# ROBOSPHERE: SELF-SUSTAINING ROBOTIC ECOLOGIES AS PRECURSORS TO HUMAN PLANETARY EXPLORATION

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## ABSTRACT

The present sequential "mission oriented" approach to robotic planetary exploration, could be changed to an "infrastructure building" approach where a robotic presence is permanent, self sustaining and growing with each mission. We call this self-sustaining robotic ecology approach "robosphere" and discuss the technological issues that need to be addressed before this concept can be realized. One of the major advantages of this approach is that a robosphere would include much of the infrastructure required by human explorers and would thus lower the preparation and risk threshold inherent in the transition from robotic to human exploration. In this context we discuss some implications for space architecture.

## 1. INTRODUCTION

Human presence on planetary surfaces or in deep space colonies will need to be preceded by robotic explorers and builders. This is will be needed for a complete understanding of the environment to be explored and for preparing a safe habitation complex for the first human explorers, including the means for in situ resource utilization.

Robotic exploration of Mars has been a "one shot" approach where each surface mission is planned typically with a lander or rover that will perform a series of experiment for a few weeks, until the robot becomes unable to operate in the harsh Mars conditions and simply "dies".

It would clearly be desirable to have robots on Mars that can last for much longer periods of time. I propose that there is an approach to sustained robotic exploration that can also pave the way to future human presence. The idea is to continue building a robotic infrastructure with every mission we send. The approach is to built teams of modular robots that could repair individual members when they break down. We could "seed" areas of interest with sturdy power stations (solar, chemical..) that teams of robots could use to recharge themselves. We could also seed parts and modules the robots could access for self-repair.

No mission could really "fail" if we simply keep adding to and maintaining the existing infrastructure. Simply landing a package of parts will be a success. In time we create a loose infrastructure that can be controlled and augmented from earth on a continuing basis, and which could eventually pave the way for human exploration.

A simple starting point for this infrastructure might consist of relatively simple modular robots. Imagine 2 "spider-like" robots built out of small modular snap-in pieces, a bin of these pieces and a bin of snap-in end effectors.

One of the spiders breaks down, i.e. one of its modules needs to be replaced. The second spider comes to the rescue and helps the first one replace the broken module. Assuming the input of fresh modules, this process can continue indefinetly. Now start separating robotic explorers from robotic "mechanics", start adding a category of mechanics that are able to fix at least some of the broken modules (and which in turn can be fixed by the original mechanics), The need for a fresh influx of modules is thus reduced. I submit that we could bootstrap a robotic ecology until it needs very little material from earth and can rely mostly on in-situ resources. We refer to such self-sustaining robotic ecologies as "robosphere". We use the word ecology to emphasize the fact that we are not dealing only with robotic cooperation and exchange of information, but also with potential exchange of energy and materials. The analogy with biological ecological systems is very strong. In this paper we review the technology considerations that are the core of the robosphere

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concept and some of its implication for space architecture.

## 2. LONGEVITY OF SURFACE EXPLORATION CRAFT

The longevity of exploration craft on the Mars surface has been varied and mainly limited by the availability of energy. The Pathfinder lander, which was solar powered, lasted 83 sols (Martian days, about 85 Earth days ). Its experimental microrover, Sojourner, was still working (daytime only; battery was dead) at the time the lander died. Primary mission plan was 30 days for the lander and 7 days for the microrover experiment. Extended mission was one year for the lander and 30 days for the rover. The Mars Polar lander, which was lost on arrival was designed to have a nominal mission of a month or two. The Mars Exploration Rovers (presently on their way to Mars) are designed to have a primary mission of 90 sols.

The Viking Landers, (nuclear powered) lasted for four to six Earth years. The Viking 1 Lander operated from 20 July 1976 until13 November 1982 when a faulty command sent by ground control resulted in loss of contact. The Viking 2 Lander operated on the surface for 1281 sols and was turned off on April 11, 1980 when its batteries failed.

The upcoming ESA lander, Beagle 2, is designed to have a primary mission of 180 sols and an extended mission of 669 sols (one Mars year). It doesn't have a rover, but it has a "mole".

