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Report

Serpentine Robots for Planetary Exploration (SERPEX)

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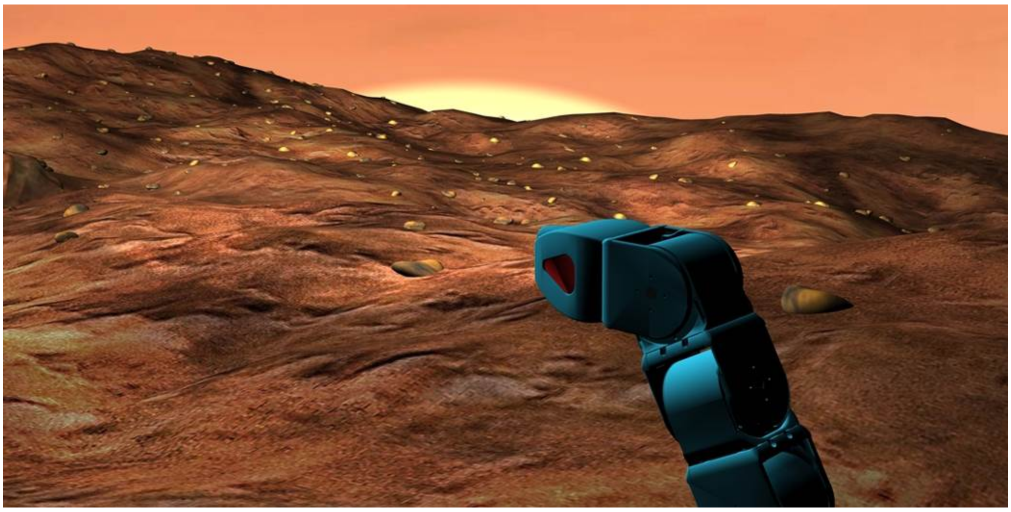

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ABSTRACT

Snake robots have a strong inherent potential to move and operate robustly in challenging environments where more conventional wheeled and tracked mobile robots may fail. Such abilities are important for planetary exploration. In this report, we have investigated the feasibility of snake robots for planetary exploration. In particular, we discuss the advantages (e.g., traversability, stability, redundancy) and disadvantages (e.g., low payload/speed/energy efficiency) for snake robots in a planetary exploration context, as well as the imminent challenges (i.e., control system and mechanism development) which need to be addressed in order to realize the potential of snake robots as transport mechanisms in cluttered and challenging terrains. Moreover, we consider operational and scientific aspects of snake robots for planetary exploration, and discuss serious spin-off possibilities to terrestrial applications within, e.g., inspection and maintenance, fire-fighting, and search and rescue. Finally, we present selected concepts involving snake robots for planetary exploration, which include rover-snake robot cooperative systems.

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Executive summary

Snake robots have a strong inherent potential to move and operate robustly in challenging environments where more conventional wheeled and tracked mobile robots may fail. Such abilities are highly relevant for planetary exploration. In this report, we discuss key aspects regarding the use of snake robots for planetary exploration.

What is a snake robot?

A snake robot is a robotic mechanism designed to move like a biological snake. Inspired by the robustness and stability of biological snake locomotion, snake robots carry the potential of meeting the growing need for robotic mobility in unknown and challenging environments. Snake robots typically consist of many serially connected joint modules capable of bending in one or more planes.

The NTNU/SINTEF snake robot "Mamba".

Technological aspects of employing snake robots in a space mission context

We discuss the main advantages and disadvantages, as well as main challenges with snake robots in a space mission context. Keywords are listed in the tables below and further discussed in the report.

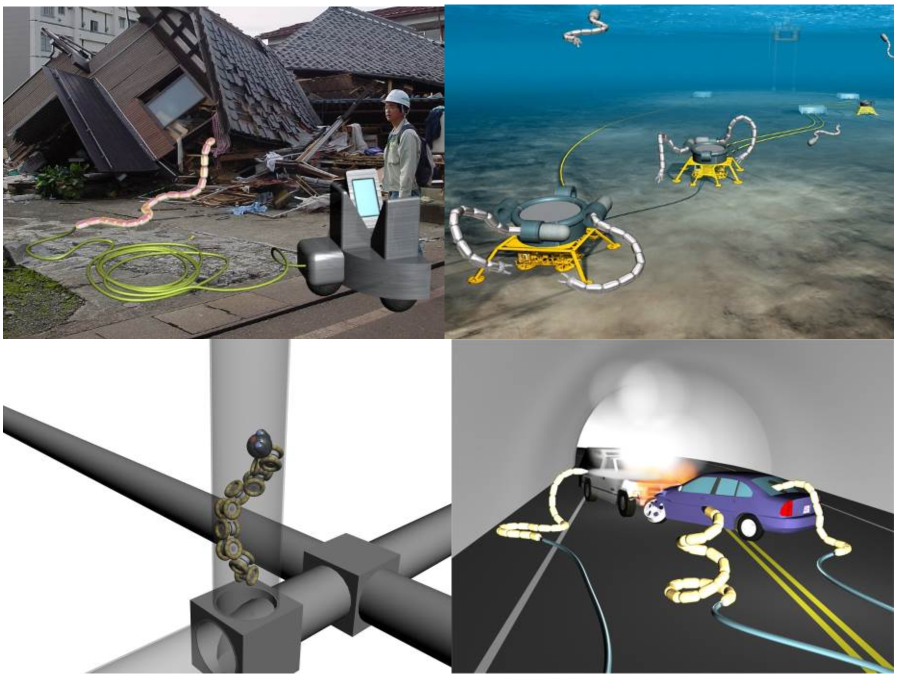
Main advantages and disadvantages of snake robots	
Advantages	Disadvantages
✚ **Stability**: A snake robot has a low centre of gravity, and its long body provides many distributed support points.	⊖ **Low speed**: Less critical for smaller distances.
✚ **Recoverability:** For most practical purposes there is no "upside down" for snake robots.	⊖ **Limited payload**: Less critical for smaller payloads.
✚ **Traversability**: Ability to traverse rough and difficult terrain.	⊖ **Complex propulsion system**: A snake robot has many joints, but at the same time a modular design.
✚ **Small cross-sectional area** allows passage through small holes and gaps.	⊖ **Relatively low energy efficiency**
✚ **Redundancy**: Propulsion may be maintained even if some joints fail.	
✚ **Mobility+manipulation**: Combined manipulator and mobile robot.	

In the following table, we point out important research challenges that must be addressed in order to realize operational snake robots in terrestrial or space-related applications.

Main challenges with snake robot development and operations	
Control system	Mechanism design
Analysable mathematical models	Environment sensing
Motion planning	Robot vision
Simultaneous Localization and Mapping (SLAM)	Power provision and solutions for tethered/untethered operations
Snake robot control based on environment sensing	Robust, strong and durable actuation mechanisms
	Ground friction force limitation
	Environment protection

Spin-off possibilities and synergies with earth-bound applications

Snake robots are already considered for a range of terrestrial applications (see illustration on this page). To this end, there are serious spin-off opportunities and synergies between terrestrial applications and planetary exploration in space. Common factors between these two application areas include lightweight and robust joint mechanisms, localization, mapping, and control of snake robots in challenging/cluttered environments.



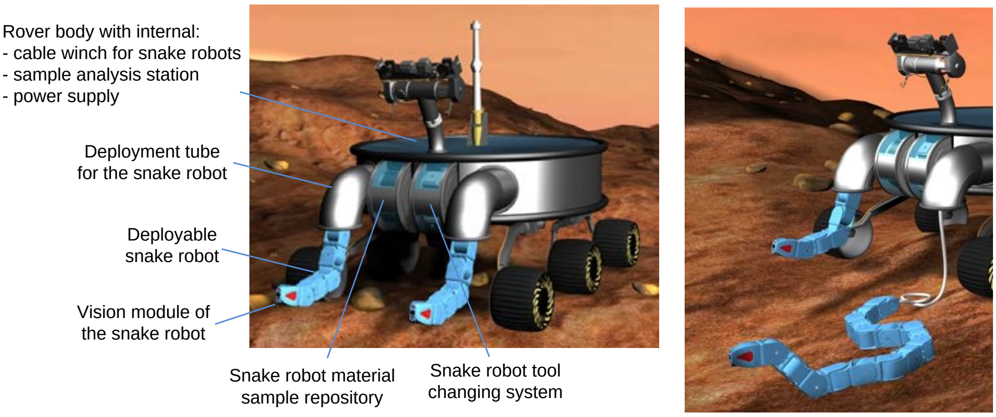
Terrestrial snake robot applications: search and rescue (top left), subsea operations (top right), inspection and maintenance (bottom left), and fire-fighting (bottom right).

Operational aspects

Operational aspects encompass considerations relevant for *how* and *where* a system is being deployed and used by operators. The operational aspects of planetary exploration with snake robots are discussed with the ExoMars mission and the NASA Human Exploration of Mars Design Reference Architecture 5.0 as frames of reference. Human-machine cooperation for snake robots includes many of the same aspects for snake robots as with more conventional large rovers. Possible future manned missions to Mars may include that an astronaut deploys a snake robot close to a cave or other challenging terrains in order to investigate these areas without comprising the safety of the astronaut (who then does not need to enter the, e.g., cave himself/herself) .

Concepts for planetary exploration with snake robots

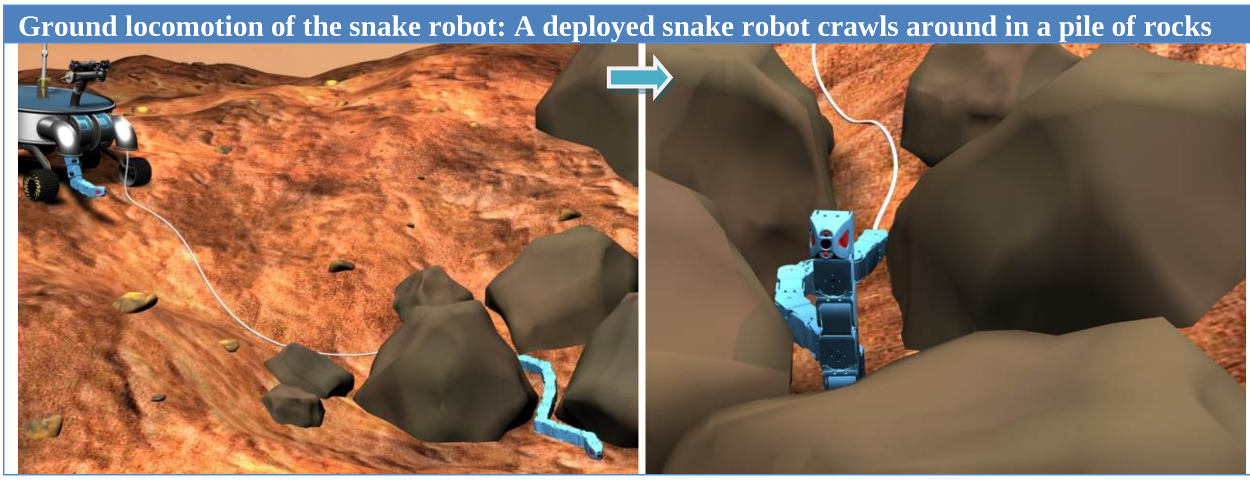
In this report, we present selected concepts for planetary exploration where snake robots complement operations with current rovers. This focus has been chosen since a cooperative rover–snake robot system can exploit the individual advantages of the two robot systems. In particular, a rover can cover rather large areas, it has a relatively high energy storage capacity, and it can transport a sample analysis station. A snake robot, on the other hand, can access narrow and cluttered terrains in order to perform sample taking, as well as acting as a detachable manipulator arm. Detailed design descriptions are outside the scope of this report. Instead, we focus on illustrating conceptual ideas in order to give an overview of possibilities.



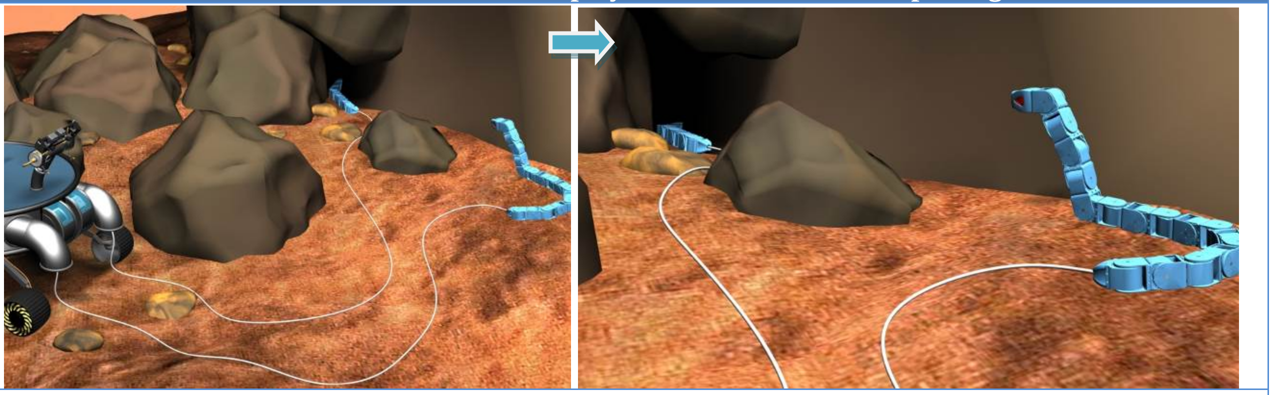
Conceptual overview of a rover equipped with two deployable snake robots.

In the following, we briefly present four concepts for snake robots in a planetary exploration setting: Ground locomotion, tool changing operation, manipulation / sample-taking, and rover assistance. Deployment of a snake robot from a rover is illustrated in the figure above.

Ground locomotion of the snake robot: A deployed snake robot crawls around in a pile of rocks

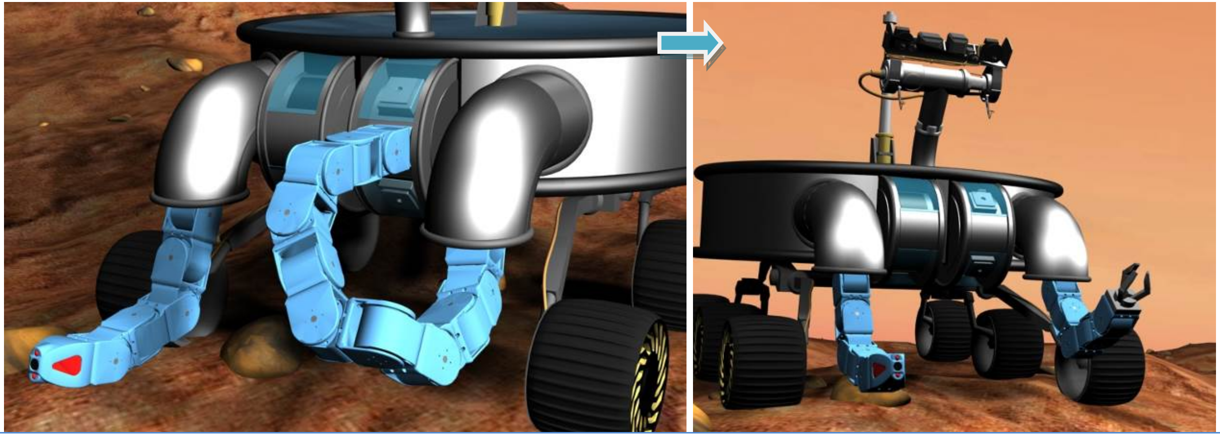


Ground locomotion of the snake robot: Two deployed snake robots are inspecting a cave



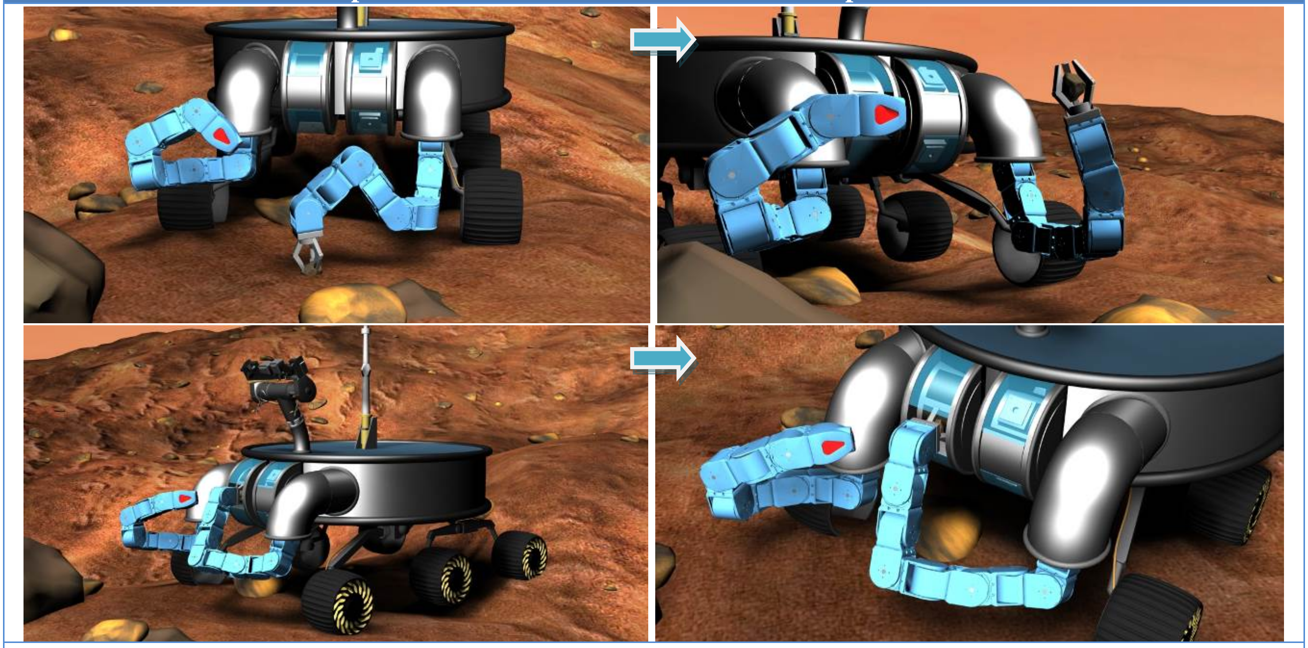
Two snake robots have been deployed in order to investigate a cave and possibly perform sample-taking.

