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A CONCEPT STUDY OF SMALL PLANETARY ROVERS

Using Tensegrity Structures On Venus

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Venus is among the most enigmatic and interesting places to explore in the solar system. However, the surface of Venus is a very hostile, rocky environment with extreme temperatures, pressures, and chemical corrosivity. A planetary rover to explore the surface would be scientifically valuable, but must use unconventional methods in place of traditional robotic control and mobility. This study proposes that a tensegrity structure can provide adaptivity and control in place of a traditional mechanism and electronic controls for mobility on the surface of Venus and in other extreme environments. Tensegrity structures are light and compliant, being constructed from simple repeating rigid and flexible members and stabilized only by tension, drawing inspiration from biology and geometry, and are suitable for folding, deployment, and adaptability to terrain. They can also utilize properties of smart materials and geometry to achieve prescribed movements. Based on the needs of scientific exploration, a simple tensegrity rover can provide mobility and robustness to terrain and environmental conditions, and can be powered by environmental sources such as wind. A wide variety of tensegrity structures are possible, and some initial concepts suitable for volatile and complex environments are proposed here.

Keywords: Planetary Rover, Venus, Tensegrity Structure

1 INTRODUCTION

Venus is a planet that is very close to Earth and similar to Earth in its mass and size, but very different in its environment and with opposite rotation with respect to the disc of the solar system. A better understanding of the atmosphere, climate, geology and history of Venus would be very helpful in understanding the evolution and potential future of Earth. In particular, Venus' enigmatic super-rotating atmosphere contains an unusual abundance of noble gases raising questions about surface volatiles, a high ratio of deuterium to hydrogen indicating a potential history of surface water, and a complex interaction of sulfur with surface minerals that is not yet well understood [1]. Many missions have focused on analysis of the relatively temperate atmospheric layers, but to fully unlock the mysteries of Venus, it will ultimately be necessary to explore the surface.

The surface of Venus is a hostile environment with a surface temperature averaging 453°C with the temperature at the peaks of the highest mountains reaching 390°C, preventing the use of conventional electronic computing and terrestrial mechatronics without cooling and isolation technologies. The Venusian solar day lasts approximately 116.75 Earth days. The atmosphere is composed mainly of carbon dioxide with clouds of sulfuric acid below 20 km altitude limiting sunlight able to reach the surface, and sulfur dioxide at the surface where atmospheric pressure reaches 9,300 KPa (91 times Earth's surface pressure). The dense atmosphere of Venus also makes it difficult for any lander or robotic mission on the surface to communicate with orbiters.

Venus has been explored at least 20 times by the missions from the Soviet Union, NASA, ESA and JAXA since 1965 [2] (Table 1). The first successful landing on Venus was by the 958 kg Venera 7 lander in 1970, which survived 23 minutes. It measured the surface temperature of the atmosphere and confirmed that Venus is not presently suitable for human life. Colour pictures were sent back by the Venera 13 lander in 1982, and the soil was studied with an X-ray spectrometer. After 1985, no other landers arrived on Venus due to the challenges that its environment poses to more complex missions. Ref. [3] provides a summary of technology needed for further exploration of Venus, including the potential of existing capabilities for Venus, short lived landers, long lived landers, and aerial and surface mobility. It is stated that a rover for Venus would require light versions of all technologies identified for both the short lived and long lived lander concepts. A rover used for a surface sample return related mission would require a balloon to lift the sample from the surface, for capture high in the atmosphere.

TABLE 1: Comparison of Venus Previous and Future Missions

Name	Year	Mass	Payload	Survival Time
Venera 7 spacecraft and lander, Russian	1970	958 kg	Measured the temperature of the atmosphere on Venus	23 mins
Pioneer Venus, NASA	1978	3*90 kg + 315 kg	4 Probes (1 large+3 small without parachutes and aeroshells	60 mins
Venera 13 lander, Russian	1982	756 kg	Camera Systems, Color pictures; Studied soil by spectrometer	12 mins
Automaton Rover for Extreme Environments, JPL	Concept	803.69–1128.84 kg	TBD	4 months
Venus Flagship Mission Lander, JPL	Concept	686 kg	TBD	2 months
Venus Rover, NASA	Concept	330 kg	TBD	1 month
Proposed Aria-Venus Rovers	Concept	15 kg	TBD	1 month

Several different Venus rover concepts for future missions have proposed in the last several years, and are compared with significant successful missions in Table 1. A rover massing 1059 kg (1.99 m x 0.33 m x 2 m) with a thermal control system has been proposed to operate at 500 degrees [4]. A much smaller wind powered rover of 70 kg (2.75 m x 0.33 m x 2 m) was proposed with studies of potential power systems, communication and radio systems [5]. The wind speeds required for this rover are between 0.3 m/s and 0.6 m/s and it can provide 30 Watts for scientific instruments and a total energy of 233 W-h per science stop. The rover complete with landing system masses approximately 256 kg (6.67 x 4.52 x 5.42) with three science instruments (camera, weather and in-situ mineralogy) [6]. To avoid the challenges of making electronics work on the surface of Venus, the use of mechanical automata and a mechanical computer were also studied [7]. The aeroshells and total EDL mass of this purely mechanical system are 1780 kg with a module 3.4 meters in diameter. The science payload masses approximately 150 kg. The different locomotion system (326.69 kg) candidates identified are the use of Jansen legs that provide 0.2 m clearance, Klan legs that provide 0.5 m clearance, wheels with 0.8125 m clearance, or tracks that provide 1.11 m clearance. All of these proposed Venus landers and rovers are very heavy and very expensive to launch due to the dense materials and environmental protection required for surviving on Venus, and it is difficult to make them deployable and adaptable to terrain. This study explores the potential of a much smaller rover using technologies that can survive natively in the Venus environment, not just for cost and deployability reasons but also to explore novel robotic solutions and provide increased potential for multi-vehicle deployment.

2 SCIENCE GOALS

To guide the development of a useful rover platform and the selection of technologies, a mission concept has been developed that is achievable for a small planetary rover: Venus surface sensing. The science goals of this rover are to examine the surface environment on Venus and explore the possibility of water and microorganisms existing in the past or present. Limaye et al. have suggested that microorganisms could potentially exist in the lower cloud layers between an altitude of 47-72 km according to the observed bulk spectra. Complex chemical cycles existing in the lower atmosphere and on the ground of Venus vary from place to place as shown in Fig. 1 [8], and it would be of great interest to send several mobile rovers to different locations for comparative measurements. As most current planetary robotics technologies are not well suited to the extreme environmental conditions, an arrival by a suitable rover at Venus in the mid-2030s is considered feasible with time to develop and demonstrate power, mobility, and communication systems.

