MOBALL NETWORK: A SELF-POWERED INTELLIGENT NETWORK OF CONTROLLABLE SPHERICAL SENSORS TO EXPLORE SOLAR PLANETS AND MOONS

Faranak Davoodi[1,4], Joel Burdick[2], Mina Rais-zadeh[3],
[1]Jet Propulsion Laboratory, [2]California Institute of Technology, [3]University of Michigan
[4]Point of Contact: faranak.davoodi@jpl.nasa.gov

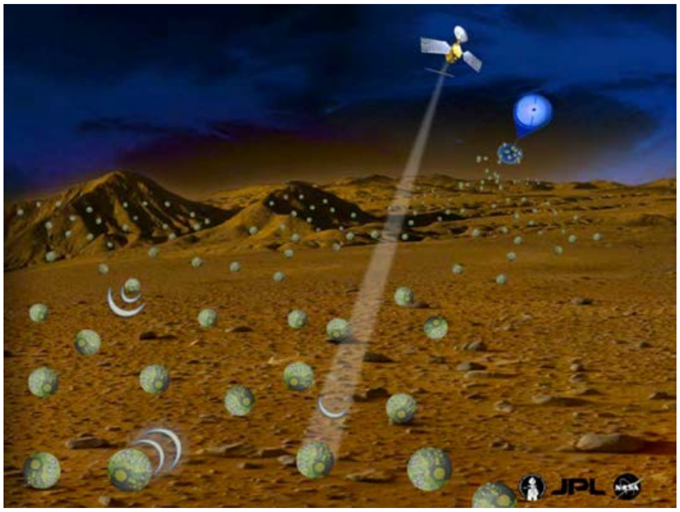


Figure 1: Moball Network a wireless mesh network explores Mars

Figure 2: (Left) The bouncy, self-rigidizable spherical multifunctioning sensor, the Moball [1]. (Right) The Moball's Mechanical Control and Linear Induction System [1] consisting of three internal perpendicular axes with movable and controllable magnetic weights moving within solenoids. Controlled movements of the magnetic weights (via the solenoids) along each of the three axes can induce rolling motions to enable precise positioning during science investigations. During wind (when used on Mars or Titan) or gravity driven movement, controlled mass movements can bias the Moball's motion, or uncontrolled movements of the masses can generate electric power as they move inside the solenoids The Moball Network can also be used on windless bodies (e.g. Moon, Europa, asteroids), by harvesting solar power, thermoelectric power, etc.).

I) Main Concept

We propose a novel architecture for studying the surface of planetary bodies such as Mars, Titan, asteroids, etc. using a distributed network of spherical multifunctioning sensors called *Moball*s[1]. A *Moball Network [1]* is envisioned to be a scalable, self-powered, controllable, distributed system that would share tasks intelligently in order to optimize its resources (power, memory, bandwidth) and the performance of its exploring and sensing responsibilities. The low-mass self-rigidizable Moball design allows for a large number of units to be packed in an aeroshell, resulting in a *Moball Network* which can in-situ map a wide range of phenomena across a much larger portion of the surface compared to many other proposed systems. It could substantially improve the possibility of finding rare phenomena such as bio signatures and areas with valuable samples through a random dynamic search. Because of its energy harvesting features, a *Moball Network* is capable of long life span missions needed to achieve many of NASA's future space exploration objectives in a cost-effective way, leaving a long lasting sensing and searching infrastructure on a planetary surface.

The Moballs can use wind, gravity, or their self-powered internal propulsion mechanism to move. They use natural resources on the planetary bodies that they are deployed to harvest the energy they need for their sensing, mechanics, data processing and communication. Moballs can exploit sunlight, wind or gravity driven motion and vibrations (e.g. Figure 2); and tiny RHU heaters, using thermo-electricity techniques; to continually harvest the energy needed for mobility control, sensing, and communications. The Moballs are lightweight (2500 - 4500 g, depending upon energy harvesting and science payload configurations), elastic (bouncy), and equipped with a novel mechanical control system shown in Figure 2. As a result of the above, *Moball Network* could explore in harsh conditions (windy, cold, sandy, and low solar energy) that were beyond the reach of previous missions, such as regions with very steep slopes, cluttered surfaces or sand dunes, or when it is dark, dusty (e.g. on Mars), or foggy (e.g. on Titan);

The Moballs would be inflatable self-rigidized structures using lightweight materials such as polyurethane, aerogel, Titanium, circuit printable Kapton, polyurea, etc. in order to keep them light and elastic but sturdy. Many deflated Moballs can be pressurized in aeroshell containers before deployment. During deployment, the Moballs would be inflated using self-rigidizing techniques without the use of a pump while being deployed. The Moballs can communicate with each other and to Earth when an orbiting satellite system is in view. Peer-to-peer communication can establish a harmonious network of shared data, computing, positioning, and science tasks, while enabling network reliability.