Tool changing operation: A snake robot replaces its camera with a gripper



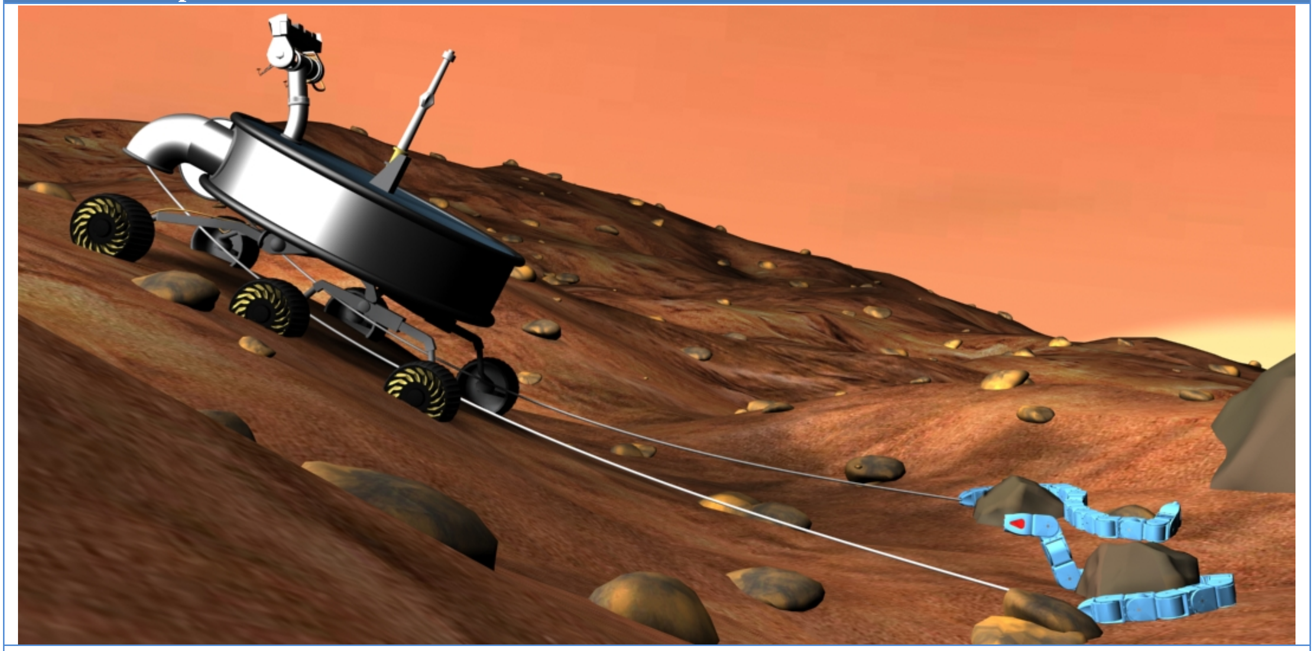
One of the snake robots accesses the snake robot tool changing system in order to replace its camera module (attached to the front of the snake robot) with a gripper module. The gripper module could also contain a smaller camera which can be used by the snake robot if it, e.g., should detach from the rover to crawl to a location in order to do sample-taking.

Snake robots used as manipulator arms to retrieve a material sample



A snake robot uses its gripper tool to pick up a piece of rock from the ground while the other snake robot attached to the rover monitors the operation using its camera module. The grasped rock is placed into the rover's sample repository for further processing by the sample analysis station inside the rover.

Snake robot provide rover assistance in extreme terrain



Two deployed snake robots are using their tether connection to help the rover loose after its wheels were trapped in the sand. The rover runs its tether winch while each snake robot anchors its body around a rock.

Further work following this report

We suggest that further work includes a quantitative analysis and development of more detailed designs of the various aspects identified in this report. Moreover, further research and development is required in order to address challenges related to snake robot locomotion and mechanism design, as well as to build a stronger foundation for concluding about the relevance of snake robots in a space mission context.

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1 Introduction

1.1 Project motivation and contribution

Robots constitute a key tool for investigating other planets. In the last decades, exceptional engineering accomplishments have brought robots to Mars for the purpose of increasing our understanding of this fascinating planet.

As activities on investigating Mars and other extra-terrestrial objects increase, the need to operate in more challenging environments also increases. To this end, we will need robots with mobility that exceeds the mobility of conventional wheeled rovers.

Snake robots are long and flexible robotic mechanisms designed to move like biological snakes. The advantage of such mechanisms is their ability to move and operate robustly in challenging environments where more conventional wheeled and tracked mobile robots are likely to fail. Future earthbound applications of these mechanisms include search and rescue operations in earthquake areas, inspection and maintenance in industrial process plants, and subsea operations.

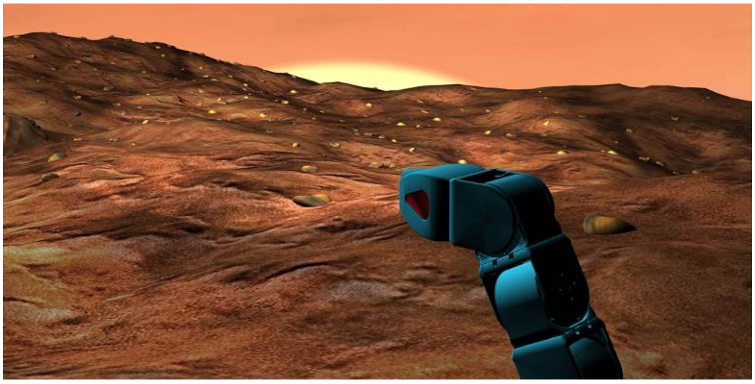

Figure 1: Illustration of a snake robot overlooking a Martian landscape.

Research on snake robots has been conducted for several decades, but their potential in terms of mobility has not yet been realized. The main reason for this unrealized potential is the complexity involved in developing and controlling a snake robot due to its many degrees of freedom. Demonstrations of real-world applications with mobile snake robots are so far very limited. During the last decade, however, there has been a boost in research and development in snake robotics, bringing us close to real-world applications of these mechanisms.

In addition to earthbound applications, there is also a significant potential in the use of snake robots to carry out operations in space and on other planets. To this end, the motivation behind this project has been to assess the feasibility of employing snake robots for space missions involving planetary exploration. In particular, in this report we:

- ☑ Provide an introductory overview of snake robots in general as well as their biological counterpart.
- ☑ Investigate key aspects of snake robot mechanisms in order to identify advantages, disadvantages, possibilities, and challenges related to the use of snake robots in a space mission context,
- ☑ Provide a comparison between snake robot mechanisms and more conventional wheeled and tracked forms of robotic mobility in order to outline the possibilities and inherent added value of snake robots.
- ☑ Further support the above perspectives by proposing several use-cases and concepts related to planetary exploration based on snake robot locomotion.
- ☑ Consider the operational and scientific aspects of using a snake robot in a space mission context.
- ☑ Identify and discuss synergies between snake robot technologies for space missions and earthbound/terrestrial applications, respectively. The many application areas of snake robots on earth imply that the technological development of a snake robot for space missions will have strong synergies with related earthbound applications. To this end, we investigate how different industries and application areas on earth can both support and make use of the technological elements of a snake robot developed for space missions.

1.2 The scope of this report

The work underlying this report has been carried out with the following four main objectives:

O1. Investigate **key aspects** of snake robots (serpentine robots) and assess the **feasibility** of employing such mechanisms for space missions involving planetary exploration.

O2. Investigate and suggest **use-cases and concepts** which illustrate possibilities and challenges of using snake robots for planetary exploration in comparison with more conventional wheeled and tracked forms of robotic mobility.

O3. Identify **synergies with earthbound applications** by investigating how different industries and application areas on earth can both support and make use of the technological elements of a snake robot developed for space missions.

O4. Investigate **operational aspects** of using snake robots for space missions.

The report focuses on future unmanned missions to Mars as these as more close compared to manned missions. Aspects such as detailed designs and detailed operational concepts, as well as experiments and detailed quantitative analyses are outside the scope of this report.

1.3 The research team behind this report

SINTEF and the Norwegian University of Science and Technology (NTNU) have acquired an internationally leading position in modelling, control and development of snake robots, and have in particular targeted research challenges imposed by snake locomotion in irregular environments.

Research on snake robots at the Norwegian University of Science and Technology (NTNU) has spawned from a research project at SINTEF. The project was initiated in 2003 after several major city fires in Trondheim, which launched an initiative to bring the fire department in closer relation with the research community in Trondheim to stimulate efforts that would improve fire safety. A specific idea which spurred from this initiative was the vision of a self-propelled fire hose as a robotic tool to aid human firefighters. This idea is clever in that the high-pressure water inside the hose can be employed as a hydraulic medium in the propulsion mechanism, a fire extinguishing medium, and a cooling medium for cooling the robot in environments with extreme temperatures. The resulting system would be a robotic fire hose that could move in extreme environments with the agility of a biological snake, or, in other words, a water hydraulic snake robot. The Applied Cybernetics department at SINTEF was brought in to investigate this idea further, and so began the research activity on snake robots at SINTEF and NTNU.

The research activities at SINTEF and NTNU related to snake robotics have resulted in:

- Publication of several papers in internationally recognized journals.
- Publication of a book (published by Springer), which is a complete treatment of snake robotics.
- The development of several snake robot prototypes, such as the fire-fighting snake robot Anna Konda, which has attracted much national and international attention, and the snake robot Kulko, which is the first snake robot that can measure the magnitude of contact forces acting along its body.
- Close relations with key research communities working with snake robotics in Asia and USA.
- Two completed and two ongoing PhD studies on snake robotics.
- The development of a robotic lab facility funded by a Norwegian oil & gas company.

CIRiS is a department of NTNU Samfunnsforskning AS with the mandate to promote and perform research and development relevant to the human exploration of space. Today the main activities are related to research activities onboard the International Space Station (ISS).

Research in space is challenging because of large geographic distances and limited recourse envelopes for space segment infrastructure. Operation of experiment hardware in space demands thorough planning, development and testing of equipment, highly specified procedures, and training of console personnel. The execution of space experiments includes use of advanced technology, in addition to communication and cooperation between space segment infrastructure, the ground segment infrastructure, and between the different Operation Control Centers.

Based on the experience from integration and operation of large complex technological space projects, CIRiS has developed a unique expertise related to understanding, development, design, and implementation of operational concepts for arenas such as control rooms, where decisions are based on (technology) mediated information. Aspects of this expertise is recognised as established research areas, such as human factors (engineering), safety, training/simulation, project management, organizational research, knowledge management, and data interoperability and standardization.

Researchers at SINTEF and CIRiS see great potential in the use of snake robots for space missions involving planetary exploration. The long-term motivation behind this project proposal is the development of a robotic propulsion mechanism which can reach and operate in locations not accessible by existing planetary rovers. A snake robot can for instance work together with a rover through a tethered connection, and can also act as the manipulator arm of the rover when it is not crawling freely. Numerous scenarios exist, some of which will be investigated in the proposed feasibility study.

1.4 Acknowledgments

This project was funded by the European Space Agency as a "PRODEX Experiment Arrangement" related to C4000107851. The authors also acknowledge the involvement of the Norwegian Space Agency both in connection to initiation of the project as well as during the project. The study was carried out between June 2013 and March 2014.

2 Snake robots – An introductory overview

This chapter elaborates on various aspects of the snake robot research field. In particular, Section 2.1 presents general characteristics of snake robots, Section 2.2 describes aspects of biological snakes which are relevant to snake robots, and finally Section 2.3 presents state-of-the-art of current snake robots.

Figure 2: Examples of snake robots (the NTNU/SINTEF snake robots Wheeko, left, and Kulko, right) and a biological snake.

2.1 What is a snake robot?

A snake robot is a robotic mechanism designed to move like a biological snake. Inspired by the robustness and stability of biological snake locomotion, snake robots carry the potential of meeting the growing need for robotic mobility in unknown and challenging environments. These mechanisms typically consist of many serially connected joint modules capable of bending in one or more planes. The many degrees of freedom of snake robots make them difficult to control, but provide potential locomotion skills in cluttered and irregular environments which surpass the mobility of more conventional wheeled, tracked and legged robots.

Development and control of snake robots is generally quite challenging for two primary reasons. First of all, a snake robot has many degrees of freedom, which means that the physical mechanism will contain a complex interconnection of sensors, actuators, and control logic. Moreover, the many degrees of freedom represent complex nonlinear dynamics which is challenging to analyse from a control design perspective. Second, the dependence on environment interaction is more complicated for a snake robot than for more conventional mobile robots. In particular, the propulsion mechanism of a wheeled, tracked or legged robot is achieved with a separate and dedicated part of the robot. A snake robot, on the other hand, has no separate part which is dedicated to propulsion. Being essentially a smooth and flexible manipulator arm, the propulsion mechanism of a snake robot is rather an integrated part of the entire body, which means that propulsion requires synchronised motion of the entire robot in order to produce appropriate environment interaction forces. Motion based on such environment interaction is challenging both with respect to control design and mechanical implementation.

2.2 The inspiration: Biological snakes

Research on snake robots is inspired by the robust motion capabilities of biological snakes. These amazing creatures are optimal in the sense that they have emerged through millions of years of evolution. In the following, we present aspects of biological snakes that we consider relevant to research on snake robots. The material is based on [1], [2], and [3].

2.2.1 The anatomy of snakes

The skeletal structure of a snake consists of vertebrae, ribs, and a skull. Snakes can have between 130 and 500 vertebrae, with ribs attached to each one (see Figure 3). The vertebrae constitute a column of movable joints that runs through the body of the snake and protects the spinal cord, which runs through a channel along the top of the vertebral column. The ribs attached to each side of a vertebra protect the internal organs.

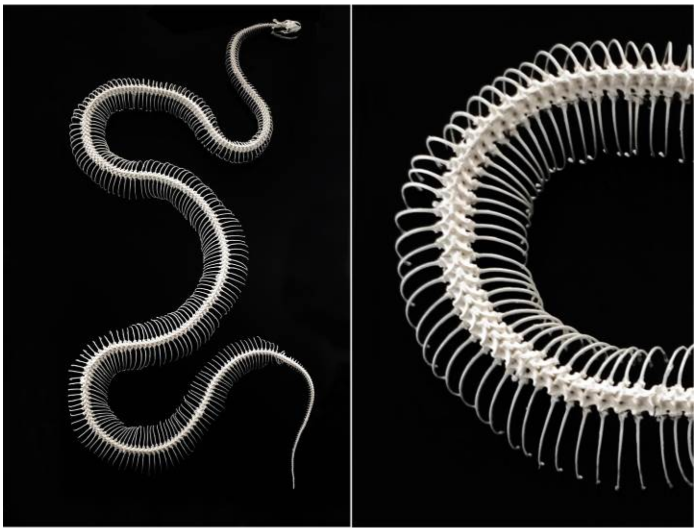

Figure 3: The skeleton of a snake consisting of vertebrae, ribs, and a skull.

The mechanical interconnection of the vertebrae is interesting. Two adjacent vertebrae are connected in a ball and socket arrangement (see Figure 4). The magnitude of the relative rotational motion between two vertebrae is quite limited. In particular, the relative rotation between two vertebrae about the vertical axis ranges between 10° and 20°, while the relative rotation about the horizontal axis is limited to only a few degrees. These limitations may appear contradictory to the flexibility that snakes are known for, but this flexibility is, in fact, produced by the sum of the small movements of many vertebrae. Moreover, limiting the range of the relative movements leads to increased strength in the connection between the vertebrae. To prevent damage to the spinal cord due to twisting of the vertebrae about the axis tangential to the body, each vertebra has a number of wing-like projections that interlock loosely with their counterparts on the adjacent vertebrae. This limits the amount of twisting.

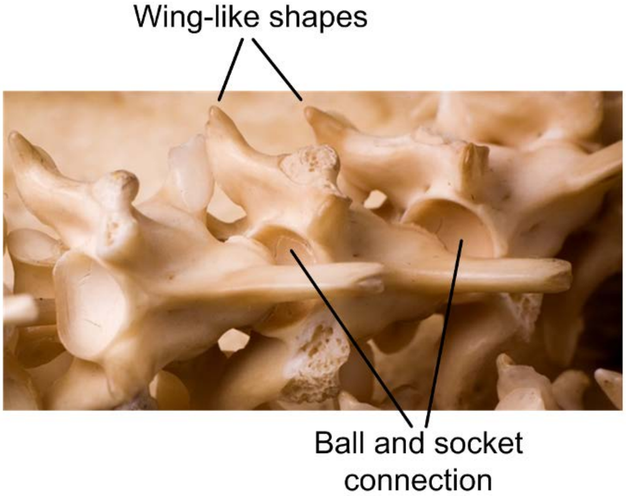

Figure 4: Close-up of vertebrae from a snake.

The body shape of a snake is changed with the help of muscles that are arranged diagonally along each side of the snake. The ends of these muscles are attached to ribs, sometimes joining adjacent ribs, but mostly joining ribs that are some distance apart. The pattern of contraction and relaxation of these muscles determines the type of locomotion that is performed. For instance, if muscles on one side of the snake are contracted at the same time as the equivalent muscles on the other side are relaxed, then the body will be bent. If, on the other hand, opposite sets of muscles are contracted or relaxed simultaneously, then the snake will, to some extent, be able to shorten or extend its body at this location.

The skin of a snake is completely covered with scales (see Figure 5). The scales are formed from thickened areas of the skin and are therefore integrated with the skin. The areas of skin between the scales allow the snake to flex its body while maintaining a smooth coverage of the scales. An important purpose of the scales is to form a physical protection from general wear and tear when the snake moves across rough surfaces. At the same time, the use of small units of armour allows greater flexibility than would large bony plates. Another feature of the scales is that they give the snake anisotropic ground friction properties, i.e. the scales give the snake a larger friction coefficient in the transversal direction of the snake body compared to in the tangential direction. Studies of biological snakes and simulation studies have indicated that this difference in the friction coefficients is important during forward gliding motion.

