MANTIS - A ROBOT WITH ADVANCED LOCOMOTION AND MANIPULATION ABILITIES

Marc Manz[1]**, Sebastian Bartsch**[1]**, and Frank Kirchner** [1,2]

[1]*DFKI - Robotic Innovation Center Bremen, Robert-Hooke-Straße 5, 28359 Bremen, Germany*
Contact: firstname.lastname@dfki.de

[2]*University of Bremen, FB3, Robotics Lab, Robert-Hooke-Straße 5, 28359 Bremen, Germany*

ABSTRACT

We present in this paper the specifications and design of a multi-legged robot with manipulation abilities for extraterrestrial surface exploration activities. The paper contains a brief description of the project LIMES as well as the major goals therein. The underlying methods of identifying system requirements are then described , including the envisaged mission scenario, resulting requirement lists and semantic graphs depicting dependencies. Included in this is the evaluation of different concepts with respect to varying criteria. A description of the functional principles and components is provided with regard to the merits of chosen forms of actuation, planned sensors, electronic devices and structural materials. Finally, a brief overview of how the system is to be realized is given as well as a description of the most important key technologies and components.

Key words: Space Robotics, Simulation, Robot Design, System Engineering, Conceptual Design, Mobility, Legged Robots, Locomotion, Manipulation, Surface Exploration.

1. INTRODUCTION

The system under development is within the scope of the LIMES[1] project funded by DLR[2]. The primary objectives of the LIMES project are the development of a robot prototype which combines manipulation and locomotion abilities, the generation and optimization of various forms of locomotion designed to provide the system with mobility in a variety of terrain as well as an intelligent control framework capable of choosing the most suitable form of locomotion depending on perceived surface conditions. The knowledge about the most suitable locomotion behavior in a specific environment will be obtained from simulations as well as by tests with the actual robot in lunar-like surface conditions. The use of robots for space exploration increased in the last decades. On one hand, this is a direct result of the increasingly greater computing capacities provided to cope with higher complexity of control algorithms and on the other hand, with the progress in the field of mechanics and electronics. This development has lead to an increase in the abilities of robots to carry out complex tasks. To this end we designed a new type of biologically inspired robot (Fig. 1). The specifications of the system are based on the requirements of a fictitious reference mission according to envisaged space missions like the upcoming "sample and return" missions [1].

Figure 1. Mantis Concept
(left: walking posture, right: manipulation posture)

There currently exist a variety of statically stable walking machines with the ability to navigate, localize and move semiautonomous. However most of these are strongly limited within their manipulation abilities. The need for extended manipulation capabilities in future space missions is mentioned within several space agency guidelines such as NASA's "Vision for Space Exploration". In order to work in cooperation with humans in prospective space missions, it is advantageous to provide dual arm manipulation. Theoretically this enables a system to manipulate objects in a similar fashion as human [2] [3].

[1]**L**earning **I**ntelligent **M**otions for Kinematically Complex **L**egged Robots for **E**xploration in **S**pace

[2]Grant No. 50RA1218 and 50RA1219

2. SPECIFICATION

For the development of a robotic prototype from scratch it is crucial to determine all the dependencies of soft- and hardware design. For this purpose a suitable exploration scenario was defined to help characterize necessary abilities, major requirements as well as components necessary to solve the mission tasks. This will be further clarified in the following section.

2.1. Mission Scenario

The scientific community disagreed on the gain of legged robots for space exploration [4]. The development of Mantis intended to help demonstrate the utility of legged robots under given circumstances such as rough uneven terrain as well as the need for dual arm manipulation. As has been made evident in the introduction, the heightened advantage of dual arm manipulation is of great use when preparing the environment and infrastructure, within following missions with humans or as an aid to humans during missions. Legs are not required for manipulation activities and a robot such as the Centaur developed by NASA would also be capable fulfilling such tasks assuming terrain is not too rough [3]. If these capabilities are also required on uneven terrain as found on boulder fields, craters and rock fissures, legs are advantageous [5]. The scenario depicted in Fig. 2 features Mantis in the crater together with installed infrastructure on the crater rim.

