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Sensor Web for *In Situ* Exploration of Gaseous Biosignatures

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Abstract - A Sensor Web is a system of intra-communicating spatially distributed sensor pods that can be deployed to monitor and explore new environments. By its very nature, the Sensor Web provides spatio-temporal data in a form consistent with that needed for environment modeling and represents a new paradigm for *in situ* monitoring and exploration. For example, a wireless web of scattered sensor pods on the Martian surface is an ideal way to pursue gaseous biosignature searches. Sensor Web climate and agricultural monitoring on Earth (particularly when coupled with remote measurements) characterize significant commercial opportunities for this technology. Recent laboratory demonstrations at the Jet Propulsion Laboratory (JPL) have shown the potential of current Sensor Web technology. These demonstrations are leading to a JPL effort to field a Sensor Web in Baja California to examine gaseous biosignatures from the microbial mats there.

TABLE OF CONTENTS

1. INTRODUCTION

Recent advances in sensor, computation, and communication technologies allow for a radically new type of scientific instrument: the Sensor Web[1,2]. This instrument contains sensors distributed spatially and communicating among themselves in a wireless networked fashion. Each network node consists of two modules, the transducers that physically interact with the environment and collect data and the communication chips that move the data around the network. The intra-web, node-to-node communication not only reduces the power required to transmit data out of the web to an uplink but also allows for power-efficient operation of node sensors when a spatially dynamic environmental front passes over the instrument. We expect that this global sharing of information will lead to pod synergism (the sum of their activity being greater than the parts) and permit intelligent resource (power, bandwidth) management by the web. Included among the obvious benefits of this scheme are the possibilities of roverless surveying, built-in fault-tolerant redundancy, and spatially scaleable experiments.

The Sensor Web provides a new archetype for *in situ* instrumentation and experiment design. Spreading a multitude of web nodes over large areas is a cost effective way of examining planetary surfaces. Interconnected Sensor Webs could become a global-scale instrument capable of providing data, for example, on the carbon and sulfur cycles on Earth. By its very nature, the sensor web would provide spatio-temporal data in a form consistent with that needed for biosphere modeling. Because of its inherent light mass and flexibility of deployment, the Sensor Web is ideal in the context of extra-terrestrial missions as well. A Sensor Web outfitted with microsensors creates an advanced, innovative, micromission-style instrument that enables extraterrestrial life-detection searches and planetary modeling.

As a specific demonstration of the Sensor Web's capabilities, we have focused on building a web for monitoring biogenic gases produced by algal mats in Baja California. Remote sensing is inadequate here because it measures over large atmospheric columns and is not capable of detecting the low concentration of gases that is expected to disperse quickly at the planet surface. Only an *in situ* instrument directly at the surface-atmosphere interface can provide the type and quality of measurements required. Only a sensor web can provide the coverage of

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measurements needed to perform detailed modeling while still subject to the dollar, power, and mass constraints associated with planetary monitoring.

By joining low-cost, low-power gas detectors with sensor webs, it will be possible not only to detect the presence of biogenic gases, but also to map the full geographic, diurnal, and seasonal variations of those gases over large spatial and temporal scales. Such data is crucial for accurate modeling purposes. In addition, the intrinsic stochastic nature of biosignatures requires multiply redundant measurements to weed out anomalous signatures. Additionally, because the *in situ* sensor web can also monitor local meteorological conditions, it will be possible to further distinguish between possible biogenic gas motion and mere mesoscale meteorology.

Finally, from power considerations, it is important that the data transferred from node to node be low bandwidth in nature. As a result, data collected must be either low bandwidth in nature or have been significantly compressed or preprocessed at the node before transmission. Most sensor measurements associated with biological activity, such as those discussed here including local atmospheric conditions and biogenic gas detection, satisfy this low bandwidth constraint.