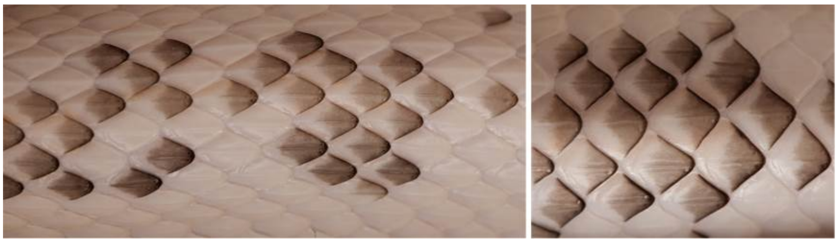

Figure 5: The skin of a snake is completely covered by scales, which are formed from thickened areas of the skin. The image on the right shows the skin when it is stretched, thereby pulling the scales apart.

2.2.2 The locomotion of snakes

Snakes are almost unique among the terrestrial vertebrates in their lack of legs. However, the lack of legs does not appear to have placed restrictions on the ability of snakes to move around. On the contrary, snake locomotion is stable, robust, and versatile. The speed of snake locomotion is, however, relatively slow, although certain species can move at speeds up to 11 km/h. Some snakes display specialised forms of motion. For instance, certain snakes can jump to heights of up to 1 m by curving their body into a vertical S-shape to serve as a spring, and then jump by stretching their body. Other snakes are able to glide through the air by throwing themselves from trees and forming their body in an aerodynamically favourable manner. In the following, the four most common types of biological snake locomotion are presented.

Lateral Undulation

Lateral undulation, also called serpentine crawling, is the fastest and most common form of snake locomotion. During lateral undulation, continuous waves are propagated backwards along the snake body from head to tail (see Figure 6). During this wave motion, the sides of the snake body push against irregularities in the surface, thereby pushing the snake forward. This form of locomotion is therefore not suitable on slippery and flat surfaces. As the snake progresses, every point along the body passes the same point on the ground, and there is never any static contact between the ground and any point along the body. During swimming, the same wave motion is produced, but the body then pushes against the resistance of the water. The weight distribution of a snake during lateral undulation is not uniform, but rather distributed so that the peaks of the body wave curve are slightly lifted from the ground.

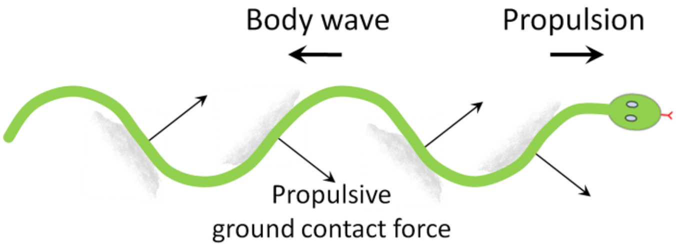

Figure 6: Illustration of lateral undulation.

Concertina Locomotion

Concertina locomotion is often employed in narrow spaces where the available range of motion is limited. The motion is carried out by first extending the front part of the body forward while the back part is curved several times to provide an anchor against the narrow environment (see Figure 7). Once the head and front part of the body are fully extended, they are subsequently used to provide an anchor in the same way so that the back part of the body can be drawn up. The sequence is then repeated.

The principle behind concertina locomotion relies on the difference between the large static friction forces at the anchor points and the low kinetic friction forces in the part of the body which is extended. The motion pattern is not very efficient in terms of energy consumption, but is often needed in order to traverse tight spaces.

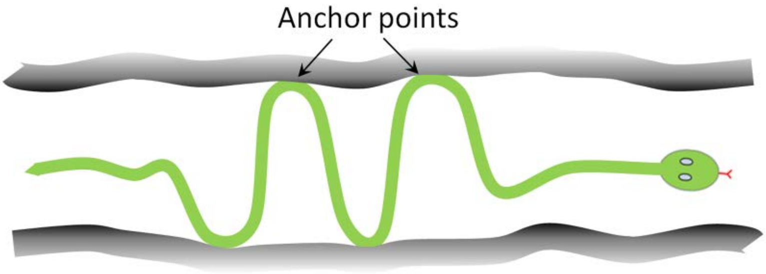

Figure 7: Illustration of concertina locomotion.

Rectilinear Crawling

Rectilinear crawling is a slow form of locomotion often employed by heavy-bodied snakes. Also snakes in the final stages of stalking their pray use rectilinear crawling to avoid alerting their intended victim. During rectilinear crawling, the snake uses the edges of the scales on its underside as anchor points to pull itself forward in a more or less straight line (see Figure 8). The operation consists of stretching forward and hooking the edges of the scales over small irregularities, then pulling the body up to this point. Alternate parts of the body will be stretching and pulling at the same time.

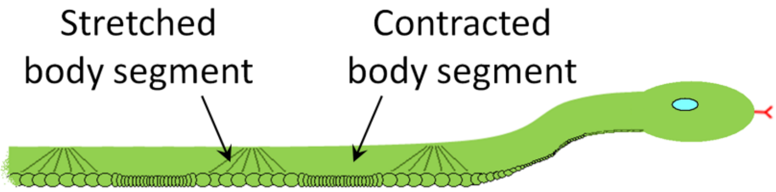

Figure 8: Illustration of rectilinear crawling.

Sidewinding

Sidewinding is a form of locomotion which is usually employed by snakes that live in areas of loose sand, e.g. desert snakes. This motion pattern is, in other words, particularly relevant for snake robots intended to move and operate on the surface of Mars. The motion resembles concertina motion in that one part of the body acts as an anchor while another part is moved forward (see Figure 9). Starting from a resting position, the head and neck are raised off the ground and thrown sideways while the rest of the body provides an anchor against the ground. Once the head and fore part of the body are again on the ground, they in turn act as an anchor while rest of the body repeats the same motion. The snake moves at about 45° with respect to its heading and leaves a trail of characteristic markings in the sand.

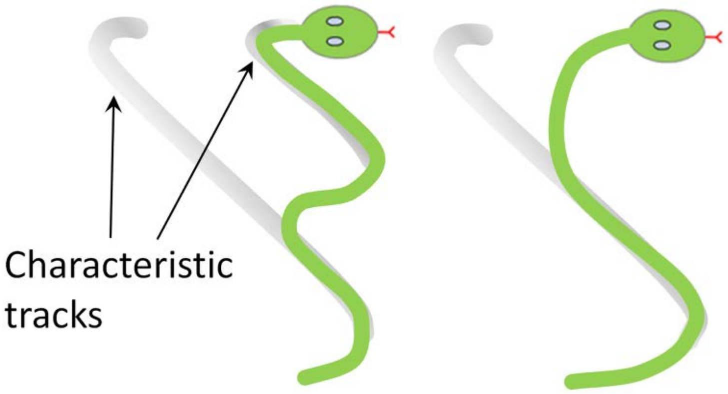

Figure 9: Illustration of sidewinding.

The Control System of Snakes

The employed locomotion method of snakes sometimes depends on the size of the snake and sometimes on the substrate over (or through) which it is moving. In fact, an interesting difference between snake locomotion and legged forms of locomotion is that the basic repeating motion that leads to propulsion of legged animals to a large extent depends on the progression speed of the animal. On the other hand, the basic repeating motion that leads to propulsion of snakes largely depends on the environment, and not the speed.

Considering the large number of muscles involved in the motion of a snake, and also the large number of contact points that are sensed by its nervous system, it is fair to say that the coordination of snake movements is both impressive and complex. Investigations of the electrical activity that accompanies the muscular contraction during movement show that the motor response is segmentary. Nerve impulses are propagated backwards along the snake body through the bone marrow. These impulses successively activate local muscle groups, which bend the snake body. Musculature is, in other words, successively, and not simultaneously, active, and only for a few elements at a time. The bending motion at a point along the snake body is also influenced by the sensory information transmitted by the skin. Simply speaking, the snake produces a relatively simple motor command which is modulated by local reflexes. This explains how every point in the body is able to follow the same trajectory.

2.3 State-of-the-art of current snake robots

In this section, we give a short presentation of some of the snake robots developed around the world so far. An overview of previous literature on mathematical modelling and control of snake robots is beyond the scope of this report, but a detailed overview may be found in e.g. [1], [4].

Motivated by the vision of a robotic propulsion mechanism with robust and agile mobility in challenging environments, researchers have studied snake robot locomotion for several decades. As illustrated in the images below, a large number of different snake robot designs have been proposed by researchers around the world so far. The locomotive capabilities of current snake robots are still limited to fairly simple and controlled lab environments, and the world has not yet seen practical applications of snake robot locomotion. However, the intensive research efforts within the snake robot research field over the last decade suggest that practical applications of these mechanisms are very close.

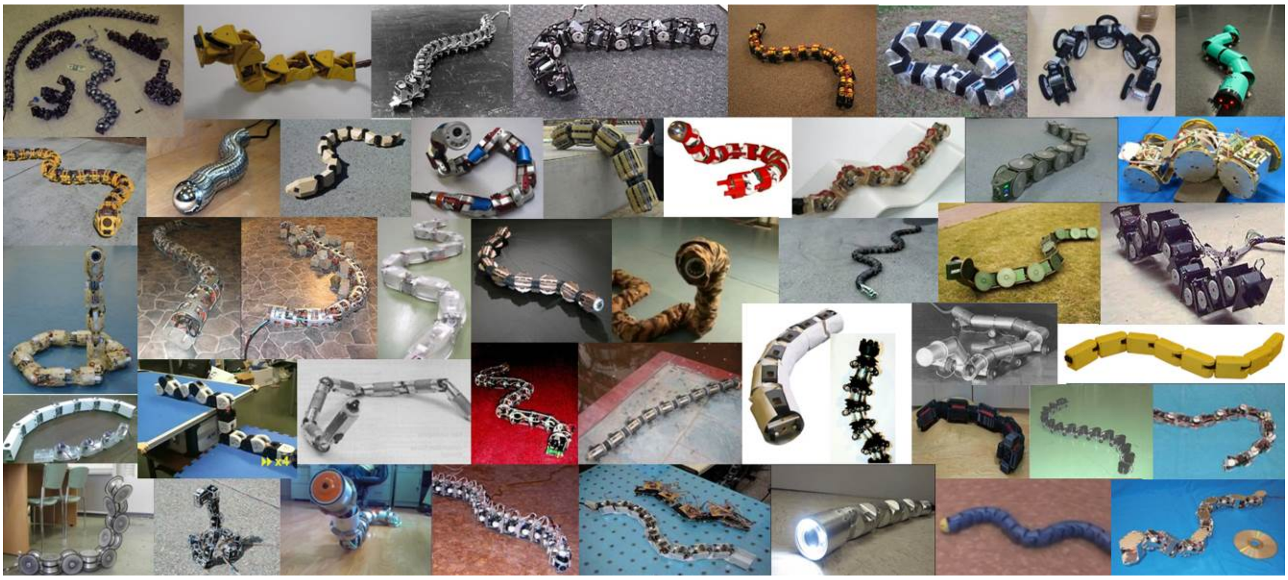

Figure 10: A collection of some of the snake robots developed around the world so far.

The snake robot research field was pioneered about 40 years ago by Professor Shigeo Hirose at Tokyo Institute of Technology, who developed the world's first snake robot as early as 1972 [5]. The robot was equipped with passive wheels mounted tangentially along its body. The wheels enabled the robot to travel forward on a flat surface by controlling the joints according to a periodic body wave motion similar to the body waves displayed by biological snakes. In the decades following the pioneering research by Professor Hirose, several agile and impressive snake robots have been developed by research communities around the world in efforts to mimic the motion capabilities of their biological counterpart.

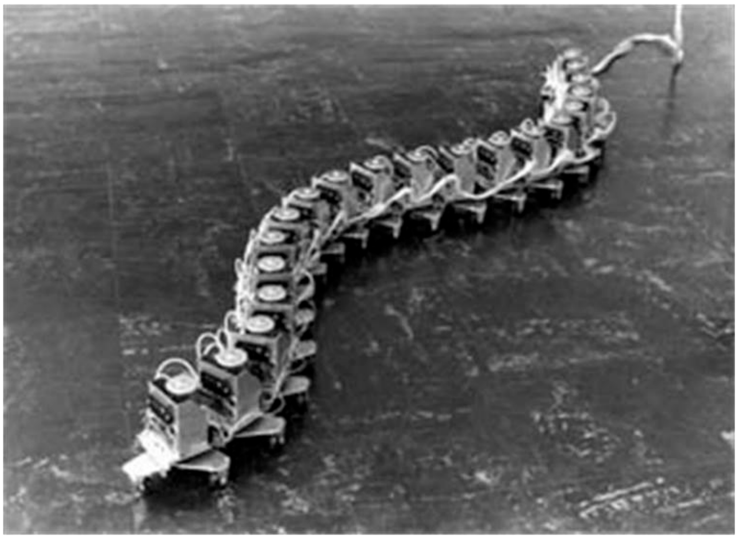

Figure 11: The snake robot ACM III[1], which was the world's first snake robot developed in 1972.

Several snake robots with passive wheels have been proposed over the years. The use of passive wheels gives snake robots beneficial ground friction properties which allow for efficient locomotion over flat surfaces. Examples of such robots include (see images below) ACM R3 [6], ACM R5 [7], S5 and S7 [8], and Wheeko [1]. Some of these robots can only display planar motion, while other robots can move their links both horizontally and vertically. Some robots have shielded joint modules that enable motion in environments with e.g. mud and dust, and even motion under water (such as the robot ACM R5), while other robots have modules with exposed electronic components which only allow them to move in clean lab environments. A common feature of these mechanisms, however, is that they are generally only able to

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[1] http://www-robot.mes.titech.ac.jp/hirose/robot/snake/acm3/acm3_e.html

move across relatively flat surfaces since passive wheels do not move very well in a cluttered environment. Such mechanisms are therefore suitable for motion on relatively flat surfaces, but not for practical applications of snake robots in more challenging environments.

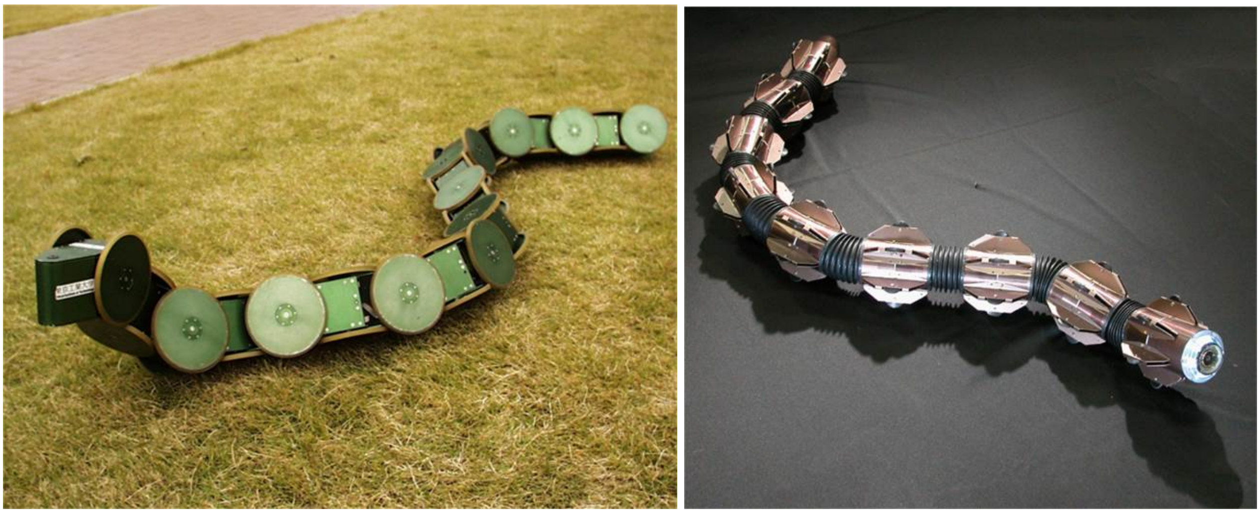

Figure 12: The snake robots ACM R3[2] (left) and ACM R5[3] (right) developed at Tokyo Institute of Technology. Both robots are covered with passive wheels. The snake robot on the right can swim under water.

Figure 13: The snake robots S5[4] (left) and S7[5] (right) developed by Dr. Gavin Miller. The robots have passive wheels on their underside.

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[2] http://www-robot.mes.titech.ac.jp/hirose/robot/snake/acm-r3/acm-r3_e.html

[3] http://www-robot.mes.titech.ac.jp/hirose/robot/snake/acm-r5/acm-r5_e.html

[4] http://www.snakerobots.com/S5.html

[5] http://www.snakerobots.com/S7.html

Figure 14: The snake robot Wheeko[6] developed by SINTEF and NTNU (the Norwegian University of Science and Technology). The robot consists of many 2-DOF joint modules covered by passive wheels.

Passive wheels will generally obstruct the motion in more cluttered and uneven environments. For this reason, there have also been developed many snake robots without passive wheels, i.e. robots that basically consist of straight links interconnected by motorised joints. Examples of snake robots without passive wheels include the robots (see images below) Uncle Sam [9], the small RCM [10], ACM R7 [11], Anna Konda [12], and Mamba [13].

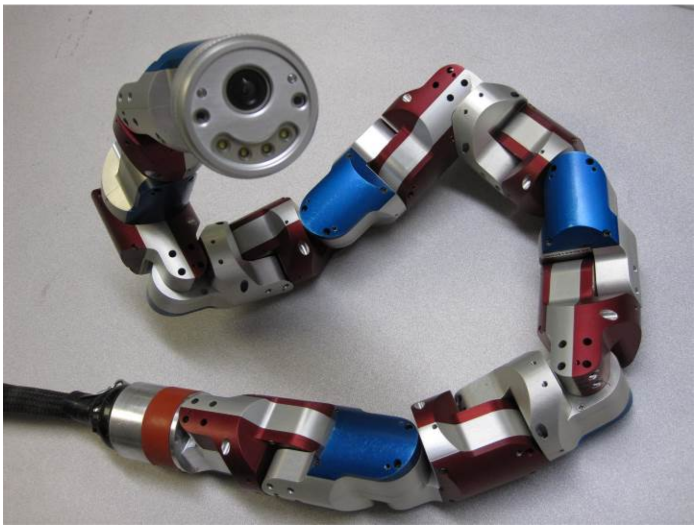

Figure 15: The snake robot Uncle Sam[7] developed at Carnegie Mellon University. The robot has a strong and compact joint mechanism and can climb up poles.

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[6] http://robotnor.no/research/wheeko-a-snake-robot-with-passive-wheels/

[7] http://biorobotics.ri.cmu.edu/media/index.html

Figure 16: Two snake robots developed at Tokyo Institute of Technology. The robot on the left [10] demonstrates a miniature joint mechanism, while the robot on the right [11] can perform so-called loop forming motion.