Moball's mechanical control system could allow them to avoid obstacles or hazardous areas by either stopping (by bringing the center of the mass down), or steer away from them by adjusting the center of the mass to lean on a side (Figure 3).

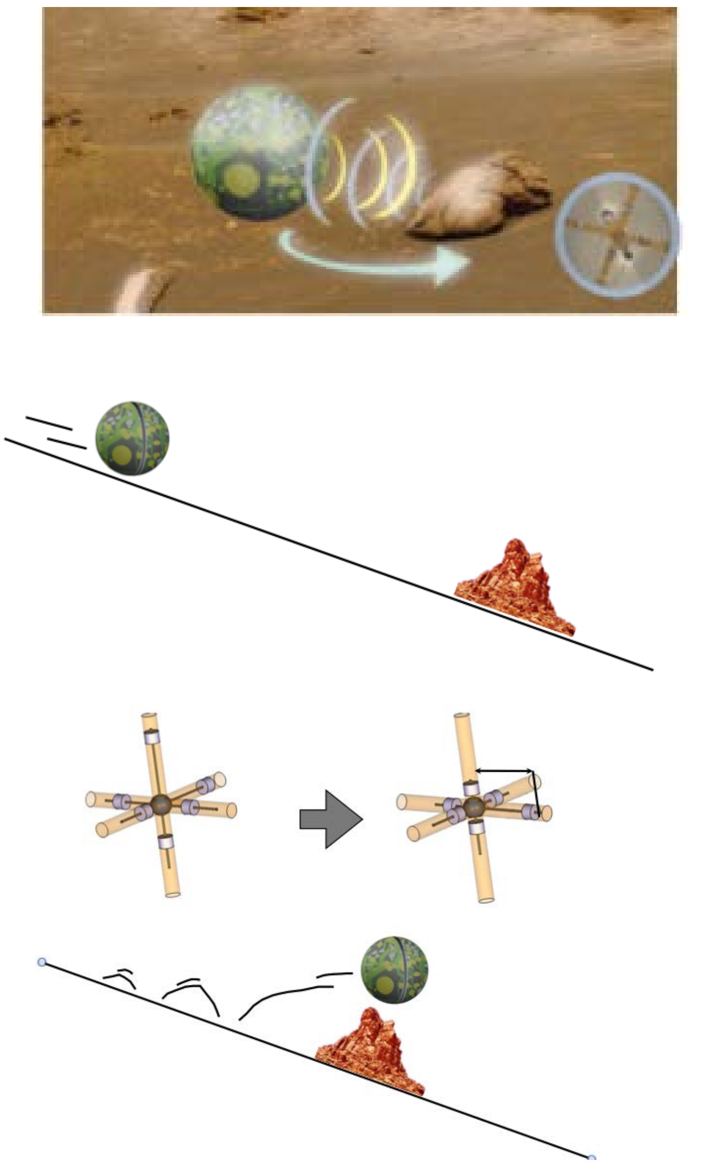


Figure 3: Moball could detect and process a hazardous object (gullies, or large obstacles) or a hazardous event (dust-devil) and would change its center of the Mass in order to stop, hop over them, steer or roll around them.

The Moballs might also be able to hop or bounce over obstacles (Figure 3) when traveling at speed. Contrary to all other hopping spherical shaped robotic instruments, such as hedgehogs, which start hopping from a still position, Moballs usually have an initial velocity which makes their hopping more feasible. Moreover, even if a Moball is stopped by an obstacle, changes in wind direction, coupled with center of mass shifts, might release it from the obstacle. Finally, the Moball could also use its mechanical control system, as depicted in Figure 3 and described in Figure 2, to roll away from obstacle.