2. THE SENSOR WEB INSTRUMENT

Description

As shown in Figure 1, the sensor web consists of a few prime nodes (boxes in the picture) with many secondary nodes (shown as spheres). Each node, here pictured as about 20 cm^3 or less, consists of a sensor transducer suite to collect data appropriate to the experimental or monitoring task at hand and a transceiver section to send/receive this data to other node points. Fault tolerance is guaranteed if the maximum communication distance of each pod is at least as great as its next nearest neighbor distance.

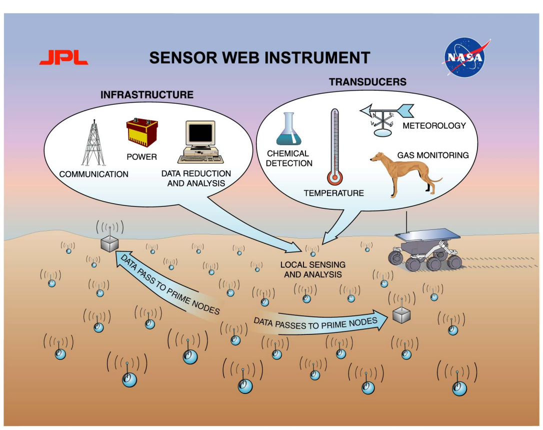

Figure 1 The Sensor Web Instrument. Note the relative size of the individual pods to that of the Sojourner rover.

The prime nodes have the additional capability of communicating signals into and out of the web. At a prime node, for example, web data can be uplinked to an overhead satellite or ported to a local field computer. Unlike architectures currently used for environmental monitoring (such as seismic activity), there is nothing particularly special about the location of the prime node relative to the rest of the web. Since each node (including the prime) is equivalent in terms of intra-web transmission, the sensor web as described goes far beyond the star-network geometries currently associated with distributed sensors.

Hopping the data from node to node not only allows for sharing locally collected data to other parts of the web but also is power efficient. From elementary electromagnetic theory, the total power required to transmit a signal that ensures a received power P_{rec} a distance D away is $P_{tran} \propto (D/\lambda)^m P_{rec}$ where λ is the wavelength of the transmitted signal[3]. Here m is 2 in free space and can range to 4 or more in environments with multiple-path interferences or local noise. As a result, the total power required to transmit a given distance with N hops is reduced by a factor of $N^{(m-1)}$ compared to the total power required by direct transmission. In the simple case of free space (m=2), this fact is easily demonstrated graphically in Figure 2. It is clear from the figure that the surface area of the collection of smaller spheres (multi-hop transmission) is much less than that of the larger one (direct transmission). The reason why hopping data is power efficient is that more of the power is directed along the path to the receiver. Since the free space case is the best case scenario in terms of transmission efficiency, the value of hopping is only increased in more hostile environments.

The very essence of a sensor web, with its multiply redundant nodes, allows for an instrument to be "reseeded" against instrument degradation. In other words, as various nodes drop out of the web because of spent batteries or damaged transducers, it is possible to redeploy new pods in

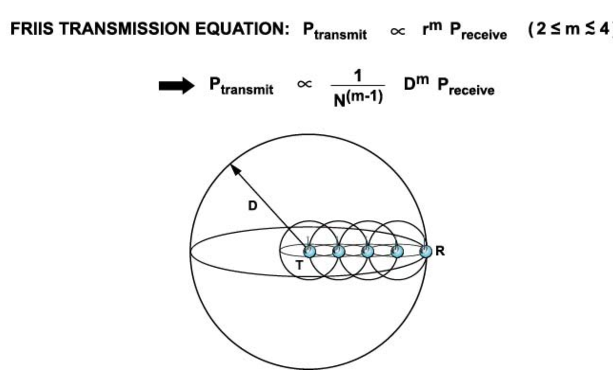

Figure 2 Multi-hopping is more efficient power-wise than direct transmission.

the instrument area that will seamlessly mesh with the existing, older web communication backbone. In this way, though the pods themselves are expendable, the sensor web instrument can continue to function indefinitely. Moreover, this reseeding allows the macroinstrument to evolve over time as new pods can be more sophisticated and technologically advanced than older ones. Finally, because the sensor web has no definitive boundaries (the prime nodes may be located anywhere in the network), multiple deployments of webs in a given area will naturally mesh with one another. Consequently, a sensor web represents an instrument whose surveying area can be expanded via multiple deployments.