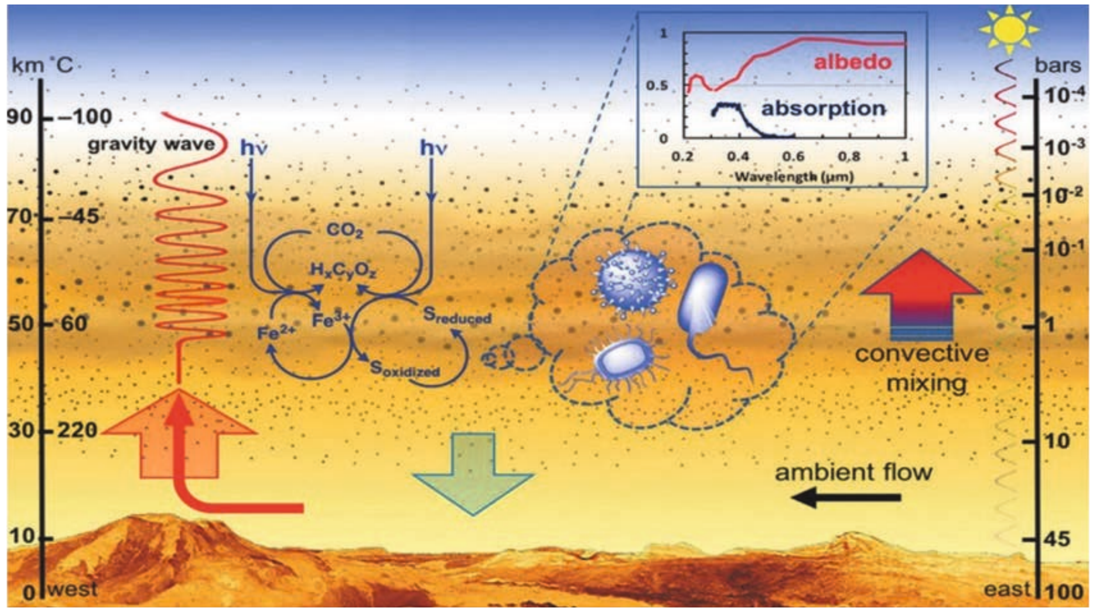

Fig.1 A schematic representation summarizing the ideas for the potential of microorganisms in the lower clouds of Venus. "Venus's spectral signatures and potential for life in the clouds" [8].

An early version of this paper was presented at the 16th Reinventing Space Conference (RiSPACE 2018) in Glasgow UK.

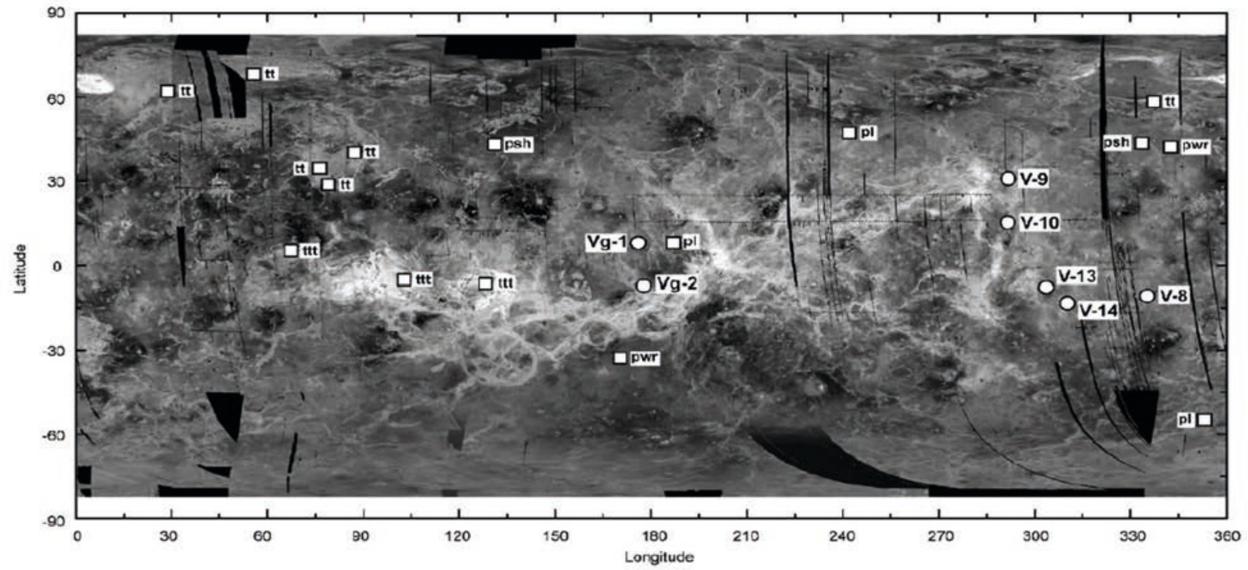

Fig.2 **A global SAR map of Venus showing volcanic features, plains, lowlands, and landing sites [9]. V = Venera sites; Vg = Vega sites; tt = tessera terrains; ttt = tessera transitional terrain; psh = shield plains; pwr = regional plains with wrinkle ridges; pl = lobate plaines.**

Small, mobile robots are useful for performing basic opportunistic science, both alone and in groups by virtue of being less well equipped but able to cover more ground and change mission plans quickly. Although the range and capabilities of these rovers is lower than a large rover, lower mission cost and the capacity to send a group provides wide rather than deep scientific coverage. The landing sites of previous missions are shown on a global SAR map of Venus in Fig. 2 [9], and due to the number of potential sites of interest with varying terrain, clusters of small and redundant rovers could potentially provide much more information than a single large rover given the limitations on what kind of data can be collected with current technology. Detection of organic matter is also desirable but may require more complex and bulky instrumentation. The basic capabilities for this kind of science include navigation of the surface, obtaining and processing environmental information, and bringing an inspection tool into contact with geological sites of interest. Increased autonomous self-sufficience is a benefit for identifying sites in real time and without extensive reliance on ground teams. With the addition of simple mapping capability and sensors for fundamental quantities such as surface and atmospheric temperature, pressure, and wind speed, a significant amount of useful scientific data can be returned from a micro-rover, as well as usefulness in prospecting for later mining or other Venus surface operations. Subsurface imaging by ultrasound or ground-penetrating radar is a potential area where small rovers could effectively collect data from a wide area, but this is dependent on further advances in high-temperature electronics. Small sample collection and return is also possible but will require high-altitude collection and orbital escape. No detailed science beyond the collection and return of sensor data is currently considered feasible on the surface of Venus. Considering a micro-rover, the most feasible payload would consist of environmental sensors and some capacity for surface material analysis.

