An Automaton Rover Enabling Long Duration In-Situ Science in Extreme Environments

Jonathan Sauder
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-3331
Jonathan.Sauder@jpl.nasa.gov

Evan Hilgemann
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Evan.W.Hilgemann@jpl.nasa.gov

Bernard Bienstock
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Bernard.Bienstock@jpl.nasa.gov

Aaron Parness
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Aaron.Parness@jpl.nasa.gov

Abstract— **The Automaton Rover for Extreme Environments (AREE) is a NASA Innovative Advanced Concept (NIAC) funded study focused on enabling long duration science on Venus by replacing vulnerable electronics with an entirely mechanical design. By utilizing high temperature alloys, the rover would survive on the surface of Venus for weeks if not months. The rover concept harvests wind energy using a turbine and stores it in a constant force spring. The mobility system would be guided by a mechanical computer and logic system, programed to carry out the mission. It would collect basic science data such as wind speed, temperature, and seismic events. Communicating the data back to Earth is the most challenging aspect of the system design with multiple options being explored in a trade: a simple electronic high temperature transponder, a retroreflector target or inscribing phonograph style records to be launched via a balloon to a high altitude drone capable of transmitting the data back to Earth. AREE is not only a new exciting in-situ rover concept, but also a paradigm shift to conducting in-situ science in extreme environments. Traditional extreme environment vehicles collect as many diverse data points as possible in the short period of time before system failure. AREE breaks that trend by exploring what can be done with only a few basic scientific measurements, but recorded over long periods of time. In addition to Venus, the concept can be useful in other extreme environments in the solar system including Mercury, Jupiter's radiation belts, the interiors of gas giants, the mantle of the Earth and volcanoes throughout the solar system.**

TABLE OF CONTENTS

1. INTRODUCTION

Venus is one of the most hostile environments in the solar system with a surface temperature that will melt solder, a pressure high enough to collapse the hull of modern nuclear attack submarines, and a sulfuric acid atmosphere. Human-made probes used to investigate the surface have extremely limited life times. Thus far, the longest any lander has operated before electronics failure is just two hours. While this record was set by the Venera lander in 1982, modern flagship mission concepts are only able to improve survival time to 24 hours. Radioisotope powered cooling engines may be able to extend life longer, but these are still under development and may be prohibitively expensive [1]. Therefore, long duration science on the surface of Venus is impossible to perform with existing space technology.

Figure 1: Automaton Rover Concept

Applying ancient technology to spacecraft may provide the solution. Over 2,200 years ago the ancient Greeks built the Antikythera mechanical computer (Figure 2 [2]). This purely mechanized device accurately predicted past and future astronomical events long before electronics existed [3]. But what is perhaps more inspiring than this ancient innovation, is the idea that the Antikythera mechanism could continue to unlock the secrets of the solar system for us today. Related to such computers, automata are purely mechanical, self-operating machines capable of performing sequences of operations and instructions. They have been credibly used for hundreds of years as computers, art pieces, and clocks. However, in the past several decades automata have become less popular as the capabilities of electronics increased, leaving them an unexplored solution for robotic spacecraft. Such mechanical devices could be the answer to achieve this long duration data from extreme environments, such as Venus.

Figure 2: The Antikythera Mechanism, a 2,300 year old mechanical computer.

2. BACKGROUND

The Challenge of Extreme Environments

There are many extreme environments throughout the solar system; the radiation around Jupiter, hot thermal temperatures on Mercury and Venus, and hot high pressure environments occurring deep beneath any planet's surface. Generally, the most environmentally sensitive components of any rover or spacecraft are the electronics, which will fail in heat, stop operating in extreme cold, or experience upsets when bombarded with radiation. As an example, only a handful of Soviet Venera/Vega landers and a couple probes from Pioneer have reached the surface of Venus. Even these robust probes survived for only 23 to 127 minutes before the electronics succumbed to the extreme environment [4]. Adding protection systems is the general approach to improve the survival of electronics, but these increase costs and only delay inevitable failures. An analysis of a modern flagship Venus mission concept costing $2-3 billion found a liquid gas cooling system to be the most practical approach, despite only ensuring survivability on the surface for less than one day before system failure [5]. While research exploring active cooling systems for Venus exists, it is still in technology development, would add great complexity, and could not operate in other extreme environments with higher temperatures or radiation [1]. This means it is currently impossible to collect in situ longitudinal science data from the most extreme environments in the solar system; data which is critical for informing models of dynamic planetary systems.