As can be seen from the comparison between the Viking landers and the rovers, the use of nuclear power can make a huge difference, but the risks of nuclear use and, to an even greater extent, the perception of risk constitute a problem space exploration must contend with. Clearly the ultimate solution is to produce power from in-situ resources, and this would be the strategy required by the Robosphere approach proposed in this paper.

## 3. ADAPTABILITY AND STABILITY

The basic challenges for long term exploration are mechanical and energetic. It can be assumed that enough energy can be made available by solar, nuclear power (as has already been demonstrated) or other in situ resources, but mechanical breakdowns remain both a practical and a conceptual challenge,

### 3.1 Small robotic teams capable of mutual repair

Biological systems provide of course the conceptual proof for the possibility of limited self-repair as well as potential models for robotic implementations. Present robotic research in the direction of self-repair is based on modular[7] (figure 1) and self-reconfigurable systems, as can be seen in figures 2,3 (Shen and Will[5]). Modular robotic systems with the ability to autonomously swap faulty modules for repaired ones have not yet been developed, but this logical first step is not too far into the future.

### 3.2. Robotics outposts

Given the fundamental challenges of energy availability and autonomous mechanical repair, robotic outposts will need to be the fundamental unit for sustained planetary robotic exploration. Outposts would include the following:

- means for energy production and delivery to robotic units,
- functional specialization of robotic units. At a minimum some units would be specialized for repair, some for maintenance, energy production and distribution and some for scientific exploration.
- Shelters to facilitate various robotic functions and to reduce mechanical degradation.
- Robotic units specialized for shelter construction and repair

The assumption we make for this type of outpost is that a supply of necessary parts and modules would be shipped regularly from earth, while energy and sheltering would rely on in situ resources. Robotic functions and activity planning would also be controlled from Earth. Only detailed low-level actions, such as swapping modules need to be conducted autonomously due to transmission time delays (about 20 min) that would prevent detailed teleoperation, but diagnosis and repair initiation could still be controlled from Earth if necessary.

It is likely that, in time, the level of autonomy of the outpost would increase and that functional specialization would grow, but many factors would determine the speed of this evolution, including availability of local resources, scientific and/or economic drive for exploration or exploitation, costs of autonomy vs. human control and, most importantly, the point where it would be deemed feasible and desirable to introduce human presence in the robotic outpost.