II) Multiple-Aeroshell Moball Network Mission: We suggest a novel *Multiple-Aeroshell Moball Network Mission* class of mission architectures, which we believe would decrease the cost, time, and risk associated with future exploratory missions. For example, a single spacecraft could place two aero-shells in the orbit of Mars (or other planetary bodies). The *Moball-aeroshell* carries the compressed Moballs while the other *rover-aeroshell* carries a rover or lander. The *rover-aeroshell* would remain in orbit while the *Moball-aeroshell* descends to the area of interest (using steering thrusters similar to the MSL's aeroshell, or perhaps a large parachute) to distribute Moballs over a large surface area. The self-rigidizable Moballs will be inflated just after the deployment. Depending on the environment and the altitude at which the Moballs are released, smaller parachutes attached to each Moball can enable safe landing (the chutes can be jettisoned after landing). The quickly spreading Moballs would use various on-board imagers, spectrometers, and sensors to identify and map the relational location of the most important and valuable sampling targets and environmental phenomena which would need more sophisticated examination by rovers. Based on the map prepared by the Moballs, the rover's descent could then be targeted to the region covering as many important identified samples as possible. Considering the very slow speed of conventional rovers (MSL's travels ~30 meter/hour), this approach will save time, cost, and risk for the mission. Furthermore, the Moballs could provide real time information and guidance directly from the landing site to the rover's descent control system regarding the environmental situation (e.g. wind speed, dust conditions, obstacles in the area) and the descending aeroshell's landing parameters (e.g. feedback on its speed, angle, direction) in order to help it land safely and precisely at the chosen landing spot. The Moballs can also potentially act as visual landmarks or radio beacons to improve the accuracy of the descent control. Another example of a *Multiple-Aeroshell Moball Network Mission* will be to place multiple smaller aeroshells containing Moballs into a planetary orbit, and then disperse Moballs to different geographical locations (e.g., one to the southern and the other to the northern hemisphere). The Moballs could be customized for each specific environment.

The Moball network design can cover larger surface areas at a significantly reduced cost. The larger coverage will allow scientists to make more informed inferences and to understand geophysical trends. It will also allow them to identify "rare" events such as the Martian "blueberries." Cooperating Moballs in close proximity can generate 3-dimensional reconstructions of a geographical area.

Since Moballs could be used as scouts for planetary rovers, and could detect the closest feasible landing location near important science targets, they can save time and cost for future missions. And since they could also be used as beacons, it could make the landing of the rovers and in general future missions less risky, and therefore more readily funded.

III) Distributed Control Architecture for Moball Network:

Figure 4: The controllable distributed systems of Moballs could share tasks and learn from each other in order optimize the usage of resources of the entire system and the coverage and performance of the tasks assigned to the system by each mission.

Moball-Network configured as a wireless mesh network provides can support a global communication and control system that will ensure desired area coverage, staying away from hazardous objects, events or areas, and optimizing Moball explorations according to their available resources (power, memory, bandwidth) and local areas of high scientific value within the region.

Moballs have a stop-and-go capability. They can be "anchored" in moderate winds by lowering their center of mass; conversely, when necessary, or when conditions are suitable, their center of mass moved upwards to resume their wind-drive motion. As a result, the motion and distribution of a group of Moballs can be controlled either through a local planning, through negotiation among neighboring Moballs, or through a centralized command (e.g., by scientists and technologists on Earth). In this way *Moball Network* could dynamically reconfigure itself using an opportunistic wind-propelled motion strategy.

We envision a *Moball Network* as a system which can learn from previous experience or other Moballs in order to identify hazardous areas[4] safe traversal paths, or significant objects (Figure 4).

Using ranging information provided by the peer-to-peer communications, or from an orbiting satellite, as well as fused IMU data[40], Moball positions can be estimated, thereby allowing them to adjust their distances from each other in order to maintain networking and to collectively explore an area as a united body.

The Moballs can also move in the absence of wind. They can exploit the mechanical control system shown and explained in Figure 2 and use their internal propulsion system (e.g. a rechargeable battery, charged by various suggested energy harvesting techniques) in order to initiate movement to an area or object of interest (for example, an interesting rock that needs more examination, or from shade to sun in order to harvest more energy) or to avoid hazardous objects or areas. .

