Multifunctional Systems for Planetary Exploration[1]

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We summarize the findings and recommendations of the Adaptive Multifunctional Systems for Micro-climate Control Study held at the Caltech Keck Institute for Space Studies. The objective of the Study was to adapt the most recent advances in multifunctional reconfigurable and adaptive systems to enable a microenvironment control to enable space exploration in extreme environments of the Solar System. The technical goal was to identify the most efficient materials, architectures, structures, system autonomy and energy management solutions needed to optimally project or generate a micro-environment around space assets. An important aspect of the Study was the consideration of distributed cellular systems as an architecture for multifunctional systems.

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I. Introduction

We summarize the findings and recommendations of the Adaptive Multifunctional Systems for Micro-climate Control Study held at the Caltech Keck Institute for Space Studies in 2014-2015 . This work, hereafter referred to as "the Study", included two workshops, one in May 2014, another in February 2015. The final report of the Study is publicly available[4].

Extreme planetary environments represent the next frontier for *in situ* robotic space exploration. Missions for exploration could be followed by robotic missions for exploitation and by notional manned missions. All these missions have one common problem, namely harsh environments, where temperature, radiation, and other factors make the missions inconceivable at present. The multifunctional system concept discussed in this paper directly addresses the "Surviving Extreme Space Environments" Challenge, one of the NASA's Space Technology Grand Challenges[1], specifically aimed at enabling robotic operations and survival, in the most extreme environments of our Solar System. One of the benefits of this initial effort has been to identify mission concepts that would otherwise be

[4] http://kiss.caltech.edu/new_website/workshops/adaptive/adaptive2.html

too technologically challenging and/or expensive, in particular those that would involve long periods of time without a reliable power source. The Study discussed permanently shadowed environments with remote deployables providing illumination, energy, computation, and communications. Other potential applications that were discussed included: sun-shields to protect rovers from very strong solar illumination; thermal blankets to help them retain heat and survive a cold night; and calibration targets for instruments. This study brought mission designers together with experts in these technologies, resulting in a better understanding of where we could best apply these ideas in space science, and leading toward focused development of the most promising concepts. Specifically, the Study explored alternative solutions that could revolutionize space missions through a dramatic increase in the ability to survive extreme environments[2], leading to: a) innovative ways to redirect solar energy into shadowed exploration sites, potentially enabling the exploration of permanently shadowed craters and caves, without use of nuclear thermoelectric power; b) types of lightweight and multifunctional structures; with multiple advancements in packaging and deployment of space structures, and c) types of robotic/autonomous systems, manufactured/printed in 1D (tensegrity) or 2D (origami) formats, but having the ability to morph into 3D shapes. Such novel advances in space robotic capabilities could improve survivability in extreme environments around the Solar System, enable new classes of missions, and possibly open new frontiers of exploration and scientific discovery in relatively close-proximity destinations (Moon and Mars). The advances would enable mission operations involving long periods of time without direct solar input at massively reduced cost; e.g. notional exploration of ice fields in permanently shaded craters and or exploration of caves could become feasible in context that otherwise may require potentially costly nuclear thermoelectric power. This novel solution is called an "energy-projecting multifunctional system" (EPMFS), which is composed of multifunctional systems (MFS) and energy-projecting systems (EPS).

The outcomes of this study included: a) identifying exploration/science drivers and discussing examples of classes of mission concepts enabled by the energy-projection capability (e.g.,solar concentration, light re-direction, and micro-climate generation/projection); b) establishing fundamentals (state-of-the-art and challenges) of the key technology areas of materials/structures, packing/deployment, and adaptive hardware and software reconfiguration; and c) identifying technology gaps of each area (as well as areas of focus where further technology investment would be required), leading to the definition of pathways for future research and development to develop, mature, and apply these concepts to EPMFS capabillities.

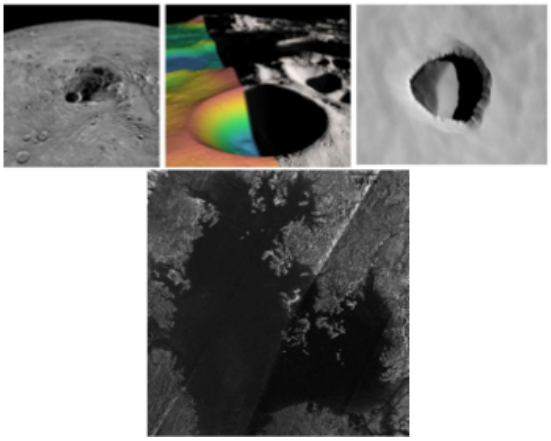


Figure 1. MERCURY: ice-harboring craters near North Pole; MOON: synthetic photo of Shackleton Crater, potential candidate for lunar outpost; MARS: cave skylight near Arsia; TITAN: Ligeia Mare.

II. Multifunctional Systems

We consider multi-functionality to imply coupling between subsystem performance and as-needed functionalities (e.g. electrical, magnetic, optical, thermal, chemical, biological, and so forth) to deliver dramatic improvements in system-level efficiency.

Components of the mechanics for "multi-functional system design" include elements such as: multi-scale modeling and simulation, interfacial phenomena among subsystems, large scale system integration, advanced manufacturing, and advanced electronics packaging. The design of multifunctional "autonomic" systems which can

sense, diagnose, respond and adjust with minimum external intervention involves: (1) damage detection, (2) neurological system-inspired sensory networks, (3) the capability to self-diagnose and self-heal, (4) the capability to reconfigure. The design of "adaptive" systems that allow alteration of shape, functionality and mechanical properties on demand relates to the mechanics of a range of concepts, including: adaptive materials, intelligent actuation, programmable materials, thermally activated reconfigurable systems, muscular-skeletal system-inspired morphing structures, and metamaterials with local resonance capability. From an integration perspective, the structural integration of power harvesting/storage/transmitting capabilities for "self-sustaining" system deals with development in the areas such as: energy harvesting, energy conversion, energy storage, energy distribution, structural batteries, hybrid energy harvesting systems, such as solar cells integrated with a structural layer. The design, manufacturing and durability of multifunctional systems involves material capable of compliant interfaces, distributed cells for sensing and actuation, damage-tolerant structural composites, and 3D printed composites as well as advanced manufacturing techniques.

Multifunctional systems provide many opportunities for technology development, some of which are: electronic (smart) composites for load-bearing/conformal/tunable antennas; antennas of reconfigurable frequency response or frequency-selective; structures with self-healing, regeneration/remodeling, self- strengthening and in-situ repair capabilities; neurological system-inspired sensing/diagnosis/actuation network; autonomic state awareness (sensing) and signal distribution; muscular-skeletal system-inspired adaptive structures using active, reconfigurable and programmable materials; structural integration of power harvest/storage/transmission capabilities; and novel classes of transducers and science instrumentation that can be additively manufactured.

Next, we extract pertinent top technical challenges and high-priority technologies in the recently released document *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*[3], henceforth referred to as the Roadmap. The study contributed to multiple Technical Areas (TA) of the NASA Space Technology Roadmaps[4] : TA03, TA04, TA12. The results of the Study would impact *TA03, Space Power and Energy Storage*, as it proposed innovative ways to redirect solar energy into shadowed exploration sites. Many NASA missions would benefit from the mass reduction resulting from the use of MFS in power system designs. The idea of incorporating power system elements into the structure of a vehicle or habitat could reduce weight and and enhance reliability and safety by allowing redundancy and dynamic re-provision of resources in response to degradation. Currently, this is not possible, as structural elements are not electrically active. However, if power system components and structural elements were co-designed in a more holistic system approach (for example, allowing part of the power system to also provide structure or embedding power features in structures), we extend modularity to involve "dual use" elements, replace the less flexible current "single purpose" elements. We might, for example, use the space/aircraft structure as the electrode materials for batteries. The electrolyte could be sandwiched between electrode plates, which would be part of the structure. The anodic and cathodic plates would of course require the strength to bear structural loads. Recent advancements in nanotechnology suggest this is possible. For example, electronics based on carbon nanotubes could provide high mechanical strength.. Boron nitride (BN) nanotube-based super capacitors could also be explored as another means of combining power storage and structure. Another possibility is to use the structure as an adaptive main power "bus bar", in which primary power would pass through the structure and automatically find the best available path (e.g., of least resistance) and could "heal" itself if damaged[15]. As mentioned in TA03, this would be a literally "smart structure". The recommendation is that, for a MFS incorporating super capacitors, it would be necessary to first demonstrate concept feasibility (to TRL 3) in three years, complete subcomponent testing in approximately six years, and provide a concept demonstration in about ten years. For MFS materials that can bear load and act as electrode materials, initial materials could be developed in five years, a structural sub-system demonstrated in six years, and a system level demonstration performed in 10-12 years. The results of the Study would also impact *TA12, Materials, Structures, Mechanical Systems and Manufacturing*, as it addressed innovative types of lightweight and multifunctional structures. For deep space missions, the trend in structural systems is toward lighter weight, more compact, and more autonomous capabilities, as these enable not-too-distant future deep space missions. The focus of these technologies would be to more highly-integrated systems with more autonomy, but with reduced mass and volume. Finally, the results of the Study would impact *TA04, Robotics and Autonomous Systems*, because EPS represents a new class of robots/autonomous systems, built in 2D, but reconfigurable to 3D shapes, with capabilities beyond the projections of the Roadmap;the important elements are: sensing and perception, mobility, manipulation, human-systems integration, autonomy, autonomous rendezvous and docking (AR&D), and robotics, tele-robotics, and autonomous systems engineering. TA04 supports NASA space missions with the development of new capabilities, and focuses on several key issues for the future of robotics and autonomy: enhancing or exceeding human performance in sensing, piloting, driving, manipulating, and rendezvous and docking; development of cooperative and safe human interfaces to form human-robot teams; and improvements in

autonomy to make human crews independent from Earth and make robotic missions more capable. A multifunctional system capability would enable robotic systems incorporating many of those elements listed above, thuse expanding the potential for novel autonomous and human-driven missions.