In its most abstract form, the sensor web can be thought of as an imaging device with each node point a pixel in the phase space represented by the transducer suite. To appreciate the analogy, consider a sensor web of the same mass as the Sojourner rover which explored Mars. The rover and its associated deployment mechanisms weighed about 15 kg. If each node pod weighs about 100 g, it would take about 144 pods for the sensor web to have the same mass. This is a 12×12 array. Assuming a minimum communication distance of 50 m between pods (attainable with commercial transceiver chips), the "image" area associated with this sensor web is 500×500 m^2 with a 50 m resolution. In addition, the image can change as a function of time, allowing for the sensor web to create virtual movies in the phase space associated with the transducers. In contrast, the Sojourner rover moved only a maximum of about 7 m from the Pathfinder lander[4]. Thus, while rovers are ideal for moving instruments around on a fine scale, sensor webs are important tools for large area surveying and establishing a virtual presence over the entire region.

Deployment

A key feature of the sensor web is the flexibility in its deployment. The relative ease of deployment permits more of the mass associated with the instrument to be the instrument itself. Because the pods are plentiful, small, and lightweight like plant seeds, it is useful to look to nature to develop efficient deployment schemes[5]. As a result, the pods may enter an environment in a number of different ways, depending on the specific application as illustrated in the land-based sensor webs of Figure 3.

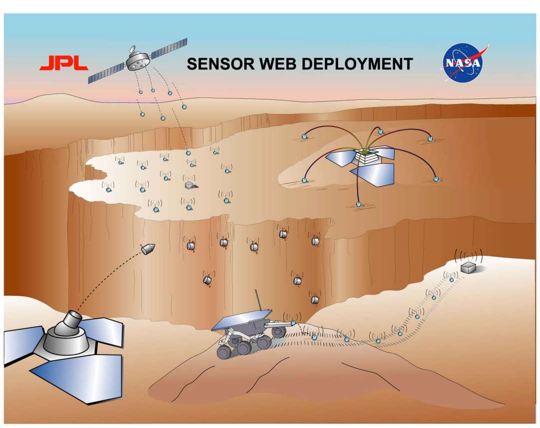

Figure 3 Various deployment schemes.

Deployment in a planetary environment can consist of dropping the pods in a stream out the back of an airplane, or, in the case of Mars, from a descending lander (similar to the Deep Space 2 probes), with small parachutes or rotors used to lessen ground impact (upper left portion of figure). Dropping the pods from balloons is also an option. These are perhaps the most energy efficient ways to disperse the pods. In another scenario, the pods can be fired from a central point (such as a lander) to surround the base station (lower left portion of the figure). This raises the possibility of ballistically driving the pods into the side of a steep canyon wall which could not be surveyed by conventional techniques. The sensor web in this case would be vertical in orientation. The pods can also be dropped out the back of a rover (lower right portion of figure). This deployment scheme allows the pods to serve not only as data collection points, but also as a communications link between the rover and lander for over-the-horizon communication (as may occur in meteor crater sites). Finally, the pods could be attached to the central craft (like streamers) via a fiber optic link (upper right portion of picture). This scheme does allow the possibility of wide bandwidth communication and is potentially useful in deep ocean environments as well.

There are also secondary deployment issues as well. For example, the pods could be covered with stickers allowing them to stay put during a wind. Conversely, the pods could be covered with aerodynamic cups like a pinecone allowing for overall web movement during a wind. A vane-like device can also be attached to the pods to allow a wind to screw the pod into the ground permitting subsurface sensing.