A Moball Network's distributed control system might ensure that Moballs intelligently share mission tasks that have been defined for different areas in order to optimize performance with respect to overall mission exploration goals as well as the usage of the system resources (power, memory, and the bandwidth). For example, when several Moballs are in close proximity, not all of them need perform the same tasks. Instead, one might measure temperature and pressure, another one might take pictures, and another might stop to perform spectrometry tests on a certain rock. The acquired data might then be transferred to a different Moball, which will be tasked with sending the data to an orbiter (perhaps because that Moball has better line-of-sight communication with the orbiter). In this fashion, system power and memory can be used intelligently respecting bandwidth limitations. The Moballs in an area can also fuse their information (say by averaging) in order to report more accurate data back; fused data is also more compressed, which will decrease communication traffic. Predefined preferences on possible events can be prioritized. For example, recognizing particular types of rocks, bio-signatures, or chemical compositions, or monitoring a passing dust devil may have a higher ranking and therefore require more attention and tests. Not only would ranking potentially save energy and system bandwidth, when a Moball encounters a highly ranked event, it can ask for help from neighboring Moballs to assist the "important" Moball in collecting, processing, and communicating its data. As a result, the "important" Moball can focus its resources on sensing, measuring and recording high priority events and not be worried about lack of memory. The ranking algorithm also comes in handy when a Moball needs to decide to get rid of its older, lower ranking, data when it is short on memory. Furthermore, when it is short on power and an orbiter happens to be passing by, it is worth only to transmit the higher-ranked events.

The orbiting system is a major component of the *Moball Network* architecture. It facilitates the communication of the Moballs with each other and with Earth, it performs power- and memory-intensive computational tasks, it gives optimized task plans to Moballs in a centralized fashion, and it updates and broadcasts the Moballs' topology map and the level of their memory and energy. Since the orbiters know the current location of the Moballs and are likely to have access to wind circulation patterns, they can "predict" the near future locations of the Moballs. The orbiters can therefore inform the Moballs of their proximity to high-ranking events so that they can conserve their memory and power in anticipation of an important encounter.. The knowledge of Moball locations by the orbiter can also be used to organize and prioritize inter-Moball communication

IV) Comparison to other approaches & concepts:

Compared to recently proposed mission concepts that share some similarities to what is proposed here, a *Moball Network* has many advantages.

***IV*.A)** Unlike the (20 kg, 6m) Tumbleweed [6] rovers which act as single wind-driven rovers, and Microbots [7], hedgehogs [8], which are not wind-driven and need a lot of energy for their locomotion (using their mechanics to hop around), *Moball Network* can take advantage of wind for its mobility and is a distributed system that share tasks intelligently in order to optimize its resources (power, memory, bandwidth) and performance of its exploration, sensing, and positioning responsibilities across a whole network of lightweight sensor platforms. Also, using the control mechanics in Figure 2, Moballs can move even in the absence of wind.

***IV*.B)** The Tumbleweed is "assumed to be a perfect, inelastic, homogeneous sphere that rolls without slip"[6], hedgehogs also "move nimbly and precisely" [8]. In contrast, the elastic and bouncy Moballs can be extremely agile, rebounding from impact with an obstacle, and can be saltated by the turbulent movements of the wind to easily pass through cluttered surfaces without requiring a lot of energy; especially, given that the Moball's preferred height for Mars deployment is about 1.5-2.0 meters, and most boulders on Mars are less than 1 meter tall [7].

***IIV*.C)** The Mechanical Control and Linear Induction System suggested for the Moballs described in Figure 2 is novel. This compact, robust, and lightweight design enables both crucial energy harvesting needed for long duration missions, and precise positioning control authority needed for science.

***IV*.D)** While the use of a pendulum for energy harvesting has been suggested for the tumbleweed design [9], this approach is not suitable for tumbling Moballs, as the internal space occupied by the pendulum is excessive, energy is harvested only for specific rolling motions, and the required mass is high. The magnetic weights in Moball's structure move linearly and securely in their solenoidal tubes covered. Any rolling or bouncing motion can induce electricity.

***IV*.E)** No energy harvesting has been suggested for the mechanics of the Microbots [7] and hedgehogs [8].

***IV*.G)** Microbots [7] and hedgehogs [8] need a great deal of energy for their motilities and therefore their activity is very limited if used on cluttered and windy Mars (or Titan). The Microbots' [7] life span is just 30 days. Also, dust on Mars and fog on Titan limits the solar energy that could be harvested by hedgehogs.