3 TENSEGRITY PLANETARY ROVERS

Historically, space robots can be classified roughly into seven categories: In-Space Assembly, In-Space Inspection, In-Space Maintenance, Human Interaction/Assistance, Surface Mobility, Science and Perception, and Instrument Deployment/Sample Manipulation [10]. Small semi-autonomous rovers without complex control can perform surface mobility, and science and perception tasks with limited capability to perform instrument deployment and sample manipulation on Earth and less challenging environments such as Mars by using embedded digital electronic systems and mechatronics. However, a fundamental re-thinking of the approach is required for Venus due to the extreme environment the prevents these digital and mechatronic systems from being deployed without large-scale protection measures.

Due to its challenging atmosphere and surface conditions, there are a number of specific technical mission design challenges specific to remote operations on Venus:

1. Entry, Descent, and Landing (EDL). Hard landings on Venus are assumed due to the complexity of controlling a soft lander, so the resilience of the frame and components to surface impact is essential.

2. Absolute localization and communications. Exact positioning is not critical for Venus science at present but approximate localization of the rover will be needed for some data collection goals, and a data uplink is essential. There is no current solution that operates in Venus' surface conditions, but radio target reflection from orbit or high-temperature semiconductor radios may be feasible in the near future.

3. Traction and control on rock and lava. The surface condition of Venus varies from place to place as indicated in the image of landing sites [9] in Fig. 2, but most of the surface is covered in rocky volcanic plains. For a wheeled rover it is critical to keep all wheels in contact with the surface. The use of legs with microspines for traction and an articulated or flexible chassis facilitates better traction on these hard surfaces.

4. System modularity. The use of networked (and redundant) components is desirable, but must satisfy power, size, and reliability requirements. Re-use of modular components is essential in a Venus mission because of the very limited selection and capability of high temperature and pressure components for use on a rover.

5. Long-term operation. Simply surviving in the environment of Venus for more than a few hours is a significant challenge to current technologies. Rather than isolating off-the-shelf components with heavy and power-hungry thermal controls, it is expected that a small rover for longer missions will need most components to operate reliably at the harsh surface temperature and pressure of Venus.

NASA's Game Changing Development Program has produced several innovative structural concepts such as the use of tensegrity [11] and foldable [12] structures for robots that facilitate transport, landing, and exploration on harsh terrain. In addition to renewed interest in small micro-rovers for exploration in swarms with lower cost and mass than large rovers such as Curiosity, the use of "hypermobile" robots with multiple articulated segments or flexible bodies has become of interest to increase the mobility and landing robustness of small robots [13].

Kenneth Snelson is generally considered to be the first user of "floating compression" structures in sculpture and in architecture. The earliest use of the work "Tensegrity" was recorded as a portmanteau of "tensional integrity" by his professor Buckminster Fuller, who also pioneered many of the underlying structural concepts in the 1960s. Skelton has published the most authoritative papers on the analysis and modelling of tensegrity structures [14]. Dynamic tensegrity structures are frequently used as analogues of biological structures due to their inherent structural softness[15]. The chassis and arm structures were inspired by the work of Tom Flemons, who has pioneered modelling of bio-inspired tensegrity structures such as spines as well as applying tensegrity over 30 years to art and architecture [16]. Dynamic tensegrity structures are also a good platform for developing evolutionary learning [17] and morphological computation [18], and have very good properties for interaction with uncertain environments, as can now be validated in simulation.

Tensegrity structures are very well suited for hypermobile designs as they are composed of repeated structures linked by compliant tension elements and can be extended easily. This also makes them inherently modular in design, such that only a simple set of control components (for example, tension actuators) can be repeated in application to build a more complex vehicle. If tension elements are elastic to some degree, they will absorb energy from impacts and distribute it throughout the structure efficiently, creating a flexible structure that will conform and adapt to the surface it is on, in turn ensuring good contact between a mobility system and the ground. Through these features, a tensegrity rover offers a solution to challenges 1, 2, and 4 above and may facilitate solution of 5 if (high-temperature controls can be developed) through the capability to design a highly robust chassis with minimal requirements for control and actuation. Tensegrity structures also have great potential for use in space as, like trusses, they are lightweight, very robust, and can often be flat-folded and re-deploy themselves using "smart" shape memory alloys (SMAs) such as Nitinol [19].

The authors have created a platform design methodology for the creation of adaptable, modular tensegrity robots for space, named the "Aria" platform for its synergy and elegance and initially focused on a rover concept for Mars [20]. The Aria platform design is intended to provide a potential solution for mechanically and functionally customized low-cost rovers for specific missions, potentially by SMEs and universities. Having flexibility and multiple degrees of freedom in both hardware and software open up the possibility of multiple functions and capabilities for a single system design [21], such as a dual use flexible arm and observation mast. The technical goals of the Aria-Mars tensegrity platform are:

Manufacturability

- Repetition of form and minimization of number of different components
- Modularization of autonomic self-managing component design
- Simplification of construction and assembly of components

Controllability

- Actuation of multiple degrees of compliant structural freedom
- Common and asynchronous probabilistic real-time communications and programming
- Ontological identification of system resources and information

Reliability

- Simplification of moving parts, power and communications between components
- Deployability in the ability to stow compactly and self-deploy
- Physical resiliency so as to handle the stresses of transport, landing, and harsh, uncertain terrains

In this study, the tensegrity structure and fully-body mechanical control principles are adopted from the Aria-Mars platform to propose an Aria-Venus rover that is specifically designed for the high-temperature Venus environment, and radiation of heat rather than insulation. The Aria-Venus rover differs from the Aria-Mars rover designs that apply a variety of digital sub-systems for guidance, navigation and control, scientific payloads, communications, power, and mobility. The proposed Aria-Venus rover uses discrete or low-integration high-temperature electronic components where electronic control may be unavoidable (e.g. communication and sensor systems) and otherwise attempts to replace electronics with corrosion-resistant and temperature-tolerant mechanical solutions for power, mobility, and basic navigation. In between the extremes of the Venus and Mars concepts, an Aria-Asteroid rover concept is being considered for use in micro-gravity planetary bodies and an Aria-Titan rover for exploring the largest moon of Saturn. A comparison of these rover concepts is given in Table. 2 overleaf.

