SNAKE ROBOTS FOR SPACE APPLICATIONS

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ABSTRACT

This paper explores relevant concepts for use of snake robots in space, specifically for use onboard the International Space Station, for exploration of Moon lava tubes and for exploration of low-gravity bodies. Key abilities that snake robots need to have in order to carry out the aforementioned operations, as well as challenges related to realizing such abilities, are discussed.

Key words: Snake Robots; ESA; ISS; Low-Gravity Body; Lava tubes; Moon Village.

1. INTRODUCTION

The paper considers the use of snake robots in space applications in the not too distant future. Different scenarios involving the use of a snake robot are considered, and three of these are selected as particularly interesting and elaborated on further; inspection and intervention activities onboard the International Space Station (ISS), exploration of lunar lava tubes and exploration of low gravity bodies. A snake robot concept is defined for each scenario and core technologies required for a successful mission are identified. The work builds on [1] that investigated the feasibility of use of snake robots for planetary exploration.

Snake robots are long, flexible robotic mechanisms that can be designed to move like biological snakes and/or to be operated as a robotic arm. A particular advantage of such mechanisms is their potential ability to move and operate robustly in challenging environments where human presence is unwanted or difficult/impossible to achieve. A good summary of snake robot research can be found in [2].

While no snake robots have yet been developed for space applications, other space robots have performed cutting edge research in space for several decades. The hostile environment and long distances makes space applications particularly attractive for use of unmanned solutions. Preceded by a large number of unmanned spacecraft/probes, the Soviet Lunokhod 1 lunar rover became the first mobile rover to explore an extraterrestrial body as early as 1970. In recent years, the Mars rovers (Sojourner, Spirit, Opportunity and Curiosity) have captured the attention of the general public. A snake robot for planetary exploration would target environments that are not suited for wheeled rovers, such as to assess the suitability of lunar lava tubes as a site for the first human settlement (Moon Village), or to explore low-gravity bodies such as small moons, asteroids and meteors.

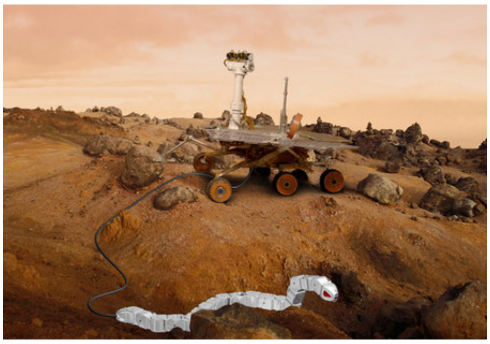


Figure 1. Artist's concept of a snake robot exploring with a rover. Credit: Copyright (Mars landscape and rover) James Steidl/Shutterstock.com.

The ISS is also host to robotic systems. The largest of these is the Mobile Servicing System (MSS) which includes a 17 meter long robotic arm with 7 motorized joints called "Canadarm2" [3]. The robotic arm is not permanently anchored at either end and is able to move around the outside of the station flipping end-over-end in an inchworm-like movement limited only by the number of Power Data Grapple Fixtures (PDGF). As the name indicates, each fixture provides the arm with power and a computer/video link to astronaut controllers inside. The arm can also travel the entire length of the space station using the Mobile Base System (MBS). An key piece of technology that has been included in the design is the Force Moment Sensor (FMS). It gives Canadarm2 the ability to feel the forces and moments involved in different operations and to adjust the magnitude and direction of the applied load. The Canadarm2 is in many ways very similar to a snake robot and similar technology, particularly for locomotion and FMS, is also relevant for a snake robot in space.