III. Need for Multifunctional Systems in Planetary Science

Reconnaissance missions to the Solar System will be followed by robotic *in situ* missions, and perhaps later by human exploration. All these missions have one common problem: harsh, extreme environments (EEs), where temperature, radiation, pressure, chemical (e.g corrosive or toxic atmospheres) and other factors make the missions inconceivable at present. The Study explored an enabling capability for operation in EE, a solution applicable to all types of *in situ* missions, based on projecting and controlling a favorable micro-environment (e.g., around a rover) in a local operating area where exploration, exploitation or human visits would take place. Using EPS approaches, it is not only possible to transform the environment necessary, but also to adapt to other needs by shape change/transformation. The EPS body surface would embed reflectors and solar cells, including antenna elements for communication, along with actuation and control elements to manage conformational (shape) change. The novel concept of projected a protected local environment from a distant point, giving *in situ* explorers of extreme environments an ameliorated micro-environment around them has potential broad implications for both robotic and human spaceflight.

The EPS concept directly addresses the "Surviving Extreme Space Environments" Challenge, one of the NASA's Space Technology Grand Challenges[3], which is specifically aimed at enabling robotic operations and survival, in the most extreme environments of our solar system. In the Study, we assessed the basic elements of micro-environment projection in EE for some relevant mission scenarios. From a science perspective, the EPS concept opens new frontiers of exploration and scientific discovery in the Solar System. From a robotic control perspective, the progress in shape-changing techniques will advance the field of "origami robotics", which could take advantage of the physical reconfigurability. From the materials and embedded electronics perspective, the integrated EPS fabric represents advancement over electronic fabrics, such as those in contemporary smart clothing and smart homes/environments. From a systems perspective, we deal with innovative multi-functional system integration for embedded materials, distributed sensing, processing, and actuation (including conformational change). Solar concentration is also an area of promise for DOE applications.

A potential mission scenario exploiting these technologies might involve energy management of assets in craters on the Moon and Mercury, or in caves on Mars, where carrying a radio isotope generator (RTG) would be problematic. This application would drive technology to deploying multifunctional materials on a crater rim or inside a cave. A second potential scenario involves Sun-energy concentration and redirection from aerostats for Titan-based mission assets, to avoid coping with heavy on-surface assets (which would involve very complex thermal management in a cryogenic environment). For Titan, an energy concentration capability is needed because Sun is at 6 atomic units (A.U.). Since Titan's high density atmosphere is extremely favorable to transportation by aerostat, this application would drive technology development for deployables and multifunctional materials combined with novel aerostat concepts and novel surface assets for *in situ* sampling powered from the aerostat. A third scenario involves Sun-energy concentration and redirection from Montgolfière for Venus missions. Since clouds dominate the atmosphere, the energy transfer (from a high altitude Montgolfière balloon) to power surface assets needs to be in a frequency band that can transfer through clouds (for example, infrared). This application would drive new technology for deployables and multifunctional materials for energy concentration and redirection not in the visible band. Such improvements in space robotic capabilities offer a novel way of improving survivability in extreme environments, enable new classes of missions and open new frontiers of exploration and scientific discovery in several solar system locations. It enables operations that involve long periods of time without direct solar input or radioisotope power, at massively reduced cost (e.g., exploration of ice fields in permanently shaded craters and or exploration of caves would become feasible). Such missions are merely a subset of what could be achieved with the use of EPSs. EPSs offer an alternative to RTG power, which are desirable even only a parity in mission performance can be obtained, due to the political and environmental concerns presently associated with RTGs. Further study is required to evaluate their utility in conjunction, for example, with landers on icy satellites in the more insolation-poor environments of the outer Solar System (e.g., Europa, Enceladus), where the anticipated benefits could be substantial, enabling major mass savings for instruments, power and communication systems. Given the major interest in some of these hard-to-access extreme environments, an increased present emphasis on technology development is important, so as to mature them for use in these compelling science missions.

A. Exploration of Mars, Moon, and Mercury

The discovery of ice deposits in permanently shadowed craters of Mercury[5] and the Moon[6] (see Figure 1) presents potential as a resource for both robotic and human spaceflight, but also a big challenge to mission planners. Such ice deposits preserve a unique record of the geology and environment of their hosts, both in terms of impact history (and possibly volcanic activity, if sufficiently ancient) and the supply of volatile compounds (mostly water), and so are of immense scientific interest. To date, these have only been studied indirectly (via remote analysis of impact ejecta) and by remote active radar, but not in a manner that constrains reliably the depths of the deposits, their purity, or the structures within them. An EPS placed on a crater rim would facilitate modulation of the environment, making it less of a challenge for rover exploration. It would provide illumination for a considerable fraction of the year, enabling the use of passive remote sensing techniques. Intense focusing of the sunlight could melt or evaporate the ice, revealing the purity of the deposits, dissolved or suspended materials (e.g., salts, impact strata, other volatiles), and possibly eliminate the need for a drill or other excavation tools. Additionally, the EPS-based communications antenna could potentially transmit science data back to Earth, possibly through an orbiting relay, at a much higher data rate (owing to the potentially improved link margin in a large aperture). Just as terrestrial caves host micro-environments on Earth, with unique and diverse biological communities, we expect the recent discoveries of caves on Mars[7] and the Moon[8] to provide intriguing new target sites for future missions. They may be the most viable habitats on Mars for either endemic life (if present) or for human exploration. Not only do such caves protect from potentially-damaging radiation, but they could also host unusual thermal and chemical environments, supporting ecosystem niches. An EPS placed outside of a cave entrance, or beneath a skylight, would be a particularly effective complement for a cave crawler mission, reflecting light into the cave system, providing many of the same advantages as discussed for shadowed craters, and serving as a communications relay. The need to collect samples from a rich and diverse set of well-characterized sites within a limited mission duration requires faster and more energy-efficient rover navigation. Better prediction of vehicle mobility via improved terrain sensing will improve mission safety and enable operation on more extreme terrains. When combined with methods to plan under uncertainty, quantitative measures of the uncertainty associated with terrain sensing and predicted vehicle mobility will enable more efficient operations, improve mission safety, and potentially enable access to more challenging terrain. Improvements in distributed global localization will enable greater leveraging of orbital data in traverse planning, thereby enabling more efficient long traverses. The Lunar South Pole-Aitken Basin Sample Return is another potential New Frontiers mission. A soft landing on the Moon, probably in rugged terrain to ensure a sampling of material from the mantle, will require vision-based target relative navigation (landmark modeling and tracking), fast and energy-efficient roving capability, precise global localization, efficient operations, advanced sample collection and sample handling capabilities, and automated path planning and optimization, all of which could be enabled by MFS approaches.

B. Exploration of Venus

A variety of Venus missions have been proposed with very distinct science objectives[9]. The 2011 Decadal Survey includes an atmospheric-focused Venus Climate Orbiter (VCO) Mission based on a wind-driven balloon, a mini-probe and two drop sondes. The surface-centric Venus In Situ Explorer (VISE) mission would place a lander on the surface capable of sample acquisition and analysis with extended mission duration. The New Frontiers Surface and Atmosphere Geochemical Explorer (SAGE) mission would require an autonomous surface excavation system in an extreme environment (e.g., 450°C, 92 bars) and *in situ* instrumentation for geochemical analysis. For all these planned missions, not only are efficient power and micro-climate generation technologies required, but also technologies enabling the survival of the EPS that itself must operate in the Venutian environment.

C. Exploration of Titan

The scientific interest in Titan primarily stems from the presence of large amounts of organic compounds in its atmosphere and on its surface[10]. Figure 1 shows the Ligeia Mare on Titan. Features on Titan such as volcanoes, sand dunes, lakes, and a nitrogen-rich atmosphere are analogous to those on Earth. The solar flux at Titan's surface is only on the order of 1 W/m^2, a value far too small to enable solar-powered vehicles. While nuclear power provided by radioisotope decay is the only electric power source in the foreseeable future, alternative options for power generation and re-direction are of keen interest and need to be researched. There are two proposed potential missions to explore Titan via different access systems: 1) based on a wind-driven Montgolfière, and 2) based on a lake lander. The Titan Saturn System Mission (TSSM), in which a wind-driven Montgolfière is used to survey the moon, and a lake lander is used to explore the methane and ethane lakes, require unique localization capabilities, assisted by efficient operations, and a sophisticated set of technologies in the areas of aerial mobility (for the balloon) and surface mobility (for the lake lander). All these capabilities will also need to rely on embedded high-performance computing hardware and software, particularly in the path planning and management and correlation of science data

collected by heterogeneous sensors. On the other hand, alternative mission concepts using passive elements such as floaters will not likely require precise localization. In general, all balloons require localization, but balloons operating near the surface require even higher levels of precision to avoid collisions and acquire surface samples from small terrain features. There is a range of possible Titan balloon missions going from uncontrolled, all-passive, helium, super-pressure balloons to sophisticated motorized blimps. Besides a lander and an orbiter, the TSSM includes a hot air balloon (Montgolfière) that might require a vertical ascent/descent control system and accurate localization ability. More advanced versions of this balloon are possible in which the balloon changes altitude to catch favorable winds and go to desired locations above the ground. This wind-assisted navigation was not part of the original TSSM, but is a logical extension. Also, it is an example of the impact of integrated multifunctional technology on a mission on a planetary scale, since innovative mission planning strategies for long-duration flights might have to be developed while keeping in mind the limited lifetime of vehicle resources. Finally, challenges common to virtually all planetary science missions beyond the orbit of Mars include limited bandwidth and high-latency communications, which preclude real-time teleoperation, thus requiring a high degree of autonomy and reliability, all of which could be enabled by multifunctional systems.