4 SUBSYSTEM TECHNOLOGIES

Any design for an automated and controllable Venus mission is constrained by the digital and mechatronic technologies available. As of early 2018, a complete rover cannot be built with existing production technologies mainly due to the temperature limitations of digital and mechatronic components. However, prototypes of selected components have been developed for extreme-temperature environments, many under the NASA HOTTech program specifically for use in Venus exploration [22]. These efforts indicate that while high temperature mechatronic systems are costly and constrained in function-

TABLE 2: Comparison of Aria Rover Platform Characteristics and Architectures for different missions

	Aria-Mars	Aria-Venus	Aria-Asteroid	Aria-Titan
Potential Mission Launch Date	2025	2035	2030	2040
Mass	15 kg	20 kg	30 kg	50 kg
Dimensions	80 cm x 30 cm x 28 cm	80 cm x 80 cm x 70 cm	160 cm x 160 cm x 15 cm	200 cm x 80 cm x 50 cm
Speed	0.03 m/s	0.01 m/s	0.01 m/s	0.05 m/s
Instruments	3	3	5	10
Traverse Length	1000 m	100 m	600 m	10000 m
Power Source	Solar + Batteries	Wind + Batteries	Solar + Batteries	RHU + thermopile
Thermal Control	Aerogel+heaters	Titanium shielding + radiator	Aerogel + heaters	Aerogel + RHU
Computer	UltraScale; VA10820	High-temperature logic	UltraScale; VA10820	Unknown
Wheel/Leg size	20 cm dia. wheel	20 cm dia. wheel or 15 cm legged	20 cm dia. wheel or 15cm legged	50 cm dia. wheel
Communication	To lander	To lander	To orbiter	To orbiter
Avionics Architecture	Distributed Autonomic Elements	Low-integration HT Electronics	Distributed Autonomic Elements	Unknown
Autonomy	Probabilistic planning and optimization	Reactive navigation, basic communication and measurement	Probabilistic global mapping and optimization	Fully autonomous science planning and investigation

ality, they are indeed possible with additional effort toward a future mission.

4.1 Locomotion

Research has shown the potential for wind driven robots to be used in the exploration of Mars, Titan and Venus [23]. The first Venus wind measurements were done by the Venera 9 and Venera 10 landers. Despite Venus' atmospheric super-rotation, the dense atmosphere slows surface winds such that they act more like gradual ocean currents, and the Venus surface wind speeds have been measured in the range of 0.4 m/s to 1.3 m/s and atmospheric density at the surface has been measured as 64.8 kg/m^3. The power $P=\rho A v^3$ provided by a rotor in wind is proportional to the product of air density ρ, rotor area A, and the cube of velocity v. Given that Venus has an atmosphere 55.3 times denser than Earth's (and 6.5% the density of liquid water), these relatively low wind speeds carry the power of relatively normal 1.6 m/s to 5.2 m/s winds on earth (though the fluid dynamics differ). From these estimates, the force and power produced by a given wind power structure such as a sail or rotor can be assumed comparable to that on Earth. A more detailed study of the anticipated winds on the Venusian surface, and the force required to move the rover across inclined terrain slopes and obstacles is still needed to determine the size and geometry of the wind power structure design, but it is still considered feasible for a rover on Venus to be motivated by the wind.

Land yachts use sailboat and aerospace technology to propel the craft across open desert terrain and sea. Most recently land wind sail walkers known as "Strandbeests" have been built by the Dutch artist "Theo" Jansen [24]. One of these, the "Wind beast", on Earth and the land sail "Zephyr" rover for Venus are shown in Fig. 3 .While the use of mechanically-linked Jansen legs has been proposed for Venus rover concepts, such as in [7], they do not embody another of the key features of the "Strandbeests" – the ability for the structure to bend and flex over terrain or bend with the wind as a means of power generation. This "bending" motion can be a source of power itself by creating cyclical "gust" powering of a mechanism. A final option for locomotion is for the wind to simply cause a rover with a circular profile and wind-catching vanes to roll across the terrain. The "tumbleweed" concept has also been explored for potential Mars exploration but is very limited in directional control [25].

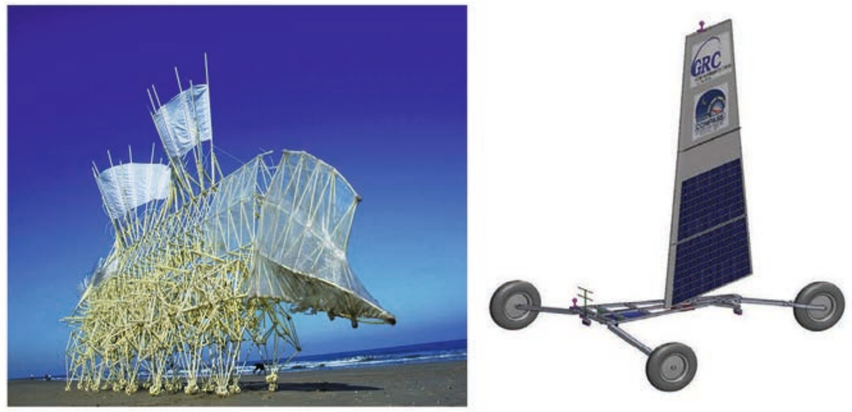

Fig.3 Wind Power Walker ("Strandbeest") [24] on Earth (left) and Wind Power Rover ("Zephyr") [6] for Venus (right).

4.2 Power Generation

Many studies have been focused on utilizing stored energy from chemicals extracted from the soil or the use of soil chemicals to produce photovoltaic power. One of the most ambitious power sources proposed for Venus is the Advanced Stirling Radioisotope Generator (ASRG) developed by the NASA Glenn Research Center. A proposed system for Venus uses the ASRG in a dual role for cooling of internal components to approximately 250°C while providing 216 W of electrical power, in an 876 kg rover at Venus surface temperature and pressure. While the capability of providing power while cooling enclosed elements is attractive, the system is complex, too large for use on a small rover, and introduces the dangers of radioisotope use to the mission.

Solar cells can also be used on Venus. The density of the atmosphere severely limits the solar spectrum that reaches the surface to the range of 0.25 $W/m^2/nm$ with a peak frequency near 650 nm. The temperature prevents most conventional cell types including Germanium cells from functioning, though triple-junction ($GaInP_2/GaAs/Ge$) cells will operate at up to 400°C, and sulfuric acid in the atmosphere will degrade solar cells over time if they are not suitably protected with glass/teflon covers. A Low Intensity High Temperature solar cell (LIHT) based on AlO_3 coated dual junction GaInP/GaAs semiconductor with band gaps optimized for the Venus surface and tolerant of 465°C temperatures is under development [26]. The atmospheric density and presence of day/night cycles on Venus limit the amount of power available from solar cells. As only ~0.65W/m^2 are available, equivalent to approximately 1% of the solar power available on Earth, a solar panel may need up to 100 times the surface area.