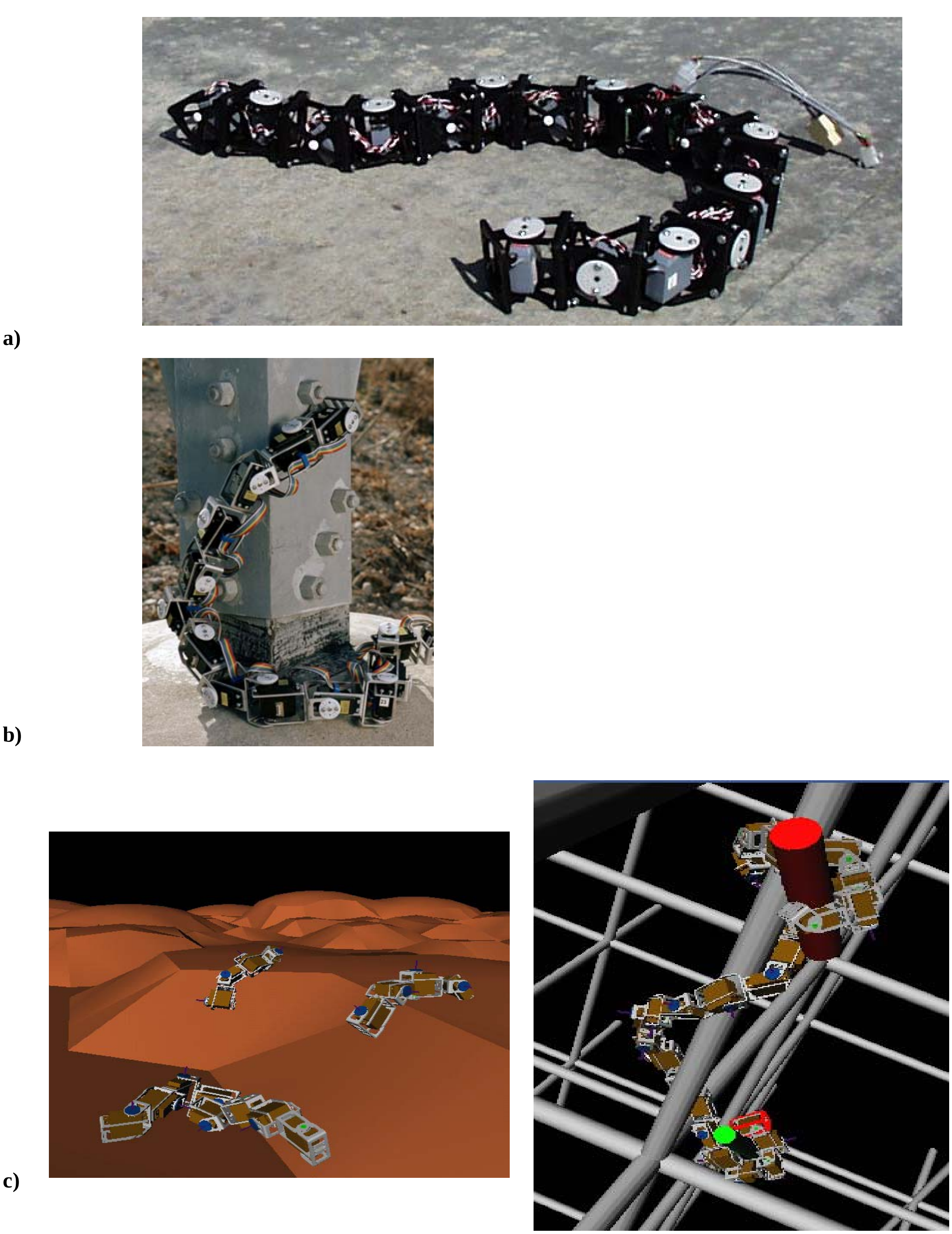

Figure 1: Work at NASA Ames Research Center. a) Snakebot based on Mark Yim's polybot modules[7] b) Lighter modules (Gary Heith) and c) Utilization concepts