Inside the space station, there is a SPHERES system which consists of 3 free-flying bowling-ball-sized spherical satellites that are used to test a diverse range of science hardware and software, typically related to docking maneuvers, formation flight or other autonomy algorithms. At the end of 2017, the SPHERES system will be replaced with the Astrobee, a new free-flying robot system suitable for performing Intravehicular Activity (IVA) work on the ISS [4]. Its main operating scenarios include performing as a free-flying low-gravity research test bed, performing as a camera system recording video images of the crew, and performing surveys using external payloads and instruments. The technology builds on the SPHERES, but the Astrobee includes a perching arm with a gripper designed to hold on to ISS handrails such that the position can be maintained without use of the propulsion system. Several technologies incorporated in the Astrobee are also relevant for an ISS based snake robot. The snake robot would be developed with the primary aim of relieving the astronauts of simple tedious tasks so that they can focus their attention on the more complex tasks.

2. SNAKE ROBOT OVERVIEW

Simply put, a snake robot is a robotic mechanism that is constructed to resemble and adopt the capabilities of biological snakes. Snake robots come in a variety of shapes and sizes depending on the application of interest, and they present a promising alternative for operating in environments where the mobility of wheeled and tracked robots are challenged.

2.1. Key Advantages

The two main advantages of snake robots that results directly from the architecture are its properties of versatility and robustness. The flexibility of the snake robot allows a wide range of locomotion strategies to address challenges posed by different types of terrain and surface characteristics. The long, thin shape is well suited to traversal and exploration of narrow spaces such as pipelines or tunnels, and also, the high degree of flexibility offered by the multiple joints allows the snake robot to scale objects and climb over various obstructions. It is versatile as a single robot entity is able to 1) traverse narrow passages, 2) move over wide gaps and 3) perform complex and light-to-medium-load manipulation operations.

For other types of mobile robot mechanisms, there usually has to be a trade-off to favor either one or two of the above capabilities. E.g., a conventional mobile robot would have to be very small to traverse narrow passages, and small robots have very limited manipulation capabilities and will have difficulty moving over gaps in the terrain. This is not the case for snake robots as they are both a mobility device and a manipulation device at the same time. Further, the robot can be attached to a rover or fixed station for dedicated use as a robotic arm, and then deployed for tasks in areas that may be inaccessible to e.g. the rover. A snake robot can also employ parts of its body as a gripping tool by enveloping around the object to be grasped. This can be used to, e.g., anchor one end of the snake robot while the other end performs an intervention operation. The snake robot can be designed in a modular fashion allowing a robust design where the robot can perform the intended function even if some modules have failed. A modular design also simplifies production, testing, logistics (concerning spare parts) and maintenance.

2.2. Key Challenges

The main disadvantages of a snake robot include low speed, limited payload, complex propulsion system and relatively low energy efficiency for surface mobility. Snake robots will achieve lower speeds than wheeled robots in terrains with a somewhat hard and reasonably flat surface. On softer terrains a wheeled mechanism may get stuck, and legged mechanisms or snake robots could possibly achieve higher speeds. If a mission involves longer transportation legs, a rover can be used to transport the snake robots and then deploy them close to the terrain that the rover is unable to access. With this approach, the low speed of the robot is less critical.

The great flexibility of the snake robot comes at a cost as the large number of robot joint mechanisms that are required in order to achieve locomotion leads to a rather complex propulsion system. The long and slim body of the snake robot also constitutes a non-ideal structure for incorporating both a power source and the accompanying hardware necessary for planetary missions. Depending on the application, it may be beneficial to pursue a tethered design where the snake robot receives power from a larger lander/rover. While a tether may get stuck, it also provides a means for a rover to pull the snake robot free. Snake robots are typically more suited to "small-scale" missions (e.g., soil sampling) rather than missions which require bigger/heavier payloads. Such payloads could instead be carried by an accompanying rover.

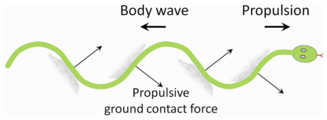
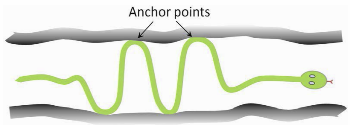
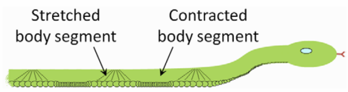
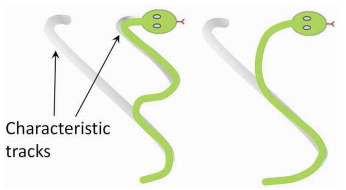
2.3. Modes of Locomotion

Biological snakes can achieve motion using a number of different locomotion strategies. The four most common types of snake locomotion includes *lateral undulation*, *concertina locomotion*, *rectilinear crawling* and *sidewinding* and are summarized in Table 1.