Construction

The Sensor Web represents, by definition, an instrument where the economy of scale can be directly exploited. Although any particular sensor web is a single instrument, it is made up of dozens, even hundreds and thousands of *identical* pieces. The cost of larger instruments therefore *decreases* on a per unit area basis.

Additionally, the sensor web hardware can leverage off of the present twin revolutions in computation and communication technology. Often the commercially available technology *is* the state of the art technology. For example, cheap, micropowered transceiver technology broadcasting in the ISM band (roughly 916 MHz) is readily available. Many of the more obvious transducers required for baseline sensing (*e.g.* temperature, pressure, light) exist in low-power commercial form as well. Furthermore, the art of integrating multiple, low-power micromachined sensors into a single package is presently being refined in the laboratory[6]. Finally, embedded microprocessors are becoming more sophisticated and memory chips are becoming cheaper. Consequently, raw data can be analyzed, interpreted, and reduced locally at the pod itself, thereby allowing pod-to-pod data transmission to be low bandwidth, and hence, low power.

3. Application Specifications

The applications for sensor webs are vast because in principle they allow for information synthesis over a large spatial area involving measurements and tracking of dynamic phenomena over multiple length scales simultaneously. Consider, for example, the situation when the Mir Space Station's hull was breached when it was hit by a cargo vehicle. It was clear to the occupants of the station that air was leaking out, the problem was which module to seal off[7]. A Sensor Web in the station would have greatly aided in leak *location* rather than mere leak *detection*.

There are 5 environments where sensor webs can be deployed: space, atmosphere, aqueous, land, and artificial (i.e. buildings and spacecraft). There are essentially two categories of sensor web uses: passive monitoring and active exploration. There are therefore a total of 10 classification of sensor webs and it is important to understand the intra- and inter-group similarities to best identify the technology needed for a specific application. Moreover, it would aid in seeing how an existing sensor web might be applied into a new scenario. The box presented to the right represents a way to organize the diversity of applications along meaningful categories.

First, of course, is a definition of what the web will do. The ultimate uplink/downlink point is important because it will impact the way in which the information gathered from the web will reach the end user.

Next, the spatial aspects of the web must be considered. Dimensionality affects the degree of intercommunication between the various node points. A sensor web for leak location along the Alaska pipeline is an example of a 1D system, while the a series of deployed balloons of differing buoyancy to determine air movement is an example of a 3D system. Because intra-web connectivity is associated with the degree of potential information synthesis, lower dimensional webs are more limited in their ability to interpret their environment. The expected physical distance between neighbors and pod distribution constrain the type of communication links between pods.

The measurements associated with the application constrain the type of sensors needed as well as the on-board computation abilities of the pod. In addition to the web-scale (global) information synthesis, a pod-scale (local) information synthesis can be required as well. This helps to limit the amount of information that need be sent pod-to-pod. The precision of each measurement is also related to

Application Issues

1.0 Sensor Web Description
- 1.1 Goal of Web Usage
- 1.2 Passive Monitoring/Active Exploration
- 1.3 Ultimate point of uplink/downlink

2.0 Spatial Scale
- 2.1 Dimensionality (1D, 2D, 3D)
- 2.2 Area coverage
  - 2.2.1 Ideal
  - 2.2.2 Minimum
- 2.3 Average distance between nearest neighbors
- 2.4 Distribution of pods (uniform/clumpy)

3.0 Measurements
- 3.1 Number of measurements at each pod
- 3.2 Frequency of each measurement
- 3.3 Precision of each measurement
- 3.4 Local processing/reduction of data
- 3.5 Total lifetime
  - 3.5.1 Pod lifetime
  - 3.5.2 Application lifetime