D. Exploration of Near Earth Objects (NEOs) and Small Bodies

This is a class of missions that would investigate NEOs for general planetary science purposes, for planetary defense purposes, for pre-mission surveys, and reconnaissance for human exploration and retrieval. These missions will share characteristics of other small body missions, including the need for autonomous surface operations, precise global localization, small body mobility, and sample collection and handling. If surface contact is going to be made, precision sample collection and handling subsystems will be required. One approach is referred to as "Touch and Go" (TAG), which is a type of autonomous rendezvous and docking autonomous systems that can make close, controlled approaches and gentle contact with the rotating surface of the body. Other approaches can also be considered, such as darts, harpoons. They will all require interaction with the surface regolith. Initial planetary defense missions such as Planetary Defense Precursors (PDPs) will explore alternative defense strategies. These may be small investigatory surveyors to assess physical characteristics of the small body and leave precision-clock-based radio beacons for precise global localization and/or mitigation technology demonstrations incorporating one or more deflection methods such as electric propulsion (EP) systems or gravity tractors. Such missions will share all of the surface autonomy new technology needs of the sample return missions. Many future small body missions are likely to be micro-spacecraft missions. Aside from the already discussed technology requirements associated with small body missions in general, micro-missions will require specialized micro-spacecraft subsystems. Because of the small, compact, and inexpensive nature of micro-missions, these spacecraft will likely need more extensive autonomous capability than simple TAG functions, including better ways to manage operations, and to handle samples collected from different locations. The New Frontiers Comet Surface Sample Return (CSSR) mission is one of several potential missions to small primitive bodies. Many of these new missions will require integrated multifunctional technologies such as TAG or different types of penetration systems such as harpoons, darts, or drilling end-effectors. Since ground testing of systems operating in microgravity is extremely costly, innovative approaches for integrated modeling and simulation of proximity operations will be needed to test system performance. CSSR will require advances in the areas of sampling and sample handling, efficient operation methodologies, precise global localization, and advanced options for surface mobility in the cometary microgravity environments, all of which could be enabled by multifunctional systems.

IV. Distributed Cellular Architectures

EPS approaches benefit from modularity, as they will like be composed into apertures of different topologies (sizes, shapes), and we consider these to be *cellular architectures*. Cellular architectures[12] represent an approach for interpreting the structure and function of systems. In this interpretation, even the most complex systems amount to at one level nothing more than a collection of primitive (albeit intelligent and flexible) building blocks that can under some set of principles allowing a collection to self organize, in this case to form MFSs. The cellular approach is especially useful (as are children's building bricks), when we wish to express a seemingly unbounded number of design variations with small number of block types. "Cellular systems" refers to systems whose construction is divided into periodic sections, such as a string of beads (1-D), tiles (2-D), or blocks (3-D). In mathematical abstractions, such as cellular automata, they can have an infinite extent. In physically buildable systems, of course, systems are not only finite but may have irregular, aperiodic, or non-uniform shapes, and may have heterogensous compositions (e.g., mixtures of different block/cell types). It is convenient, for example, to think of cellular

architectures as tilings, analogous to floor tiles, which can arranged periodically to cover arbitrary floor plans. The primary difference in the tiles we are interested in is that they are in general multifunctional, having built-in intelligence, sensing, and many internal subsystems, just as the cells in a biological organisms (though not the same types of subsystems). As in multi-cellular organisms, we are interested in combining many of these smart tiles to form larger structures.

We envision that cells represent "atomic" units, and that a cellular *system* is a structure involving one or more of these units. Cellular systems can be pre-built at the factory (so to speak), but it is interesting to consider the idea of self-organizing cellular systems, whose momentary configuration can adapt or evolve (i.e., in departure with a stock or factory configuration). It is also possible, rather than pre-assembled on the ground, that the cellular building blocks are brought together in the field to form a cellular system. Nature gives us many interesting examples, such the formation of virus capsid from a set of protein building blocks, as suggested in Figure 2.

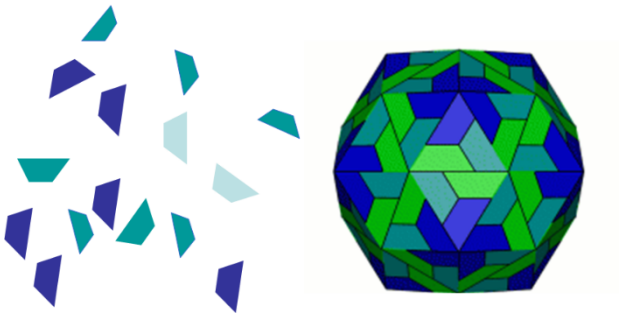


Figure 2. Self-assembly of a plant virus (cowpea mosaic virus) shell (capsid) from 120 protein building blocks.

We do not think of ourselves as a collection of many cells, but as sentient organisms with dreams and purposes. In this regard, cells – especially the artificial ones we discuss in this chapter – are but a means to an end. In the Study, we focussed on using cells to create an "energy-projecting multifunctional system" (EPMFS), in effect establishing an energy infrastructure using cellular building blocks. Cells in the Study were not only cast a potential means of achieving this end, but due to the need to embed other functions associated with "care and feeding" (setup and maintenance), they would opportunistically bring other functions as by-products, to include intelligence (computation, memory), communications (both locally between cells and globally to allow command and control), and the ability to bind physically, in some cases to possibly include the ability to physically orient or move (support locomotion). In this sense, cells form an extensible "smart substrate".

The primary motivations for cellular designs are: (1) inherent flexibility (aided by reconfigurability multifunctionality) to build an infinite variety of structures from a small palette of individual cell types; (2) composeability; (3) scalability; (4) potential defect/fault tolerance; (5) ease and speed of construction (potentially enhanced through self organization). They are proposed as a *disruptive* technology concept for space exploration. The concept of disruptive technology was proposed by Clayton Christensen[13]. While it is possible to describe the characteristics of disruptive technologies, we cannot always identify a particular concept is being "disruptive", simply on the basis of it possessing these characteristics. It is often only in retrospect that we come to understand that some of society's prevalent concepts (such as the personal computer) had their basis in the humble, ignorable beginnings of a disruptive technology. In the developmental ecosystems that give rise to disruptive technology, we seek to improve the state-of-the-art in dominant mainstream approaches (these are sometimes referred to as incumbent technologies). Many ideas (good and bad) are tried, and most of them are shuttered, never seeing the light of day. Even though some of these ideas are better than even the incumbent approaches, they are considered to impractical or too expensive to sufficiently mature to be competitive. Some of these ideas work, but seem at first at least to be far worse than the incumbent ideas that they compete with. If, however, some of these "shelved ideas" had been properly nurtured we might find that over time they perform better and improve faster than the incumbent technologies, so much so that they eventually eclipse those older mainstream ideas. This phenomenon (Figure 3) is the key behind disruptive technologies. These technologies are not always appreciated by the companies that study them, who often discard them long before their disruptive potential becomes clear to the competitors and upstarts that bring them to market. In a number of cases where they are brought to market, they eclipse and displace the previous incumbent technology. Since not every possible technology is disruptive, it is easier to simply dismiss entire bodies of research than to devote the potentially significant amount of energy required to curate and nurture most promising gems. This explains why, paradoxically, many of the disruptive technologies that eventually

eclipsed incumbent mainstream approaches were also funded (and ignored) by the companies who competitively suffered from their eventual success.

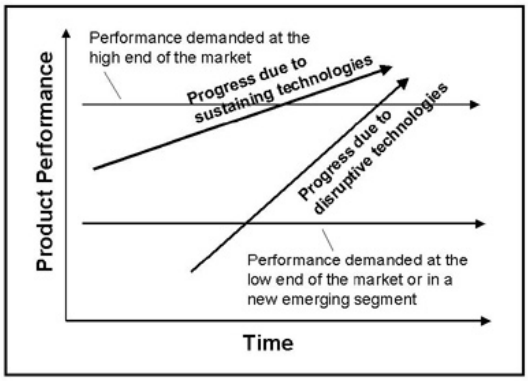


Figure 3. Product performance vs. time (From[13]).

Cellular technologies, if they succeed, will do so under a disruptive model. Their competition, which is the traditional methods that aspire to create optimized customized systems (involving usually expensive and protracted development processes), seems initially a better method. Disruptive approaches start as a non-obvious, even disadvantaged approach. But over time, this is not true, as suggested in Figure 3. Here, we see the interplay between the approaches, that of the conventional (traditional or "sustaining" technologies) and the cellular method (like the "disruptive technologies"). Through additional technology investment, however, the gap between the two can be brought down. Overhead and efficiency may not be the right measures; rather, it may be flexibility, scalability, defect tolerance, and possibly other metrics which are not considered as important in the "sustaining technology". This is because the sustaining technology model serves us well today, and some see no need to alter the model as our ambitions scale to interplanetary destinations.

Abstractly, the use of the cellular building block system is prospectively attractive for interplanetary applications, since it allows for maximum flexibility in forming a variety of structures in orbit and on planet surfaces, particularly when (1) any indeterminism exists in the number, size, and shape of desired structures exists; (2) there is a possibility of repurposing structures, (3) increased adaption is desirable to accommodate defects, faults, and hazards. It also embraces reconfigurability concepts throughout the energy, computation, and communication subsystems, in complement to the notion that systems are themselves different configurations or arrangements of cellular building blocks. These features are possibly more difficult in the traditional model of development. We believe reconfigurable cellular systems can be formed in ways that are robust, adaptive, scalable, leading to concepts that are compelling when considering mission designs for remote and inaccessible destinations.

Energy infrastructure: Under the cellular approach, an energy grid could be formed on planet surfaces as a ground network of energy harvesting sites. This is notionally suggested by Figure 4, which depicts a "fabric" formed with a cellular construction. The fabric, in actuality comprised of a number of nodes dropped densely on the surface of planets and interconnected, forms the energy infrastructure.