IV*.H)** The multiple-aeroshell deployment strategy suggested for *Moball Network* in section ***II) is novel. The use of low cost and parallel "scouts" to improve a rover's landing site value is also novel.

IV*.J)** The autonomous and Distributed Control Architecture suggested for *Moball Network*, described in ***IV) is novel. The hedgehogs are not autonomous and Microbots don't reconfigure themselves based on the priority of the region and the resources available.

V) Technical Rationale:

Prototypes of the main Moball sub-systems (structural shell, mechanical energy harvesting and control system, on-board computing and sensor processing, and energy management) are currently in development. This section summarizes some of the preliminary calculations and simulations which support the feasibility of future Moball devices.

V.A) Mass and Volume Budget:
Moball mass will determine the amount and type of sensors that can be incorporated into its structure, while its volume will influence the amount of energy that can be harvested (since the energy scavenged from thermoelectricity, piezoelectric, the wind-driven motion, etc., depends on the volume available). Moball mass and volume cannot be chosen arbitrarily. They are tied together by virtue of the fact that they should allow for wind-driven motion under the typical conditions. Considering surface conditions Mars (wind speed of 10-15 m/s, atmosphere's density of 20 g/m^3) and Titan (wind speed 1 m/s, atmosphere of 1.88 g/ cm^3), using formulas developed in previous studies [9] a diameter of ~1.5 meter is sufficient to guarantee a wind-driven motion for a Moball with mass of 500-5000 grams.

VI.B) Energy Budget and suggested sensors:

A key issue for energy-scavenging systems is the level of available power, and whether this power is sufficient for operation. At any instant the power which can be scavenged is a function of conditions in a Moball's environment, which are apt to vary significantly. , Figure 4 shows a summary of power vs. volume for some of the most recent power scavengers (primarily inertial and thermal), highlighting the different transduction technologies, including piezoelectric (PE), electromagnetic (EM), electrostatic (ES), and thermoelectric (TE). The most important conclusion is that most scavengers produce on the order of 10-100µw/cm3 for smaller devices, and perhaps on the order of several 100µW to several mW per cm3 for larger systems.

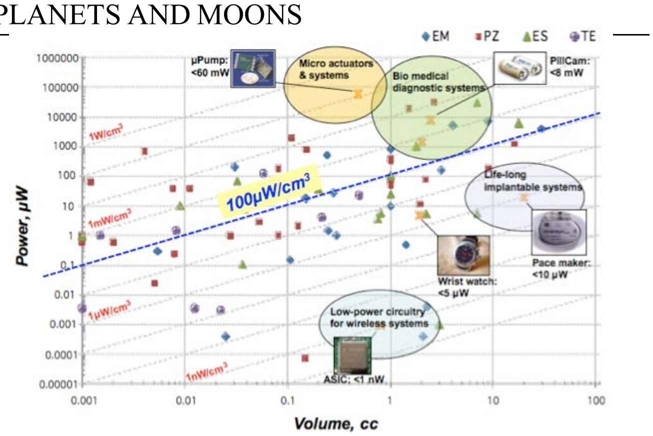


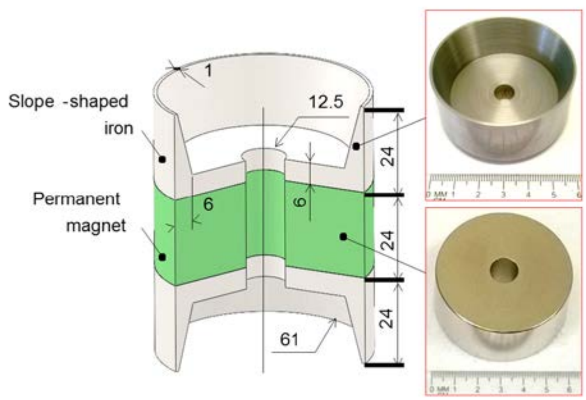
Figure 5: Power generated Vs. Volume for most recent power scavengers