4.0 Information Scale
- 4.1 Transmission of measurements (hopping)
  - 4.1.1 Frequency of transmission
  - 4.1.2 Size of transmission packet
- 4.2 Maximum latency tolerated to receive information at uplink/downlink
- 4.3 Event driven requirements
  - 4.3.1 Reaction to environment
  - 4.3.2 Reaction to internal web conditions
  - 4.3.3 Maximum latency tolerated to react to event
- 4.4 Measurement dropout tolerance
- 4.5 Node dropout tolerance

5.0 Web Environment Description
- 5.1 Static/Cyclical (and time scale of cycle)
- 5.2 Wet/Moist/Dry
- 5.3 Thermal Stress
- 5.4 Pressure Stress
- 5.5 Chemical Stress
- 5.6 Ecological Issues

6.0 Pod Description
- 6.1 Maximum size of pod tolerated
- 6.2 Maximum weight of pod tolerated
- 6.3 Power source (e.g. battery, solar cells)
- 6.4 Pod uniformity (task differentiation)
- 6.5 Mobility

7.0 Pod Deployment
- 7.1 Placement strategy
- 7.2 Location
  - 7.2.1 Absolute to environment
  - 7.2.2 Relative within web

this issue; the more bits required, the more information need be sent. Some measurements, such as those associated with wet chemistry, require consumables onboard the pod. Again, environmental conditions, as determined by the overall web, may need to be monitored before performing such measurements. Finally, the individual pod lifetime must be weighed against the total lifetime of the application to determine if reseeding or multiple deployments is required.

The node-to-node communication issues are closely related to measurements issues but form their own class because the measurements may well be interpreted locally before needed to be transmitted. Latency is a key concern here, particularly when examining situations where delays are not tolerated (like battlefield examples) or where information is collected on an event-triggered basis (like earthquake monitoring). Lost information to the end user, either from a lost packet or a lost node, needs to be considered as well. This will influence decisions about transmission coding schemes, from very robust, but more power-hungry ones, like spread-spectrum for military applications, to more simple ones, like on-off keying for routine monitoring in some agricultural applications.

The next two categories describe issues associated with pod construction and packaging. As sensor web pods are expected to be deployed in large numbers in many delicate environments, the impact of the hardware and pod-to-pod communication on the environment must be considered carefully. This may require a total recovery of the sensor web after a specified amount of time. Pods also need not all be identical, and task differentiation is possible. For example, consider a large collection of pods containing low-cost, low-maintenance, electronic noses that are sprinkled with a few more power-hungry, but more sensitive and precise mass spectrometers. In this arrangement, the electronic noses detect gaseous fronts that trigger when the mass spectrometers need to be turned on. The web assets are thus internally managed. Pod mobility also raises interesting possibilities from one extreme of anchored pods, through passive, unconstrained motion (such as buoys on an ocean surface), to active, web-determined motion (such as pods integrated into mini-rovers).

Finally, pod deployment is an issue that will impact both pod construction as well as inter-pod communications. The ability to specify the spatial position of a particular measurement is crucial not only for passive mapping of phenomena but also for local information synthesis and decision making.

4. Laboratory Demonstration

Over the past year, we have gained significant experience in working with and developing Sensor Webs. A demonstration of the concept has been made at the Jet

Figure 4 Functional Sensor Web pod (on left). Extraterrestrial on right. Note size of quarter.

Propulsion Laboratory using commercial components, a typical pod is shown in Figure 4. Contained in this small package are the transmit/receive chips (from RF Monolithics[8]) which operate at 916 MHz and are capable of data transmission at rates up to 20 kbs using amplitude shift keying. Over a duty cycle of one set of measurements per second, it is estimated that 50 microwatts of power are needed and thus there is low power drain associated with the communication backbone of the Sensor Web. The sensors contained in the package measure local light level and temperature. The pod is powered by a 3 V Li battery hidden in the base. Total pod mass is about 50 g.