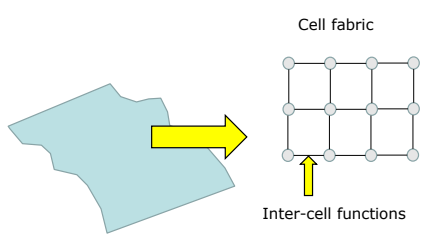


Figure 4. Fabric construction as a set of interconnected cellular sites.

The nodal sites, as part of the cellular network, could serve as the basis for an energy, communications, processing, and sensory infrastructural network. The approach could be considered to be an artificial type of terraforming, an

attempt to provide the energy and data networking grids that exist on our own planet in a fundamentally different way. Ostensibly, the sites forming these grids could be planted, augmented, and reused indefinitely as our ambitions to explore the solar system progress. Each cell itself is a system, capable of autonomous operation. They could extract sources of power on planet (e.g. possibly below the surface) and off planet (direct or relayed solar power), as well as sustain flexible modes of communications (namely the type of command, control, and data infrastructure needed to effectively conduct missions). Anyharvested energy above an ideally minimal threshold (for self-sustainment) would be available to be "invested" in missions. While the cells could themselves carry out simple missions (such as participating in mapping various sensory readings at different sites on planet), it is compelling to consider that they could contribute to a persistent service (in the spirit of an enduring infrastructure) for exploitation augmentation in the future by variety of missions, which might dock to a multiplicity of cell sites, preplaced in regions of interest, possibly further augmented over time (analogous to the phased upgrades of terrestrial energy grids), as suggested in Figure 5..

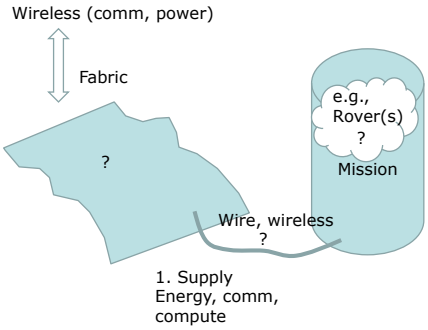


Figure 5. Simplistic depiction of energy harvesting scheme based on a cellular fabric. Cellular fabric is powered remotely. Missions tethered to the fabric can draw power and communications (and possibly other services).

Habitat construction: Although not a consideration of the original Study, cellular tiles and blocks might be a viable methodology for constructing all manner of base/facility surface structures in support of subsequent manned and unmanned missions, in conjunction with her separately from the offer mentioned energy infrastructure role. Here, again, the notion of MFS serves as a principle of economy, in which part of the terraforming of energy is also used to contribute to structural affordances.

Orbiting applications: As motivated in the original purposes of the Study (EPS applications), cellular structures would be useful not just on planet surfaces but in orbit. They would be formed by deploying a quantity of stowed cells/tiles to self-organize into structures on orbit. In principle such structures would be indefinitely scalable, permitting their augmentation by future missions to form larger structures for energy, communications, or space stations in general.

Energy capture through scalable solar arrays: Cellular designs seem naturally suited for creating scaled solar panels. Solar panels are essential in most spacecraft designs, except the very few that so far have been based on nuclear power (RTGs). The solar panels in spacecraft are either body mounted or deployed, the latter being necessary to overcome the surface serial limits of body mounted designs. Large spacecraft employ correspondingly large solar "wings", in which the goal is to optimize the ratio between deployed surface area and stowed volume. Custom-built deployed structure designs, due to their optimization, would undoubtedly outperform a cellular version (since cellular designs would carry additional overhead). However, the cellular design permits a greater variety of shape configurations, scalability due to the ability to cascade a theoretically unbounded number of cellular units, and flexibility to accommodate damage after deployment. They also have potentially superior resilience, since the cellular units can potentially manage their own power, allowing collections to overcome defects and hazards that might otherwise render an entire string or wing inoperable.

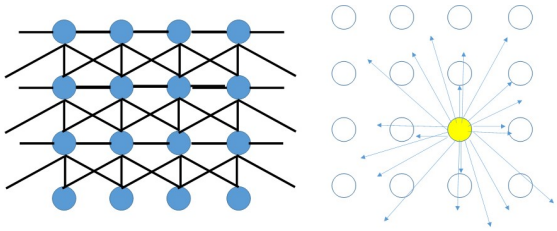
Energy redirection: For the EPS applications discussed previously, the cellular design could permit improved flexibility for steering and focusing light energy by programmably changing physical conformation of the overall structure as a set of primitive (cell by cell) shifts in position and angle. While the simplest approach involves steering and refocusing light energy from the sun, there may be advantages in re-radiating the energy and microwave form. In this case, cells would carry the ability to translate photovoltaic energy into radiofrequency form,

and transmit the energy (presumably through efficient solid-state power amplifiers embedded in the unit cell) either directly to the surface or to other points in orbit.

Communications apertures: Cellular designs permit the distributed formation of communications apertures, in which antenna as well as receiver and transmission electronics can be amortized across a number of tiles. Each tile, in addition to supporting a reconfigurable antenna/array system, could be supported by software/cognitive radio electronics, allowing for the exploitation of a variety of electromagnetic services beyond communications, to including ranging, timing distribution, microwave radiometry, and other functions.

E. Connecting Concepts

One of the important ideas that underlie cellular systems is the notion of local connectivity between neighboring cells. In the formalisms of cellular automata, complex behaviors of entire systems can be coordinated through an ensemble of primitive interactions over time. This restriction of cellular automata (which could be relaxed in the mechanizations described here) means that each cell can only connect to its nearest neighbors, as suggested in Figure 6a. This is an unnecessary restriction, as we often have the ability to broadcast signals over a large group of nodes (Figure 6b). Nevertheless, being able to design a system is collective behavior can be specified by local interactions is useful. In the cases of remote planetary exploration, a set of widely dispersed cells may in fact degenerate to local only (nearest neighbor) connections. We also must be concerned over defects in the structure of the network, to include missing links and missing nodes. These and many other departures from the ideal mathematical abstraction of cellular automata will be necessary in order to effectively harness these in real-world constructions. For this work, we are concerned with cellular systems based in two different regimes: tightly coupled and loosely coupled.



(a) (b)

Figure 6. Local and non-local neighborhood connectivity. (a) Local cellular connectivity. (b) Long-range connectivity (not locally confined).

Tightly coupled: The tightly coupled regime refers to cellular structures whose cells are in close physical proximity, based on regular tessellations or tilings. In one dimension, this results in forming a string or strand, and in two dimensions this amounts to surface tilings (like a flat floor were over a curvature as in the capsid of a virus). in three dimensions this amounts to a stacking of blocks, spheres, icosahedrons, etc., forming (in homogeneous cell groups and some heterogeneous cell groups) a class of crystalline structures. Even in the tightly coupled regime, we can depart from purely periodic order, leading to tangles, braids and knots (1-D), aperiodic tilings (2-D), and quasi-crystalline structures (3-D). Periodicity can be disrupted in other ways through defects, and the design of cellular systems can take these departures from ideality into account. In our spacecraft applications, the tightly coupled regime corresponds to fully connected aperture surface designs, and the formation of other structures. In, structures formed through the connected arrangement of individual tiles (each tile being called a "protosat"[12]) were referred to as macro-sats. Figure 7 illustrates these concepts. In the tightly coupled regime, a nontrivial structure is formed through a deliberate arrangement of primitive cell types. The case where the cells are identical is referred to as homogenous, whereas the case where cells are of a mixed time is referred to as heterogeneous. The heterogeneous cases is very useful as it allows for tile specialization. Even with reconfigurable multifunctionality, it is likely that not every function will be available in every tile. Some tiles may for example have a larger current concentration of energy storage, while others may have more advanced locomotion features. It may be useful to consider tilings that have some sparsity in some functions. In any case, we can consider the global specification of the overall structure to be a type of digital DNA. The DNA can be loosely compared to the biological version, but in only crude ways. Like in the biological case, the DNA in this case provides the blueprint of a complete system, to include specific notions of arrangements by type, location, and the details that would need to be programmed into the cells at each site. This DNA does not explain how the cells must be constructed however, and in order for the self-assembly in

this approach to work, it is important to establish mechanisms for geographic awareness, to include protocols for intercell communication, selective binding, and resource pooling/sharing.

Loosely coupled: The loosely coupled regime follows the cellular scheme, but works with highly distorted, discontinuous, and irregular neighborhood structure. It may superficially bear little physical resemblance to the periodic order of a traditional cellular automata. But loosely coupled cellular systems borrow heavily from the many concepts that work well with more tightly coupled designs, especially the mechanisms for cellular communication and ordering protocols. Whereas we might traditionally expect a tightly coupled cellular system to drive a recognizable, ordered structure (e.g., macrosat), loosely coupled cellular systems can be thought of more as scalable fabrics, having no expected and consistent structure, but work as an ad hoc collective. For the purposes of this study, we consider the methods for forming energy grids on planet surfaces to follow the loosely coupled model. It is in fact possible that the same tiles and protocols can be used in both cases.

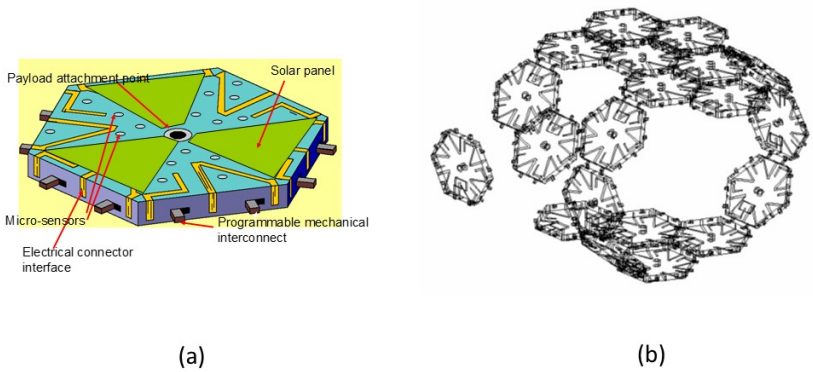


Figure 7. Tightly coupled cellular construction method for spacecraft. (a) fundamental cell, referred to as a "proto-sat." (b) Partial formation of larger spacecraft structure, referred to as a "macro-sat"[12].