As wind on Venus is constant, dense, and everpresent according to current models, the use of wind for both mechanical and electrical power generation is considered to be the most practical for a small rover. Vertical axis wind turbines such as Darrieus or Savonius types are preferred so as to simplify the mechanical design and avoid the need for directional control. Savonius turbines are of particular interest as they are higher torque in low wind velocities despite having lower efficiency [27], and helical Savonius turbines follow the morphology of some kinds of tensegrity prisms. Mechanical energy storage and transmission from the turbine is feasible using Iconel springs. Electrical energy generated from a turbine could charge high-temperature battery cells with high specific energy, generally 200 Wh/kg and up. High-temperature battery chemistries include Na-S, Li-S, LiAl-FeS_2, and Na-$NiCl_2$ battery cells [22] Li-S is projected to have the highest specific density of 300 Wh/kg or more and a lifetime of 100-150 cycles. If non-rechargeable primary cells are used, Li-FePS3 or Li-CoPS3 cells are a potential solution [22]. With a high-temperature battery technology, a mission of 30 days or longer at 500°C would potentially be possible.

4.3 Mechanical Actuators

If electrical power is available, then controlled electrical actuators could potentially be used for wheeled or legged actuation. The most common robotic actuators are based on rotary motors, but the extreme temperature and pressure requires a highly specialized design. A high temperature switched-reluctance motor was developed in 2003 that can operate at up to 540°C if a suitable S-R motor controller is available [29]. More recently, a 0.8 kg motor with commutation sensing capable of operating at temperatures in excess of 460°C has been made available by Honeybee Robotics – the only commercial unit with these tolerances. To avoid the challenge of engineering even smaller actuators, the number of motors used in a rover would need to be minimized, and the use of shared mechanical power from a single source can be considered. In concert with the use of wind power, directly driving multiple actuators from a single source has the advantage that efficiency is higher than using multiple electrical actuators with the associated losses in a generator and each electronic controller, actuator, and gearbox.

Deployment and any controlled motion such as steering in the tensegrity body would also require actuators, though their duty cycle may be much lower than those used in locomotion. Actuators that can provide variable tension on the actuated tensegrity elements in the frame and the arm as well as releasing the rover for deployment can make use of high temperature shape memory alloys of Ti, Ni, and Pt [30] that change their strain characteristics above temperatures of 250°C. Using this alloy for springs and tensional elements in the tensegrity structure with mild thermal insulation within the lander would result in the body and mast structures tensioning and deploying themselves after landing as the heat of Venus' surface warms the rover. A bidirectional cobalt-iron linear actuator for high temperature applications has also been designed but not yet produced, with an 800°C tolerance and 300N force in 1mm stroke [31] that could provide a controlled alternative to shape memory alloy actuators for small linear movements.

4.4 Control Systems

Future space robotic systems will be constructed using distributed architectures with electronics capable of working in the extreme environments of other planets. These challenges are compounded by a complementary set of packaging and assembly issues that address the reliability of the system from a mechanical point of view. Relying on a centrally cooled enclosure inside a pressure vessel greatly limits the budget for mass and power of the system. Instead, new commercial electronics technologies are relied upon to provide operation at high temperatures, such as SOICMOS devices capable of operating to 250°C, and SiC and GaN devices capable of operating to 500°C [32]. Diamond-based PIN diodes and bipolar junction transistors (BJTs) that could operate with low noise above 500°C are also being investigated [22]. These devices are not yet production-ready as of this writing, but with sustained effort, discrete logic circuits complex enough to synthesize simple robot control could be available for a mission in the 2030s.

The control of a rover through purely mechanical means, in the manner of a mechanical automaton or a mechanical computer, has been proposed and investigated. It is entirely possible to build a simple mechanical computer to control the movement of a rover on Venus without the use of electricity and semiconductors [33]. However, a purely mechanical rover is not considered practical because the cost and capabilities of the automaton architecture are comparable to current high-temperature electronics technologies, and electronic components are more flexible in use [7]. The use of mechanical components as a complement to electronics, where mechanical solutions are particularly efficient or well suited to the task, appears to be a better approach. Power requirements and the chance of critical faults are reduced by having some simple tasks allocated to mechanical control. Another possibility is the use of "programmable structures" that behave in a prescribed and safe manner in given situations, for example turning when an obstacle is encountered or a slope goes beyond kinematic limits. The proposed tensegrity platform has sufficient design adaptability that "programming" the structure for a given behavior is possible, and the transmission of power and locomotion control is done mechanically for reasons of reliability and efficiency.

The primary task that cannot easily be performed by mechanical systems is high-rate communications. A key challenge for radio systems and other digital control devices in a high-temperature environment is the creation of stable clock resonators and oscillators. A wireless communication clock chip for temperatures up to 600°C is under development for radio communication uses, and a PWM IC that operates at up to 500°C has been demonstrated for power converter control [34]. A sealed prototype component package design has also been developed that is suitable for the Venus environment. GaN devices currently appear to be the most mature for high-temperature microcontroller and electronic microsystem devices [7] and continued development is expected to provide simple but feasible electronic designs for Venus missions.

4.5 Materials

Although the material choices for the tensegrity chassis and component enclosures are very flexible, care must be taken in selecting materials for a long-duration mission to Venus. Aluminum and soft metals do not retain strength at Venus' temperatures, but tool steel, titanium, and some stainless steel alloys maintain their properties well above 500°C. Iconel alloys and other exotic materials are also capable of tolerating well above 1000°C. These materials are typically much heavier than the aluminum and light materials used in other Aria rover platform variants. However, the tensegrity chassis concept remains some 20%-30% lighter than solid designs using the same types of materials and would still be lighter than solid body designs for the degree of function and resilience achieved.

5 TENSEGRITY ROVER CONCEPTS

A great variety of tensegrity structural designs have yet to be explored for their value in robotics. Most tensegrity robot designs are based on the properties of geometric primitives [11] or structures in nature [35]. The Aria rover platform concepts described here are based primarily on a previous study of the use of tensegrity structures for flexible mobile robots [36] and the biotensegrity structures designed by Tom Flemons [37].

5.1 Tensegrity and Structural Programmability

The tetrahedral complex spine was selected as the most promising structural basis for adaptable wheeled tensegrity mobile robots. The first wheeled tensegrity planetary rover prototype – the Aria-Mars platform – places the electronics in modular 10 cm cubes and connects them through a tetrahedral spine structure to achieve full-body flexibility. Control of body movement is achieved using independent twisted-string tension actuators controlling the lengths of the longitudinal tension members [38]. Front and rear drive wheels are placed on "floating" tensegrity axles while mid-structure wheels are attached to electronics modules. This prototype is shown in Fig. 4.

Testing of this Aria-Mars prototype illustrates the desirable properties of a tensegrity structure on complex terrain. The multi-segmented flexible spine structure allows all wheels to maintain relatively consistent contact with the ground over large variations in surface height, as shown in Fig. 5. This is a property of hypermobile rovers, and as more segments are added to the structure, the same wheel surface area per segment will maintain contact with the ground, making wheeled tensegrity rovers very scaleable without traction performance penalties.