History of Automata and Mechanical Computers

Automata have been used to perform complex calculations, draw intricate pictures, play music, shoot an arrow at a target and much more [6], [7]. In general automata can be put into two categories: mechanical computers, which process human and environmental inputs, and semi-autonomous machines, which perform a detailed series of pre-decided actions using stored energy.

Mechanical computers, like the aforementioned Antikythera, are designed to provide a specific output from a series of inputs [3]. Development of mechanical computers greatly expanded in the early 1900's and were at their zenith by the 1940s. During this period mechanical computers advanced from solving simple arithmetic problems to guiding bomb trajectories and aiming battleship guns, all while accounting weather and atmospheric conditions [8]. Even more fascinating was the Globus mechanical computer, an automaton which provided spacecraft trajectory data used on every Soviet launch until 2002 [9]. However, mechanical computers are more commonplace than these extremely complex mechanisms. Perhaps the simplest, but most widely used, mechanical computer are watches and clocks. The oldest mechanical clock has operated for 700 years [10] and mechanical watches have operated for decades without maintenance. Amazingly, many of these devices were built decades to centuries ago without advanced manufacturing technology. With modern advances, projects like the 10,000 year clock, designed to run for 10 millennium with no maintenance, are possible [11].

Figure 3: Strandbeest designed to be self-sustaining mechanical creatures

A number of the most famous and intricate automata were semi-autonomous and designed to replicate human or animal traits. While the most basic draw a picture, play a musical instrument, or appear to digest food, others take on a much more detailed humanoid form by simulating intricate motions like breathing, or following the actions of their hands with their eyes. Some of the most complex automata even had the ability to be re-programmed. While the construction of semi-autonomous automata declined in the 1900's, the Dutch artist Theo Jansen has recently revived the automata. His massive "Strandbeest" creatures (Figure 3 [12]) are constructed of plastic tubes and canvas, powered by wind, and walk across the beaches of the Netherlands. They have the ability to respond to the environment, staking themselves to the ground if wind speeds get to high, or reversing directions when they walk into the water, with an ultimate goal of existing entirely autonomously [13]. These sophisticated modern automata provided the inspiration for AREE.

A Paradigm Shift

One of the core measures of value for a science mission is the amount of data the mission is able to return to earth. High performance electronics have enabled missions to maximize this parameter. However, electronics are short-lived in extreme environments, thus making it impossible to collect longitudinal data regardless of how highly instrumented the mission is. Current missions to Venus focus on packing a temperature controlled volume with as many electronic instruments as possible to maximize the science return of the short mission. We are proposing a paradigm shift by replacing electronic components with ingenious mechanical devices to enable attaining long term data from extreme environments. This work seeks to combine the best of mechanical computers and semi-autonomous automata to produce an entirely autonomous extreme environment planetary surface explorer.

3. Systems Concept for an Automaton Rover

The proposed automaton consists of several key subsystems, including energy collection and storage, mobility, computing and control, communications and instruments. A depiction of a potential systems level flow chart is shown in Figure 4, with all the major components identified.

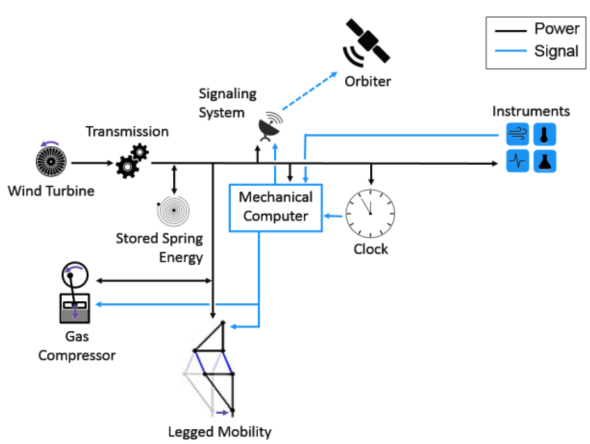


Figure 4: System flow chart

Energy Collection and Storage

In a traditional spacecraft, electrical energy is harvested using solar panels or an RTG, stored in batteries, and later converted to mechanical energy as needed. For an automaton rover on Venus, utilizing wind energy is the most practical. Wind speeds on the surface of Venus vary from 0.3-1.3 m/s (v) with an average at 0.6 m/s, well below the operating speed of most existing wind turbines. However, the atmospheric density of 65 kg/m^3 (ρ) is significantly higher than that on earth and therefore provides more energy [14]. The total energy that can be harvested from the wind is given by Equation 1.