We have performed a more detailed study of the solenoidal mechanical energy harvesting and control system [30]. A 2m diameter Moball can potentially generate at least ~2 watts continuously during wind-driven motion in Earth's polar regions. Scaling this result to Mars yields an expected 500 mW of continuous energy generation during typical wind-driven motions. Assuming scavenging for 8 hours per Martian sol, one can expect to harvest 3500-4500 Joules of energy per sol. This amount of energy can operate many sensors, an onboard microprocessor, and communication system. Moball sensors and micro-devices that fit within this energy budget could include a MEMS Inertial Measurement Unit (IMU consisting of 3-axis gyro, accelerometer, and magnetometer), CMOS Panoramic Imager, Silicon MEMS Pressure Sensor, TES bolometers, MEMS wind vector sensors, uncooled infrared cameras, acoustic sensors (for Titan), Raman spectrometer with a VLOK microchip laser integrated within a Raman probe-head, Multispectral Microscopic Imager, Miniature Mass Spectrometer (MMS), Compact curved focal plane array camera (UV/Vis/NIR) with a large field of view, MEMs Gas detectors, microfluidics, and bioMEMS chips..

VI.C) RF Communications Link Budget: Although the level of communication required by the heads up and collaborative task sharing strategies of the Moball may look power-intensive, the Moballs are programmed to keep expensive satellite communications to a minimum, and use low power micro-RF for peer-to-peer communication. Assigning a 100 mW continuous transmit power, more than 10 hours of consecutive peer-to-peer communication per sol is possible while still allowing for on-board sensing and computation. In order to increase the communication distance with reasonable data rate, QPSK modulation can be used for both uplink and downlink communication. QPSK provides a spectral efficiency of ~1.6 bits/Hz and a required SNR of ~14 dB for 10^{-6} bit-error-rate (BER). The frequency band of 433 MHz-434 MHz available for ISM applications is chosen due to longer propagation distance with appropriate antenna size (< 10 cm), which is less than the diameter of the Moball. Based on this assumption, the link budget the realizable communication distance is estimated to be 100 km between Moballs with the maximum date rate of 320 kb/s.

VI) Current Status

Our initial prototyping efforts have focused on optimizing and validating the mechanical self-energy harvesting system [30,31]. We have found



[31] through extensive simulation studies that the maximum energy can be generated from the solenoidal tubes of Figure 2 using a moving mass having the geometry shown in the figure above (consisting of a central Neodymium Iron Boron magnet and low carbon "back-iron" end caps). This geometry provides the most radial field lines for the minimum combined mass of the mover. Our stimulations suggest that this magnet combined with a copper coil 1-cm thick, 35 mm high, and 62 mm

inner diameter can generate peak voltages of 30 volts during wind-driven motions. Experiments are currently underway to validate our energy scavenging model predictions, and to optimize the mechanical structure of a 2m diameter prototype Moball.

VII) Conclusion

While the Moball design is seemingly simple, a fleet of networked Moballs can be deployed in a cost-effective to provide wide-area, persistent and sophisticated coverage of planetary surfaces. Their networking capabilities also provide high science throughput with high resiliency and redundancy. We believe that this architecture offers many potential advantages for future space exploration initiatives.

Acknowledgement

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

References

[1] Faranak Davoodi et al. "AUTONOMOUS AND CONTROLLABLE SYSTEMS OF SENSORS AND METHODS OF USING SUCH SYSTEMS", U.S. Patent Application No.: 13/776,652, 02/22/2013

[5] Low Cost Mars Surface Exploration: The Mars Tumbleweed NASA/TM-2003-212411
[7] http://robots.mit.edu/publications/papers/2005_02_Dub_Iag_Lib_Lam.pdf
[8] http://news.stanford.edu/news/2012/december/rover-mars-phobos-122812.html