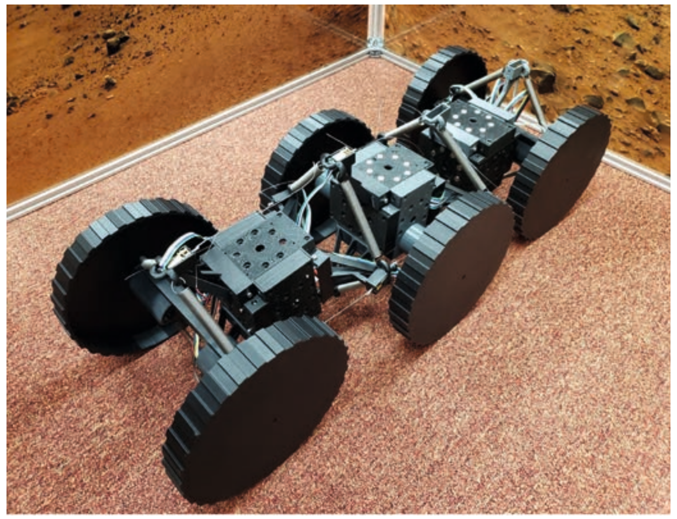

Fig.4 Planetary Aria-Mars Rover prototype using tetrahedral complex spine tensegrity structure.

Another key property of tensegrity structures is their "programmability" to perform differently based on the large number of degrees of freedom available by varying tension and compression elements in the structure. This can be done by making elements out of "smart" materials that change properties based on environmental and kinematic changes, or by directly changing the structure using controlled actuators. The tetrahedral complex spine structure can be made more rigid by increasing the tension in the longitudinal actuators and spring elements. Fig. 6 shows how the rover is affected by a slope, causing it to turn itself without control input if elements are compliant and to continue straight if elements are stiffened by increasing tension. Designing structures that respond in a "programmable" manner to factors in the environment such as obstacles, slopes, and different kinds of terrain can form the basis of a navigation and control system that is mechanically implicit within the design of a rover and does not require complex path-finding and sensory response algorithms.

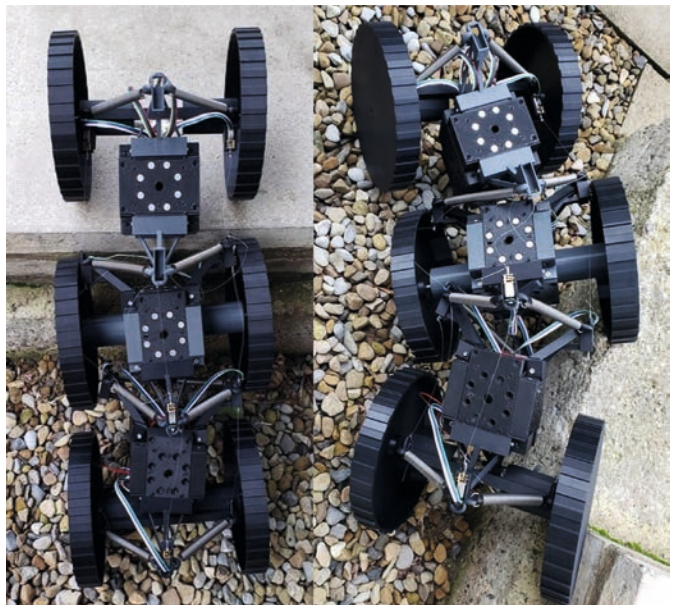

Fig.5 Tensegrity Structure: Illustration of the advantages of hypermobility. The structure keeps all wheels on the ground over complex terrain.

Fig.6 Tensegrity Structure: Example of Structural Programmability. The degree of turning on a slope is determined by varying the stiffness of the tensile elements from compliant (left) to rigid (right).

5.2 Aria-Venus Locomotion and Power Concepts

Many locomotion modes have been investigated for exploring the land surfaces of the Moon, Venus, Mars, Mercury, Phobos, comets, and near-earth asteroids [39]. Tracked rovers, legged rovers [40], track-legged rovers, and wheel-legged rovers have all been studied extensively by the robotics community. "Tumbleweed" rovers shaped like a ball or a sphere and hoppers have also been proposed [25]. Aerial and submarine locomotion modes have also been investigated by the robotics community, with the intent to one day explore the gas giants, the ice giants, the dense atmospheres of Venus and Titan, the subsurface oceans of Europa and Enceladus, and the lakes, seas, and rivers of liquid hydrocarbon of Titan. The proposed solutions are extremely imaginative and include a variety of balloons, airships, helicopters, ornithopters, airplanes, gliders and others [41].

By virtue of their tensegrity structure, the Aria platform vehicles can embody many different forms of locomotion, and several concepts have been developed based on study of Venus' challenging environment. The simplest initial concept for a surface vehicle followed a "tumbleweed" philosophy in which the wind would roll a rover with approximately circular cross-section across the surface of the planet. The tensegrity structure employed for this concept is the spiral vertebral mast [37] which remains approximately circular when tensed and can integrate large deployable vanes to catch the low-velocity wind in a single direction of movement, collapsing under the rover as it rolls. Fig. 7 shows a potential structural design for this vehicle. The tensegrity structure allows it to bend freely and collapse to approximately 20% of its original size (with the exception of any mechanics or electronics in the core of the structure) before deployment. As the spiral vertebral mast can be bent by adjusting the tension along three primary spiralling axes of the structure, the rolling direction can be "steered" in a limited fashion using actuators or SMAs that change in length or rigidity. However, directional control is extremely limited as locomotion is entirely dependent on wind direction, and there is very limited terrain obstacle tolerance of less than half the structure's height. It is very likely to be caught on small obstacles, and this kind of rover is therefore only suited to traverse relatively flat plains and lowlands on Venus.

The surface of Venus is mostly rocky surfaces in the form

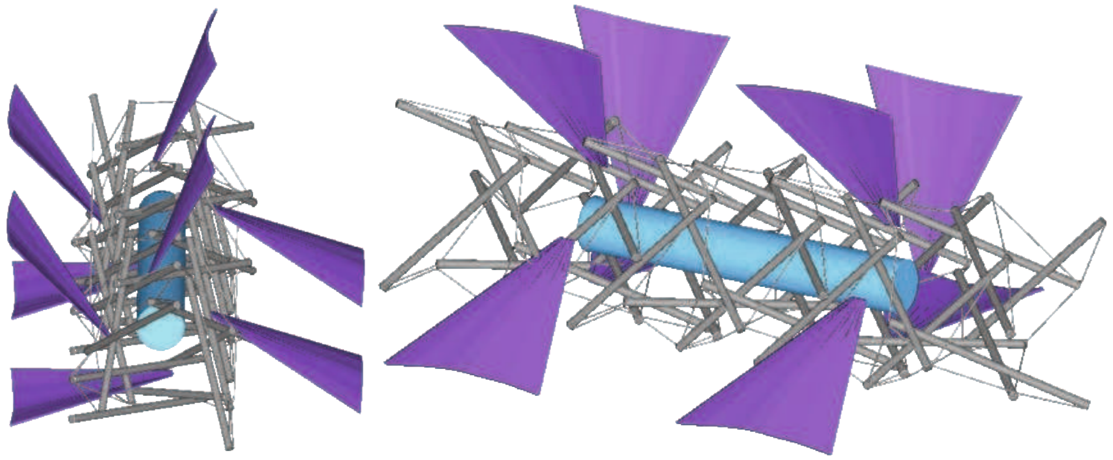

Fig.7 Structure of rolling "tumbleweed" Aria-Venus rover concept.