3. SCENARIO AND CONCEPT DEVELOPMENT

There exist a large number of tasks that an articulated robot could perform in space. Examples include manipulating out-of-reach or hard to access objects as part of equipment servicing, explore otherwise inaccessible areas (remote planets/asteroids or constrained spaces) or relieve humans from mundane inspection work.

Table 1. *Snake Locomotion Types*

Snake Locomotion Type	Description of Motion
LATERAL UNDULATION  	• Fastest and most common snake locomotion. • The sides of the snake push against irregularities, thus pushing the snake forward. • Not effective on flat, slippery surfaces.
CONCERTINA LOCOMOTION  	• Best suited locomotion to traverse narrow spaces • The body curves to form anchors allowing the snake to push the body forward. • This type of motion is energy inefficient, so only to be used when necessary.
RECTILINEAR CRAWLING  	• Slow form of locomotion often employed by heavy snakes. • The snake uses the edges of the scales on its underside as anchors to pull itself forward. • At any time, alternate parts on the snake will stretch and pull
SIDEWINDING  	• Employed by certain snakes to move across loose or slippery substrates, such as loose sand or mud • The head is thrown sideways while the rear part of the body provides the anchor to the ground. Then the body follows while the head is anchored and then the motion repeats.

3.1. Selection of Promising Scenarios

We have selected three candidate snake robot scenarios in collaboration with experts at the European Space Agency (ESA) based on criteria which include a foreseen need, the relevance of snake robot technology versus other options and considerations related to mission complexity:

- **Scenario 1**: Snake robots to perform inspection and intervention tasks on-board the ISS.
- **Scenario 2**: Snake robots for exploration of lunar lava tubes to assess their suitability as enclosures for a permanently inhabited base (Moon Village).
- **Scenario 3**: Snake robots for exploration of low gravity bodies such as asteroids.

A snake robot concept to fit each scenario is discussed in the next three sections.

3.2. Inspection and Intervention Onboard the ISS (Scenario 1)

A snake robot could move around inside the ISS either completely autonomously or with some astronaut assistance/supervision and perform inspection and intervention operations. In particular, the snake robot would be able to crawl into hard-to-access spaces, such as in between and behind infrastructure. In case of autonomous operation, the snake robot could have a docking station from which it could automatically detach in order to carry out scheduled work. The core technologies to enable a successful snake robot concept for this scenario include:

- Microgravity locomotion onboard the ISS
- Protection against harm and damage to crew and other infrastructure onboard the ISS

3.3. Exploration of Lunar Lava Tubes (Scenario 2)

For a mission requiring planetary exploration with a snake robot, the most basic scenario involves deployment directly from a (stationary) lander. Of specific interest currently, is the use of snake robots to explore the lava tubes on the Moon to determine if they are suited to house the first human settlements (Moon Village). An underground settlement is advantageous since the temperatures will reach a stable -20 degrees (as opposed to the extreme temperatures on the surface) and also provides protection from solar ”storms”, cosmic rays and the frequent micrometeor impacts. As the main strength of the snake robot is traversability as opposed to payload capacity and speed, the landing site should be close to the entrance of the lava tubes that desires further investigation. Such precise landings constitute a considerable challenge. Thus, the first realistic use of snake robots for use in this type of exploration involves collaboration with a (mobile) rover as illustrated in Fig. 2.