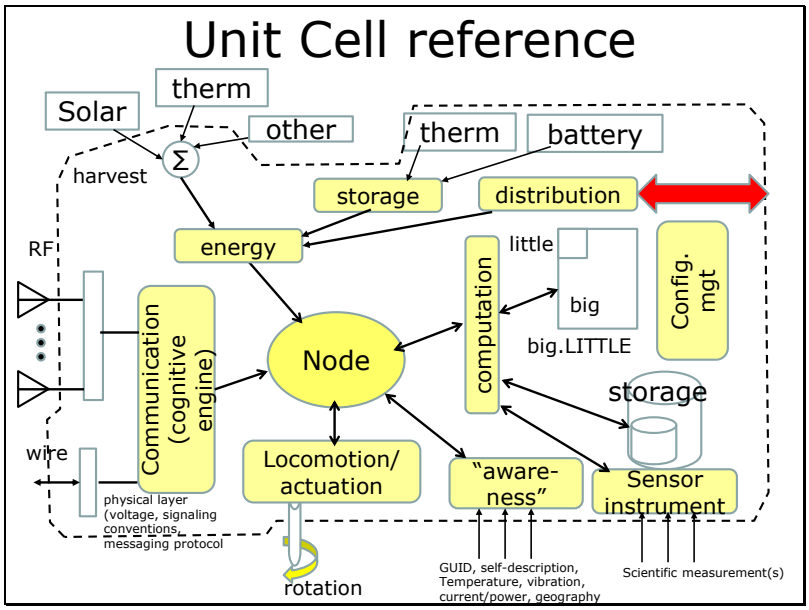


Figure 8. Unit Cell as a generic building block for cellular systems.

F. Fabric-Sat

"Fabric-Sat"[12] refers to a continuous sheet of unit cells that are pre-connected and fabricated together in the same overall process. It is a special case of the tightly-coupled regime, excepting that no physical self organization is required (cells are not expected to enforce or implement arrangements to create a system), however many of the concepts for intercell communication and collective resource sharing/pooling are applicable. It is convenient to think about the "fabric" as being a large roll (like wrapping paper or linoleum tile) which could be deployed to form the satellite as a free-standing "smart sheet". In principle, the Fabric-Sat could be cut into shapes from a larger roll, with the idea that the cells of that contiguous section would self organize to form a collective. These sections could be bonded to other structures as an appliqué, converting them in effect to a "spacecraft". The sections could be bonded together some way, presuming that the hooks for scaling our present and the connections are made in a proper way, so that multiple sections and rolls can be aggregated to form larger cellular systems.

Next, we consider the generic anatomy of a unit cell as the building block for the multifunctional, reconfigurable cells that we believe will be used form energy infrastructure in the solar system. The ideas described here are of generic appeal, not fundamentally limited to the role of energy infrastructure. In fact, as will be clear energy is only one of many potential grid-like infrastructure concepts. The basic idea of unit cell reference architecture is shown in Figure 8. This is considered a logical specification, not bound to any physical concept. As such, we can consider variations (or adaptations) of this idea for use in one-dimensional (e.g. tensegrity) designs, two-dimensional (e.g. origami, pixellated) designs, and three-dimensional designs. Features of this unit cell will apply in both tightly-coupled and loosely-coupled regimes

G. Subsystems

Just as a biological organism can be thought of as having a number of subsystems (e.g. skeletal, muscular, circulatory, etc.), collectives as well as cells can be thought of as having a number of subsystems. This section discusses a number of the subsystems associated with these artificial cells.

Electrical power distribution: Power distribution is a fundamental requirement in the concepts pertaining to scalable (i.e., more than one cell) energy infrastructure. The easiest way to imagine this is using a programmable switch matrix and a number of termini present in each cell. The basic concepts are shown in Figure 9.

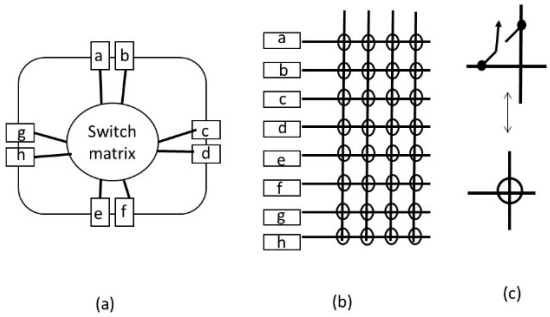


Figure 9. Cellular programmable power distribution concepts. (a) symbolic rectangular tile unit cell, having a total of eight power connection termini (two per edge). (b) details of switch matrix. (c) equivalency of circle to programmable switch point.

Each unit cell presumably can connect to its nearest neighbors, both mechanically and electrically. Here, we show eight termini capable of accepting or delivering power, two on each edge in a so-called "north-east-west-south" (NEWS) network. This concept can be of course adapted to hexagonal, trigonal, and other two-dimensional shapes, as well as one-dimensional (e.g., termini on each end of a one-dimensional segment) as well as three-dimensional (e.g., termini on "up" and "down" surfaces for cubes, or on other facets for more complex polyhedra). Each participating terminal is routed inside the unit cell to a switch matrix. There are many possible ways for constructing such a matrix, and schematic of a typical one is shown in Fig. 9b. In this case, all termini become rows of the matrix, and columns are wires. Each crossing is a switch point in this diagram, and the schematic equivalency's are shown in Fig. 9c. Fig. 10 shows how we can programmably route power connections through tiles. For the moment, we are not concerned with internal generation – sourcing-- or internal usage – sinking -- of power, just transmission. The concept is straightforward. If we know which power connections we wish to form (the same idea works for any type of electrical signal, hence these ideas can be extended to route analog, digital, or microwave/radiofrequency signals), we can establish a netlist (defined as a set of distinct connection specifications). For the problem shown in Fig. 10a, the netlist is {a-f, c-e-g, and b-h}.

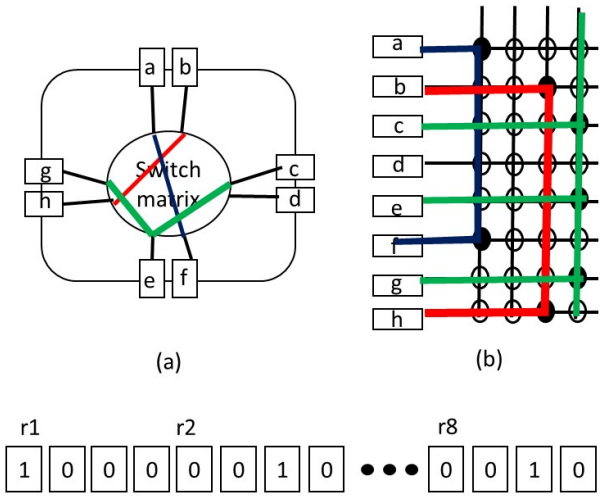


Figure 10. Power routing examples in which a unit cell bypasses connections between different edges. (a) Three different connections ("nets") are shown in color-coded form. (b) example solution using switch matrix, with switch closures completing the desired color-coded connections.

With a netlist specification, we can establish a pattern or "schedule" switch closures that will realize the desired conductivity, as shown in Fig. 10b. Since this pattern is programmable, we can define a convention, in particular a binary juxtapositional notation that unambiguously translates binary pattern to these switch closures. This is shown in Fig. 9, based on a convention of juxtaposing the Boolean state of each row. In hexadecimal form, we can then specify the pattern as "82101812". This can be viewed as a very tiny piece of digital DNA. Of course, the more interesting problems involve scale, and a straightforward(but extended) example is shown in Fig. 11 involving an arrangement of 16 unit cells. In this case, the power routing specification (Fig. 11) spans multiple tiles. This is a "global specification", which is implemented by translating it into a set of local specifications, each pertaining to a specific unit cell. The unit cells then individually implement patterns as required (following the Fig. 10 concept) to realize the global wiring solution. As the reader can verify, there are many possible solutions to this problem. Without further elaboration here, the astute reader can verify how removing one or more of the unit cells can impact the existence of a global solution. Some tiles can be removed, without affecting the existence of at least one solution to the global problem.

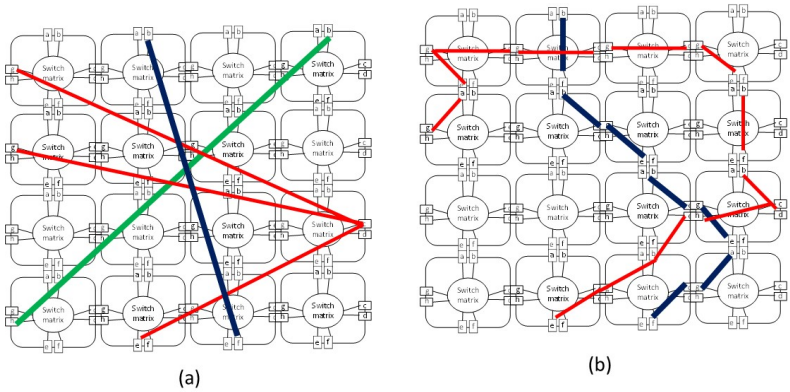


Figure 11. Multiple tile power routing problem. (a) Global specification of a 3-net wiring problem. (b) Translation into (non-unique) set of local wiring specifications.