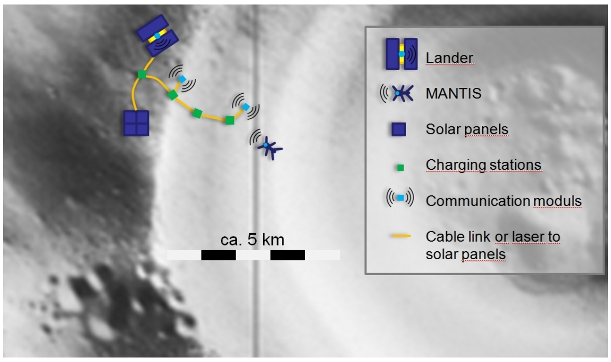

Figure 2. Example mission for in-situ analyses, Credit (Backround Picture): NASA/Zuber, M.T. et al., Nature, 2012

The German governmental space strategy specified the exploration of the moon as the next target of scientific discovery within the solar system and an ideal setting for test and usage of robotic technology [6].

Due to the low angle of incidence with which light reaches the moon at its poles, these regions receive very little to no light at all. This makes craters in the moon's extrema of particular interest to science, as it may allow the existence of volatile compounds such as water - a vital geological ingredient as well as the basis of all life on earth. This suspicion is supported by the results of the LCROSS and LRO missions. To gain further insights into the existence of ice, and to perform further analysis an in-situ mission is vital. A possible candidate for such missions is the Shackleton crater, just outside of which exist peaks of continuous light of up to 70% during winter and 100% in summer. This could potentially form a basis for a solid solar power supply. Assuming that it is possible to land next to the crater ($d < 500$m) a legged robot would be able to travel from the lander's position to the crater rim. The robot should then be able to carry a payload to the crater rim and then be capable of installing necessary infrastructure.Upon reaching the rim it needs to be able to climb into the crater to take samples or to prepare the area for later human access.

These capabilities will be demonstrated by Mantis by the end of this project within the parameters of a simplified mission. This mission will contain the following elements:

- Extract recharging station (payload 1) from payload bay
- Connect payload 1 with the lander by cable
- Transport payload 1 to its destination and initiate it
- Return to the lander and recharge
- Extract next recharging station (payload 2) from payload bay
- Transport payload 2 to the destination of payload 1, connect it with payload 1 by cable
- Transport payload 2 to its destination and initiate it
- Recharge at recharging station
- Return to lander and recharge

During the mission Mantis will be confronted with boundary conditions like steep slopes and uneven terrain. LIMES is a preliminary study for future space missions as a result it is mainly about demonstrating key robotic concepts and thus details relating to actual operation in an extraterrestrial environment such as thermal management will be excluded from development. Nevertheless most decisions made pertaining to the selection and design of key components and principles were made taking these special requirements into consideration to enable further development in following projects.

2.2. Requirements

The envisaged mission scenario makes demands on several functions on both hardware and software levels. The system needs to cope with uneven terrain and slopes of up to 35° even on loose surfaces. Components have to be sealed to protect from dust and other substances as to