Figure 17: The snake robots Anna Konda[8] (left) and Mamba[9] (right) developed by SINTEF and NTNU. Anna Konda is a water hydraulic snake robot developed to demonstrate firefighting applications. Mamba is watertight and can measure external contact forces using a strain gauge based force sensor system.

Although snake robots without passive wheels generally have isotropic ground friction properties, these robots can still move forward on flat surfaces by resorting to motion patterns where parts of the body are lifted, such as sinus-lifting, sidewinding, inchworm motion, or lateral rolling. However, the most challenging environment for these robots is cluttered and uneven environments. A very relevant area of ongoing research is to enable snake robots to actively use their environment for propulsion by curving their body around irregularities and external objects and using them as push-points to aid the propulsion. This type of motion is called *obstacle-aided locomotion* [1] and is precisely how biological snakes slither forward.

To achieve efficient obstacle-aided locomotion, a snake robot should be able to sense its environment in order to intelligently adapt the motion to the environment. Previous research on environment sensing for snake robots is very limited. An example of a snake robot with such contact force sensing capabilities is the Mamba snake robot [13] developed by SINTEF and NTNU (see Figure 17). This robot measures contact forces using a strain gauge based sensor system installed inside each joint module.

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[8] http://robotnor.no/research/anna-konda-the-fire-fighting-snake-robot/

[9] http://robotnor.no/research/mamba-our-new-modular-snake-robot/

There are also works which consider active propulsion along the body of a snake robot, for example by equipping each link with motorised wheels, by installing tracks or legs along the body of the robot, or by employing a screw drive mechanism of some sort. Examples of snake robots that employ active propulsion along their body include (see images below) the OmniTread robot [14], the skin drive robot [15], and the salamander robot [16].

Figure 18: The OmniTread snake robot [14] developed at the University of Michigan. The robot has pneumatic joints and is covered by motorised tracks.

Figure 19: A snake robot with a skin drive[10] propulsion system developed at Carnegie Mellon University. A motor drives the outer skin backwards along the snake body in order to propel the robot forward.

Figure 20: A salamander-like snake robot[11] developed at Ecole Polytechnique Fédérale de Lausanne (EPFL). The robot uses motorised legs to propel itself forward and can operate under water.

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[10] http://biorobotics.ri.cmu.edu/robots/skinDrive.html

[11] http://biorob.epfl.ch/salamandra

3 Technological aspects of employing snake robots in a space mission context

In the following, we discuss the main advantages and disadvantages of snake robots in relation to a space mission context. In particular, the focus is on planetary exploration of Mars. Moreover, we discuss the main challenges related to snake robot control design and hardware design.

3.1 Advantages and disadvantages of snake robots

Like their biological counterparts, snake robots are unique in the sense that they have no separate part which is dedicated to propulsion. The propulsion of more conventional wheeled, tracked and legged robots is achieved with a separate and dedicated part of the robot. A snake robot, on the other hand, is essentially a smooth and flexible manipulator arm whose propulsion mechanism is an integrated part of the entire body. Consequently, the propulsion of a snake robot requires synchronised motion of the entire robot in order to produce appropriate propulsive environment interaction forces.

This unique form of propulsion has both advantages and disadvantages. In the following two tables we elaborate on the main advantages and disadvantages of snake robots and comment on these in relation to a space mission context.

Table 1: Main advantages of snake robots.

Main advantages of snake robots	Space mission context
Stability: The long body of a snake robot provides many distributed support points, as well as that it has a low centre of gravity.	Snake robots may provide a stable mobile system for locomotion in rough and steep terrains such as craters and caves.
Recoverability: For most practical purposes there is no "upside down" problem for snake robots.	A snake robot may roll down a hill or lose balance (and fall on its "back") while traversing a rock without this having any consequence for further locomotion capability. This is because snake robots in general work just as well "upside down".
Traversability: Ability to traverse rough and difficult terrain.	Planetary exploration may offer rocky and difficult terrains which need to be traversed. Biological snakes offer excellent traversability, and this is attempted recreated in snake robots in order to traverse, e.g., terrains at Mars. Such traversability can be utilized in order to carry out, e.g., geological and exobiological investigations through sample taking in challenging terrains.
Small cross-sectional area allows passage through small holes and gaps.	The small cross-sectional area of snake robots can be beneficial with respect to, e.g., traversing rocky terrains (the snake robot could potentially slither in between the rocks), and for exploring small tunnels in connection with subsurface caverns.
Redundancy: Propulsion may be maintained even if some joints fail.	For unmanned planetary exploration missions, there are few if any possibilities of maintenance if something go wrong with a robot system. Snake robots can possibly achieve mobility even if one or more of the robot joints fails. For such scenarios the energy-efficiency of the robot system will most likely be reduced.
Mobility+manipulation	In cooperation with a rover, a snake robot can be utilized both as a manipulator as wells as a mobile robot. E.g., a snake robot can attach itself to a rover and be utilized as a manipulator arm, or it can be deployed for the rover in order to investigate areas not accessible to the rover.

Table 2: Main disadvantages of snake robots.

Main disadvantages of snake robots	Space mission context
Low speed	Snake robots are expected to achieve lower speeds than, e.g., wheeled robots in terrains with a somewhat hard and reasonably flat surface. On softer terrains wheeled mechanism may get stuck, and legged mechanisms or snake robots could possibly achieve higher speeds. A rover can be used to transport snake robots for larger distances in order to deploy the snake robots close to, e.g., entrances to grottos or other terrains which the rover is unable to access. With this approach, the low speed of the robot is less critical.
Limited payload	Snake robots should be employed for more "small-scale" mission (e.g., soil sampling) rather than missions which require bigger/heavier payloads. Such payloads could instead be carried by an accompanying rover.
Complex propulsion system	A large number of robot joint mechanisms are required in order to achieve locomotion with snake robots. This lead to a rather complex propulsion system. On the up-side, a snake robot can be designed modular with a large degree of similarity between the different snake robot modules. This in turn simplifies the robot design and manufacturing processes.
Relatively low energy efficiency	Snake robots should be tethered and connected to a larger rover for power supply. The long and slim body constitute a non-ideal structure for incorporating both a separate power source and the accompanying hardware necessary for planetary missions. A tether imposes a challenge with respect to that it can get stuck, but the tether can also possibly be utilized in order to pull the rover free if it has gotten stuck. See Section 5.3.2 for further discussions regarding tether usage.

The following table gives a comparison of the propulsion mechanism of snake robots and other more conventional types of robots.

Table 3: Comparison of snake robots with other more conventional types of robots.

Property	Snake robots	Wheeled robots	Tracked robots	Legged robots
Propulsion speed	− −	+ +	+	−
Mobility in rough terrain	+ +	− −	+	+
Mobility through narrow passages	+ +	− −	− −	− −
Mobility over large obstacles	+ +	− −	−	+
Redundancy in the propulsion system	+ +	− −	− −	+
Payload capabilities	− −	+ +	+ +	+
Simple control system	− −	+ +	+ +	−

3.2 Snake robot development and design challenges

In the following, we point out important research challenges [1] that must be addressed before we will ever see useful snake robots operational in terrestrial or space-related applications. Non-planar (3D) locomotion in cluttered environments based on environment sensing and body shape adaptation is a key enabler for making use on snake robots in such applications. To our best knowledge, such locomotion has not yet been demonstrated. Our primary claim is therefore that future applications of snake robots require significantly more research on adaptive behaviour during motion in unknown and cluttered environments. In the following, we elaborate on the challenges in relation to enabling such snake robot applications, and discuss it in a space mission context.

3.2.1 Control design challenges

Analysable mathematical models

Future control design efforts for adaptive motion of snake robots should go beyond pure heuristics and instead base the controllers on analysable mathematical models and well established control design techniques. This will allow for a more generic and general understanding of the properties and control challenges of snake robots. Model-based control design for snake robots is, however, a major challenge. Mathematical models of the dynamics of a snake robot on a flat surface are very complex due to the many degrees of freedom of the robot. When contact forces from a cluttered environment (which, e.g., describes relevant environment on Mars) are included, the model becomes even more complex because the discrete nature of the contact forces turns the model of the robot into a hybrid system. However, model-based control design can be achieved by pursuing simplified mathematical descriptions of the interaction between a snake robot and its environment that can be analysed from a control perspective. In particular, a simple relationship between body shape changes of a snake robot during environment contact and the resulting translational and rotational motion of the robot could enable an analytical derivation of the joint torques that will produce the desired motion. Snake robot controller development shown in, e.g., [17] is based on a simplified model of snake robot locomotion is an example of how a simplified modelling approach can be employed to derive model-based control strategies for these systems.

Snake robot control based on environment sensing

Environment sensing is a requirement for efficient snake robot locomotion in unknown and cluttered environments such as on the surface of Mars on in grottos at the planet. The challenge of utilising this sensor information intelligently to maintain the propulsion of the robot is closely related to the challenge of developing analysable models of the robot. With a suitable description of how the environment interaction affects the motion, it is possible to analytically derive the control action that, in a given environment, will propel the robot in a desired direction. Control design for snake robots is also challenging because these mechanisms are generally underactuated, i.e. they have more degrees of freedom than actuators.

Simultaneous Localization and Mapping (SLAM)

Enabling a mobile robot to generate a map of its own environment and simultaneously determine its own position in this map is called simultaneous localisation and mapping (SLAM). SLAM represents an extensive and important research area today since such capabilities are generally essential for autonomous operations of mobile robots. SLAM is also very relevant for snake robots since they will typically be employed in situations where a map of the environment is not available in advance. To our best knowledge, previous literature has not considered SLAM explicitly in the context of snake robot locomotion.

Although SLAM is, in many ways, independent of the specific propulsion mechanism of the robot, there are features of snake robots which make SLAM for these mechanisms particularly interesting. In particular, most applications of SLAM involve map creation based on different types of vision sensors. While such sensors are also relevant to snake robots, these robots will generally also be able to extract information about their environment from the contact sensing capabilities along their long and slender body. We therefore claim that future research on SLAM for snake robots should focus on map creation by combining data from vision sensors with data from the contact force sensors of the robot. Moreover, since snake robot locomotion is highly dependent on the interaction between the robot and its environment, SLAM for snake robots should not only focus on mapping the specific geometries of the environment, but also on mapping other properties of the environment which influence the motion. In particular, the contact force sensing capabilities of a snake robot can for instance be used to extract information about the friction coefficients of surfaces and objects which come into contact with the snake robot. The elasticity and plasticity of external "objects" (e.g., loose rocks or sand on the surface of Mars) are also important parameters which should be mapped since these parameters determine if an object is completely rigid, or if there is a spring effect in the interaction with the object, or if the object is displaced when the robot makes contact with it.

Motion planning strategies

With an efficient system for SLAM in place, a snake robot may be able to make intelligent decisions about where to go in order to solve a specific task. Motion planning for snake robots is in many ways similar to motion planning for mobile robots in general. However, the unique features of snake robot locomotion suggest that motion planning for these mechanisms should be attacked with a somewhat different approach than motion planning for more conventional mobile robots. In particular, while obstacle avoidance is an important topic for wheeled, tracked and legged robots, a goal of snake robot locomotion is rather obstacle utilisation since objects in the environment of a snake robot represent push points that the robot can use for propulsion. While conventional wheeled, tracked and legged robots will usually try to find the shortest path to a given location, a snake robot should rather seek out the most efficient path, which for instance may involve taking small detours in order to reach locations with push points that can be used for propulsion. This will be the case when traversing a rocky surface on Mars.

3.2.2 Hardware design challenges

Environment sensing

Measuring external contact forces on the snake robot is a natural approach for sensing the environment. The force sensing system of a snake robot is, however, particularly challenging since the robot is articulated, which introduces the challenge of preventing the joint motion from interfering with the measurements of the external forces. Measuring forces directly along the body of a snake robot is, in other words, a significant design challenge. In addition, the harsh environment on Mars (e.g., dust, extreme temperatures) will provide significant wear and tear on externally mounted sensors on a snake robot.

An alternative approach is to estimate the external forces acting on the robot solely through force measurements at each articulation point along the robot. The instrumentation system of this solution is significantly simpler than the instrumentation required to measure external forces on the robot directly. A snake robot developed by NTNU and SINTEF called Mamba [13] demonstrates this approach.

Research on environment sensing for snake robots is also highly relevant to many other application areas within robotics, which suggests that researchers working with snake robots should identify and pursue synergies with other robotic research areas where environment adaptation is important.

Robot vision

The above discussion regarding SLAM and efficient motion planning strategies suggests that future snake robots need to be equipped with a suitable vision system. Vision for mobile robots is a large and active area of research where progress is continuously being made. Although there has been very limited focus in previous literature on vision specifically for snake robots, the available hardware that can be employed to implement such a system is continuously being improved. Note that a snake robot has limited payload capabilities, which means that the hardware of the vision system should be both small and of limited weight. Hence, vision systems from small Unmanned Aerial Vehicles (UAVs) can be relevant.

Power provision and solutions for tethered/untethered operations

In many future applications of snake robots, a tethered connection between the robot and the human operator will not be possible. Consequently, the robot must carry its own power supply and also communicate with some human operator or accompanying rover through a wireless connection. The onboard power supply of a snake robot represents a significant design challenge since snake robot locomotion is an energy demanding form of propulsion, and at the same time, a snake robot will generally have limited payload capabilities (i.e., too limited space for, e.g., solar panels or radioisotopic systems). Moreover, since many future applications of snake robots involve motion in environments which are inaccessible by humans, it will usually be impossible to retrieve the robot if it runs out of power before it can make its way back to the human operator.

Operations in inaccessible environments also introduce challenges related to the wireless communication between the snake robot and the human operator. In particular, maintaining a reliable wireless link in such environments may often be difficult. Moreover, in situations where the communication link with the human operator and/or rover is lost, the snake robot must be able to operate autonomously until the communication link is re-established.

A possible first application of snake robots for planetary exploration will most likely be carried out with a tethered snake robot connected to a conventional rover or a lander. The disadvantage of using a tether is that it may get stuck. As an alternative, a snake robot could carry a limited amount of power within onboard batteries and somewhat often go back to the rover to recharge. However, in such a scenario, there is a risk of losing the snake robot in case it does not make it back to the rover in time. See Section 5.3.2 for a further discussion regarding the advantages and disadvantages of using a tether.

Ground friction force limitation

If the propulsion of the snake robot is based on forward gliding motion similar to the motion of biological snakes, then a sufficiently smooth exterior surface is very important since any irregularities along the body may potentially induce large obstructive friction forces on the robot. Obtaining a smooth surface combined with contact force sensing at articulated parts of the robot represents a significant design challenge. The friction forces opposing the motion of a snake robot can also be limited by introducing active propulsion along the body. Examples of this approach were presented in Section 2.3. The drawback of active propulsion along the body of a snake robot is that the mechanical complexity of the robot is significantly increased. To limit the mechanical complexity of a snake robot, the ideal solution is a snake robot with a passive and smooth tactile skin that can glide forward like a biological snake. Mechanism simplicity is important to future use of snake robots since this increases robot reliability and reduces development cost.

Robust, strong and durable actuation mechanisms

In order to move in challenging environments, the snake robot must generally be able to lift parts of its body. This means that there is some lower limit to the ratio between the strength of the actuators and the weight of the robot. Developing joint mechanisms for snake robots where this ratio is maximised is an important design challenge that must be addressed. Furthermore, locomotion in cluttered environments generally requires that the actuators can work against environment contact forces over time without overheating. A compliant joint mechanism is advantageous during locomotion in cluttered environments. However, compliance can also be enforced by the controller of the robot if the contact forces along the body are measured.

Environment protection

In order to make use of snake robots outside the generally clean lab environments, the robots must be able to operate despite of mud and dirt in their environment. Moreover, electrical components must be shielded from the radiation and extreme temperatures on, e.g., Mars or the Moon. Environment protection a snake robot is challenging, in particular when we also require force sensing capabilities and a smooth exterior surface.

4 Operational aspects

Operational aspects encompass considerations relevant for *how* and *where* a system is being deployed and used by operators. Most often, users of a system are not the same as the developers of the system. However, the effect of this is not always fully considered in the development phase of a system and may lead to unnatural or even wrong trade-offs between the usability of a system compared to, e.g., intrinsic safety, and efficiency. It was deemed useful to apply known exploration mission concepts as a frame of reference when addressing operational aspects with relevant involvement of snake robots. The operational aspects described in this chapter will be discussed with the ExoMars missions [18], [19], and the Human Exploration of Mars Design Reference Architecture 5.0 [20] as frames of reference. Although not part of this project's main objectives a short reflection on possible role of snake robots in lunar exploration mission is also provided

This section also offers some considerations on human and organizational aspects that should be considered with same attention at technological aspects when designing and describing mission concepts and scenarios for space exploration. Some of the human and organizational aspects discussed are specific to human exploration but the basic approaches also apply to robotic exploration, including the use of snake robots.
However, the main focus for this report is the snake robot systems in robotic space exploration scenarios.

4.1 Mars planetary science

The Mars scientific goals, objectives, investigations and priorities for the exploration of Mars have been described in detail by the Mars Exploration Program Analysis Group (MEPAG) in 2006 [21] and form the frame of reference for the discussions of scientific objectives in Section 4.

Current understanding of the Martian environment indicates that extant life may be more viable in subsurface areas where temperatures, radiation levels, and potential access to liquid H2O are closer to those conditions where life is known to exist and thrive.

The three overall scientific goals, objectives, investigations, and priorities for Mars exploration defined by MEPAG [21] are:

I. Determine whether life ever arose on mars.
II. Understanding the processes and history of climate on mars.
III. Determine the evolution of the surface and interior of mars.

4.2 The "Reference missions"

The scientific exploration of Mars by humans will be preceded and prepared by use of orbiting satellites, landers, rovers and other robotic probes. Accounts of several successful missions such as the NASA Mars Science Laboratory (MSL), aka Curiosity, do already exist[12].

When discussing the operational aspects of a planetary exploration mission that would be undertaken several years from now one need to take into account the missions that are likely to be scheduled before the first mission utilising snake robots. This applies in particular for human missions. One need to consider if operational aspects, based on today's requirements and mission objectives, may become obsolete due to results obtained or new technology development as part of existing or planed missions. E.g., one need to re-evaluate the operational aspects of a 2030 mission based on our projected state of the art as of approx. 2025, not as of 2014. The possibility of re-evaluation must be included in early designs such that these designs facilitate replacement of key technologies which may have significantly evolved between the time of start-up of a project and the time a system is ready for space flight.