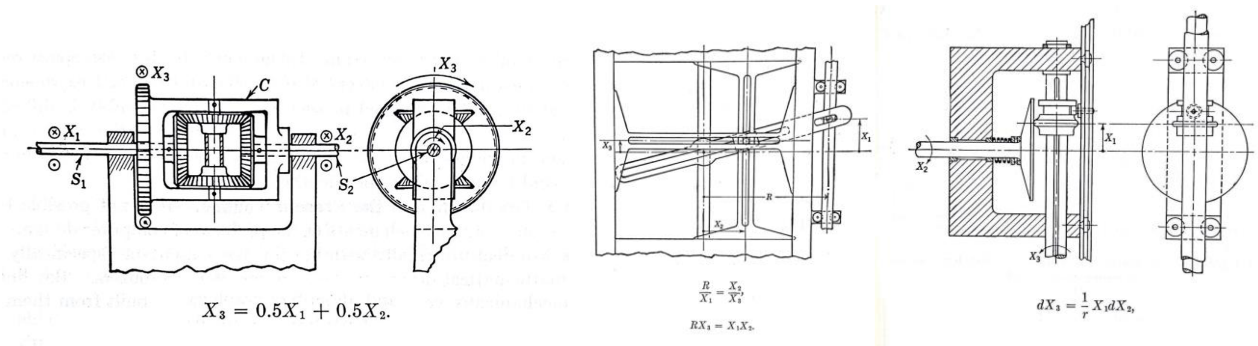
$$P_{wind} = 0.5A\eta\rho v^3 \quad (1)$$

Assuming a wind turbine diameter of 1.5 meters (A = 1.8m^2), an efficiency of 50% (η) the turbine can collect 14 W under average wind conditions and up to 141 W at peak wind speeds. Honeywell's Windtronic wind turbine was designed to operate at low speeds, claiming a cut-in speed of 0.2 m/sec and an average efficiency of 56% [15, p. 6]. Therefore, it is reasonable to expect a wind turbine with 50% efficiency could be developed for Venus. As a comparison, the Sojourner rover was only able to collect 16 W of power on peak [16], and Spirit and Opportunity only generated 140 W (gradually dropping to about 90 W after 90 days due to dust) [17]. While wind power on Venus would not provide large amounts of power, it would be adequate for rover operation.

Energy collected through the wind turbine would then go through a transmission to increase the amount of torque. This energy could then be distributed throughout the rest of the rover. Energy not immediately needed would be stored in clock springs. The clock springs would be designed such that energy could be drawn by the system and gained from the turbine at the same time. Further, some additional energy could be used to run a gas compressor, which would compress Venus atmosphere for later use in in signaling and pneumatic computers.

Mobility System

The mobility system is responsible for the physical movement of the automaton. Multiple solutions are being considered. The simplest approach is to utilize a wheeled system which aligns with the heritage of planetary rovers. Alternatively, a track system could be used and may provide greater stability. However, both the wheels and the track system have challenges with transferring energy from the rover body to the driving wheels, while maintaining a good seal against Venus dust. Another compelling option is the "walking" Jansen mechanism [13], as the legged devices would keep the area contact the surface well below the rover (no chance of kicking up dust on itself), while the drive shaft could stay within the rover, with no direct rotational connection that could carry dust upwards. To make the legs even more robust against wear caused by dust contamination, compliant mechanisms can be used as joints only require a limited range of motion. However, the legged mobility would



(a) **(b)** **(c)**

Figure 5: Examples of mechanical analog mechanisms: (a) adder, (b) multiplier, (c) integrator.

have greater limitations with regards ability to handle hazardous terrain. The mobility trade is still being explored.

Computing and Control System

The control system is responsible for determining the motion and actions of the automaton. A combination of two different control types, mechanical computing and reactive mechanisms, will be utilized.

Traditional models of robotic intelligence rely on a centralized processor to manage high level decision making. The processor functions by taking in sensor information which deliver a symbolic representation of the world. The processor then directs the robot based on the programmed instructions. This works well when ample processor space and an adequate sensor suites are available. Neither are the case with AREE. Fortunately, alternative schemes have been developed. The most relevant model may be the subsumption architecture which completely eliminates the need for a central processor. The decision making process is broken down into layers with each layer responsible for a simple action. Although each layer may seem trivial, they can be stacked in such a way that the resulting behavior is surprisingly complex [14]. This mentality must be used when designing a control system for AREE to reduce complexity and the overhead on a limited processing system.

The first way to approach computing is with traditional logic gates, for which mechanical analogs exist. For example, a mechanical OR gate is depicted in Figure 6. One could go about replicating electronic computer circuits this way, however, this method would result in an exceptionally complex system.