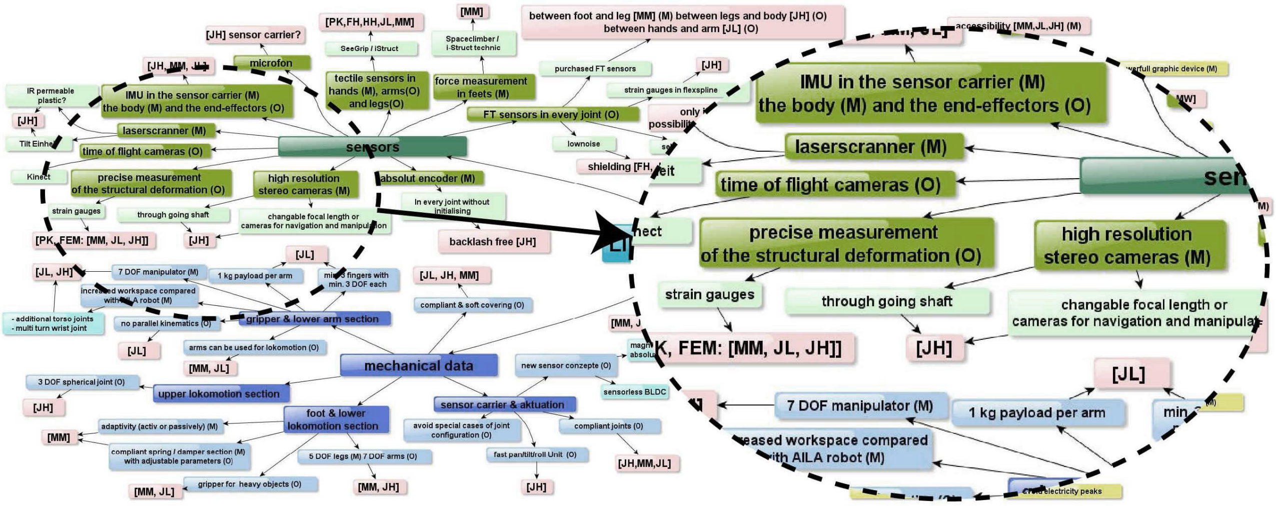

Figure 3. Requirements — (M) = mandatory , (O) = optional

avoid abrasion and short circuits. Sensors are required to sense the integrity of the surface underfoot, the system state, the environment and the objects to be manipulated. Redundancies are required on software and hardware levels to respond to changes of environment and unforeseen failures of subcomponents such as single legs or sensors [7]. To provide redundancy, aid stability and render the design more efficient the arms can also be used as legs. The system should be capable of stable movement whilst manipulating objects with its arms. To walk in a statically stable pattern at least four legs are required because one needs to be lifted and set to a new position while the others support the body.

The requirements are the outcome of mission analyses. Based on knowledge and experience from previous projects the most advantageous configuration pertaining to the success of the mission was selected. The plan was to combine and improve existing technologies developed in previous projects and thereby create a new design with maximum efficiency. The first requirement that was established was the degrees of freedom (DOF) necessary for the manipulation and locomotion. To allow remote operators an intuitive interaction with the environment it make sense to provide an anthropomorph arrangement of the arms or at least similar capabilities [8][9].

For this purpose was a seven DOF manipulator design chosen. Furthermore it was apparent from previous projects that dual arm manipulation requires an additional DOF in order to increase the workspace of the dual arm configuration.

A further advantageous DOF that was defined upon was an axis of rotation around the midriff in order to allow the upper body to turn whilst the torso remains static. Each leg has six DOF, four of which are used to position the foot on the ground, the remaining two adapting to the surface for increased traction.

3. MECHATRONIC DESIGN

After defining the design constrains in the specification phase the overall concept and those for components such as the body, arms, legs and sensor carrier were defined. In order to meet varying requirements, some aspects such as the torso were designed top down and others such as the legs were designed form the bottom up.

3.1. Concept

The required DOF, defined by analysing the mission, formed the basis of concept development. How these needed to be realized was neglected during that step. It was determined that a minimum of six extremities were necessary to accomplish the combined tasks of stable walking and concurrent dual arm manipulation. Furthermore it made sense to reduce the number of extremities to the minimum required number. The first step was to position the six extremities around the body. The inspiration for this implementation were existing systems such as CENTAUR [3], Spidernaut [10] or ATHLETE [11] from NASA and biological systems such as ants, spiders, crabs and praying mantis.

The highest rated concepts from this development phase with regard to the necessary joint torque and stability are depicted in Fig. 4. Especially the static stability in manipulation posture is critical to most of the concepts, as a result of which this criteria was decisive to the selection of the second configuration as this afforded the use of the arms for manipulation as well as locomotion which not only reflects the mantis-inspired configuration but furthermore it minimizes the complexity for straighten the body for manipulation tasks due to the decoupled joint constellation.