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[12] Mars Science Laboratory: http://mars.nasa.gov/msl/

4.2.1 ExoMars missions

Establishing if life ever existed on Mars is one of the outstanding scientific questions of our time. To address this important goal, the European Space Agency (ESA) has established the ExoMars programme to investigate the Martian environment and to demonstrate new technologies paving the way for a future Mars sample return mission.

The scientific objectives of the ExoMars programme, in order of priority, are:

- Search for possible bio signatures of Martian life, past or present.
- Characterize the water and geochemical distribution as a function of depth in the shallow subsurface.
- Study the surface environment and identify hazards to future manned missions to Mars.
- Investigate the planet's subsurface and deep interior to better understand its evolution and habitability.
- Achieve incremental steps ultimately culminating in a sample return flight.

Another important goal of the ExoMars programme is the demonstration of a number of essential flight and in-situ enabling technologies that are necessary for future exploration missions, such as an international Mars Sample Return mission. These technological objectives include:

- Landing of large payloads on Mars.
- Exploit solar electric power on the surface of Mars.
- Access the subsurface with a drill able to collect samples down to a depth of 2 metres (6.6 ft)
- Develop surface exploration capability using a rover.

The ExoMars program includes two missions to Mars. The 2016 mission includes a Trace Gas Orbiter (TGO) and an Entry, Descent and Landing Demonstrator Module (EDM). The Orbiter will carry scientific instruments to detect and study atmospheric trace gases, such as methane. The EDM will contain sensors to evaluate the lander's performance as it descends, and additional sensors to study the environment at the landing site. The 2018 mission includes a rover that will carry a drill and a suite of instruments dedicated to exobiology and geochemistry research.

For the purpose of providing a frame of reference in this project the 2018 rover mission is of main relevance.

Technologies relevant in connection with the above scientific and technological objectives are presented in in Section 3, Section 4.4, Section 5 and it is discussed how snake robots can contribute to the relevant technologies and complement current rover technology.

4.2.2 Human Exploration and the Mars Design Reference Architecture

The Mars Design Reference Architecture (DRA 5.0) [20] describes the systems and operations that could be used for the first three missions to explore the surface of Mars by humans. The concepts described in DRA 5.0 report do not constitute a formal plan for the human exploration of Mars but provides a vision of a potential approach to human Mars exploration that is based on best estimates of what we know today.

These first three missions would span over a 10 year period and occur on three consecutive trajectory opportunities sometime within the next several decades, a period of time that is sufficient to achieve basic program goals and acquire a significant amount of knowledge and experience needed to consider new goals and concepts for human space exploration. The DRA 5.0 assumes that the human Mars missions have been preceded by a sufficient number of test and demonstration missions on Earth, in the ISS, in Earth orbit, on the moon, and by robotic precursors at Mars, to achieve a level of confidence in the architecture such that the risk to the human crews is considered acceptable.

Much of the DRA 5.0 content is not directly relevant for this study of snake robots; however we will highlight some mission objectives and architecture where we believe snake robots present interesting alternative or complementary solutions.

Any present or traces of ancient Martian life is more likely to be found in subsurface biospheres where it has been shielded from the harsh environment on the Martian surface [22]. Also, the caves and other underground structures, including lava tubes, canyon overhangs, and other Martian cavities would be potentially useful for manned missions, for they would provide considerable shielding from both the elements and intense solar radiation that a Mars mission would expose astronauts to. They also offer easier subsurface access for direct exploration and drilling and might offer access to minerals, gases and ices.

The Caves of Mars Project [22] was a program funded by the NASA Institute for Advanced Concepts to assess the best place to situate the research and habitation modules that a manned mission to Mars would require.

Snake robot concepts could play a vital role when determining the performance requirements and operational aspects for sub-surface exploration. Snake robots could have unique capability to access grottos and subsurface caverns either via natural entrances (see Section 5.3.1 for a relevant concept description) or through holes drill into caves identified by ground-penetrating radar. In this way, snake robots could complement current rover technology by providing increased accessibility and terrainability. More on the advantages, disadvantages and challenges regarding usage of snake robots is found in Section 3. More on robot – astronaut cooperation is described in Section 4.3 and Section 5.

4.2.3 Lunar exploration scenario

The Moon has been a subject of interest of space agencies as a candidate to establish a permanent outpost in space. Although the search for life is of limited interest on the Moon many of the aspects that make snake robot systems interesting for Mars also apply for the Moon.

The RIMRES project [23] envisions a lunar crater exploration where a wheeled system is used to transport the highly mobile six-legged scout system to the crater rim. The scout is then deployed and starts to climb down into the crater to explore the permanently shaded regions of the crater.

Snake robot systems could be considered as an alternative to “spider-robots” for extreme terrain due to their potential to traverse difficult terrains. See, e.g., the snake robot concept descriptions in Section 5.3.1.

4.3 Human and organizational aspects

Existing literature refers to ‘human error’ as a causal or contributing factor in 40 - 90 percent of accidents, depending on the industry, [24], [25], [26], [27]. This makes the human element an important factor within the domain of dependability, safety and reliability and the human element is influenced by organisations, technology and workplace design and environment such as stress, situational awareness and other factors.

In the “new view” of human error, it is therefore seen more as a symptom of problems with the system, thus being an effect rather than a cause, [28]. Human dependability encompasses the risk of human errors, but also the human capacity to perform well, even beyond expectations, and to anticipate and solve problems. Thus, one should address both human error and how it can be avoided, as well as how one can depend on humans to create safety in space operations. To understand the ability of humans to perform safely in high technological organizations, it is necessary to study human action in light of technology and the organizational context. Errors do not happen in isolation, and there is a reciprocal relationship between these factors.

It is clear that there are numerous possibilities for applications of robotic assistants and that it is vital to determine the safety and trustworthiness of these robotic assistants before they can be used effectively.

Most robotic systems are today limited in their range and capacity for motion in order to increase their safety. Most industrial robots will only work within a restricted area where people are not allowed during operations. Assuring the safety of robotic assistants will not be so easy, as robotic assistants will need to share our environments in a much more intimate way.

The robotic systems, e.g. snake robots, are autonomous systems that can and must be verified just like any sensors, actuators, and other hardware. Same apply for their computer programs that can and will go through formal verification to increase our confidence that they are safe and reliable.

The ongoing evolution of how humans and robots work side by side represents one of the untapped potential for increased efficiency and quality in our society. To fully harvest from this potential we also need methods and verification of how dependability can be designed and built into systems, technology, organisations and humans. Thus, the human dependability and organizational aspects need to be taken into consideration during definition and design phases with the same attention given to technical safety and dependability.

4.4 Technology roadmaps for space exploration

This chapter consider aspects from available NASA technology roadmaps [29] and research and development objectives where snake robotics should be considered as alternative or complementary concept.

The main source of reference have been the Robotics, Tele-Robotics and Autonomous Systems Roadmap [30] that address mobility, manipulation and autonomy research and addition to sensing and perception, rendezvous & docking, systems engineering and human-system interface research. For the purpose of this section we only address the first three of these. Aspects of the human-system research are addressed in Section 4.3.

The NASA roadmap defines mobility research to includes surface, subsurface, aerial and in-space locomotion, from small machines to large pressurized systems that can carry crew for long excursions, using modes of transport that include flying, walking, climbing, rolling, tunnelling and thrusting. Mobility relevant for the consideration of snake robots in space exploration includes moving between places on a planetary surface or to reach a point in the subsurface.

4.4.1 Extreme terrain mobility

Challenges related to extreme terrain include both vertical and lateral mobility on steep or vertical surfaces, overhangs and access to lava-tubes and skylights.

As of today the Mars exploration Rovers (MER) and the Mars Science Laboratory (MSL) represent the state of the art in extra-terrestrial mobility and use a technology base for extreme terrain mobility that has significant terrestrial synergies, especially in the defence and commercial applications. This technology has evolved from 6+ wheels with passively-articulated suspensions to active suspensions to master–slave or mother–daughter systems. Systems proposed for future space exploration include many robotic test-beds, including rappelling systems for steep terrain or cliff access.

Several robotic exploration concepts envision (large) wheeled transportation system transporting the highly mobile scout system to the rim of craters, skylights or caverns. The highly mobile scout is then deployed and climbs into or onto the extreme terrain to explore the other vice inaccessible areas.

The DuAxel project [31] and the Reconfigurable Integrated Multi Robot Exploration System (RIMRES) project [23] are examples of concepts for extreme terrain rovers (see Figure 21). A great overview of rovers employed for planetary exploration can be found in [32].

Figure 21: The RIMRES project combines a six-legged robot (Crex) that can be picked up and moved with a faster wheeled transporter. Credit: DFKI Bremen via IEEE Spectrum (left). The “DuAxel" concept is an example of rappelling rover systems used to explore cliff sides. Credit: Issa Nesnas / Caltec Media relations (right).

Snake robot systems tethered to large rover systems could be one relevant application for extreme terrain exploration. The use of tethered snake rovers could also be considered to “anchor and/or winch” rover systems entering extreme or unknown terrain. See Section 5.6 for a concept description for such a scenario.

4.4.2 Below-Surface Mobility

Science requirements for a Mars mission will call for both shallow (tens of meters) and deep (hundreds of meters) drilling and collection of samples from the subsurface of Mars. The NASA roadmaps definition and state of the art of below-surface mobility are related to use of abrasion tools and rotary-percussive drills. Also DRA 5.0 and ExoMars focus on drilling technology when addressing the topic of subsurface access.

However, current understanding of the Martian environment indicates that extant life may be more viable in caves and other underground structures where temperatures, radiation levels and potential access to liquid H2O are closer to those conditions where life is known to exist and thrive. Caves, lava tubes, canyon overhangs, and other Martian cavities would also be potentially useful for manned missions as they would provide considerable shielding from both the elements and intense solar radiation that a Mars mission would expose astronauts to. They also offer easier subsurface access for direct exploration and drilling and might offer access to minerals, gases and ices.

Under these circumstances we find it interesting to include access to these subsurface regions as a part of the below-surface mobility discussions.

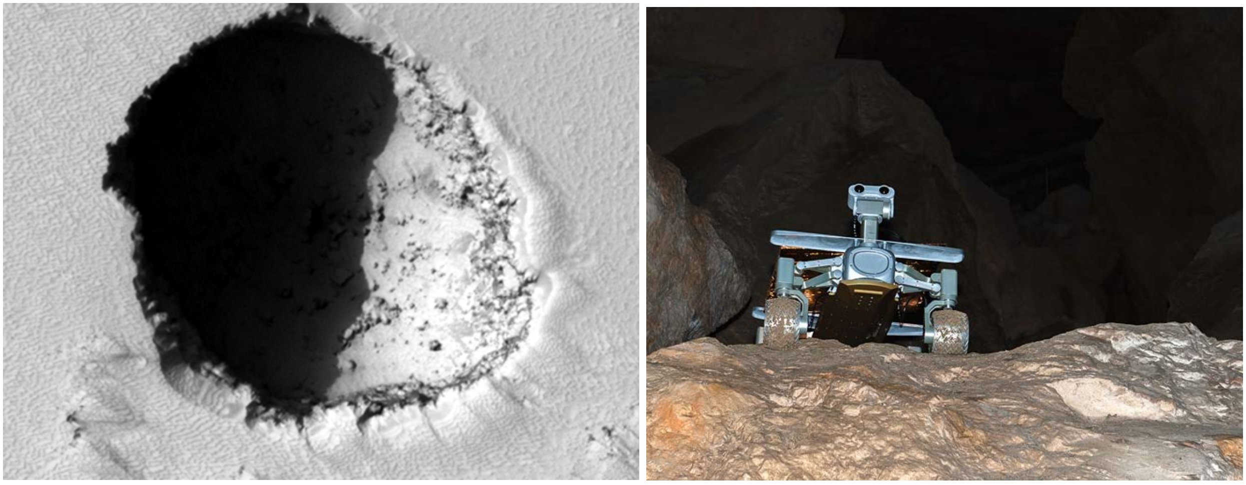

Figure 22: A picture from NASA’s Mars Reconnaissance Orbiter showing a 180 meters wide cave skylight on the flank of the large Martian volcano, Pavonis Mons. Credit: NASA/JPL/University of Arizona (left). A rover exploring the giant ice caverns of the Dachstein region in Austria during a Mars Analogue field campaign. Credit: Austrian Space Forum (right).

Snake robot concepts could play a vital role when determining the performance requirements and operational aspects for sub-surface exploration. Snake robots could have unique potential capability to access caves and subsurface structures either via natural entrances or through holes drilled into caves identified by ground-penetrating radar. See Section 5.3.1 for a relevant snake robot concept description.

4.4.3 Manipulation Technology

Manipulation is defined as making an intentional change in the environment using arms, cables, fingers, scoops, and combinations of multiple limbs are embodiments of manipulators. We shortly repeat the areas related to manipulation technology covered in Robotics, Tele-Robotics and Autonomous Systems Roadmap [30].

The Robonaut 2, Phoenix arm, Orbital Express and MSL arm represent the state of the art for the use of *robotic arms* in space exploration. Previous arms flown include the Shuttle Remote Manipulator System (SRMS), ROTEX, ETS-VII, MFD, JEM-RMS, MER arm, SSRMS and SPDM. Technology has advanced from position control, to impedance control with end point force sensing, to embedded joint torque control.

Figure 23: Orbital Express, Phoenix Arm, MSL arm, Robonaut 2, SSRMS & SPDM, JAXA MFD, ETS-VII. Credit: NASA.

The state of art for space systems is represented by the Robonaut 2 limb system, combining a manipulator that has a dexterous workspace with a multi-fingered end-effector able to make compliant grasps on natural objects.

Main challenges related to *dexterous manipulators* include integrated tactile perception, force control, grasping reflexes, grasp learning, tool use, and autonomous object manipulation. Dexterous manipulation includes working with human interfaces and offer beyond human performance to smaller scale and greater agility.

The assembly *contact modelling* for the International Space Station assembly with the SSRMS represent state of the art for space systems. Challenges related to modelling of contact dynamics include soil terra-mechanics, object mating, tools shifting in a robot’s grasp, modelling disconnect mechanisms, and multi point contact problem

Mobile manipulation involves systems that have both the ability to move great distances, but also manipulate once static or while in motion. Coordinated moves allow the manipulation subsystem to aid in management of the centre of gravity for mobility, and the mobility function to expand the range of motion for manipulation. Challenges include coordinated motion, force control across the entire system and the state of the art is represented in the MER, MSL and Robonaut 2 arm operations.

The state of the art for *collaborative manipulation* in space systems is to be found in the SSRMS, where a human is positioned by a robot arm. On the ground the start of the art includes robotic handling of large objects, measurement systems positioned by hand, and experiments with Robonaut and HRP humanoids. Terrestrial multi-robot handling systems- include large/fine combinations and swarm approaches. Challenges include a wide array of human interaction modalities superimposed on a force control problem, multi-point contact problems, and safety.

Robotic drilling & sample processing are on the ground dominated by down hole tooling for oil and gas exploration and sample processing is primarily medical or hazardous material handling. The state of the art for space systems is found in the Phoenix, MER and MSL arm and challenges for space exploration mission include dry drilling, sample conveyance, and cleanliness/contamination.

The positioning of sensors, handling objects, digging, assembling, grappling, berthing, deploying, sampling and bending are tasks considered to be the type of manipulation relevant for snake robots. See Section 5.4 and Section 5.5 for relevant snake robot concept descriptions.

4.4.4 Autonomy

Autonomy, in the context of a robotic system is the capability for the system to operate independently from external control. Two application areas of autonomy are: (i) increased use of autonomy to enable an independent acting system, and (ii) automation as an augmentation of human operation.

When deciding the level of autonomy of a system the trade-offs to be considered are; is the system operations capability increased, are cost savings via increased human labour efficiencies realised and are the mission assurance or robustness to uncertain environments improved.

For space missions there is a spectrum of autonomy in a system from basic automation, e.g. mechanistic execution of action or response to stimuli, through to fully autonomous systems able to act independently in dynamic and uncertain environments.

Snake robots for planetary exploration require at least a minimum degree of autonomy mainly for two reasons: (i) due to communication delay with earth, a snake robot, similarly to any other robot traversing the surface of, e.g., Mars, must be able to operate on its own for short-to-medium periods of time (this demand can be lifted in case there are astronaut present on the planet), and (ii) the complex propulsion mechanism for snake robots results in that a certain level of autonomy is needed in order to transfer mobility commands such as "move forward" to the actual coordinated joint movements of the snake robot in order to realize the commands.

4.4.5 Extravehicular activity (EVA) and surface mobility

For Mars surface exploration, scientific diversity is obtained by extending the range of human explorers via both unpressurized and pressurized rovers. Such rovers may be large, complex machinery upon which much of the mission success depends.

A snake robot system can be foreseen fill similar task in a human mission as in a robotic mission, e.g. extreme terrain, subsurface and mechanical handling. With the option of real time operations supplementing the system autonomy one could foresee even more flexibility with remote crew operation of the snake robot system. See Section 5.2.2 and Section 5.3.3 for discussions regarding the possible role of a human operator in operations with a snake robot for two selected concepts.

4.4.6 Planetary protection

Planetary protection is a guiding principle in the design of an interplanetary mission, aiming to prevent biological contamination of both the target celestial body and the Earth. There are two types of interplanetary contamination. Forward contamination is the transfer of viable organisms from Earth to another celestial body. Back contamination is the transfer of extra-terrestrial organisms back to the Earth's biosphere, if such exist. Planetary protection requirements reflect both the unknown nature of the space environment and the desire of the scientific community to preserve the pristine nature of celestial bodies until they can be studied in detail [33], [34]. Contamination between two or several sites on Mars could also be considered a form of unwanted contamination

The requirement for planetary protection must be coupled with the demands of field science, active exploration and robotic functionality. The nature of snake-robots systems may provide some advantages for the development and operational implementation of planetary protection requirement when exploring pristine Martian caves and sub-surface areas considered high probability areas for Mars life detection. Such advantages could possibly be implemented by, e.g., having some kind of replaceable protection cover that a snake robot is fitted with when docking into the rover or being deployed from the rover. This protection cover is then replaced for each new cave the snake robot visits in order to avoid contaminating samples from the new cave with residue from a cave previously visited. See Section 5.2 for a description of a concept for deployment and retrieval of snake robots from/to a rover.