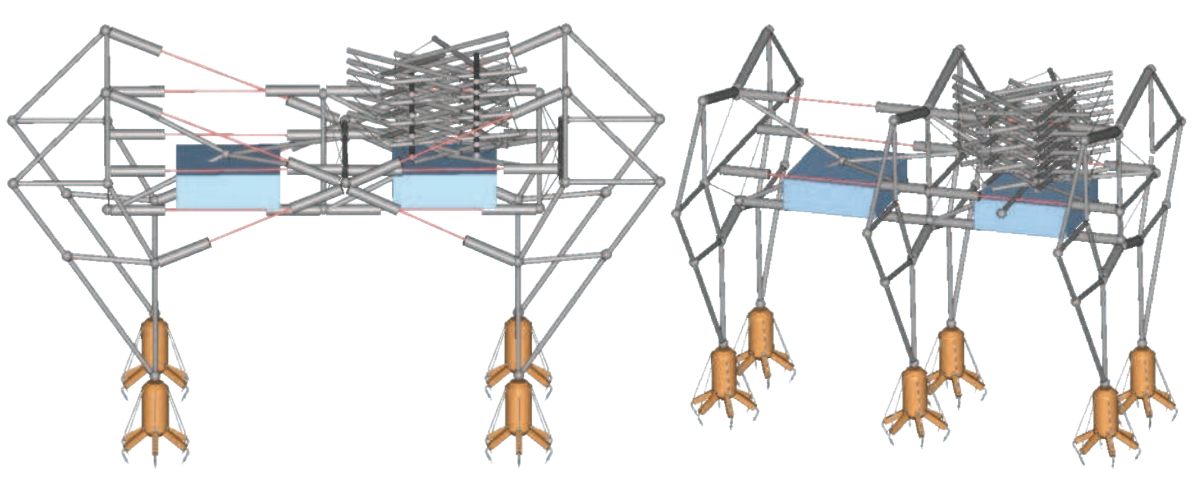

Fig.8 Structures of longitudinal (left) and transverse (right) walking Aria-Venus rover concepts.

of flat planes interspersed by volcanic slopes, and many of the most interesting geological science targets are identified by being on slopes or unique surface features. Wheeled rovers are simpler in mechanical design, and a wheeled Aria-Venus rover similar to the Aria-Mars prototype is feasible for further development. However, much better traction and traversability for sloped and uneven rocky areas is possible through hooking or catching of a locomotion system on rough and irregular edges or tiny holes and asperities characteristic of igneous rocks. The use of legs with microspine grippers [42] for traction and an articulated or flexible chassis facilitates better traction on these hard surfaces, and concept development of the Aria-Venus rover is directed to explore these possibilities.

The initial concept for a walking tensegrity rover uses longitudinal movement based on Jansen legs and individual linear actuators. The Jansen leg, while usually actuated by a rotary crank, can also be controlled similarly to a tension-actuated tensegrity structure for increased detail of movement. However, considering the technological challenges of powering and controlling actuators on Venus and taking the kinematics of a tetrahedral complex spine chassis into account, a crank-operated transverse walking configuration was chosen instead for higher stability and to facilitate mechanical power transmission. Both concepts are shown in Fig. 8.

Based on the use of wind power for locomotion of the rover and the need for correspondingly higher stability and horizontal size, the chassis was widened by linking two parallel tetrahedral spines to become the Aria-Venus concept shown in Fig. 9. One form of wind power can be harnessed by using alternating wind gusts to drive unidirectional rotating movement, and this concept includes two sails on spiral vertebral masts in different directions that drive rotational movement as they are cyclically bent by the wind. This “gust-powered” movement in turn drives the Jansen legs through transmission shafts. While feasible, the amount of energy generated is expected to be lower and less consistent on Venus than an omnidirectional turbine.

The most successful and current concept for the Aria-Venus rover uses a Savonius wind turbine for power as shown in Fig. 10. In the manner of a tensegrity prism, a helical turbine with flexible surfaces can fold and deploy as the rest of the tensegrity structure does so, and this is mounted on the top of a spiral vertebral mast to catch higher winds. The turbine provides mechanical rotation that can also generate a small amount of electrical power for electronic subsystems and is transmitted through mechanical gearboxes and by shafts made of high temperature super-elastic SMA that also fold within the structure before deployment. When folded for transit to the surface, this structure can shrink to approximately 80% of its length and width (constrained by the tetrahedral spine elements and enclosures for electronics and instruments) and 20% of its height. The structure with turbine, drivetrain, and legs is deployed automatically by SMA actuators when exposed to the temperatures of the Venus surface for a length of time. The microspine grippers are also sprung using SMA wires to grip surface asperities when the crank-driven Jansen legs are lowered during walking motions.

A conceptual support system for a group of of Aria-Venus rovers is shown in Fig. 11. It is considered very likely that communication through the thick atmosphere of Venus from small rover will not be possible with the limited electronics available. However, one alternate option is the use of a heavy, environmentally isolated lander module that serves as a relay point to an orbiter and a deployment point for rovers.

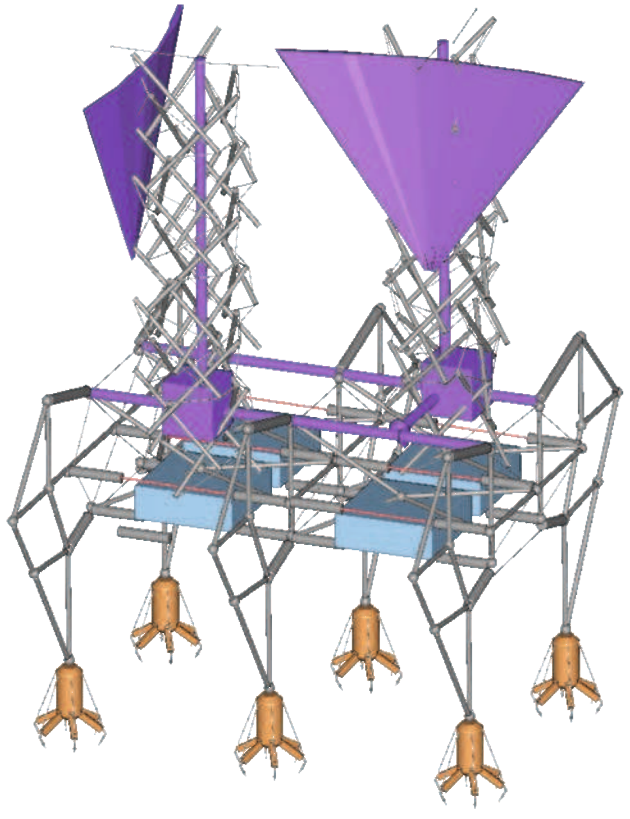

Fig.9 Structure for Aria-Venus gust-powered transverse walking rover concept.