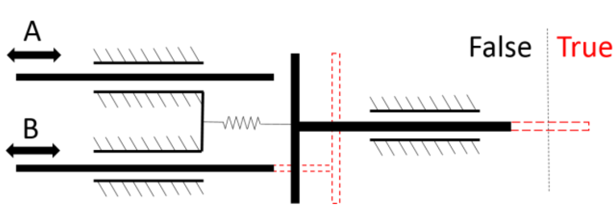


Figure 6: Mechanical OR gate

A more general approach to binary logic is digital computing. This refers to any computing system that uses discrete points as inputs as opposed to continuous variability. Excellent examples include early attempts to mechanize calculations, such as the Babbage Engine [18]. All digital mechanical computers share similar characteristics. They are generally large, mechanically complex, and unwieldy, but are more exact and can solve more generalized problems than alternatives.

Analog computers, on the other hand, can be made more compact, have fewer parts, and operate more quickly than digital counterparts. They were also a subject of significant study during World War II, and were implemented on a large scale as fire control computers for ships and airplanes [8]. Therefore, there is a large body of technical work relating to analog computing. Examples of analog computing mechanisms are shown in Figure 5 [19].

Clever reactive mechanisms will also be utilized to automatically compensate for the terrain and obstacles. An example of a reactive mechanism is the rocker-bogie system already employed on the Mars rovers. This system maintains vehicle stability over a wide range of terrain without any computer input. A similar mentality of using clever mechanism design to avoid computational complexity could be expanded to other mobility subsystems such as obstacle or steep slope avoidance.

Lastly, pneumatic controls have been used in industrial applications for decades and more recently, small micro-fluidic devices have been built with impressive capabilities, such as the 12 bit processor described in [20]. These devices are compelling as they are compact and well understood, but would naturally require the added complexity of implementing a fluidics system on AREE.

Manufacturing Considerations

While traditionally mechanical computers are considered large and bulky, the systems could be miniaturized by utilizing modern manufacturing technologies such as 3D printing and MEMS manufacturing methods. Micro-mechanical devices are already used commonly available sensors such as gyroscopes and accelerometers. Notably, Sandia National Laboratories has demonstrated an ability to create more complex mechanisms, such as drive trains, on a micro level [21]. Using these already existing technologies as a guide, it is reasonable that one could make a single computing element in volume of around 50x50x15μm. Extrapolating this value, 100 million logic gates would fit within a volume the size of $0.16m^2$ (a plate 0.4m x 0.4m). If each logic gate represented one bit, each 0.4m x 0.4m plate would hold 8 megabytes of information. While this is low by modern standards, early rovers had under 1 megabyte of storage [16]. However, there would still be significant challenges to be overcome relating to frictional effects in the system.

Signaling

Perhaps the most challenging aspect of an automaton spacecraft is how to record and transmit data. Traditional spacecraft use a high power radio and large antenna. The communication challenge is readily solvable by laser retroreflectors for the case where the automaton is visible from a vehicle placed outside the extreme environment (e.g. Mercury), potentially in orbit. Similar schemes have been credibly proposed prior to widespread use of wireless communications. Robert Goddard suggested that the first automated lander on the moon ignite flash powder to signal a successful landing. Similarly, the British Interplanetary Society suggested using flashing lights to communicate with humans on the moon [22]. More recently, MIT roboticist Rodney Brooks suggested that a swarm of micro-robots be equipped with tiny comer reflectors that could be rotated or uncovered to signal to an orbiter that is scanning the surface with a laser [23].

However the system becomes much more complex on Venus, because of the thick, dense atmosphere. Several solutions are currently under consideration, and trades are being explored.

An indicator could be mounted with radar target retroreflector (essentially a passive antenna) operating on a frequency able to penetrate the atmosphere. These radar retroreflectors are often used on sailboats to make them visible to larger ships. Communication could be accomplished with a simple binary on/off shutter, but a more effective communication approach would be achieved by using a dial with 16 positions, each indicating a hexadecimal bit, improving the data rate by four times. A radar instrument in orbit or a high altitude drone would distinguish the position of the antennas relative to each other to detect the information and relay it back to Earth. As the rover would be unable to track the orbiting craft, it would have to be designed to continuously transmit a message.

Another viable alternative would be a hybrid automaton that uses specialized electronics for communication and mechanical systems for all other components. Vacuum tubes are able to survive much higher temperatures than their semi-conductor successors. Therefore, it is possible to build a simple data recorder and radio transceiver based on vacuum tubes that could operate in the Venusian environment. However, given their large size, it would be undesirable to replace all the mechanical logic components with vacuum tubes. Recent research in silicon carbide and carbon nanotube electronics may provide solutions for miniaturized high temperature electronics for these specialized systems [24], [25].