5 Concepts for planetary exploration with snake robots

In the following, we present selected concepts for planetary exploration with snake robots. The main focus for the concepts presented in this report is on snake robots cooperating with rovers and how snake robots can complement current rover operations. This focus has been chosen since a cooperative rover–snake robot system can exploit the individual advantages of the two robot systems. In particular, a rover can cover rather large areas, it has a relatively high energy storage capacity, and it can transport a sample analysis station. A snake robot, on the other hand, can access narrow and cluttered terrains in order to perform sample taking, as well as acting as a detachable manipulator arm. Detailed design descriptions are outside the scope of this report. Instead, we focus on illustrating conceptual ideas in order to give an overview of possibilities.

In the following, we first present a concept for a rover equipped with two detachable snake robots. In the subsequent sections, we elaborate on how and what operations can be carried out with such a cooperative system.

5.1 Overall concept description

An overview of the rover-snake robot system is presented in Figure 24 and includes the following main components:

- **Rover propulsion system**
  The propulsion of the rover is based on a six-wheel configuration similar to many previously developed planetary rovers.
- **Snake robots**
  The rover is equipped with two snake robots that serve as manipulator arms when they are fixed to the rover, and that also can be detached in order to crawl around on their own.
- **Power supply**
  A power supply system (whose type is not specified) is located inside the body of the rover and supplies electric power to the rover and the snake robots.
- **Tether and winch system**
  A tether containing power and communication lines connects the rover to each snake robot. The two tether winches are located inside the body of the rover. The tether allows the snake robots to be winched back to the rover. Moreover, the physical tether interaction between the rover and the snake robots may also help resolve situations where the rover is trapped.
- **Rover vision system**[13]
  The vision system fixed to the rover gives and overview of the motion and operations of the rover and the snake robots.
- **Tool changing system**
  The snake robot head modules (i.e., tool/sensor modules which can be mounted at the front of a snake robot) are interchangeable with any of the tools located in the tool repository in the front of the rover.
- **Material sample repository and analysis station**
  Material samples retrieved by the snake robots are placed in a compartment of the material sample repository located in the front of the rover. The samples are then processed by a sample analysis station located inside the rover body.

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[13] Rover design (included sensors, tools, etc.) is outside the scope of this report. Please refer to, e.g., the Mars Science Laboratory (MSL), the ExoMars rover, or [32] Bartsch, S., *Development, Control, and Empirical Evaluation of the Six-Legged Robot SpaceClimber Designed for Extraterrestrial Crater Exploration*. 2012, University of Bremen. for examples of the state of the art on rover systems.

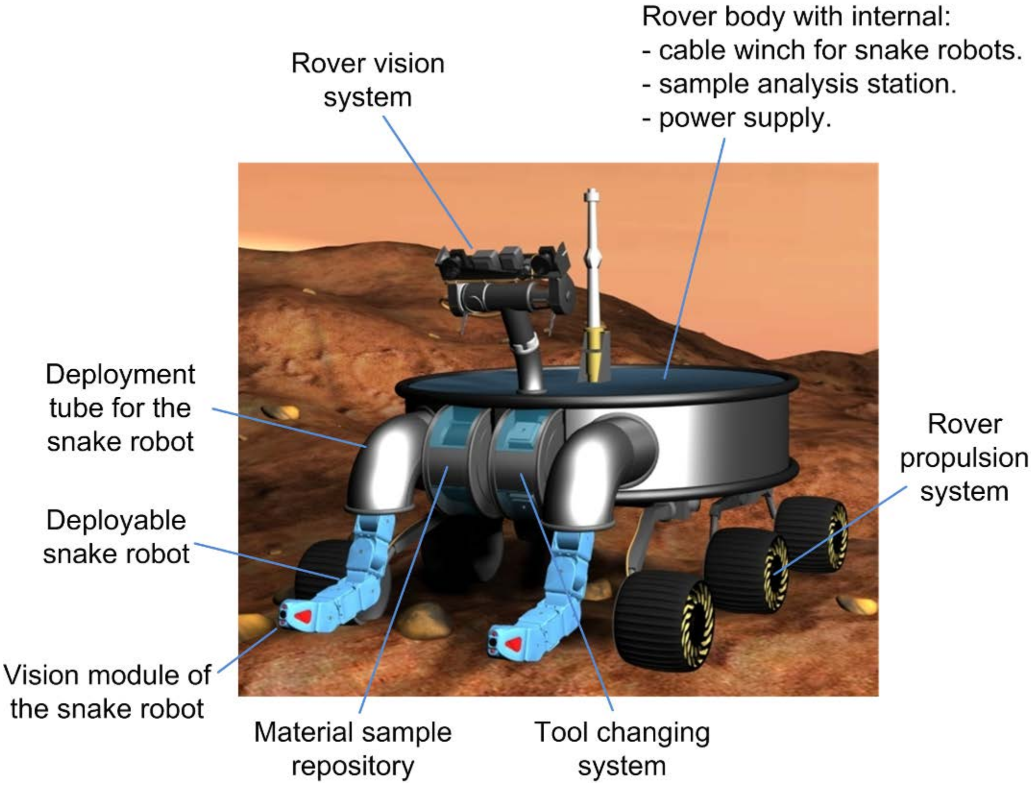

Figure 24: Conceptual overview of a rover equipped with two deployable snake robots.

As an alternative to a rover, one could imagine that snake robots are deployed from a (stationary) lander instead. This would significantly reduce the potential benefit of snake robots as their main strength is traversability and not payload capacity and speed. In such a scenario, the lander should be landed very close to a cave or other challenging environment which is of interest to investigate further. Such precise landings constitute a considerable challenge. The above indicates that the first possible use of snake robots should be in cooperation with a (mobile) rover.

5.2 Deployment and retrieval of the snake robot

5.2.1 General scenario description

A snake robot is detached from the rover by running the internal tether winch and thereby releasing the tether connecting the snake robot to the rover. The snake robot is retrieved by winching the tether and the snake robot back into the rover.

As shown in Figure 25, the snake robot is released through a deployment tube pointing downwards in the front of the rover. Through this simple mechanism, the retrieval of the snake robot becomes less dependent on the geometry of the ground beneath the rover and the location of the snake robot with respect to the rover. In particular, deployment based on lowering some compartment containing the snake robot to the ground would require a relatively flat surface underneath the rover. Moreover, retrieval by winching the snake robot back into the lowered compartment would probably require that the snake robot is located appropriately with respect to the entry point of the compartment. These issues are less critical for a launch tube pointing downwards as shown in Figure 25.

5.2.2 Possible roles of a human operator

Although not visualized in this report, one may also envision human (astronaut) intervention in the context of deploying and retrieving snake robots for planetary exploration. A manual deployment and retrieval system may for instance involve one or several snake robots stored in fixed compartments inside the rover. In order to deploy a snake robot, the astronaut could manually take the snake robot out from its compartment in the rover and place the robot on the ground near the location where some operation shall be carried out. After the operation is complete, the astronaut may place the robot back in its compartment in the rover. In this scenario, the rover serves the role as the transportation system of the snake robots.

Another scenario, which does not involve a rover, is where the astronaut himself/herself carries one or several snake robots in, e.g., a backpack of some sort. In this scenario, the snake robot must either carry its own power supply system or alternatively have a tether that connects the snake robot to an external power supply system in the backpack of the astronaut. With the last option, the astronaut could manually pull back the tether in order to retrieve the snake robot. This is particularly relevant in situations where the robot becomes stuck in a cluttered terrain (e.g., inside a cave).

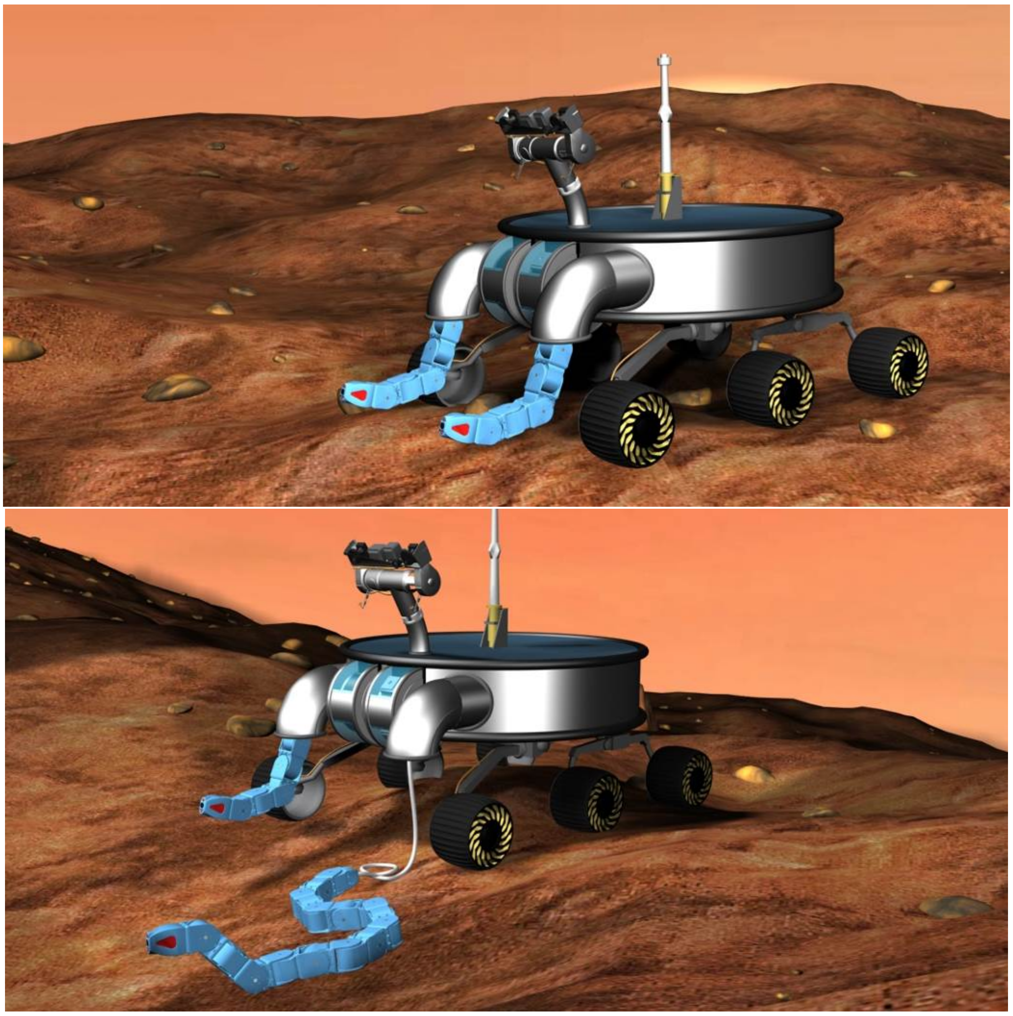

Figure 25: A snake robot is detached from the rover by running the internal tether winch in order to release the tether connecting the snake robot to the rover. Retrieval is achieved simply by winching the snake robot back into the rover.

5.3 Ground locomotion of the snake robot

5.3.1 General scenario description

The snake robots act as manipulator arms when they are fixed to the rover. However, once the tether has been released by the winch inside the rover, a snake robot becomes free to crawl around on its own. Figure 26 illustrates a deployed snake robot crawling around in a pile of rocks, while Figure 27 illustrates two deployed snake robots inspecting a cave.

A deployed snake robot may choose from a number of different motion patterns depending on the properties of its environment. In order to move over surfaces with sand, a sidewinding-like motion pattern may be employed, which is often displayed by desert snakes (see Section 2.2.2 for a description of motion patterns used by snakes). In environments cluttered by rocks, on the other hand, snake robots might rather resort to an adaptive motion pattern where obstacle contact forces are used actively to propel the motion. This type of motion is called obstacle-aided locomotion [1].

Wheels or tracks mounted on snake robots may possibly provide increased speed and traversability in some terrains. However, the integration of wheels/tracks on a snake robot results in an even more complex robot mechanism. Moreover, wheels are not suitable for propulsion on soft sand and the wheels/tracks incorporated on a snake robot are likely to be relatively small which reduces the traction obtained by the wheels/tracks. Based on this, we have therefore focused in the following on a snake robot with a smooth exterior. Such an exterior facilitates that snake robots could be able to move as their biological counterpart, snakes.

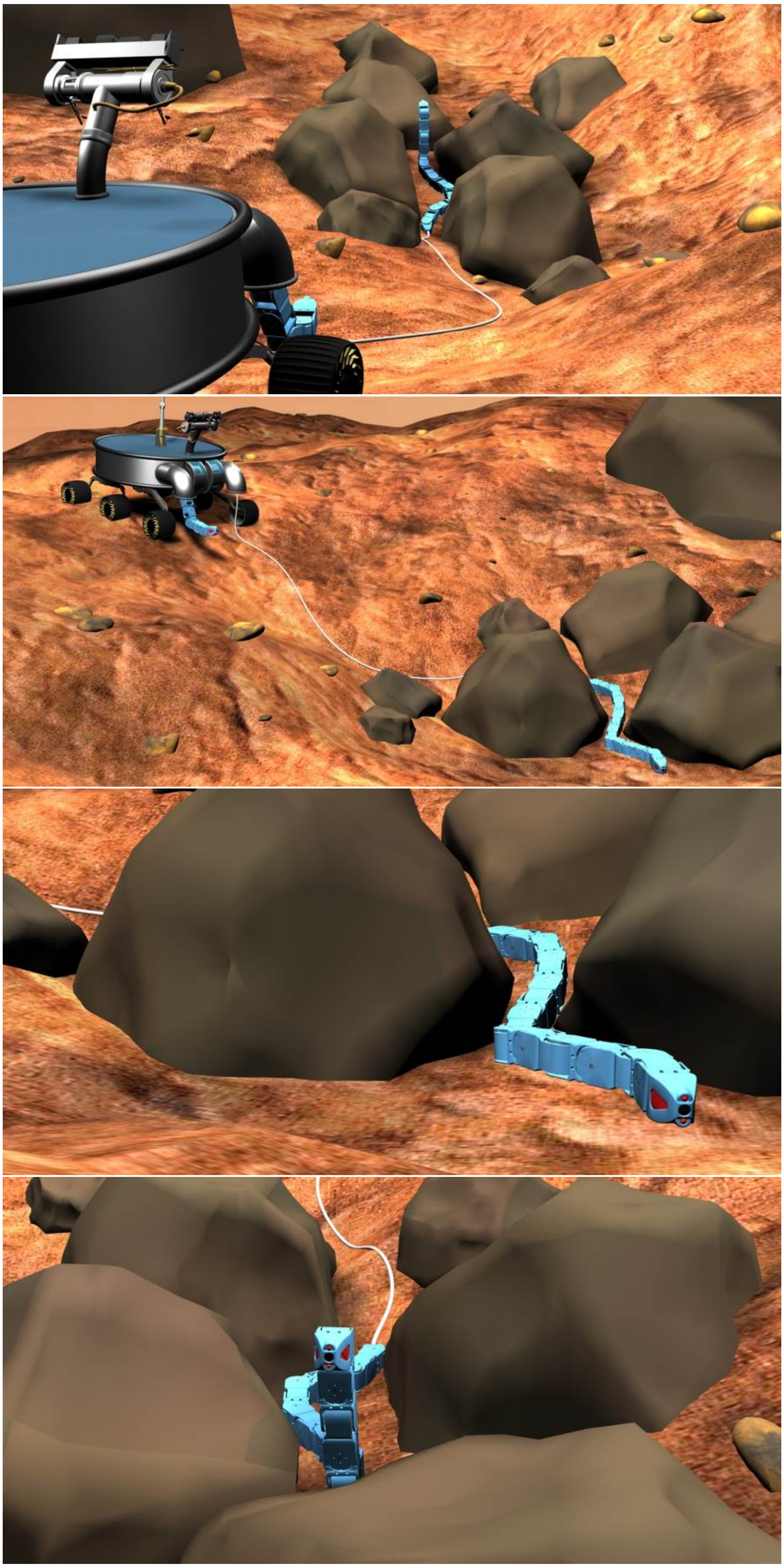

Figure 26: A deployed snake robot crawling around in a pile of rocks.

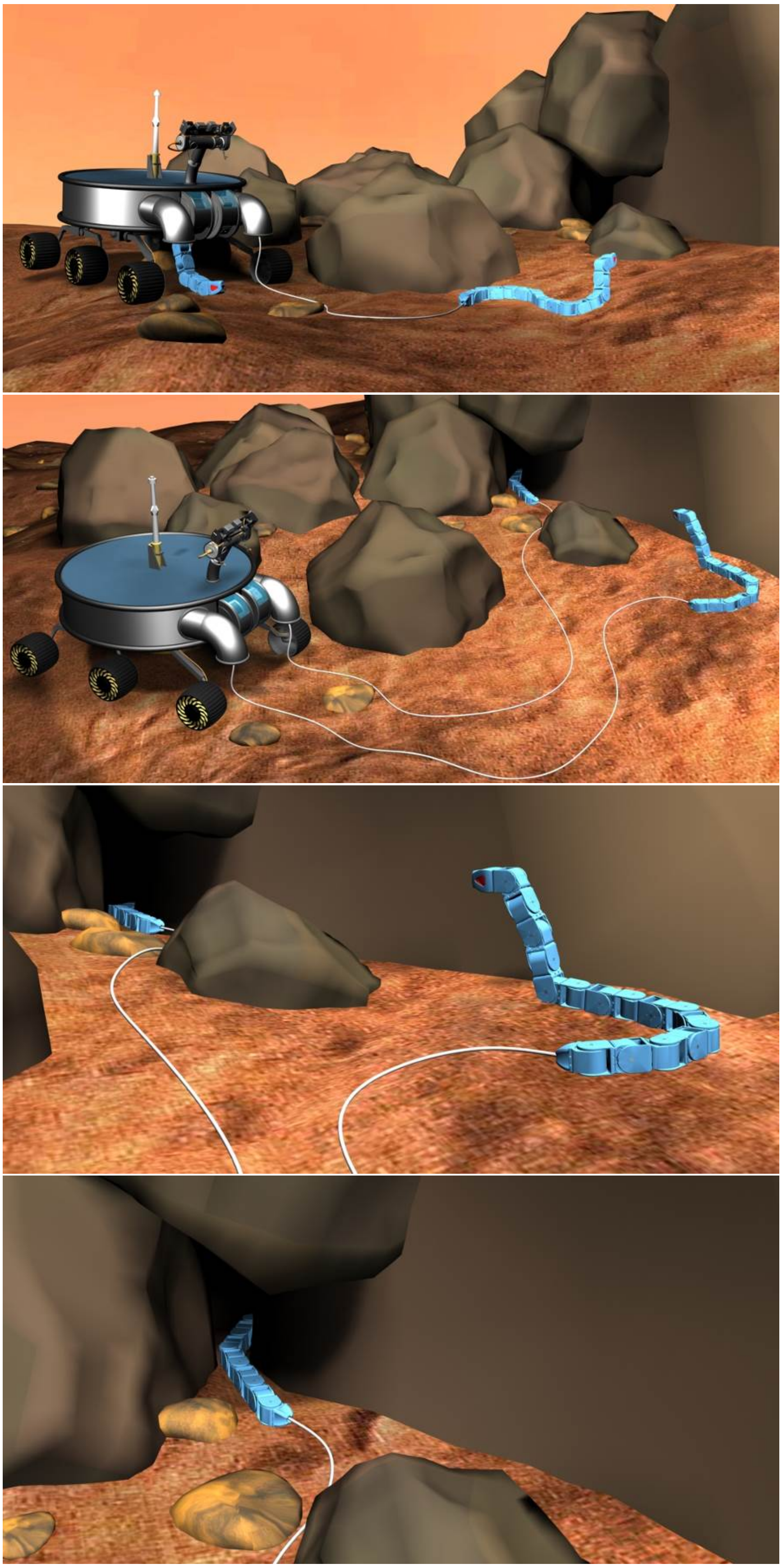

Figure 27: Two deployed snake robots inspecting a cave.