[9] P. F. Gorder, (2003) "Sizing Up Smart Dust", Computing in Science & Engineering, Vol 5, No 6, pp 6-9
[10] The information presented here is from: the International Committee of the Red Cross [ICRC] document Anti-personnel Mines: An Overview, 1996. The ICRC bases all its figures on landmine numbers on the UN Demining Database
[11] ETFE's specification: http://www.boedeker.com/etfe_p.htm
[12] Kapton's specification: http://www.boedeker.com/kapton_p.htm
[13] "Ultralight Metallic Microlattices", T. A. Schaedler, A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit, W. B. Carter1. Science 334, 962 (2011); DOI: 10.1126/science.1211649
[14] Carbon Nanotubes specification: http://www.nanocyl.com/CNT-Expertise-Centre/Carbon-Nanotubes
[15] cryogenic and inert gas http://www.lindecanada.com/en/aboutboc/safety/cryogenic_liquids/characteristics.php
[16] Lorenz et al. "The Sand Seas of Titan: Cassini RADAR Observations of Longitudinal Dunes", R. D. Science 5 May 2006: Vol. 312 no. 5774 pp. 724 727 DOI: 10.1126/science.1123257
[17] K. Najafi, H.S.Kim, T.V. Galchev, (2012), "Energy Scavenging From Low Frequency Vibrations", NIST-funded project at the Engineering Research Center for Wireless Integrated MicroSystems, http://www.eecs.umich.edu/najafi/files/energyscavenging.pdf
[18] E. Romero, T. Galchev, E. Aktakka, N. Ghafouri, H. Kim, M. Neuman, K. Najafi, and R. Warrington, (2008) "Micro Energy Scavengers", COMS 2008, Puerto Vallarta, MX
[19] N. Ghafouri, H. Kim, M. Atashbar, K. Najafi, (2008) "A Micro Thermoelectric Energy Scavenger for a Hybrid Insect", IEEE Sensors, pp 1249–1252
[20] K. Najafi, B.L.Peterson, H.S.Kim, N. Ghafouri, (2012), "A Micro Thermoelectric Generator for Microsystems", DARPA-funded project at the Engineering Research Center for Wireless Integrated MicroSystems, http://www.eecs.umich.edu/najafi/files/microthermgen.pdf
[21] R.O. Warrington, K. Najafi, E. Romero, (2012), "MEMS-Based Energy Harvesting for Low-Frequency Vibrations", WIMS ERC-funded project at the Engineering Research Center for Wireless Integrated MicroSystems, http://www.eecs.umich.edu/najafi/files/MEMSbased.pdf
[22] D. Bouchouicha, F. Dupont, M. Latrach, L. Ventura, (2010) "Ambient RF Energy Harvesting", International Conference on Renewable Energies and Power Quality (ICREPQ 2010), Granada, Spain, pp 1-5
[23] I. Ferreira, B. Brás, N. Correia, P. Barquinha, E. Fortunato, R. Martins, (2010) "Self-Rechargeable Paper Thin-Film Batteries: Performance and Applications", IEEE Journal of Display Technology, Vol 6, No 8, pp 332-335
[24] Stephen A. Sarles Donald J. Leo, "ACTIVE COMPOSITE RIGIDIZATION USING TEMPERATURE-CONTROLLED RESISTIVE HEATING" Advisor Virginia Tech, Center for Intelligent Material Systems and Structures, Blacksburg, VA 24061
[15] W. Khun, N. E. Lay, E. Grigorian, D. Nobbe, I. Kuperman, J. Jeon, K. Wong, Y. Tugnawat, X. He, (2007) "Microtransceiver for UHF Proximity Links IncludingMars Surface-to-Orbit Applications", Proceedings of

the IEEE, Vol. 95, No. 10, pp 2019-2044

[26] K. Najafi, T. Galchev, E.E. Aktakka, R. L. Peterson, J. McCullagh, "Microsystems for Energy Harvesting," Invited Paper, *16th International Conference on Solid-State Sensors, Actuators, and Microsystems (IEEE Transducers)*, Beijing China, pp. 1845-1850, June 2011

[27] Mitri, G.; Showman, Adam P.; Lunine, Jonathan I.; Lorenz, Ralph D. (2007). "Hydrocarbon Lakes on Titan". Icarus 186 (2): 385–394. Bibcode:2007Icar..186..385M

[28] "What is the typical temperature on Mars?". Astronomy Cafe. Retrieved 2007-09-08

[29] http://phys.org/news/2013-02-fujifilm-thermoelectric-material.html

[30] M. Burkhardt, F. Davoodi, J.W. Burdick, and F. Davoudi, "Energy Harvesting Analysis for Moball, A Self-Propelled Mobile Sensor Platform Capable of Long Duration Operation in Harsh Terrains," (to appear) *Proc. IEEE Int. Conf. Robotics and Automation*, May-June 2014, Hong Kong.

[31] J. Asama, M. Burkhardt, F. Davoodi, and J.W. Burdick, "Design Investigation of a Tubular Coreless Linear Generator for Energy Harvesting Applications," (submitted) *IEEE Energy Conversion Congress and Expo, Sept. 14-18, Pittsburgh, PA, 2014*