The main characteristic of the chosen concept is the high stability which is achieved by a low center of mass (CM) with respect to the length and width. A low CM is one of the main factors which enable insects to scale steep slopes [12]. Possibly this is the result of diverging optimization goals in the evolutionary development of mammals and insects. Insects attain great stability through the number of their legs (always six) which allows stable walking and running patterns as well as an unusually low CM. Even mammals, with a high CM with respect to their body length try to reduce the hight of their CM when dealing with steep slopes but the main strategy is to shift the center of mass [13]. This is a primary reason to choose an insect body layout to realize a stable walking machine. For the intended use this is one important

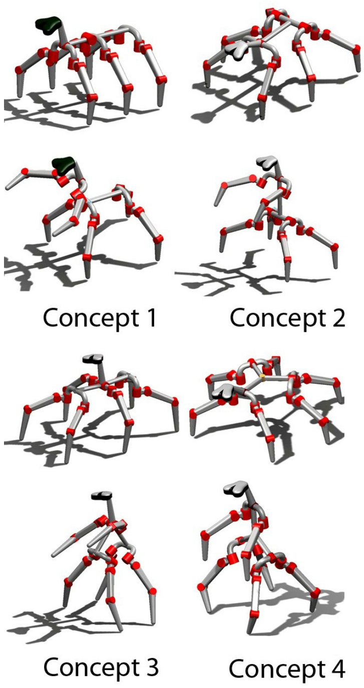

Figure 4. Concepts for the body configuration

feature, the other is a high static stability in manipulation postures and low torque required to straighten up the body. To achieve this it needs to force the location of its center of mass near to the leg rockers where the two leg pairs are mounted on. To this end most of the components are located in a kind of abdomen to form a counter weight to the arms and the upper body (see Fig. 5). If the body is in manipulation posture the center of mass still remains near to the center of the support polygon and thereby the system's statical stability persists. The two rockers are actuated by linear drives. If the robot is in the manipulation posture these linear drives enable the robot to vary its manipulation height by extending or contracting them simultaneously. If they move opposite the body tilts to the left or right.

The next step was to choose the required components and calculate their weight and dimensions. This information determines the size of the overall system and the actuators. Afterwards it was possible to approximate the system weight to around 60kg with a footprint of 1,5m x 2m in the walking posture and 1,5m x 1,5m in the manipulation posture. The height in manipulation posture will be at roughly 1,6m. These are the dimension of the first draft which will be optimized regarding to the needed torque, power consumption and stability in evolutionary simulation-based morphology optimization in a manner similar to those of SpaceClimber [14].

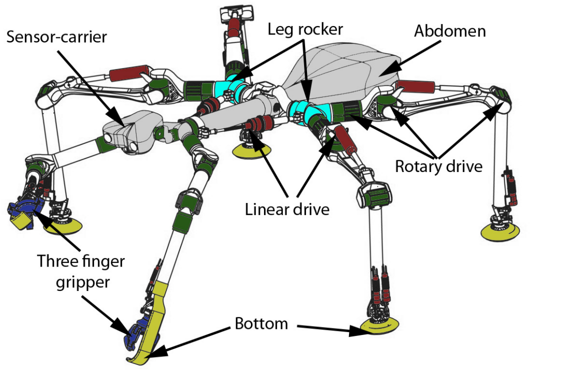

Figure 5. Concept Sketch

After defining the configuration of the legs relative to each other a decision was made regarding the arrangement of the DOFs in the locomotion extremities. Several concepts regarding the actuators and DOF were made to finally make a decision on the optimum design. The main constraint besides the workspace for the proposed type of locomotion was power consumption. This constraint drove the idea to counterbalance torques generated by gravity, allowing the design to remain in manipulation or walking postures with minimum energy consumption. Finally the legs will be realized with six DOF whereat the last two located at the foot will be either active or passive ones.

The concept of the bottom are different for the legs (hind four extremities) compared to the arms (first pair of extremities). The feet for the legs will be adaptable, which will be accomplished passively with compliant materials and structures or active with some form of fingers or claws. A dexterous gripper needs filigree fingers in order to manipulate small objects with all fingers as well as sensitive sensors to reconstruct the object and the contact forces. Due to this basic condition it was chosen to separate the gripper and feet like structure at the arms.