5.3.2 Advantages and disadvantages of the tether connection

The use of a tether between a snake robot and the rover has several *advantages*:

1. The tether simplifies the retrieval process since the snake robot may simply be winched back into the rover by running the cable winch.

2. The tether connection allows the snake robot to be retrieved even in the event that the snake robot breaks down.

3. The winch can apply forces on the tether that may help the snake robot resolve situations where it has become stuck in the sand or jammed in a rocky and difficult environment.

4. The tether may supply the snake robot with power, which eliminates the need for a power supply system on board the snake robot. The tether may also provide a tethered communication link with the rover. An option could be to only supply power through the tether and instead employ a wireless communication link between the rover and the snake robot. However, a wireless link may fail if for instance the snake robot is located in an underground tunnel or inside a cave.

The main *disadvantage* of a tethered connection is that the snake robot needs to propel itself **and** the tether in order to move forward. The friction forces between the ground and the tether may become significant if the length of the released tether becomes long and/or if the tether needs to be pulled past several sharp bends. There are, however, several ways in which this issue may be addressed (these issues are not visualized in this report):

1. One or several active snake robot segments may be installed along the tether. For instance, following the snake robot in the front of the tether, there may be 10 meters of passive tether followed by another active snake robot segment. Subsequently, there may be 10 meters of passive tether followed by another snake robot segment, etc. The tension caused by a jammed tether (e.g., due to ground friction forces or sharp bends of rocks) might then be resolved by the snake robot segments on each side of the jammed tether.

2. The tether may be constructed from a light-weight and smooth material which induces very small ground friction forces.

3. Passive wheels/rollers may be installed along the tether to limit environment friction forces.

4. The tether is connected to the snake robot through several passive castor (pulley) modules installed in the backmost part of the robot. The backmost castor module is deployed each time the robot crawls passed a sharp bend. The deployed castor module will then act as a low-friction support point for the tether at this location while the snake robot continues to move forward. All deployed castor modules are automatically retrieved when the snake robot is winched back to the rover.

5.3.3 Possible roles of a human operator

There are several possible levels of autonomy (i.e., levels of human interaction necessary) in the locomotion control system of the snake robots. The required degree of autonomy will generally depend on the available communication link between a snake robot and its operator, in addition to many other factors.

- **Human astronaut at the operation site on the Martian surface**
  A human astronaut on the Martian surface may manually deploy the snake robot at the site where some operation shall be carried out (e.g., taking material samples inside a cave or underground tunnel). Furthermore, the operator may use a remote control unit to command the motion of the

snake robot. These commands may be issued either based on visual feedback as long as the robot is within visual range of the astronaut, or based on images from cameras in the head of the snake robot that are displayed on the astronaut's control panel. In any case, the astronaut should be able to issue high-level commands related to the overall motion of the robot ("move forward", "turn left", "look up", etc.) and not need to be concerned with the motion of individual joints. In other words, the snake robot should in any case have a level of autonomy which enables it to carry out coordinated motion of its joints to achieve the higher level motion commands from the operator.

- **Human astronaut in orbit around Mars**
  A human astronaut in orbit around Mars may still be able to issue real-time commands to a deployed snake robot based on the camera images from the snake robot. In this situation, the snake robot may, to some extent, be controlled in the same way as if the astronaut was located on the Martian surface outside visual range of the robot. However, this situation does not allow for manual deployment and retrieval of the snake robot, and the astronaut's ability to intervene is limited in situations where the robots encounter problems. Moreover, this approach requires that a communication link between the astronaut and the snake robot is available.
- **Human operator on Earth**
  Due to the time delay for control signals between Earth and Mars (in average around 20 minutes), it will not be possible for operators on Earth to command the motion and operations of a snake robot in real-time. Earth-based operator control therefore requires the snake robots to have a more sophisticated and intelligent control system compared to Mars-based operator control. One possible and relevant control approach would be a SLAM-based approach (SLAM = Simultaneous Localization And Mapping), where the snake robot uses on-board sensors to automatically make a map of its environment and determine its own location in this map. The map is then sent to operators on Earth so that they may specify reference paths and target locations in this map, and also plan the specific operations to be carried out. The snake robot should in any case be able to intelligently adapt its motion to non-modelled features in the environment in order to maintain its motion towards some specified target location. The experiences made with monitoring and control from Earth of rovers deployed on Mars will, of course, also provide valuable insight into how such remote monitoring and control can be successfully achieved with snake robots.

5.4 Tool changing operation

The operations that a snake robot can carry out (either while fixed to the rover or while crawling on its own) are generally dependent on the tool/sensors installed in the head of the robot. To increase the range of operations where the snake robots can be employed, the rover is equipped with a tool repository (see Figure 24). While fixed to the rover, the snake robots can connect to any of the tools in this repository. Figure 28 illustrates a snake robot carrying out a tool changing operation by replacing its camera module with a gripper module.

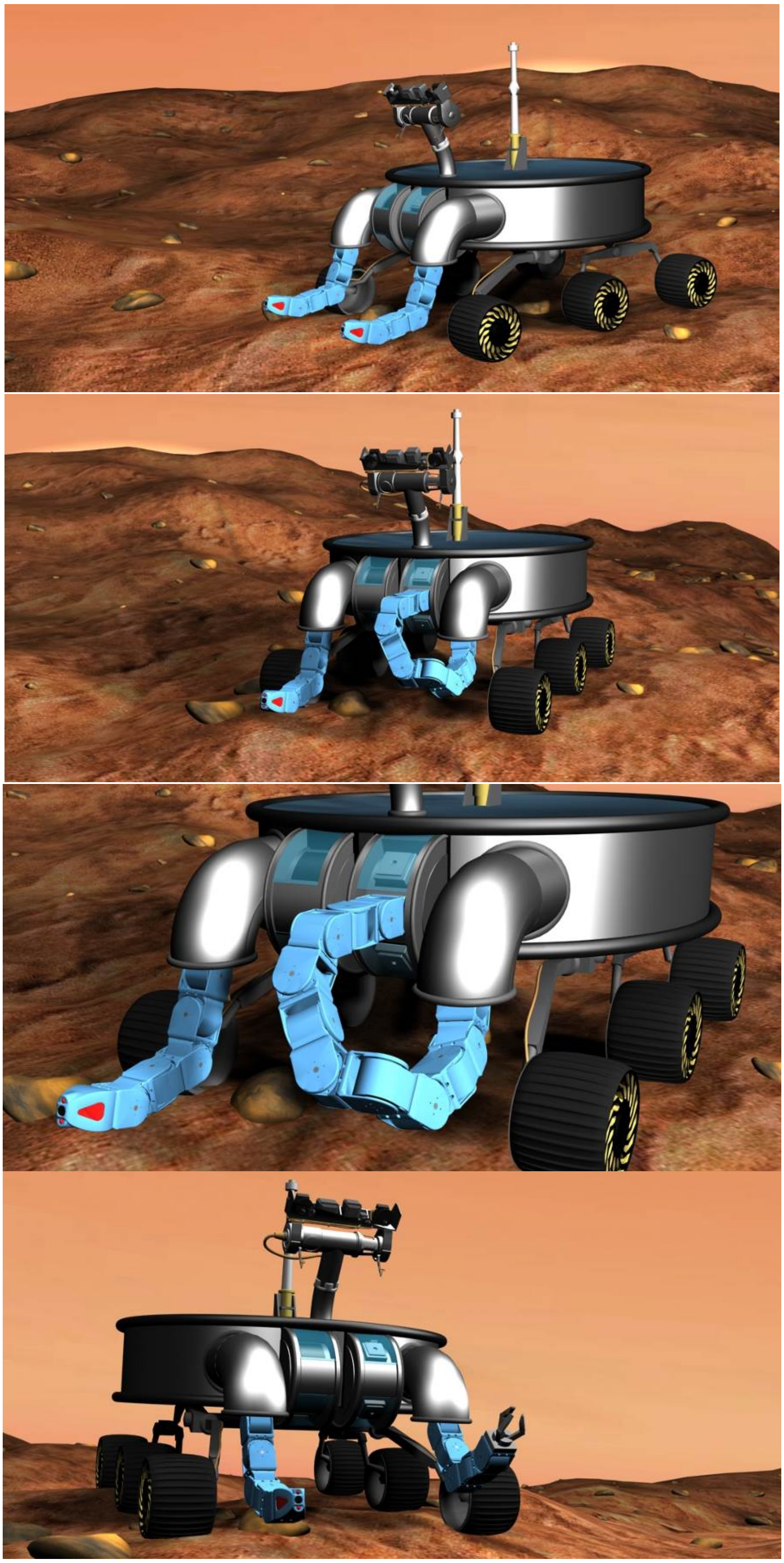

Figure 28: A snake robot carrying out a tool changing operation by replacing its camera module with a gripper module.

5.5 Snake robots used as manipulator arms to retrieve a material sample

When the snake robots have been winched into their deployment tubes, they will be more or less fixed to the rover and can serve as flexible manipulator arms. Equipping the rover with two such arms is advantageous since the arms may then cooperate and solve complex tasks which cannot be performed by a single arm (much like a human sometimes requires both arms to solve a task).

A manipulator operation performed by the snake robots is illustrated in Figure 29. In particular, the figure shows how a snake robot can use its gripper tool to pick up a piece of rock from the ground while the other snake robot monitors the operation using its camera module. The snake robot places the grasped material into the rover's sample repository for further processing by the sample analysis station inside the rover.

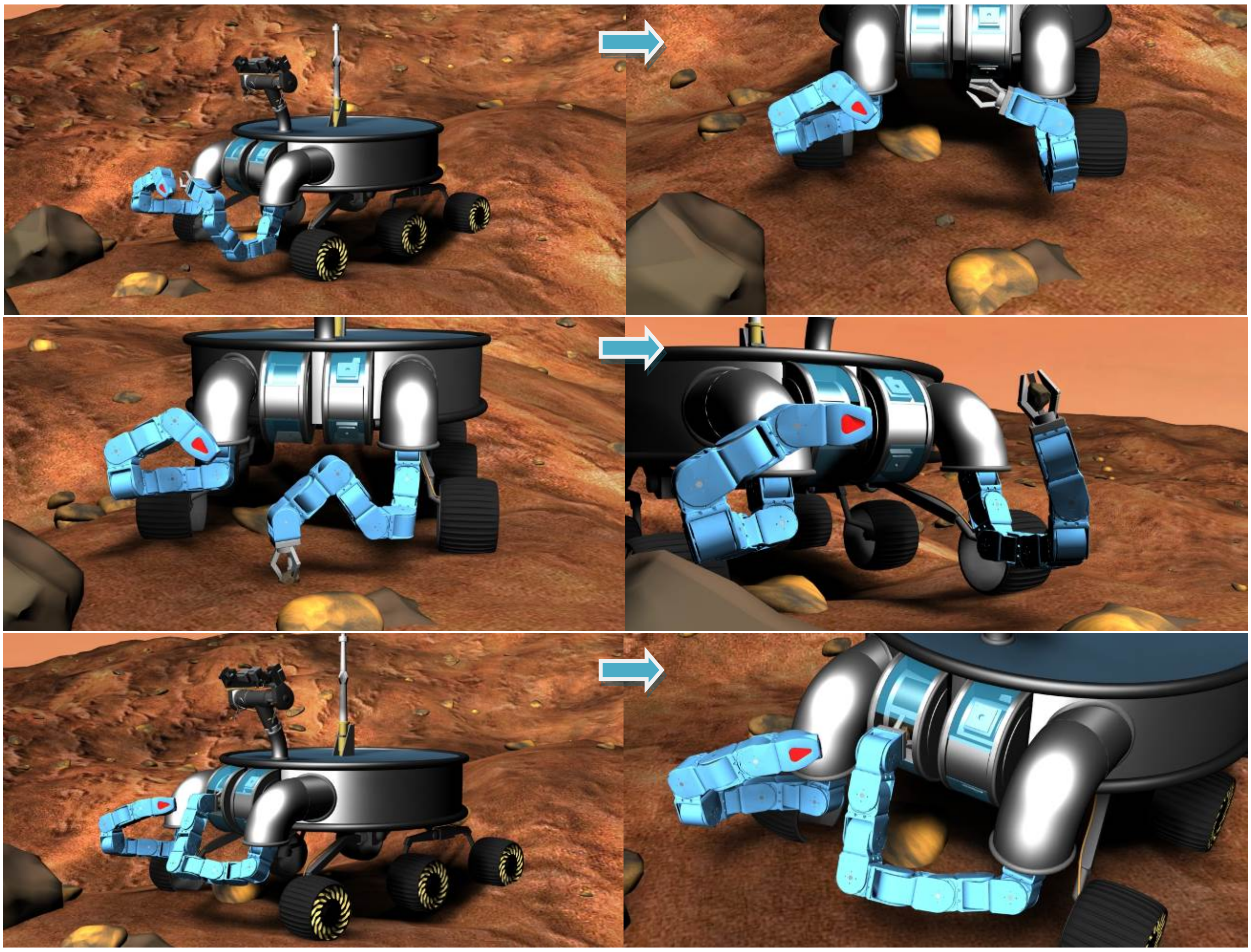

Figure 29: A snake robot using its gripper tool to pick up a piece of rock from the ground while the other snake robot monitors the operation using its camera module. The grasped rock is placed into the rover's sample repository for further processing by the sample analysis station inside the rover.

5.6 Snake robots provide rover assistance in extreme terrain

The physical tether connection between a deployed snake robot and the rover is in many situations a great advantage. In particular, the robot in one end of the tether may assist the propulsion of the robot in the other end by inducing forces through the tether. Since the snake robot is generally much smaller than the rover, a natural scenario would be where the rover runs its tether winch in order to help loosen a trapped snake robot. It should be noted, however, that such assistive efforts may also be supplied to the rover by help of the deployed snake robots, which is illustrated in this section.

This concept is illustrated in Figure 30, where both snake robots have been deployed since the rover has become stuck in the sand after attempting to drive up a hill. To help loosen the rover, each snake robot anchors its body around a rock. Subsequently, the rover runs both tether winches in order to drag itself loose from the sand. In the envisioned scenario, the snake robots attempt to drag the rover downwards the hill since this is likely to require less forces than dragging the rover up the hill.

Figure 30: Two deployed snake robots using their tether connection to help the rover loose after its wheels were trapped in the sand. The rover runs its tether winch while each snake robot anchors its body around a rock.

6 Spin-off possibilities and synergies with earth-bound applications

Snake robots capable of planetary exploration, in the following denoted a "SERPEX system", will provide a range of serious spin-off possibilities to terrestrial applications. It is highly likely that the first use of snake robots in a commercial setting will occur in terrestrial applications and not planetary exploration. However, the strict requirements which snake robots need to meet when moving to a planetary exploration setting may result in significant improvements and increased commercial potential for terrestrial applications. Moreover, SERPEX system technologies will also contribute to the area of "conventional" robotics. In the following, we elaborate more on this as well as the new application and market opportunities which may arise from having operational, robust and durable snake robot systems.

6.1 Contributions to cutting edge robotic research in Europe

A SERPEX system represents technology beyond current state-of-the-art. The system is highly multi-disciplinary and requires leading expertise and know-how related to:

- Autonomy and artificial intelligence techniques
- Motion planning and control theory
- Localisation and mapping (SLAM)
- Human-robot interaction and communication
- Sensor technologies
- Mechatronics
- Actuator systems
- Material technologies

These disciplines are generic since they are also required in other areas of robotics. Consequently, research and development related to SERPEX will benefit academia, industry and research centers within robotics on a national and also a European level. Progress beyond state-of-the-art within these disciplines will strengthen robotic research in Europe and stimulate educational activities related to robotics.

The added value for Europe in targeting SERPEX is also ensured by the fact that no European organisation has alone the necessary spread and depth of expertise to develop such a multi-disciplinary system. The required range of disciplines and expertise only exists on a European level. Consequently, the successful development of SERPEX must necessarily benefit a wide range of European research communities.

6.2 New applications and market opportunities in robotics

The technological elements of a snake robot developed for space missions have many application areas both individually and as a whole. In particular, the generic element of a SERPEX system is an intelligent and robust mobile robot which can move and operate in harsh and challenging environments inaccessible to humans. To this end, a snake robot may be regarded as a general transportation system for application-specific tools and sensors in challenging and hostile environments (see Figure 31). The specific application of this robust transportation system will be determined by the sensors and tools installed on the robot. Since robust robotic mobility in challenging environments have applications in many different domains of our society, the development of a SERPEX system will have strong synergies with many earthbound applications. Different industries and application areas on earth can both support and make use of the technological elements of a SERPEX system.