Or finally, the most extreme but perhaps most interesting concept would be to engrave the data on phonograph style records. The data could then be carried by balloons into the relatively calm upper atmosphere of Venus where it is retrieved and processed by an aerial drone. Instead of records, the automaton could also send surface samples to the drone. This idea is within the realm of feasibility as Venus balloons have been studied extensively in the past [4], [5], [26], were used on two Vega missions [27], and drone technology on earth (which has extremely similar conditions as high Venusian altitudes) is highly sophisticated [28], [29].

Instruments

AREE can make measurements of anything that manifests itself by a change in displacement which can be read or recorded mechanically. The most obvious data to record is basic weather data such as wind speed, temperature and temperature. Wind speed data can be collected by measuring the speed of the rotating wind turbine. Temperature can be measured by the displacement of material due to thermal expansion. Pressure can be measured by measuring the expansion and contraction of a control volume as the pressure outside varies.

However, while basic weather measurements are important, they are not sufficient to warrant the cost of the mission. Perhaps the most significant measurement that can be made is seismic activity. A cantilevered mass will vibrate with seismic disturbances, and if mechanically amplified, will produce a measurement. The measurements of seismic activity perfectly fit a long duration mission, as it is unlikely a 24 hour mission would provide valuable seismic science data. However, a mission that could operate for 3 months would operate long enough to obtain a statistically significant data set.

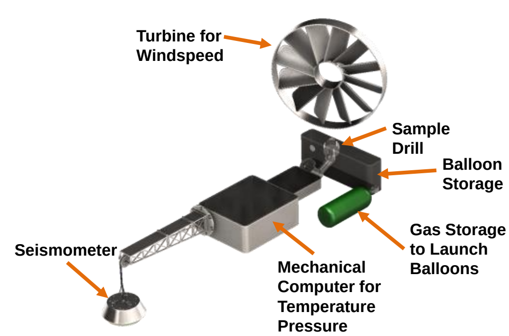


Figure 7: Instruments integrated into the rover

In addition to these simple measurements, there are a few additional complex science measurements which could be made mechanically. Chemical composition measurements could occur by having rods the react to certain desired chemicals. If the rods had a load applied, chemical concentration could be measured by observing how long it takes the rod to break. Higher chemical concentrations would cause the rods to lose strength more quickly. Another potential science target is sample analysis. While the automaton rover would not have the means to fully analyze a sample, it could move around on the surface of Venus, collect samples, and then return them via balloon to a solar powered high altitude drone. This drone, operating in the lower temperature upper atmosphere would have electronic systems to perform the usual sample analysis. Figure 7 depicts an overview of sensor systems on the rover.

Supporting Architecture

The supporting architecture components for an automaton rover would be similar to previously proposed systems. A satellite would be required for telecommunications relay, and depending on the communications approach, possibly a high altitude solar powered drone similar to Helios [29] or Aquila [28]. EDL for the rover has already been developed for prior Venus studies on payloads up to 700kg using a heatshield, drogue chute, and parachute [5] and landings were demonstrated by the Vega/Venera missions [30]. From these previous studies, 700kg will be used as a maximum mass for the rover. Other options for the mission architecture, such as using multiple smaller rovers or a small rover in conjunction with a flagship mission will be explored.

Materials

Spending a significant amount of time on the surface of Venus presents interesting material science problems, however, none that are insurmountable. All materials on the automaton must survive for months exposed to temperatures in excess of 450°C and the high atmospheric pressure. This field is quite mature due to industry applications in the areas of oil drilling, power generation, and engine design. For example Figure 8 shows various materials' yield strength performance vs. temperature. While aluminum performs poorly, stainless steels performs extremely well, and titanium performs adequately [31]–[33]. Beyond common metals,

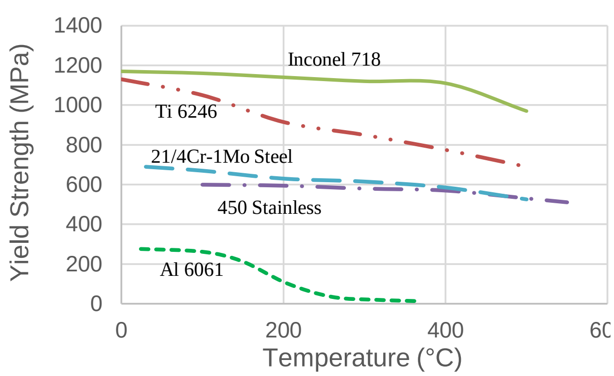


Figure 8: Material strength degradation as a function of temperature.

there are a number of specialized alloys which work well at high temperatures including Inconel 625, Haynes R-41, and Aktiebolag 253 [34]. Industry also has a number of solutions for high temperature lubricants. To avoid mechanism binding due to thermal expansion, the automaton's mechanisms will be designed to only engage under high temperatures. As the temperature on Venus only varies slightly between day and night, little additional expansion or contraction will occur after the baseline thermal expansion has been accommodated. However, considerations for material corrosion and welding through work at high temperature still require consideration.