3.2. Components

The actuators will be based on the actuators developed in the projects SpaceClimber [15] and i-Struct [16]. These consist of brushless DC Motors combined with Harmonic Drive gears. There currently exist three different actuator sizes; 140 W, 270W and 370W. The motor electronics, three PCBs, will be integrated into the joint housing equipped with an FPGA for the motor controller and processing of sensor information. Two absolute off-axis hall effect sensors will be incorporated, one to sense motor speed and position and the other one to obtain the actuator position. Most of the actuators will be rotation drives besides those which should compensate the gravity, which will be linear drives with parallel springs.

Data exchange between the actuator processing units, the other sensors, and the main computer will be realized using LVDS standard and 8b10b codification, which allow data rates up to 320MSym/s. For environmental perception the robot will be equipped with:

- Stereo cameras in the head
- Laserscanner in the upper body or head
- Inertia measurement units in the head and the body
- Tactile sensors in the hands
- Force-torque sensors between the arms and hands and between the legs and feet
- Force sensors in the feet
- Strain gauges to detect structural deformation
- Position and torque sensors for the joints

After a comparison of different gripper designs, a three finger gripper system, similar to a barret gripper system was chosen.

4. SOFTWARE

Mantis will will provide an extremely flexible locomotor system with substantial sensory equipment. The following sections describe the general control architecture which will be realized to control the robot utilizing a distributed network of intelligent subsystems. Furthermore, it will be presented how different behaviors could be generated, optimized and utilized to achieve performant locomotion under varying surface conditions.

4.1. Control Architecture

As depicted in Fig. 6, the control architecture is divided into three levels of control.

The low-level control is responsible for the local control of the subsystems as well as the communication network connecting all peripherals with central control unit. Therefore, each component (such as actuators, feet, and grippers) is equipped with a local FPGA-based controller for sensor data acquisition and preprocessing, motor control, and communication handling. On this level the highest control frequencies and hence the fastest response

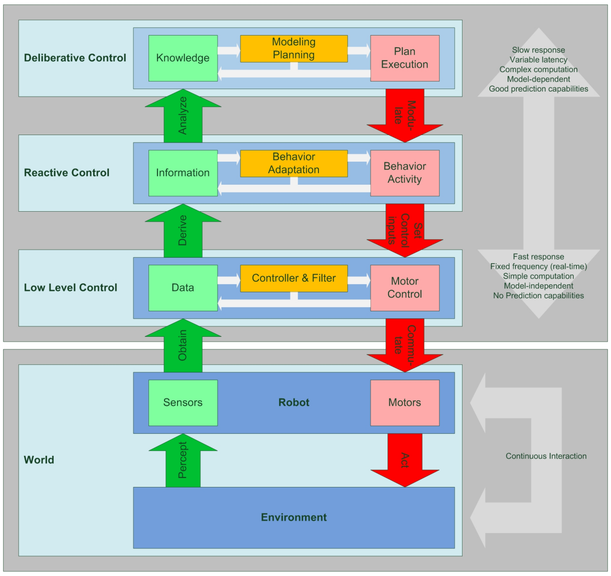

Figure 6. General control concept

times can be achieved. The subsystems are the first components that are able to perceive and react on irregularities to increase the adaptability an robustness of the overall system.

Reactive locomotion control will be realized utilizing the PCR approach already successfully used to control the motion of previous legged-robots such as Scorpion [17], ARAMIES [18], and SpaceClimber [15]. In this behavior-based control approach postural behaviors adapt the pose of the system, Central Pattern Generators (CPG) generate rhythmic oscillating walking motions and reflexes are responsible to perform reactions on irregularities. All behaviors are executed in parallel with a fixed frequency to achieve fast response times. In previous work the flexibility [19] and fault-tolerance [7] of this approach was already proven.