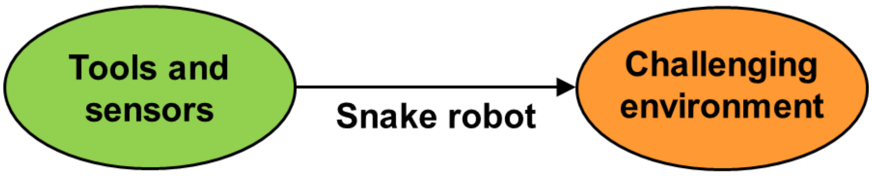

Figure 31: Snake robots constitute an intelligent transport mechanism for bringing tools and sensors into challenging environments.

Among owners and developers of complex technological systems, there is an increasing recognition of the importance of understanding, and of early inclusion in design and development, the cultural and organizational conditions the system is planned to be operated under. The emergence of integrated operations as a concept for operation and utilization of oil and gas infrastructure on the Norwegian continental shelf is a prominent example.

Unlike more conventional wheeled, tracked and legged robots, where propulsion is achieved with a separate and dedicated part of the robot, snake robots are unique in the sense that they have no separate part which is dedicated to propulsion. Being essentially a smooth and flexible manipulator arm, the propulsion mechanism of a snake robot is rather an integrated part of the entire body. This unique feature of snake robots also allows them to use their flexible body to carry out manipulation tasks using tools mounted, e.g., to their head.

Thus, when we in the following exemplify earthbound applications which will benefit from the development of SERPEX, this encompasses operational as well as technological aspects.

6.2.1 Subsea operations

Similar to biological snakes and eels, snake robots can easily propel forward under water. Being essentially a flexible manipulator arm, a swimming snake robot can be employed to perform tasks under water in locations which are inaccessible to more conventional underwater vehicles. An second possible advantage of snake robots compared to the more conventional propeller-based vehicles (Autonomous Underwater Vehicles, AUVs, and Remotely Operated Vehicles, ROVs) employed today is that the undulation of a snake robot under water does not whirl up as much particles from the sea-bed that restricts the sight of cameras and other vision-based sensor on board the robot. Moreover, the slender and flexible body of a snake robot allows it to reach and carry out inspection and maintenance tasks in narrow locations not accessible to larger propeller-based vehicles.

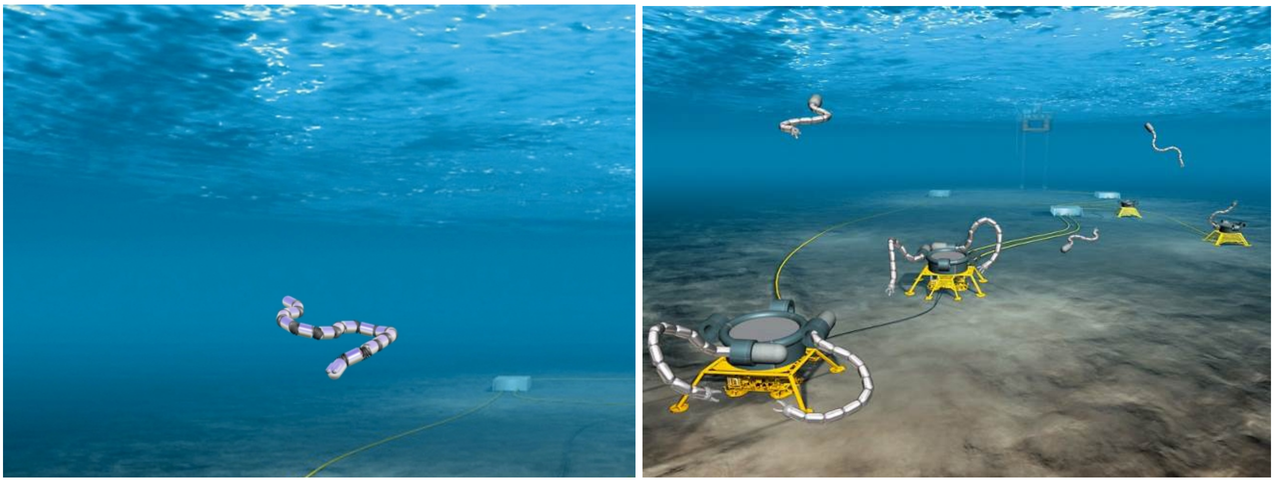

Figure 32: The undulatory motion of a snake robot is promising propulsion mechanism under water. Snake robots could therefore be used for e.g. inspection and maintenance of subsea installations.

An application which is particularly relevant for both Norwegian and international industry concerns inspection and maintenance of subsea structures in conjunction with oil & gas production (see Figure 32). The research on snake robotics at SINTEF and NTNU has strengthened the fruitful collaboration with the Norwegian oil & gas industry and led to new projects. The collaboration is motivated by the development of new robotic technologies for inspection and maintenance of current and future installations.

There are strong synergies between a SERPEX system and a snake robot for subsea operations. In particular, a SERPEX system would probably be applicable for subsea operations with few adjustments. Moreover, subsea operations have similar operational conditions as space missions in the sense that communication with a robotic system under water is challenging and generally cannot occur in real-time.

6.2.2 Inspection and maintenance

The slender and flexible body of a snake robot is ideal for reaching inaccessible locations inside ventilation systems as well as industrial process plants in general (see Figure 33). Inspection and maintenance in such environments is therefore a very relevant application of snake robots. A particularly relevant application concerns inspection and maintenance inside process pipes and inside pressure vessels of various types. Pipe and pipeline inspection has a significant market potential in a growing market characterised by increasing safety requirements and quality awareness from the industry, legislators and citizens. Refineries, chemical plants, nuclear plants, the petroleum industry, households, and large buildings have millions of meters of pipelines, some of which are exposed to harsh inside or outside environments. As a result, the industry and citizens are continuously challenged to ensure that the quality and state of the pipe structures meet the standards set by regulatory bodies.

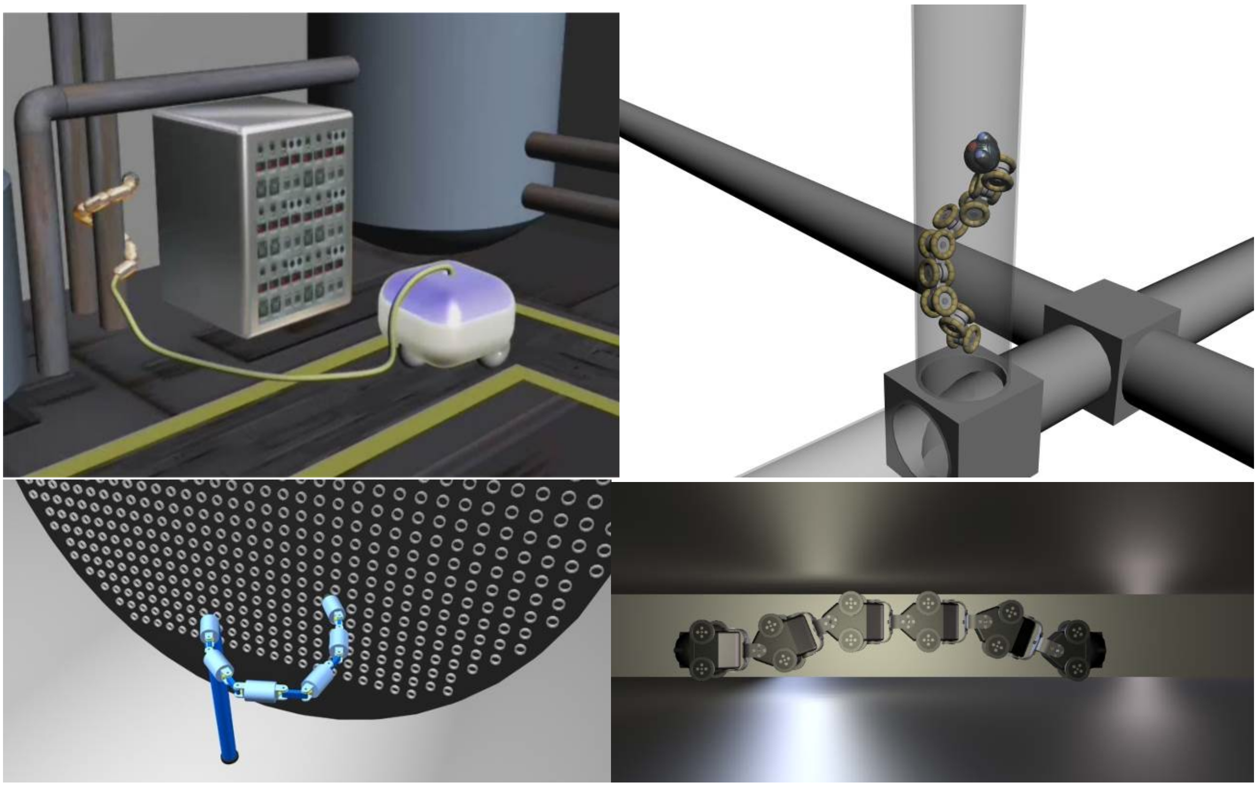

Figure 33: Snake robots can be used for inspection and maintenance inside industrial process plants, e.g., for inspection of pipes and pressure vessels.

The long and slender body of a snake robot makes it ideal for internal inspection and maintenance of pipe structures. The technologies of a SERPEX system would therefore greatly benefit applications such as:

- Inspection of pipes in refineries, chemical and nuclear plants, and the petroleum industry.
- Inspection of urban infrastructure such as water and sewerage systems.

- Inspection of interstate infrastructure such as oil and gas pipelines.
- Inspection of air duct systems.

In Norway, there is a significant market for new technologies for automated inspection of pipe structures since the Norwegian industry is heavily based on oil & gas production. The situation in Norway also reflects the situation internationally.

6.2.3 Search and rescue operations

Snake robots can be employed for search and rescue support after earthquakes and other disasters. In particular, snake robots can employ their long and flexible body to locate and help victims trapped in locations which are inaccessible to human rescue personnel. SERPEX will directly benefit such applications since key characteristics of a Mars landscape can also be found in search and rescue settings (e.g., rocks and unstructured environments).

Figure 34: The robust locomotion capabilities of snake robots facilitate search and rescue operations in hostile environments, e.g., in areas struck by earthquakes.

6.2.4 Exploration of caves and underground tunnels

Our planet contains a countless number of underground caves and tunnels created either by nature or by humans. The need for inspecting such underground structures occurs in many different applications. Since snake robots are potentially ideal for this purpose, a SERPEX system would have strong synergies with these applications.

A snake robot system for search and rescue operational in areas, e.g., struck by earthquakes, will require much of the same capabilities as a system for exploration of caves and underground tunnels. Hence, there is a strong synergy between these two fields of application.

6.2.5 Fire-fighting operations

Snake robots can be employed for fire suppression and extinguishing in tunnels and other locations which are inaccessible (or pose particular risks) to human fire fighters. A relevant scenario is to base the snake robot on a water hydraulic actuation system such that the pressurized water inside the fire hose is used as a hydraulic medium, a fire extinguishing medium, and a cooling medium for the robot. SINTEF has previously demonstrated this application by developing the water hydraulic snake robot Anna Konda [12]. The technologies of SERPEX are very relevant for robotic fire-fighting applications since they enable robust transport mechanisms for carrying and distributing a fire extinguishing medium.

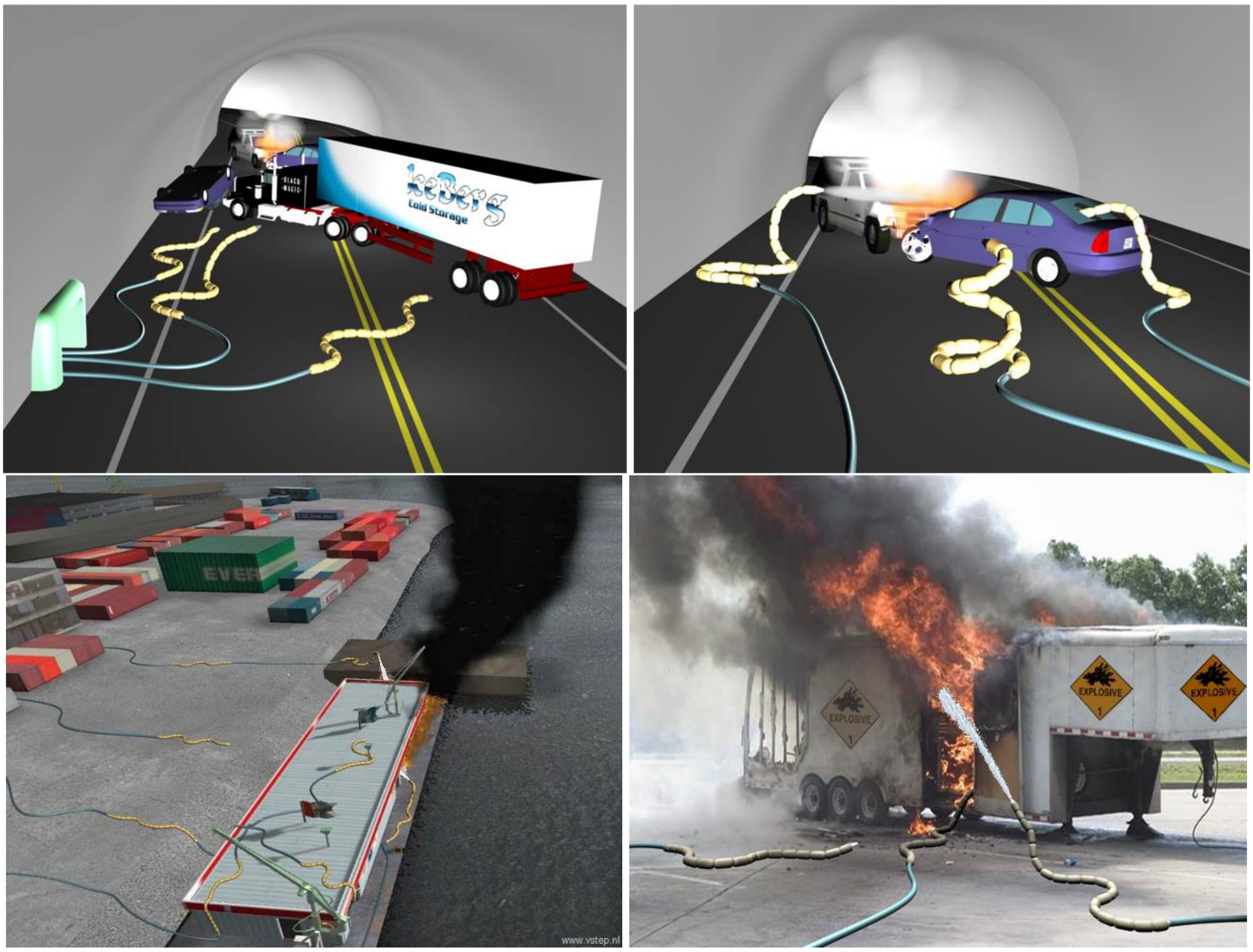

Figure 35: Snake robots in the form of self-propelled fire hoses powered by water hydraulic actuators have great potential in firefighting applications.

7 Conclusions and further work

Snake robots have a strong inherent potential to move and operate robustly in challenging environments where more conventional wheeled and tracked mobile robots may fail. Such abilities are important for planetary exploration. In this report, we have investigated the feasibility of snake robots for planetary exploration.

We have investigated advantages and disadvantages of employing snake robots for planetary exploration. Snake robot features such as potentially high traversability and stability are important factors in order to enable close-up investigations in cluttered or steep terrains. Low-payload capability and low energy efficiency indicate that snake robots should be used in cooperation with a lander or rover from which energy can be obtained through a tether and/or battery charging.

There are significant challenges to be met in order to enable operational snake robots in a space or terrestrial setting. These challenges encompass both software (control system design) and hardware (mechanism design). To this end, the control system and onboard sensors of a snake robot must enable it to traverse difficult terrains. This is a challenging task given that the interaction between a snake robot and its environment constitute a highly complex control problem. However, during recent years, research groups such as one at SINTEF/NTNU[14] have been working actively in order to solve this. Challenges regarding mechanism design and hardware include development of robust and lightweight joint mechanisms which are sufficiently strong and agile in order to be used for efficient snake robot locomotion. Development to meet this challenge will also greatly benefit conventional robots since manipulators and robots can be built even more slim and light-weight without lowering strength and agility. On-board battery capacity is also a significant challenge if the robot is to operate for extended periods of time without an external power source. Therefore, tethered operations are suggested as a first step.

We have considered operational and scientific aspects of snake robots for planetary exploration. In particular, we have considered the ExoMars missions and the Human Exploration of Mars Design Reference Architecture 5.0. Moreover, we have commented on how snake robots can contribute in relation to key technologies for space missions as identified in the NASA Technology Roadmaps.

The many application areas of snake robots on earth imply that the technological development of a snake robot for space missions will have strong synergies with related earthbound applications. To this end, we have identified such synergies by investigating how different industries and application areas on earth can both support and make use of the technological elements of a snake robot developed for space missions. Relevant terrestrial applications include fire-fighting, search and rescue and industrial operations within, e.g., inspection and maintenance.

We have presented concepts for planetary exploration with snake robots. A focus has been on snake robots cooperating with a rover since this is the scenario that we believe will constitute a first possible usage of snake robots for planetary exploration due to, e.g., challenges with energy storage on a snake robot. The concepts outline solutions for using snake robots both as detachable rover manipulator arms as well as snake robots as transport mechanisms employed in order to investigate areas previously inaccessible to conventional rovers.

Snake robots are complex mechanism with limited payload capability, poor power efficiency and a high number of degrees of freedom. Nevertheless, snake robots have the potential of great traversability and capability of inspecting narrow places. They can also be made very robust to environment factors by covering the robot completely with a shell, and they can even change from being a transport mechanism to

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[14] Snake robots at NTNU/SINTEF: http://robotnor.no/expertise/robotic-systems/snake-robots/

being employed as a manipulator arm. These are all aspects which we believe indicate that the possibility of snake robots contributing to planetary exploration should be investigated further.

This report constitutes a first step into the investigation whether or not snake robots should be employed for planetary exploration. Important challenges, advantages and disadvantages have been discussed. We suggest that further work includes a quantitative analysis and development of more detailed designs of the various aspects identified in this report. Moreover, a further research and development effort is required both in order to address challenges related to snake robot locomotion and mechanism design, as well as to build a stronger foundation for concluding about the relevance of snake robots in a space mission context.

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