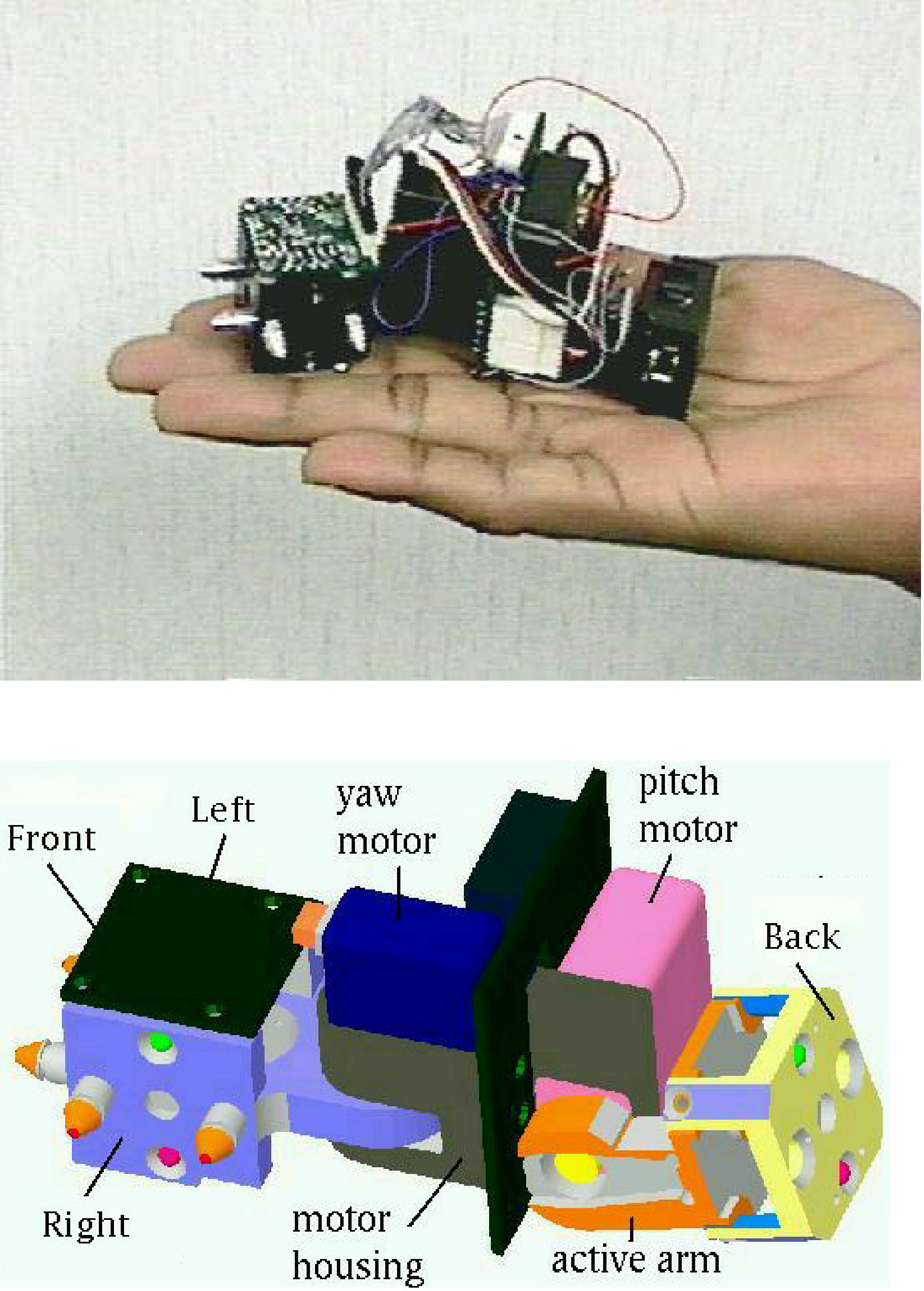

Figure 2: The CONRO self-reconfigurable system. http://www.isi.edu/conro

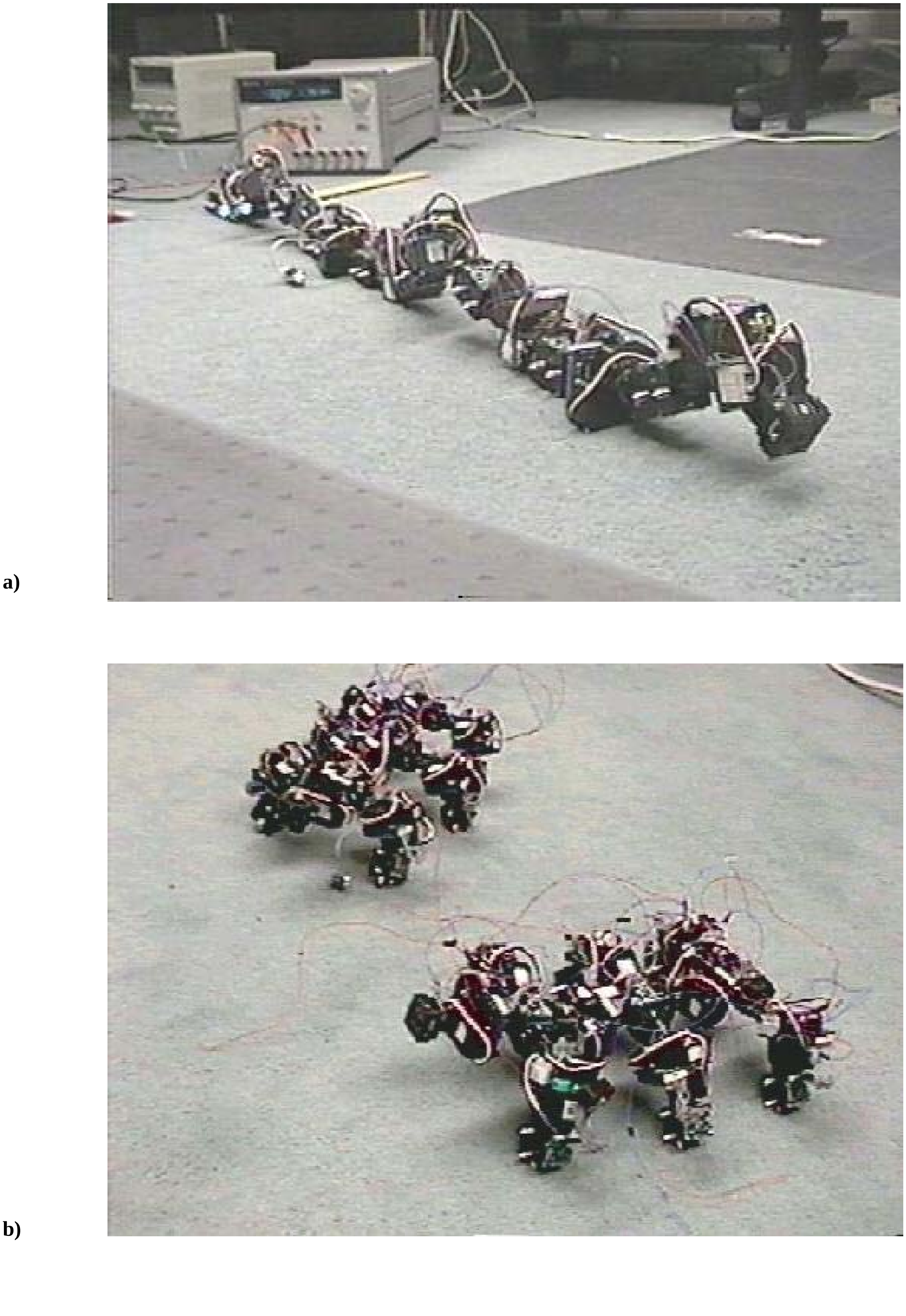

Figure 3: CONRO modules in (a) “snake” and (b) “spider” configurations

### 3.3 The arrival of human explorers

Human presence would of course be the ultimate goal of preliminary robotic infrastructure development, at least for planetary surfaces that could be reasonably hospitable to humans. In this case most of the functionalities developed for robotic survival will be readily transferable to the needs of human explorers. The major transferable functions will be energy production and shelter construction. Of course sheltering and infrastructure suitable to humans would require major reprogramming of the constructor units, but the basic capabilities would be in place and would be well tested.

This approach should be compared with the current one, which views robotic exploration as a separate endeavor form that of eventual human exploration, except for gathering necessary information. Robotic explorers are also sent as “single missions” with specific scientific goals and limited lifetimes, as discussed at the beginning. This makes robotic exploration constantly open to the possibility of failure and vulnerable to changes in public and/or congressional interest. At the point when a decision will be made to send a human crew, their survival and success will require a completely separate plan of action that will include not only the trip to Mars but, also the means of supporting the crew on the planetary surface for (typically) longer than a year (if the energetic cost of travel needs to be minimized).

Building a self-sustaining robotic infrastructure would certainly be more costly at the start but it would start a long term commitment to planetary exploration with small risk of major failures. Most missions would be limited to sending parts and modules and exploration could be staged on the planetary surface with available resources. All missions could be adaptable and flexible.