To demonstrate the low-power hardware envisioned for the Sensor Web, three identical sensor pods were assembled. A fourth pod was attached to a laptop computer; this served as the prime, or mother, node where the data were displayed. The protocols developed organized the pod broadcasts by specific time slots.

The 4-node Sensor Web was demonstrated in two arrangements as shown in Figure 5. The first consisted of a linear layout, where each pod could only communicate with its nearest neighbor. The mother node was able to receive the temperature and light data from all points, thus demonstrating triple hopping as the data was transmitted along the line in a daisy-chain manner. The second demonstration consisted of a dense diamond layout. Here, two of the pods could communicate with all nodes

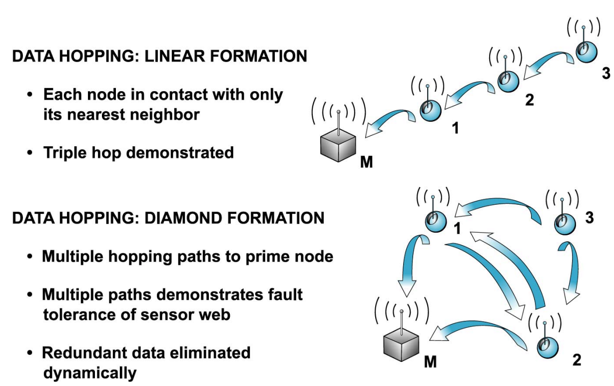

Figure 5 Sensor web geometries demonstrated.

simultaneously. Because of this redundancy, the removal of either these nodes from the web did not interrupt the flow of data from the farthest point on the web to the mother node, demonstrating the fault tolerant property of the sensor web. Moreover, the redundancy in the web creates redundancy in the data transmitted in the web. The web protocols are designed, however, to eliminate this redundant data dynamically, lest the Sensor Web be overwhelmed with information. Again, the temperature and light levels at all three node points were displayed correctly at the mother node. In both demonstrated geometries, the mother node is not located centrally, showing how a sensor web is more than a simple star-network.

5. Gaseous Biosignature Monitoring

Scientific Motivation

The use of gases as biosignatures has become an important thrust area for NASA. For example, the Terrestrial Planet Finder represents a space interferometry program to probe atmospheres of extra-solar planets for gases driven out of chemical equilibrium, presumably by biological activity[9]. From a similar scientific rationale, we propose that a Sensor Web can be used as an *in situ* instrument to detect life by looking for trace amounts of biogenic gases that are too low in concentration to be observed remotely.

It is not known *a priori* which gases would be biogenic on other planets. Therefore, one promising method to search for chemical signatures of life is to do a broad, unbiased chemical survey of an atmosphere. This can be followed by detailed modeling that identifies those detected species whose atmospheric distribution cannot be explained by thermodynamic, geochemical or photochemical processes. By elimination, we arrive at the possibility of biological processes (sources and sinks) that may be operating on the planet.

Because bacteria are thought to be the most primitive and ancient life forms on Earth, they are the logical target for searching for life on other planets. Planets that harbor bacterial life will likely have a metabolic signature in their atmospheres.

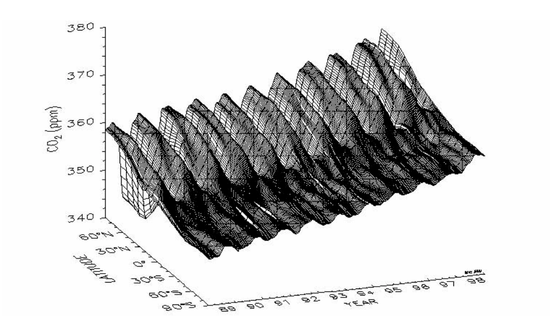

Figure 6 Global CO_2 data from NOAA. See also http://www.cmdl.noaa.gov/ccgg/figures/co2rug.gif.