The deliberative control is intended to be responsible for navigational tasks such as path planning and trajectory following for which, in contrast to a purely reactive control, preexisting knowledge such as an continuously updated world model is required. Controlling the walking direction of the robot to let it walk in the intended direction is achieved by modulating the activity of the behaviors implemented on the reactive control layer. Furthermore, the availability of knowledge about the surface structure allows a reasonable selection of suitable behaviors of the reactive control layer which would provide the best mobility under specific conditions.

4.2. Behavior Generation and Optimization

The robot has to provide mobility on varying surface structures and subsoils. Thus, it has to be able to adapt its behavior to achieve efficient and stable locomotion depending on the currently perceived environmental conditions, its internal state, and the defined task. Therefore, a set of behaviors, each optimized for a specific condition, is required. This behaviors will be generated utilizing a simulation-based behavior generation and optimization approach. For this purpose suitable simulation models of the robot and the environment are required to perform virtual experiments in order to evaluate the system's performance in predefined scenarios.

It is planned to generate and optimize behaviors in two ways. The first approach is to implement parameterized behaviors and to identify suitable parameter sets for different conditions utilizing parameter optimization algorithms such as evolution strategies. The other approach is to automatically generate and optimize behaviors on a structural level. Therefore, a flexible modifiable representation of the behavior is required. As a possible solution genetic algorithms could be used to evolve neural networks, as presented in [20].

5. OUTLOOK

With this paper we propose a concept for a dexterous manipulation and high mobility locomotion robot. To realize this concept we develop several components from scratch such as an dexterous gripper with tactile sensors, passive or active adaptive feet, new electronics for the actuators and control software. The software architecture used for the SpaceClimber Robot is being expanded with an learning framework and behavior libraries for flexible adaption to different situations. In the next three years the concept will be completed to demonstrate that such a combination of a dual arm manipulating upper body and a high mobile legged lower body provides the needed abilities for the realization of complex extraterrestrial surface exploration missions.

ACKNOWLEDGMENTS

Parts of the presented work were done by the LIMES Team to which belong, apart from the authors, in alphabetical order, Fabian Adam, Alexander Dettmann, Hendrik Hanff, Jens Hilljegerdes, Florian Hühn, Peter Kampmann, Malte Langoz, Johannes Lemburg, Lorenz Quack, Timo Stoffregen, Wiebke Wenzel and Malte Wirkus.

The project LIMES is funded by the German Space Agency (DLR, Grant number: 50RA1218 and 50RA1219) with federal funds of the Federal Ministry of Economics and Technology (BMWi) in accordance with the parliamentary resolution of the German Parliament. LIMES is a cooperation between the DFKI Bremen - Robotics Innovation Center and the University of Bremen.

REFERENCES

1. N. C. on the Planetary Science, "Visions and voyages for planetary science in the decade 2013 - 2022," *Decadal Survey Space Studies Board*, 2011.

2. "The vision for space exploration," National Aeronautics and Space Administration, Tech. Rep., February 2004. [Online]. Available: http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf

3. J. Mehling, P. Strawser, L. Bridgwater, W. Verdeyen, and R. Rovekamp, "Centaur: Nasa's mobile humanoid designed for field work," in *Robotics and Automation, 2007 IEEE International Conference on*, april 2007, pp. 2928 –2933.

4. A. Seeni, B. Schäfer, and G. Hirzinger, "Robot Mobility Systems for Planetary Surface Exploration-State-of-the-Art and Future Outlook: A Literature Survey," in *Aerospace technologies Advancements*, T. T. Arif, Ed. Intech, 2010, no. 01, ch. 10, pp. 189–208.

5. D. Kar, K. K. Issac, and K. Jayarajan, "Gaits and energetics in terrestrial legged locomotion," *Mechanism and Machine Theory*, vol. 38, no. 4, pp. 355 – 366, 2003, national Conference on Machines and Mechanisms.

6. BMWi, "Für eine zukunftsfähige deutsche raumfahrt - die raumfahrtstrategie der bundesregierung," Bundesministerium für Wirtschaft und Technologie (BMWi), Tech. Rep., 2012.

7. D. Spenneberg, K. McCullough, and F. Kirchner, "Stability of walking in a multilegged robot suffering leg loss," in *Proceedings of the International Conference on Robotics and Automation (ICRA04)*, 2004.