Ultimately, as stated above, human presence could be accomodated as a natural evolution of the robotic infrastructure and the means for substinence on the planetary surface would be well tested. For instance, while oxygen and food production would not be required by the robotic outpost for its own maintenance, these tasks could be included as a long tem mission and be ready for the arrival of the crew.

A test for such a task had already been included in the ill-fated Mars Polar Lander mission. The flight demonstration, called Mars ISSP Precursor (MIP), where ISSP stood for “In-Situ Propellant Production”, comprised five distinct experiments to test environmental constraints on solar energy production and to generate pure oxygen from the Martian CO2 atmosphere[3]. Unfortunately this demonstration has been postponed to some undetermined future time.

## 4. ROBOTIC ARCHITECTURE

The adjective “robotic” could signify both architecture that uses robots for construction and another, potentially controversial, notion:. is there a role for architecture in machine “societies”? Is the sheltering required by intelligent robots on a planetary surface purely an engineering problem? Does the fact that machines will eventually acquire high levels of perception and “consciousness” imply that architectural thinking will become part of the environments that will support these machines? While it may seem premature to worry about machine consciousness, architectural thinking follows a continuum from practical space elements to facilitate activities, to satisfying esthetic needs. The boundary is not always clear for humans and it may eventually become increasingly fuzzy for machines as well.

### 4.1 Evolution and Emergence

At the very least any successful approaches to automated construction can be applied to the human environment. More interesting is the notion that sheltering for robots should be able to be adapted to human presence, so that the architecture should be able to evolve from machine use to human needs.