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. Also, a snake robot has the ability to traverse vertical obstacles (or steep sections of the lava tube) to a certain extent. If several tools are needed for the snake robot, the docking station on the rover should support a tool changing possibility. The rover may also need to include a repository for material samples collected by the snake robot. The core technologies to enable a successful snake robot concept for this scenario include:

- Efficient locomotion in challenging terrains
- Power supply and communication inside a lava tube
- Protection against the harsh environment

3.4. Exploration of Low Gravity Bodies (Scenario 3)

The main challenge tied to exploration of low gravity bodies such as asteroids, comets or small moons, is how to successfully land in a desirable location and furthermore how the surroundings can be explored in a controlled manner when traction is virtually absent. Mobility is a challenge since the low gravity results in a high risk of bouncing off such bodies. As opposed to Scenario 2, the snake robot would not have a companion rover, but would likely have a separate landing vehicle. In addition to protecting the robot during the landing phase, having the separate lander would have the additional benefit of

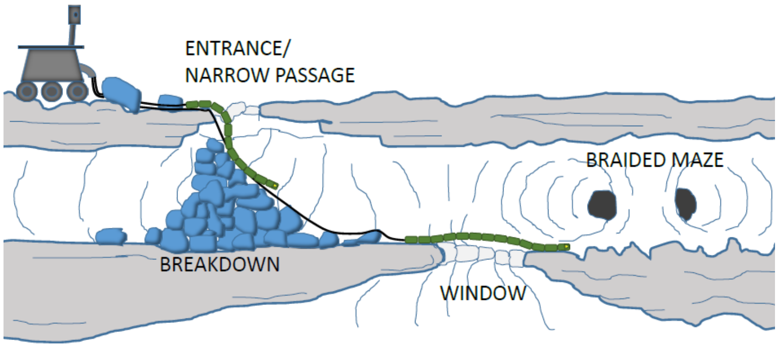


Figure 2. Snake Robots Exploring Lunar Lava Tube with Rover

limiting the amount of equipment/instrumentation necessary to carry onboard the snake robot.

The ESA lander Philae became the first spacecraft to land on a comet in 2014. However, due to unexpected events the lander came to rest in a spot mostly shadowed from the sun, rendering it unable to recharge its batteries. Two important lessons learned from this mission should be considered in the design of a snake robot and lander system for low gravity bodies. First, even if the snake robot is tethered to the lander, the risk of a failed mission could be reduced by ensuring some degree of power independence between the two (plus the ability to sever the tether) in case of failures. Second, snake robot locomotion should be functional for different types of surfaces. The core technologies to enable a successful snake robot concept for this scenario include:

- Locomotion in microgravity and unknown terrain with unknown surface properties
- Protection against the harsh environment

4. CORE TECHNOLOGIES AND POTENTIAL FOR REALIZATION

This section discusses the details and availability of the core technologies that are necessary for near term realization of the selected snake robot concepts.

4.1. Efficient Locomotion

To properly take advantage of the flexibility offered by the snake robot design is key to the success of all snake robot concepts in space. Ideally a snake robot will have several options for motion towards a desired target, and the best choice will be a function of the terrain, the surface properties and mission details such as the time and energy available. Previous research on snake robot locomotion have been inspired by real snake motions as presented in Table 1. A particular field of interest for locomotion on the Moon and on asteroids is obstacle-aided locomotion – inspired by lateral undulation – where

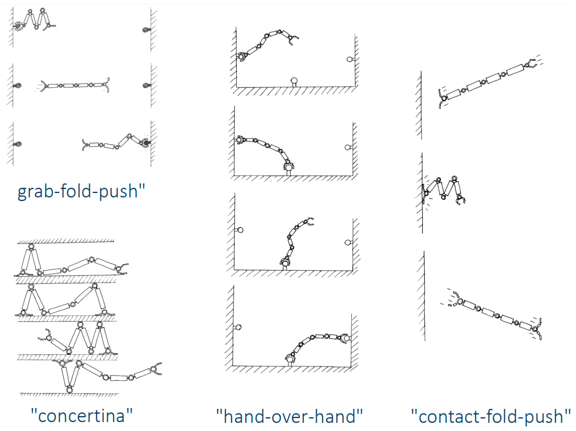


Figure 3. Potential Locomotion Types onboard ISS

a snake robot would push against indentations on the ground to move forward [2]. However, no research covers snake robot locomotion in a zero/low gravity environment. Obstacle-aided locomotion and concertina locomotion is of interest for this latter scenario as a snake robot could push against its surroundings for locomotion. One may consider to add some caterpillar features for additional gripping capability inspired by the ”inchworm method”. The geometer moth caterpillar (or inchworm) is equipped with appendages at both ends of the body. It clasps with its front legs and draws up the hind end, then clasps with the hind end (prolegs) and reaches out for a new front attachment.