A network of measurements is needed so that models can be applied to the data over spatial and temporal scales. The modeling will address whether the chemical species detected are produced by a putative bacterial community distinct from atmospheric constituents resulting from photochemical and geochemical processes. As an illustration, consider the global data of CO_2 taken by the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostic Laboratory shown in Figure 6. The data clearly shows pronounced seasonal and latitudinal variations of CO_2. The variations are of such magnitude as to be incompatible with chemical or geochemical processes. A very simple modeling effort will lead to the conclusion that the CO_2 variations are the results of an active biosphere.

The microbial mats in Baja California are a confined, terrestrial target where all the features of a Sensor Web can be examined in an biological context. The top layer of a microbial mat is generally composed of filamentous cyanobacteria[10]. These bacteria produce oxygen during daylight, which diffuses through the upper portion of the mat to be consumed by heterotrophic and other bacteria involved in, for example, H_2S, FeS, NH_3, or CH_4 oxidation. Within a few millimeters, the O_2 is completely removed, and the anaerobic bacteria thrive. These organisms produce copious amounts of H_2S by reducing sulfate[11]. Also, denitrifyers, methanogens, and anoxygenic photosynthesizers are often present in the anaerobic zone of microbial mats. All of these bacteria are involved in either the production or consumption of gaseous compounds. Indeed, the rise of O_2 in the Earth's atmosphere was entirely due to production by cyanobacteria.

Prototype Sensor Web

A Sensor Web to monitor the metabolism of the algal mats is currently being constructed and illustrated in Figure 7. The pods will be scattered over an area of order 100×100 m^2 which will provide stochastic measurements as well as encompass several different microenvironments. The prime node will be stationed at the home base campsite and will

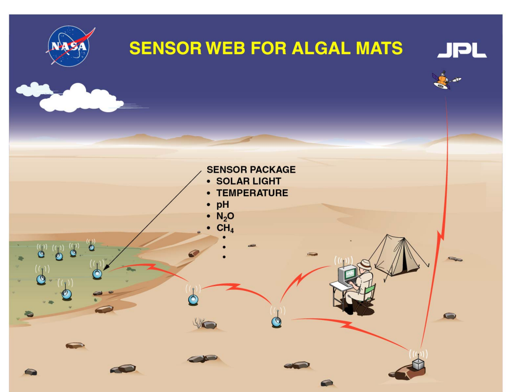

Figure 7 Algal mat experiment.

provide 24 hour monitoring over two diurnal cycles. Ground-truth for the field instrument will be established by collecting and analyzing gas samples around the microbial field by hand using a gas chromatograph/mass spectrometer.

A sample pod is shown in Figure 8. There are a total of 6 sensor measurements that will be made by each pod. H_2S and O_2 gas sensors (from Figaro Inc.[12]) are located on the right side of the pod. Ambient humidity and temperature will also be measured as well as the temperature of the mat itself (this last measurement is made by the thermocouple hanging outside the pod seen in the inset). Finally, ambient light is measured on the top of the pod.

Because the H_2S sensor is relatively high power, solar cells (seen in the inset) enable local energy harvesting and will trickle charge the battery. The rest of the pod is micropowered. In the future, an electronic nose could increase the number of gases examined and still allow for low power consumption. The two vertical circuit boards at the top of the main photo are the receiver and transmitter (available commercially from Linx Technologies [13]). These micropowered units can handle data over 8 channels at rates of up to 50 kbs using frequency shift keying. They have a range of about 400 m. Our application uses burst transmissions at 28.8 kbs. Despite the relative small size of the pod, no attempt has yet been made to compact the design.

