, we have compared legged with wheeled locomotion and derived performance metrics. The capabilities of legged systems to traverse highly unstructured terrain, overcome large obstacles and climb steep, soft soiled slopes outperform wheeled locomotion.

Next, we have reviewed state of the art terrestrial legged robots and compared them to extraterrestrial legged robot prototypes. As was expected, we noted a technological gap between the terrestrial and extraterrestrial systems. Most notably, terrestrial systems are energy efficient, dynamically walking robots, whereas extraterrestrial prototypes are statically stable walkers which use less demanding technologies.

Afterwards, we analysed the subsystems of dynamically walking legged robots further and identified corresponding key technologies. In order to conclude where additional work is needed, we estimated the TRL of the key technologies. Most of the mature space exploration technology are also used by legged systems or could be adopted by them. However, not all technologies have reached a sufficient maturity. The estimated TRL is at an intermediate level in compliant actuation and respective thermal control, LiDARs, tactile feet sensors, computational power for dynamic locomotion and power generation.

Finally, we investigated optimal gaits in terms of energy efficiency. We show that for reduced gravity, running gaits with full flight phases become ultimately the most efficient gaits. Generally, dynamic gaits gain drastically in terms of energy efficiency in low-gravity environment.

Environments of celestial bodies are very challenging, especially in scientifically interesting sites such as lunar craters. Legged systems are very well suited to reach those areas. To bring today’s legged robots into space, further research is needed to raise the TRL of the underlying technologies. Nevertheless, the development of legged space robots is an important building block for future exploration. They will open the door to thus far inaccessible destinations and become an essential component of space exploration.

Acknowledgement

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