The strategies for getting around the ISS, will require a significant amount of development in order to reach maturity. Again, the ”hand-over-hand” or ”inchworm” method of locomotion is relevant, in a similar fashion as used by the Canadarm2. This and other strategies that warrants further investigation are illustrated in Fig. 3. While certainly expected to be challenging, locomotion is not viewed as a likely ”show-stopper” for the ISS snake robot concept. Several promising technologies to help achieve this exists, such as gecko-like adhesion for high friction contact, however a risk includes having to install more handles inside the ISS that the snake robot can use to get around.

4.2. Protection of ISS Equipment and Crew

It is critical that a snake robot developed for use onboard the ISS will not harm the crew or the ISS infrastructure. High impact loads are a function of both the material stiffness of the robot as well as the effective inertia. While the effective inertia can be limited by use of software and sensor technology, unpredictable behavior may still occur as a result of hardware or software faults. Thus, the mechanical characteristics of the robot must be considered in order to improve the overall safety. The almost ISS ready Astrobee, incorporates several such precautions into the physical design [4]. The perching arm is designed to be flexible and backdrivable with a grip not strong enough to cause any crew injuries. The Astrobee is also encased in an impact-absorbing foam shell which is designed to deform and absorb most of the impact energy in case of a collision at the worst-case velocity.

Robot joints can be designed to be flexible using both active and passive mechanisms. A variable stiffness actuator is a mechatronic device that is developed to build passive compliance robots [5]. However, such devices add significant complexity to both the design and control of robot joints. A snake robot called "Mamba" is designed such that all torques and forces acting on each joint can be measured [6]. These measurements can be used to implement flexibility as an active mechanism since the robot will be aware of any abnormal forces acting on the snake robot body. Flexibility is important both to reduce the potential harmful effect of pinch points, as well that a snake robot can change the shape of its body to reduce impact forces during collisions.

To prevent collisions through software algorithms, the snake robot must be acutely aware of the position of it's (entire) body relative to the position of nearby objects. Several technologies exist that can be adopted for this purpose, including camera-based (Time-Of-Flight, mono, stereo), ultrasound, Ultra Wide Band (UWB), InfraRed (IR) and laser. To develop a good solution for the proximity detection functionality is viewed as somewhat challenging given the shape and size of the snake robot, but it is not expected to present any major implementation problems.

The snake robot concept for use onboard the ISS, requires each snake robot segment/module to be encased in an impact-absorbing foam shell to prevent the robot from damaging any ISS infrastructure or equipment or hurting any of the crewmembers in case a collision were to occur despite the efforts outlined above. The main uncertainty related to this functionality is how the shell can be designed to cover all relevant portions of the snake robot without limiting the flexibility of the robot.

4.3. Power Supply and Data Communication

For planetary exploration where the snake robot is accompanied by a rover or lander of reasonable size, the snake robot could be designed to operate with or without a tether, but the tether would greatly increase the duration of the mission as well as provide a reliable high-bandwith data link. Housing the main power supply outside the snake robot allows for a more slender and highly maneuverable design. Additionally, the tether also allows the snake robot to be winched back to the rover. To increase the redundancy of the mission, a minimum level of power supply and communication capability should be available on the snake robot.