4. OTHER ARCHITECTURES AND TARGETS

Alternative Implementation Architectures

The rover discussed thus far is an example of a "flagship rover" where one fully mechanical rover is the primary focus of the mission. However, multiple other architectures are being considered. The complexity of the rover could be decreased if it was allowed to drift in the wind in a similar manner to previously proposed "tumbleweed" rovers [35].

To make the automaton even simpler, mobility could be dropped altogether. This would result in a fixed weather station that could still accomplish the major science goals like weather and seismic activity. More computational power required for mobility control could instead be put towards storing, processing, and transmitting science data. Further, a series of weather stations would be even more effective.

Instead of being an independent mission, the automaton could also work in coordination with an existing mission. For example, it could augment a traditional short lived lander mission by continuing to operate for months after the primary mission had died.

A particularly attractive architecture to fly as a secondary payload on a traditional lander would be to reduce the system to a simple weather station by combining the signaling system and instrument into one part. Examples of such a system could be a retro-reflector which is covered with a wind turbine. As the wind turbine would blow, the retro-reflector would flash with regards to the wind speed. Another variant measuring temperature could consist of two retro-reflectors, joined by a material that expands significantly with the coefficient of thermal expansion. The distance between these two retroreflectors could then be measured to obtain temperature.

Other Targets in the Solar System

Beyond Venus, there are many other extreme environment targets suitable for an automaton rover. The most obvious would be Mercury, which has similar temperature extremes to Venus. Jupiter and the Jovian moons (like Europa and Io) would also be good targets due to the high radiation doses in the system which quickly upset traditional electronic systems. Also, another potential application would be gas giant probes, for Jupiter, Saturn, Venus, and Neptune. Such a probe could potentially descend to a point where it was buoyant, and then carry out a mission at that altitude.

An automaton rover could be subjected to much higher contamination control procedures than traditional rovers. It could be baked at extremely high temperatures, irradiated, and subjected to multiple chemical baths to kill any bacteria. Thus, automatons would be valuable in highly contamination control sensitive environments, like collecting samples from the dark, water streaks on Mars. In this type of situation, the automaton would likely be working in tandem with a traditional Mars rover.

Closer to home, automatons could be used in observations of lava flows and volcanos, or in radioactive environments. Such a device would not be sensitive to electro-magnetic pulses or nuclear detonations.

5. Conclusion

Instead of operating for just hours on the surface Venus, an Automaton Rover for Extreme Environments would continue operating for weeks or months, enabling longitudinal data collection. While high fidelity short term data is important, there is currently no way to obtain longitudinal measurements in the most extreme environments, critical for informing dynamic models of solar system formation. Further, some data, like seismic activity, can only be taken over long periods of time. AREE could take these critical long duration science requirements.

It is exciting to consider how a technology originally developed millennia ago, and often times pursued only as an art form stands to unlock the secrets of space guarded by extreme environments.

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

The authors thank the following individuals for contributions to this study: At the Jet Propulsion Laboratory: Jeff Hall, Scott Hensley, Simone Tanelli, Mike Pauken, Bruce Banerdt, Rosaly Lopes, Laura Kerber, Ofir Atia, Lori Nishikawa, James Cutts, Brian Wilcox, Arbi Karepetian, Brett Kennedy, Kim Aaron, Douglas Hofmann, Jessie Kawata, Kevin Baines, Sue Schmekar, Yuki Maruyama, and Katie Stack
Elswhere: Theo Jansen (Strandbeest), Kyle Colton (Planet Labs), Nathanael Miller (LaRC), Charlie Manion (Oregon State)

References

[1] R. Dyson, B. Penswick, P. Schmitz, and G. Bruder, “Long-Lived Venus Lander Conceptual Design: How to Keep It Cool,” in *7th International Energy Conversion Engineering Conference*, American Institute of Aeronautics and Astronautics.

[2] “NAMA_Machine_d’Anticythère.” [Online]. Available: https://upload.wikimedia.org/wikipedia/commons/6/66/NAMA_Machine_d%27Anticyth%C3%A8re_1.jpg. [Accessed: 09-Oct-2016].