Electrical power storage: Tiles can contain local energy storage mechanisms. The most common of these would be a battery, but batteries are neither the only storage solution, nor are they always the most effective solution. For example, ultra capacitors can be used. In some cases, while energy densities in the state-of-the-art ultracapacitors are below that of state-of-the-art batteries, they have the ability to deliver more power more quickly, and may maintain

storage at lower temperatures. There are also thermal energy storage concepts that can be converted to electrical power._With these concepts in mind, it is possible to extend the ideas discussed for power distribution to include internal electrical termini corresponding to power storage nodes, thereby extending the switch matrices to accommodate internal connections. As such, it is possible to shuttle power from one node to another, potentially combining these sources to aggregate and deliver power from many tiles to a single point.

Electrical power harvesting: Power generation and/or harvesting is an important consideration in tile design. Fundamentally, must power comes from solar. On the surface of planets, it is possible to exploit geothermal power, using some type of conduit from the surface to a point below (e.g., a spike) that connects to a thermally stable point. By using temperature gradients, a type of power harvesting mechanism can be established. Remote planets may offer grim prospects for power harvesting, hence multimodal schemes may be necessary to generate even modest amounts of energy. On planet such as Venus, assuming tiles could be built to withstand a hostile environment, there are many more lucrative forms of power harvesting. In addition to solar and thermal, there are excessive amounts of wind energy, tremendous pressure, and chemically active/corrosive atmosphere. As in the case of power storage, power generation can become part of the routable grid through accessory interior nodes which augment the routing switch matrices previously described.

Structural: The structural subsystem of the tile simply refers to the tiles physical embodiment. Ideally, tiles are initially dense for efficient stacking and storage. Once deployed, tiles could conceivably expand (if making them thicker provides an advantage for energy storage were structural rigidity). There are many possible ways of constructing the unit tile. One multilayer approach might be based on the following conventions:

- A top layer of each tile is a thin, transparent photovoltaic sheet (permitting capture of visible and infrared sunlight).
- A second layer is a thin, transparent sheet printed with a variety of antenna geometries, interconnected by PIN diodes, MEMS switches, or other electromagnetically suitable switching mechanisms.
- The third layer would contain the electronic brains of the operation, with microprocessors, memory, sensors, and transmitters and receivers both to handle the minimum for care and feeding and additional resources for externally supplied applications. The processes would run a lightweight but powerful software architecture capable of managing distributed systems and managing local interpretation of global rules and configuring tile internal subsystems
- A fourth layer is it possible thermal regulation / storage system
- A fifth layer would provide for power storage and distribution resources.
- A sixth layer could support physical accommodations for programmable attachment and optional deployments of standoffs and/or a mechanical structure to form a ~1m length spike, which could form the basis of the geothermal energy harvesting concept to exploit the energy differential between the surface and the soil a meter down. The burrowing concepts, and even efficacy of the approach, or problems requiring further study.

Programmable attachment: For tightly coupled regimes, the notion of programmable attachment becomes an important consideration. Notionally, it is beneficial to have the ability to selectively bind one or more edges of tiles to each other, so as to be able to form structures in deliberate design patterns. We present the basic set of concepts in this section. There are many possible mechanisms for establishing a programmable edge attachment. In our examples, we use magnets. We specifically allow for two different programmable states, one in which the North Pole the magnet faces the edge, the other being the inverse (South pole faces the edge), as shown in Fig. 12. We could also have employed mechanical gripping concepts for the attachment, programmable glues based on rapid cure thermoplastics, and other mechanisms. Ideally, the mechanism selected would be reversible permitting future rearrangement. Concepts for programmable attachment are also straightforward. As suggested in Fig. 13, two possibilities are permitted. In the first case, edges may promoted to attach to each other by ensuring that one tile has a different polarity on its connecting edge to the other tile (Fig. 13a). The other possibility is repulsion, which is done by ensuring that both edges of the same polarity (Fig. 13b). In fact, it would be desirable to have a third state, which is simply a passive state (neither attractive nor repulsive). That concept would be a simple extension of the ones shown here (we could be implemented for example a passive "stickiness" by permitting a half rotation, in the case of magnetic attachment concepts, as suggested in Fig. 14). The obvious extensions of the single edge programmable connection are shown in Fig. 15. As before, these illustrative examples are based on square geometries, and of course they could be extended to other polygonal (polyhedral for 3-D cases) geometries. Each edge/facet supports programmable attachment. As in the case of the routing matrices, it is convenient to encode the state of edges for programmable attachment as a binary vector using juxtapositional notation. We can define a default stickiness case ("0000" or 0 hexadecimal), and set bits accordingly. Programmable attachment is only

sensible for the ensemble (multi-tile) case. One configuration is shown in Fig. 15a. Here, we show the equivalent numerical representation of a multi-tile ensemble (Fig. 15b), based on the conventions illustrated in Fig 14. Based on the conventions established, it is necessary to program several cell states in order to have a stable structure. In other words, the default state (0000) will cause all tiles to repel in all edges. For example based on the scheme, we adopt a notion of "right stickiness" and "bottom stickiness", which leads to compact formula set. All tiles use "formula" or "rule" 0110 ("stick right", "stick bottom") unless:

- Right edge: terminate right stickiness. In this case, we set the local rule = 0010
- Bottom edge: terminate bottom stickiness. In this case, we set the local role equal à 0100.
- Bottom right corner: it is necessary to terminate the stickiness (i.e., "stop the sticky") by using the default rule =10000

These are the conventions necessary to make contiguous planar surfaces. Of course, nontrivial possibilities can be accommodated by appropriate rule configurations in the different tiles forming a complex structure. One example of the planar structure with "knockouts" is shown in Fig.16.

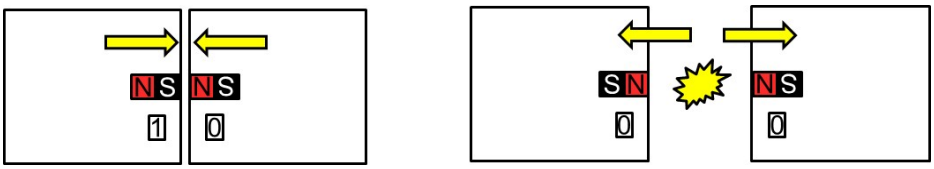


Figure 12. Programmable attachment using magnets. (left) default edge state. (right) programmed in version of default state (e.g. edge = "1").

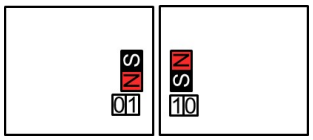


Figure 13. Passive "stickiness" using programmable attachment based on magnetic force, requiring 2-bit Boolean state to encode a third condition.

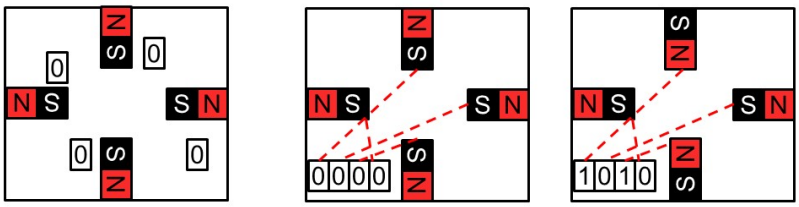
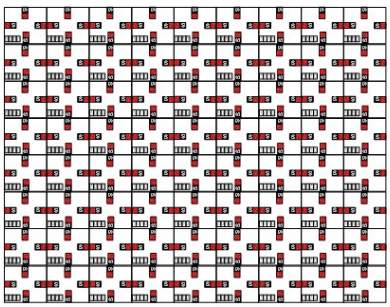


Figure 14. Programmable attachment using magnets. (left) default edge state. (right) programmed in version of default state (e.g. edge = "1").



(a)

0110	0110	0110	0110	0110	0110	0110	0110	0010
0110	0110	0110	0110	0110	0110	0110	0110	0010
0110	0110	0110	0110	0110	0110	0110	0110	0010
0110	0110	0110	0110	0110	0110	0110	0110	0010
0110	0110	0110	0110	0110	0110	0110	0110	0010
0110	0110	0110	0110	0110	0110	0110	0110	0010
0110	0110	0110	0110	0110	0110	0110	0110	0010
0100	0100	0100	0100	0100	0100	0100	0100	0000

(b)

Figure 15. Tile ensemble supporting programmable mechanical attachment. (a) 8x9 ensemble. (b) equivalent numerical representation.

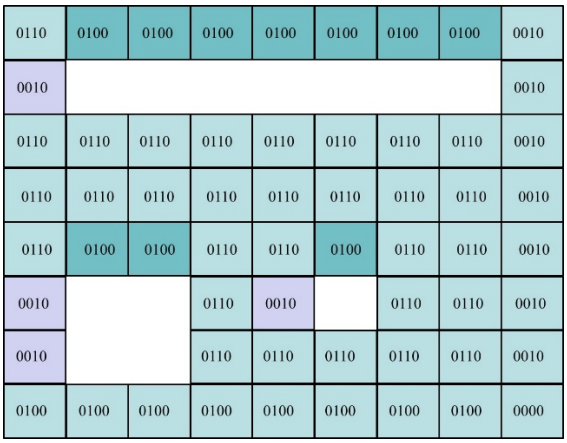


Figure 16. Planar tile surface with three "knockouts", formed by rule conventions.

Intelligence/computation: Even the most rudimentary of the features described requires some digital intelligence to manage state, mediate local and global rules, and handle other care and feeding issues. This could be accommodated by a very simple microcontroller, enriched with a special type of distributed software framework that allows extensions, scaling, and handles faults/defects in the cellular structures and systems formed.