6. SUMMARY

The Sensor Web is a macroinstrument, ideally suited for *in situ* environment monitoring and exploration, where relatively simple pods interact with one another to enable more complex operations and behavior. The key insight about Sensor Webs is that *a node point can be a web itself* which leads to an "interweb" concept of linked webs as illustrated in Figure 9. This allows for local analysis to create distributed control at an unprecedented level. Though we have focused here primarily on land applications, the concept is flexible and can be applied to aqueous, atmospheric, and space environments as well. The cooperative behavior among the pod enables them to be micropowered, relatively cheap, and individually expendable. In addition to having demonstrated a simple Sensor Web in the laboratory, we are currently experimenting with a web deployment in Baja California. It is expected that data from this web will be scientifically significant.

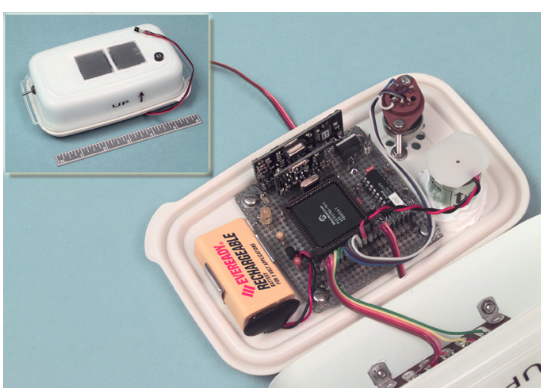

Figure 8 Gaseous biosignature Sensor Web pod. The scale seen in the inset is 6 inches.

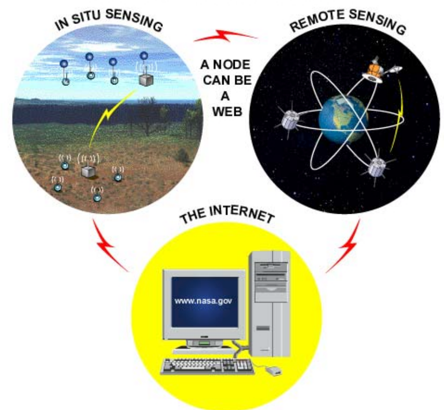

Figure 9 The recursive concept of a Sensor Web.

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REFERENCES

[1] K.A. Delin, S.P. Jackson, and R.R. Some, "Sensor Webs," *NASA Tech Briefs*, **23**, 1999, 80.

[2] J.R. Agre, L.P. Clare, G.J. Pottie, and N.P. Romanov, "Development Platform for Self-Organizing Wireless Sensor Networks," *Proceedings of AeroSense '99, SPIE International Symposium on Unattended Ground Sensor Technology and Applications*, 1999, 257-268.

[3] M.N.O. Sadiku, "Wave Propagation," in *The Electrical Engineering Handbook*, R.C. Dorf, ed., CRC Press, Boca Raton, 1997, 925-937.

[4] *Science*, **278**, 1997, 1734-1742.

[5] D. Attenborough, *The Private Lives of Plants*, Princeton University Press, 1995.

[6] A. Mason, N. Yazdi, A.V. Chavan, K. Najafi, and K.D. Wise, "A generic multielement microsystem for portable wireless applications," *Proceedings of the IEEE*, **86**, 1998, 1733–1746.

[7] J. Oberg, "Shuttle-Mir's Lessons for the International Space Station," *IEEE Spectrum*, **35**, 1998, 31.

[8] See http://www.rfm.com.

[9] C.A. Beichman, N.J. Woolf, and C.A. Lindensmith, (eds.), *The Terrestrial Planet Finder*, JPL Publication 1999, 99-3. See also http://tpf.jpl.nasa.gov.

[10] J.F. Stolz, "Distribution of phototrophic microbes in the flat laminated microbial mat at Laguna Figueroa, Baja California, Mexico," *BioSys.*, **23**, 1990, 345.

[11] D.E. Canfield, and D.J. Des Marais, "Biogeochemical cycles of carbon, sulfur, and free oxygen in a microbial mat," *Geochim. Cosmochim. Acta.*, **57,** 1993, 3971.

[12] See http://www.figarosensor.com.

[13] See http://www.linxtechnologies.com.

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