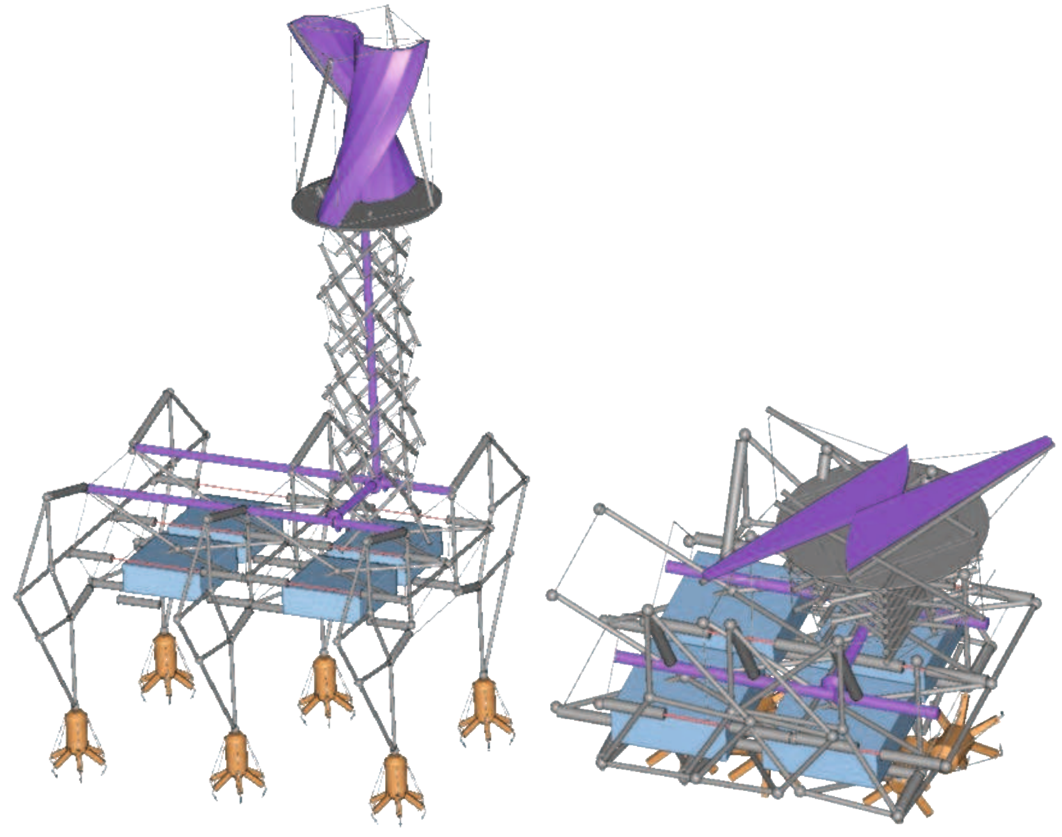

Fig.10 Current Aria-Venus Savonius wind turbine powered rover concept fully deployed (left) and in collapsed form for transit before deployment (right).

6 CONCLUSIONS

In this paper, the authors have proposed a novel conceptual direction for small planetary rovers that could explore the surface of Venus and other extreme environments. By applying innovative technologies such as a flexible and adaptive tensegrity structure, deployable wind power capture, smart materials, and minimal high-temperature technologies, it is believed that exploration of the Venus surface may be feasible using small, lightweight rovers with lower cost and complexity than previous landers. Although there are still technical challenges to be overcome, primarily in the areas of control and communications, the more important message is that they can certainly be overcome in the near future with sustained effort. Rethinking the technical approach to Venus surface exploration could lead to a viable mission in the time scale of a decade. The technology to create environmentally tolerant tensegrity structures and mechanisms is currently available, and early prototypes of high-temperature semiconductor technology are approaching industrial viability. The proposed rover concept would have the capability to operate as a short-distance walker to traverse rough, rocky terrain, and the authors believe such a rover could be fielded to benefit a future Venus lander mission.

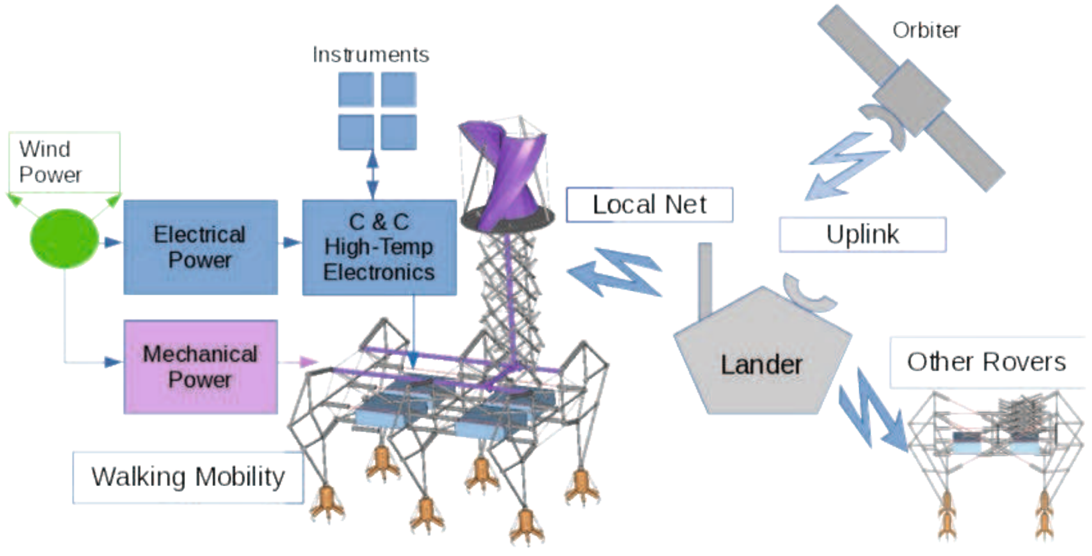

Fig.11 Aria-Venus Rover System Framework.

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