A deeper issue is how the increasing symbiosis of humans with (intelligent) machines, especially in space and planetary environments will affect architectural thinking and practice. We have already mentioned two aspects: machines as constructors and machines as possible “consumers” of architecture. A third one involves machines as an architectural medium, in the sense that any shelter, especially in a space or planetary environment will in fact be itself a machine or will incorporate strong machine features.

What this indicates is that architecture becomes a natural part of the integration process of robotic and human systems and must arise as part of the process just as the natural architecture of living systems, such as a shell or the canopy of a forest, arises as part of a complex web of interactions. The architect can no longer produce a design to be instantiated independently of the system to be sheltered, s/he must rather intervene in the process to cause the appropriate architecture to emerge.

### 4.2 Robosphere

Just like terrestrial architecture needs to find harmony with surrounding nature, space and planetary architecture will need to co-evolve with the robotic machine environment that human life will strongly depend on.

The robosphere concept is inspired by Biosphere 2, the experiment intended to test the stability of artificial ecosystems. A robosphere facility will test the stability of a self-sustaining robotic ecology. In addition, along the lines described above, it will test how an environment that can sustain human life can be co-evolved with the necessary robotic functionality.

One point to be stressed is that any human exploration of space will necessarily require a robotic phase. In other words robots will always be **first**. If we develop the technology for efficient, stable, long term robotic exploration, then human access to new space frontiers will be facilitated as well, from distant planets to asteroid resource exploitation.

## 5. TOWARDS ROBOSPHERE: TECHNOLOGY PROGRESS.

Most robotic research deals with increasing autonomy, path planning, vision and, in general, making robots ever more capable of performing complex tasks with little or no human supervision. Multi-agent work is progressing as well, but mostly in the area of robots cooperating on a single task (e.g. Schenker[4*]). All this work is certainly essential, but what is needed is to make robotic repair and survival the most important robotic task.

The most reasonable approach for progress in this area is likely to be that of modular robotics [6,7]. Clearly faults need to be localized to modules that can be easily replaced by another robot. If the repairing robot is similarly modular we begin to see a system that, in principle and with a supply of modules, could continue to operate indefinetly. Good progress in the area of automated replacing of modules is being made in the area of self-reconfigurable robotics (Shen[5] , op. cit.). The goal of this work is to allow robots to autonomously snap modules in and out to achieve different shapes. Clearly this technology is what is required for modular self-repair.

Similar work, although focused more towards automated construction of human habitats is that represented by A. Scott Howe (e.g.Howe[2]). This work would be both applicable to construction and repair of other robots and to the construction of the environments that would be readied for the human explorers.

### 5.1 Self-reproduction and multiple-scale robotics

At a broader system's level consideration must be given to the possibility of robotic self-reproduction. This is of course the quintessential form of self-repair. At the level of robotic technology we can envision at present and in the near future, the self-reproducing entity needs to be a "robotic factory" [1], but, if we enter the realm of nanotechnology and push all the concepts we have discussed so far down to the nanoscale, including modules and self-repair, we can conceive of robots built out of nano-bot units along the same principles that guide the biology of multicellular organisms. In this case each macro-robot can be the robotic factory of nano-bots that assemble themselves into a copy of the original macro-robot. Here we enter a new level of discourse where the boundary between robotics and biology becomes even more blurred and requires new theoretical and practical considerations that are beyond the scope of this paper.

It should be mentioned, however, that the Robosphere concept, at the point where we push the extreme of complete autonomy, even without the shipping of modules and terrestrial control, easily accomodates and perhaps requires robotics at multiple scale levels. This becomes crucial as technologies become obsolete and recapture of resources requires utilization of more basic materials. Again, we leave these considerations for further study.

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## 6. CONCLUSIONS

We propose that it would be feasible and desirable to approach robotic exploration of planetary surfaces as an infrastructure building program that relies on the concept of self-sustaining robotic ecologies (robosphere). Current ideas in modular and reconfigurable robotics, as well as work on robot based construction, show that progress in this area can be made relatively short term. We argue that typical architectural concepts need to be expanded to allow for increasingly blurry distinctions between what are "human centered" and "machine centered" environments. More esoteric notions of robotic self-reproduction and multi-scale (down to the nano level) robotics are discussed in the context of future and still unclear technological development.

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