[3] T. Freeth *et al.*, “Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism,” *Nature*, vol. 444, no. 7119, pp. 587–591, Nov. 2006.

[4] A. Bachelder *et al.*, “Venus Geoscience Aerobot Study (VEGAS),” in *International Balloon Technology Conference*, American Institute of Aeronautics and Astronautics.

[5] J. L. Hall, M. Bullock, D. A. Senske, J. A. Cutts, and R. Grammie, “Venus flagship mission study: Report of the Venus science and technology definition team,” *Natl. Aeronaut. Space Adm. Jet Propuls. Lab. Calif. Inst. Technol. Task Order NM0710851*, 2009.

[6] R. Lammle, “8 Amazing Automatons & the Minds Behind Them.” [Online]. Available: http://mentalfloss.com/article/28800/8-amazing-automatons-minds-behind-them. [Accessed: 07-Dec-2015].

[7] D. J. de S. Price, “Automata and the Origins of Mechanism and Mechanistic Philosophy,” *Technol. Cult.*, vol. 5, no. 1, pp. 9–23, Jan. 1964.

[8] A. G. Bromley and University of Sydney. Basser Department of Computer Science, *The Vickers anti-aircraft gun predictor no. 1 mk. III / Allan G. Bromley*. [Sydney]: Basser Dept. of Computer Science, University of Sydney, 1982.

[9] “Tiapchenko, Information Display Systems for Russian Spacecraft: An Overview.” [Online]. Available: http://web.mit.edu/slava/space/essays/essay-tiapchenko1.htm. [Accessed: 07-Dec-2015].

[10] P. Olson, “The World’s Oldest Working Clock,” *Forbes*. [Online]. Available: http://www.forbes.com/2008/02/28/oldest-work-clock-oped-time08-cx_po_0229salisbury.html. [Accessed: 07-Dec-2015].

[11] “Principles - 10,000 Year Clock - The Long Now.” [Online]. Available: http://longnow.org/clock/principles/. [Accessed: 07-Dec-2015].

[12] J. Theo, *adriaan kok 2Animaris Currens Ventosa Oostvoorne 1993 kopie*. .

[13] J. Theo, “My creations, a new form of life.”

[14] “Venus Fact Sheet.” [Online]. Available: http://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html. [Accessed: 07-Dec-2015].

[15] “WT6500 Wind Turbine.” Honeywell, Feb-2011.

[16] “Mars Pathfinder FAQs - Sojourner.” [Online]. Available: http://mars.jpl.nasa.gov/MPF/rover/faqs_sojourner.html. [Accessed: 16-Dec-2015].

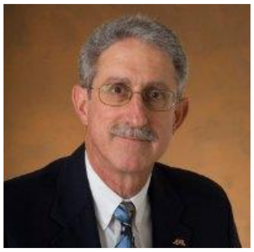
[17] “Mars Exploration Rover Mission: The Mission.” [Online]. Available: http://mars.nasa.gov/mer/mission/spacecraft_rover_ene