8. C. Smith, Y. Karayiannidis, L. Nalpantidis, X. Gratal, P. Qi, D. V. Dimarogonas, and D. Kragic, "Dual arm manipulation - a survey," *Robotics and Autonomous Systems*, vol. 60, no. 10, pp. 1340 – 1353, 2012.

9. G. A. Landis, "Teleoperation from mars orbit: A proposal for human exploration," *Acta Astronautica*, vol. 62, no. 1, pp. 59 – 65, 2008.

10. F. Rehnmark, R. O. Ambrose, B. Kennedy, M. Diftler, J. Mehling, L. Bridgwater, N. Radford, and S. M. Goza, "Innovative robot archetypes for in-space construction and maintenance." Space Technology and Applications International Forum (STAIF 2005), 2005, pp. pp.1070–1077.

11. B. H. Wilcox, T. Litwin, J. Biesiadecki, J. Matthews, M. Heverly, J. Morrison, J. Townsend, N. Ahmad, A. Sirota, and B. Cooper, "Athlete: A cargo handling and manipulation robot for the moon," *Journal of Field Robotics*, vol. 24, no. 5, pp. 421–434, 2007. [Online]. Available: http://dx.doi.org/10.1002/rob.20193

12. M. Günther and T. Weihmann, “Climbing in hexapods: A plain model for heavy slopes,” *Journal of Theoretical Biology*, vol. 293, no. 0, pp. 82 – 86, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0022519311005261

13. S. jun Zhang, J. Tong, K. Hapeshi, and D. hui Chen, “Optimising body layout design of limbed machines,” *Journal of Bionic Engineering*, vol. 4, no. 2, pp. 117 – 122, 2007. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1672652907600237

14. M. Langosz, D. Kuehn, and F. Kirchner, “Robot design for space missions using evolutionary computation,” in *IEEE Congress on Evolutionary Computation. IEEE Congress on Evolutionary Computation (IEEE CEC-2009), May 18-21, Trondheim, Norway*, 2009.

15. S. Bartsch, T. Birnschein, M. Langosz, J. Hilljegerdes, D. Kuehn, and F. Kirchner, “Development of the six-legged walking and climbing robot spaceclimber,” *Journal of Field Robotics*, vol. Volume 29, Issue 3, Special Issue on Space Robotics, no. Part 1, pp. 506–532, 6 2012.

16. D. Kühn, F. Beinersdorf, F. Bernhard, K. Fondahl, M. Schilling, M. Simnofske, T. Stark, and F. Kirchner, “Additional dofs and sensors for bio-inspired locomotion: Towards active spine, ankle joints, and feet for a quadruped robot,” in *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2012), September 4-6, Turin, Italy*, 9 2012.

17. F. Kirchner, D. Spenneberg, and R. Linnemann, “A biologically inspired approach toward robust realworld locomotion in legged robots,” *Neurotechnology for Biomimetic Robots. MIT-Press, Cambridge, MA, USA*, 2002.

18. D. Spenneberg, M. Albrecht, T. Backhaus, J. Hilljegerdes, F. Kirchner, A. Strack, and H. Zschenker, “Aramies: A four-legged climbing and walking robot,” in *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2005), September 5-8, Munich, Germany*, 9 2005.

19. D. Spenneberg and F. Kirchner, “Omnidirectional walking in an eight legged robot,” in *Proc. Symp. on Robotics and Automation (ISRA)*, 2000.

20. Y. Kassahun, J. H. Metzen, J. de Gea Fernndez, M. Edgington, and F. Kirchner, “A general framework for encoding and evolving neural networks,” in *KI 2007: Advances in Artificial Intelligence. 30th Annual German Conference on Artificial Intelligence (KI-2007), September 10-13, Osnabrck, Germany. September 10-13, Osnabrck*, ser. LNCS, J. Hertzberg, M. Beetz, and R. Englert, Eds., vol. 4667. Osnabrck, Germany: Springer, 9 2007, pp. 205–219.