Previous Mars rovers are used as inspiration for how to generate energy onboard the robot for scenarios where a lander/rover cannot be relied on to supply the power. Spirit and Opportunity used triplejunction solar arrays, that would charge two lithium-ion batteries, as the main power supply. Curiosity, which weighs about 900 kg (nearly 5 times heavier than Spirit and Opportunity), instead incorporated a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) in order to generate constant power regardless of the availability of the sun. Both of these options could likely be adopted for the exploration of low-gravity body scenario, but for exploration of lunar lava tubes only MMRTG is a practical option for longer missions. While both types of energy generation technologies are well proven through years of service, the main uncertainty is associated with the ability to size the power generation devices to the snake robot.

4.4. Protection Against Harsh Environments

It is essential to the success of the snake robot mission that the robot systems can survive the harsh environment they will be operating in. The specific requirements to environmental protection will vary significantly between the three selected scenarios. However, the key properties that need to be optimized on for a given snake robot concept includes structural protection (against puncture, rupture etc.) of delicate internal components and thermal control of the critical robot systems such that they are working within their allowable temperature range. In the remainder of this section, the discussion is focused on a snake robot concept for exploration of lunar lava tubes or low-gravity bodies, and the technologies used for the Mars rovers have been reviewed for inspiration into how this can be achieved.

First off, a robust shell is required in order to protect the internal components of the robot from impacting objects such as micrometeors and from more general wear and tear as the robot traverses challenging terrain. Extreme temperature changes is a major threat to the essential computer and electronics components onboard the robot, and these should be housed inside a protective box, which will likely be the same as the robust outer shell. On the Mars rovers this box is referred to as Warm Electronics Box (WEB). In order to trap heat inside the body walls a special layer of lightweight insulation made from a substance such as Solid Silica Aerogel (used on the Mars rovers) should be incorporated. To further minimize heat radiation, the robot body should be painted with a reflective coating such as sputtered gold film.

For heating, the Mars rovers rely on electrical heaters that operate when necessary (using thermal switches) and Radioisotope Heater Units (RHUs) which are constant heaters the size of a C-cell battery that generate about 1-watt heat through the radioactive decay of a low-grade isotope. Mars rover Curiosity incorporated a Mechanically Pumped Fluid Loop (MPFL) Heat Rejection System (HRS) consisting of pumps and a fluid loop to distribute heat between the different robot components as necessary, including excess heat from the MMRTG. This represented the first use of such a system on a rover or lander on the surface of a planet. It may also be relevant to provide means to allow heat to escape the WEB to prevent the electronics from overheating during daytime. The radiator is typically a conductive panel with a high-emissive coating. To deal with changing thermal conditions, some way of modifying the emissivity is ideal, this is traditionally done by installing louvres on top of the radiator.

It is not likely that all the technology developed for the Mars rovers discussed above is suited for implementation onboard the quite differently shaped, smaller and lighter snake robot. In fact, thermal control is viewed as one of the last hurdles to developing miniature spacecraft. A promising emerging technology that is particularly relevant for micro spacecraft includes advanced thermal control coatings that can change their effective emissivity in response to a control signal. Several technologies are being developed, including electrochromic solutions, electrostatic solutions and micro-louvers. A good example of such an advanced "thin skin", is developed by Ashwin-Ushas Corporation in collaboration with NASA, and is presented in [7]. Additionally, the distributed fashion of the snake robot modules may require a pumped liquid cooling system to thermally couple all the modules. A concept for a MEMS-based pumped liquid cooling system for future micro/nano spacecraft is presented in [8]. In summary, recent advances and research focused on thermal control strategies for micro spacecraft, renders adequate thermal control of a snake robot in space still challenging but technically feasible.

5. CONCLUSIONS

The paper has identified and explored three promising scenarios in space where a snake robot design may be relevant. Snake robot concepts have been developed for inspection and intervention activities onboard the ISS, for exploration of lunar lava tubes and for exploration of low gravity bodies. The core technologies for each concept have been identified, these primarily relate to locomotion in challenging terrain, environmental protection, power supply and protection of ISS crew and equipment. While a successful snake robot design faces many challenges, emerging technologies aimed at micro spacecraft, renders these concepts feasible in the not too distant future.

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