rgy.html. [Accessed: 07-Dec-2015].
[18] M. Lindgren, “Glory and failure : The difference engines of Johann Müller, Charles Babbage and Georg and Edvard Scheutz,” 1987.
[19] Antonin Svoboda, *Computing Mechanisms & Linkages*. .
[20] M. Rhee and M. A. Burns, “Microfluidic pneumatic logic circuits and digital pneumatic microprocessors for integrated microfluidic systems,” *Lab. Chip*, vol. 9, no. 21, p. 3131, 2009.
[21] “Five Level Surface Micromachining Technology Design Manual,” Sandia National Laboratories, 1.3, Aug. 2005.
[22] R. D. Launius and H. E. McCurdy, *Robots in Space: Technology, Evolution, and Interplanetary Travel*. Johns Hopkins University Press, 2012.
[23] R. A. Brooks and A. M. Flynn, “Fast, Cheap and Out of Control,” Dec. 1989.
[24] “Silicon Carbide (SiC) - APEI.” [Online]. Available: http://www.apei.net/Applications/Core-Technologies/Silicon-Carbide.aspx. [Accessed: 07-Dec-2015].
[25] H. M. Manohara, E. W. Wong, E. Schlecht, B. D. Hunt, and P. H. Siegel, “Carbon Nanotube Schottky Diodes Using Ti−Schottky and Pt−Ohmic Contacts for High Frequency Applications,” *Nano Lett.*, vol. 5, no. 7, pp. 1469–1474, Jul. 2005.
[26] V. V. Kerzhanovich, A. H. Yavrouian, J. L. Hall, and J. A. Cutts, “Dual Balloon Concept for Lifting Payloads from the Surface of Venus,” presented at the 36th Annual Lunar and Planetary Science Conference, 2005, vol. 36, p. 1223.
[27] R. S. Kremnev *et al.*, “VEGA Balloon System and Instrumentation,” *Science*, vol. 231, no. 4744, pp. 1408–1411, Mar. 1986.
[28] A. Hern and agencies, “Facebook launches Aquila solar-powered drone for internet access,” *The Guardian*, 30-Jul-2015.
[29] “NASA - Helios.” [Online]. Available: http://www.nasa.gov/centers/dryden/news/ResearchUpdate/Helios/. [Accessed: 07-Dec-2015].
[30] D. M. Hunten, *Venus*. University of Arizona Press, 1983.
[31] *Metals Handbook Ninth Edition Volume 2; Properties and Selection: Nonferrous Alloys and Pure Metals*, First Edition edition. ASM International, 1982.
[32] *ASM Handbook Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys*, 10 edition. Materials Park, Ohio: ASM International, 1990.
[33] *Asm Handbook: Properties and Selection : Nonferrous Alloys and Special-Purpose Materials (Asm Handbook) VOL. 2*, 10th edition. ASM International, 1990.
[34] Z. G. Yang, D. M. Paxton, K. S. Weil, J. W. Stevenson, and P. Singh, “Materials Properties Database for Selection of High-Temperature Alloys and Concepts of Alloy Design for Sofc Applications,” Pacific Northwest National Laboratory (PNNL), Richland, WA (US), PNNL-14116, Nov. 2002.
[35] G. J. Basic, “Power-scavenging Tumbleweed Rover,” Thesis, 2010.

BIOGRAPHY

Dr. Jonathan Sauder *is a mechatronics engineer at Jet Propulsion Laboratory, in the Technology Infusion Group, which seeks to bridge the TRL "Valley of Death" for innovative, promising technology concepts. Dr. Sauder focuses on developing unique and innovative solutions for deployable antennas, sunshades and other complex mechanical systems, taking concepts from ideation to verification by testing. Dr. Sauder is currently the Lead Mechanical Engineer on the RainCube Spacecraft, PI on a Phase I NASA Innovative Advanced Concept (NIAC), "Automaton Rover for Extreme Environments (AREE)" and Co-PI on a Research and Development Task for "Large Aperture Deployable Reflector (LADeR) for Small Satellites" with the California Institute of Technology. Prior to coming to JPL he had worked for Microsoft, Mattel, and several high-tech startups. He completed a Ph.D. in Mechanical Engineering from the University of Southern California in 2013 focusing on how collaboration aids engineers in creating innovative designs.*

Evan Hilgemann *is a mechanical engineer at the Jet Propulsion Laboratory where he focuses on technology development and infusion into flight. Recent project work includes meter scale deployable CubeSat antennas, the StarShade Technology Development Project, and a number of small technology projects. Evan has an M.S. degree in Aerospace Engineering from the University of Michigan and a B.S. degree in Mechanical Engineering from the University of Nebraska Lincoln. His academic study incorporated diverse topics such as satellite ADCS design, high altitude balloon systems, space mechanism design, and combustion.*



Bernard Bienstock *is a systems engineer at the Jet Propulsion Laboratory, and is a capture lead and proposal manager. He has worked on a number of Venus mission concepts.*

Dr. Aaron Parness *is the Group Leader of the Extreme Environment Robotics Group at JPL and the head of the Robotic Rapid Prototyping Laboratory. He received two Bachelors degrees from MIT in Mechanical Engineering and Creative Writing and an MS and PhD from Stanford University in Mechanical Engineering. At JPL, Dr. Parness currently works on the Asteroid Redirect Mission, leading a team that is developing robotic grippers to extract a 20-ton boulder off the surface of an asteroid and demonstrate the ability to alter that asteroid's orbit, a method that could prevent asteroids from impacting the Earth in the future. Dr. Parness additionally formulates and leads several technology development projects. Dr. Parness also assists work in JPL's Office of the Chief Scientist and Chief Technologist focused on innovation and low TRL technology infusion. He and his work have been featured in the Economist, Time Magazine, and as a Popular Science Top 100 innovation of the year as well as on the Discovery Channel, BBC, and in JPL's own Crazy Engineering YouTube series. In 2015, Dr. Parness was awarded JPL's Lew Allen Award for individual accomplishments or leadership in scientific research or technological innovation by JPL employees during the early years of their professional careers.*