Communications: Communications infrastructure involves the use of reconfigurable antennas, which can be formed by distribution of conductors connected by switches that could be set in a matter similar to that described for electrical power distribution and programmable stickiness mechanisms. Each cell would require a flexible software radio-based transceiver concept. Ideally the cells could work alone, in combination, and in phased arrays

Sensory: A number of sensing mechanisms are required in the cellular unit cell to accommodate essential care and feeding, such as variety of thermal sensors, current monitors, pressure sensing, and other mechanisms to ensure proper functioning of other subsystems. Additionally other sensors could be embedded the unit tiles to provide useful science, and support other interesting mission objectives. These range from the symmetry and analytic science instruments, to include more sophisticated cameras, vibration sensors, and other devices. In principle the communications subsystem could be fashioned into a rudimentary microwave radar, and distributed tiles can use a number of mechanisms if they possess precision timing facilities (such as Chip scale atomic clocks) to create a basic ad hoc implementation of the global positioning system.

Locomotion: Locomotion may be an important concept in some of the cellular tile concepts. It is not absolutely essential however, nor is it essential that all tiles carry locomotive facilities. Self organization self-assembly can exploit a number of passive principles and rely on opportunistic arrangements, such as a mechanisms used by some simple viruses which rely on ambient energy for transport.

Reconfiguration and configuration management: We have already discussed a number of reconfigurable subsystems, in which state information is conveyed through a Boolean string. In general, an entire unit cell is the juxtaposition of many sections of these reconfigurable subspaces. Hence a local tile has essentially a local digital DNA. The global configuration of many tiles is at one level the collection of all local digital DNA substrings, with additional information governing the positions of each local tile within the global construct. There are many interesting research problems that could be explored straightforwardly. It is not clear for example if it is necessary to rigorously specify all local digital DNA settings. As we've seen in the case of power distribution, there are for example many non-unique ways specifying power arrangements. Blocking these down as permanent patterns restricts flexibility. Hence we are more interested in specifying the global netlist is part of the digital DNA specification, and somehow equipping the collective to cooperatively solve the non-unique local specification problem. Moreover we are interested in a degree of robustness, such that if we lose local tiles for whatever reason, the collective can attempt to resolve the global problem and generate new local subproblems.

Cell specialization and heterogeneity: The concepts described here so far assume a homogenous reconfigurable unit cell. It is possible some tiles may have more wiring resources, more computation, more sophisticated radiofrequency facilities, etc. it is straightforward to consider heterogeneous arrangements as mixtures drawn from a library of cell types. We do not believe that this requires introduction of new concepts that careful thought in terms of the layout of physical design as well as the ability to accommodate heterogeneous bitstring specifications for the

different tiles. If, for example, there are five different tile designs and each is capable of doing some routing, it's important to understand these differences as global routing this mapped to local (nonuniform) cell types.

VI. Findings of the Study

The first workshop was held on May 19-22, 2014, and the second workshop was held on February 17-19, 2015. The goals of the first workshop were to determine a set of reference missions, system capabilities/architectures, and technologies that have the best chance of enabling energy-projecting systems in future missions. Based on the feedback received at the end of the first workshop, the goals of the second workshop were to report the results of a prototypical technical trade study for microclimate control involving exploration of alternate architectures and the identification of technology needs in the following technical areas: a) multifunctional systems; b) energy harvesting, conversion, distribution; and c) distributed system architectures. These areas are shown in Figure 17. Mission applicability was addressed in terms of relevance to extreme environment, and enabling aspects of NASA mission classes. The three main technology pillars that were identified in the Study are shown in Figure 18. These are: hybrid solutions for energy harvesting, multifunctionality and reconfigurability of critical components, and a paradigm to make these solutions possible based on distributed cellular architectures. These are described next.

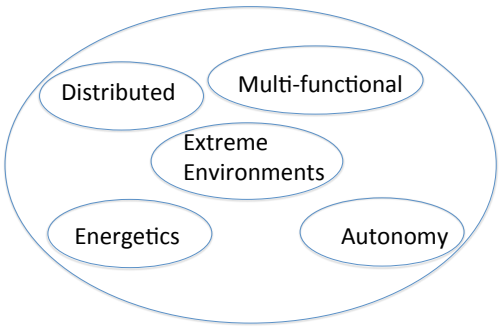


Figure 17. Technology parameter space discussed in the Study.

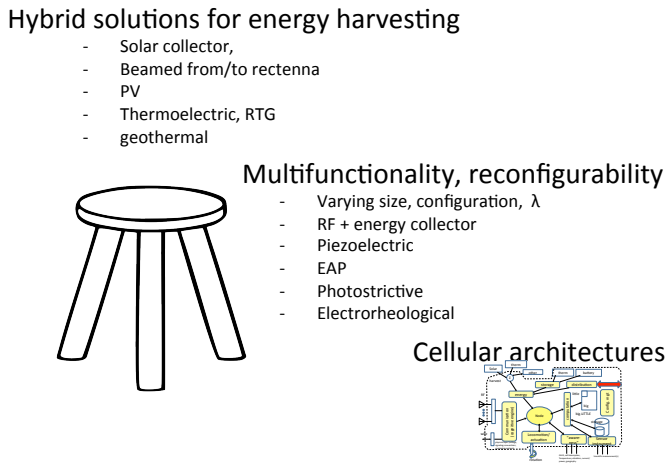


Figure 18. Three technology pillars that were identified in the Study.

Four planetary environments were considered in the Study: Titan, Craters/caves on Moon, Craters/caves on Mars, Venus. The mapping between the capabilities and the planetary environments is outlined in Table 1. Six promising high-level technologies were identified that could provide those capabilities and enable new planetary science missions to those environments. These are shown in Table 2 and are:

- Reflecting solar energy to a small photovoltaic (PV) array

- Converting solar energy (via PV approaches) to another wavelength (microwave, laser) and beaming that energy (either orbiting or ground based)
- Concentrating solar energy locally and converting directly to another wavelength (analogous to a solar pumped laser)
- Aerial "power plant" that would harvest energy from atmosphere (not solar energy) and transmit it to a lander station (cable, beaming) – possibly involving kites, balloons, etc.
- Ground based windmills, used as electrical generatorss.
- Large area deployed arrays, possibly suited for a stationary lander.

Capabilities	Lunar South Pole	Venus	Asteroid	Titan Missions	Mars caves	Mercury caves	Human exploration
In situ Energy generation	X	X	X	X			X
Energy storage	X	X	X	X			X
Energy distribution	X	X	X	X	X	X	X
Long term Survivability		X	X	X			
Leverage multiple assets	X	X	X	X	X	X	X
Flexible energy infrastructure	X		X		X	X	
Ensure line of sight	X				X	X	
Energy harvesting		X	X	X	X	X	

Table 1. Mapping between the capabilities and the planetary environments.

	Titan	Crater/Cave– Moon	Crater/Caves - Mars	Venus	Assessment
Reflecting solar energy to a small PV array	X	X	X		Works great to provide low power to a wide area (like a swarm of low power rovers or ground base station) – not so good on Titan or Venus due to low efficiency and losses through atm.
Converting Solar via PV to another wavelength (microwave, laser) and beaming that energy (either orbiting or ground based)	X	X	X		More efficient conversion and can be optimized for the desired wavelength. Needs receiver hardware. Highly directional with minimal collateral damage.
Concentrating Solar locally and converting directly to another wavelength (think solar pumped laser)	X	X	X	X?	Avoids inefficiency of PV conversion. Needs energy conversion tech development. Same advantages as above.
Areal "power plant" that harvest energy from atmosphere and transmits energy to lander station (cable, beaming) – kites, balloons.	X		X	X	Could use wind or thermal variations. Poses difficult steering problems for beaming. Need to assess the value of this architecture.
Ground based Windmills - electrical generator.	X		X	X?	
Large area deployed array for a stationary lander	X			X	Roll out thin film arrays to provide low power

Table 2. Identified high-level technologies.

Twelve different low-level technologies were deemed to be relevant to realize the above capabilities. These are shown in Table 3, and are:

- Large low mass flexible PV arrays
- Large low mass reflective surfaces
- Shape changing membranes
- Energy conversion systems
- Deployable structures, low load
- Load bearing/constructed structures
- Steering, pointing, and targeting
- Multi-functional communication (embedded antennas in structure, or dual use beam)
- Placement of distributed assets
- Extreme temperature materials (high and low), including PV cell
- Robust, light-weight cables
- Tailored PV cells for optimum efficiency (high intensity, or frequency).

	Large Low Mass Flexible PV arrays	Large low mass reflective surface	Shape changing membranes	Energy conversion systems MW, laser, turbines	Deployable structures – low load	Load Bearing / Constructed Structures	Steering, pointing targeting	Multi-function Comm (embedded antennas in structure or dual use beam)	Placement of distributed assets	Extreme temperature materials (high and low) incl PV cells	Robust, light weight cables	Tailored PV cells for optimum efficiency (high inten., or freq)
Reflecting solar energy to a small PV array	X	X	X?		X	X	X	X	X	?		X
Converting Solar via PV to another wavelength (microwave, laser) and beaming that energy (either orbiting or ground based)	X			X	X	X	X	??	X			
Concentrating Solar locally and converting directly to another wavelength (think solar pumped laser)		X	X	X	X	?	X	X	X	X		
Aerial "power plant" that harvest energy from atmosphere (NOT SOLAR) and transmits energy to lander station (cable, beaming) – kites, balloons.			X	X	X	?	X	X		X	X	X
Ground based Windmills - electrical generator.			X	X		X				X	X	
Large area deployed array for a stationary lander	X				X			X		X		X

Table 3. Identified low-level technologies.

Tables 4 and 5 summarize the hardware requirements involved in reflectors with multi-hopping capability, active support structures, manufacturability, solar cell arrays, actuation, sensing, control, and sensor types. Table 6 shows the computational classes that were identified.

Hardware requirements	
Reflectors for multi-hop	• High surface quality (wave length considerations) • Low thermal expansion coefficient • Thermal conductivity • Heat capacity • Foldability (large reversible deformations) • Survivability • Mechanical robustness
Active support structure	• High actuation efficiency (strain vs. power) • Thermal robustness • Mechanical robustness • Damping capacity • Foldability (large reversible deformations) • Mobility
Manufacturability	• In-situ space fabrication (e.g. 3D printing) vs. on-ground fabrication • Robotic assembly • Deployability

Table 4. Hardware requirements involved in reflectors with multi-hopping capability, active support structures, and manufacturability.

Hardware requirements	
Solar cell array	• Photovoltaic cells: high efficiency • Low mass density • Waste heat recovery
Actuation, Sensing & Control	• Correctibility: *high actuation strain and high sensitivity* • Low power needs (set and hold capability) • Low mass density • Survivability and robustness (*e.g. on Venus*)
Sensors	• Temperature • Wind speed • Pressure • Microwave power sensor • Pointing • Structural and system health sensors (SHM)

Table 5. Hardware requirements involved in solar cell arrays, actuation, sensing, control, and sensor types.

Computation Class/ Risk	Low Risk	Medium Risk	High Risk
Class 1	Next Generation Signal Processor (NGSP) (dual/quad core) / Use in small array	"Cloud" computation framework (100 servers), managed by NGSP	40k-core / neuromorphic architectures with tandem cloud / NGSP backbone
Class 2, expected controlled env for operation, but storage at extreme temp	Rad 750 or NGSP, with special packaging (hot environment may not work)	Rad 750 or commercial core in rad-hard HiTemp SOI technology (150 deg C)	Rad 750 or commercial (low) in exotic tech (hi) (SiC, vacuum tube, MEMS)
Class 3, operate at temp in env	(hot) none / (cold) rad6000 (verify operate at 90k)	(hot) none / (cold) lower-power core (verify at 90K)	(hot) 16-bit in exotic tech/(cold) 32-bit ULP CMOS
Class 4, operate at temp in env	(hot) simple FSM or analog/(cold) 8-bit CPU	(hot) 200-2k-gate FSM / (cold) low-power CPU	(hot) 8-bit CPU / (cold) ultra-low power (ULP) 8-bit

Table 6. Computational classes.

We next describe some key capabilities that will enable or enhance the missions outlined in the previous section that were the scope of the Study. The list of missions outlined demonstrates the multitude of challenges presented by future surface missions. Challenges general to virtually all of the surface missions include:

- Limited bandwidth and high-latency communications preclude real-time teleoperation (except to the Moon); thus, requiring a high degree of autonomy and reliability.

- Harsh environments lead to rapid degradation of components/systems and significant aging during longer missions. Achieving the required robustness and fault-tolerance in a cost-effective manner is a challenge of growing importance.
- The limited capability of available radiation-tolerant, flight-qualified processors constrains onboard processing even while avionic and software systems continue to grow in complexity. Currently, the performance gap between standard commercial processors, where the trend is toward greater parallelism, and flight processors remains large. Obtaining the levels of robustness and reliability required for space applications in the face of increasing cost constraints remains an open problem.
- Perhaps the single greatest determining feature of surface missions is the need to operate in a complex and only partially understood environment. We should point out that natural environments on planets are not always analogous to Earth. For example, comet surfaces, cryo-lakes, thermal extremes in shadows, etc., can require novel system designs and autonomy algorithms tailored for these new environments. Many of the future missions detailed above involve levels of interaction with the environment (terrain and soil, atmosphere, and lakes) far beyond those previously demonstrated. There is a need for improved environmental models as well as for planning and control algorithms that are robust to significant uncertainties to better address the challenges of steep slopes, operations in low gravity, or for aerial vehicles operating in changing and poorly understood winds.

Table 7 maps each identified capability (rows) to the mission types (columns) discussed above. The capabilities will be discussed in detail in the next section.

Capabilities	Lunar South Pole	Venus	Asteroid	Titan Missions	Mars caves	Mercury caves	Human exploration
In situ Energy generation	x	x	x	x			x
Energy storage	x	x	x	x			x
Energy distribution	x	x	x	x	x	x	x
Long term Survivability		x	x	x			
Leverage multiple assets	x	x	x	x	x	x	x
Flexible energy infrastructure	x		x		x	x	
Ensure line of sight	x				x	x	
Energy harvesting		x	x	x	x	x	

Table 7. Mapping between Mission types and Capabilities.

Table 8 describes key technologies that will enable the capabilities outlined in the previous section. These technologies are organized as follows:

	In-situ energy generation	Energy storage	Energy distribution	Long term survivability	Leverage multiple assets	Flexible energy infrastructure	Ensure LOS	Energy harvesting
Deployables					X		X	
Multifunctional				X				
Reconfigurable				X				
Multi-hop					X	X	X	
Dual-hybrid		X		X		X		X
Tethered distribution			X	X	X	X		

Table 8. Identified critical technologies.

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Finally, Figure 19 shows the outline of a proposed concept of deployable multifunctional, multilayer system based on a cellular architecture. An origami-like deployment is shown in Figure 19, top left, indicating the need for a highly compact, thin-film substrate that unfolds in a specific sequence, such as origami, as discussed in[14]. Once the (fabric-sat) system is deployed (Figure 19, top right), multiple subsystem functions such as communication, locomotion, and science instrumentation, are enabled by the on-board energy storage elment (battery). The cell fabric, shown in Figure 19, bottom left, is conceived as an aggregate of nodes, each one operating as a unit cell as the system described in Figure 8. Finally, each unit cell (Figure 19, bottom right), is conceived as a two-dimensional multilayer arrangement of multiple embedded functions, such as electromagnetic energy-harvesting, energy conversion, energy storage, and high-performance computing capabilities capable of enabling novel science instrumentation in planetary extreme environments.

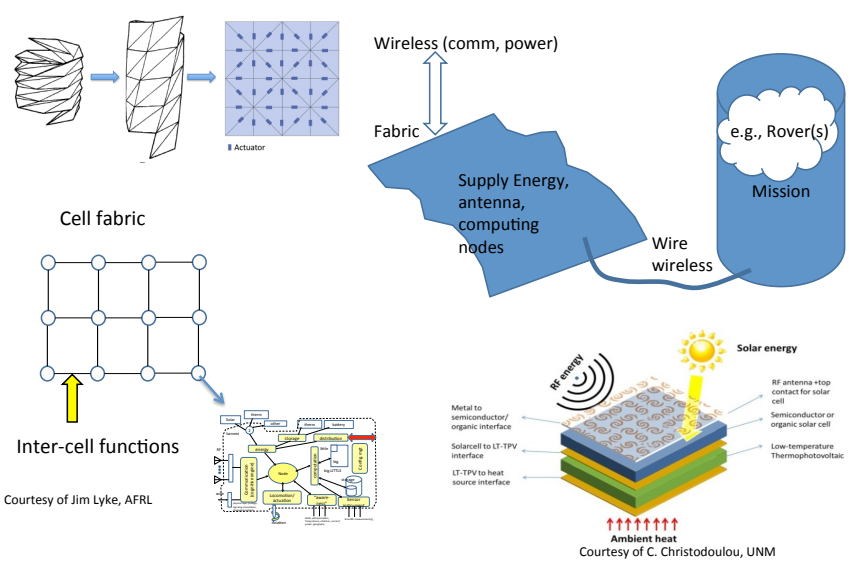

Figure 19. Outline of deployable multifunctional, multilayer system based on a cellular architecture.

V. Conclusions and Recommendations

This paper summarized the work done during the *Adaptive Multifunctional Systems for Micro-climate Control* Study held at the Caltech Keck Institute for Space Studies in 2014-2015, which we refer to throughout this paper as simply as "the Study". The Study included two workshops, one in May 2014, another in February 2015. The technical goal of the Study was to identify the most efficient materials, architectures, structures and means of

deployment/reconfiguration, system autonomy, and energy management solutions needed to optimally harvest energy around space assets in extreme environments. This novel solution is called an energy-projecting multifunctional system. For example, compact packed thin-layer reflective structures unfolding to large areas can reflect solar energy, warming and illuminating assets such as exploration rovers on Mars or human habitats on the Moon.

The outcomes of this study included: a) identifying exploration/science drivers, and discussing examples of classes of mission concepts enabled by the energy-projection capability: solar concentration, light re-direction, and micro-climate generation/projection; b) establishing fundamentals (state-of-the-art, challenges) of the key technology areas of materials/structures, packing/deployment, and adaptive hardware and software reconfiguration, and c) identifying technology gaps of each area, as well as areas of focus where further technology investment would be required, leading to the definition of a path for future research and development programs that would develop, mature and apply these capabilities in order to enable the energy-projection capability.

Several technology disciplines are involved in this challenge: distributed architectures, multifunctional systems, extreme environments, energetics, and system autonomy. Among these, the Study has identified three critical technology areas that would enable an energy infrastructure capable of supporting new challenging planetary science missions in EE. The first area is **hybrid solutions for energy harvesting**, in which energy gathered via solar collection/concentration using photovoltaic elements is beamed via microwaves to an in-situ thermoelectric conversion element, with energy storage capability. The second area is the paradigm of **distributed cellular architectures**, in which multiple intelligent nodes (each node a highly compact unit integrating multiple sub-functions such as power, communication, computing, energy-harvesting) are part of a scalable network architecture that could take the form of a "fabric-sat," compactly stowed and deployable to a large area. The third area is **multifunctional and reconfigurable systems**, which combine the versatile actuation capability of intelligent materials (electro-active polymers, photo-strictive, piezoelectric, magnetostrictive) to realize foldable and deployable two-dimensional flexible electronic devices with geometric morphing capabilities which, as they harvest energy at the nodes, can also operate as a reconfigurable electromagnetic aperture of large area, leading to high data rate communication at varying bandwidths.

VI. Acknowledgments

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