THE ROBOSPHERE: THE CONCEPTUAL EXPANSION OF THE HUMAN FACTORS

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ABSTRACT

A technology of self-sustaining robotic ecologies (called "robosphere" by the co-author) is likely to emerge in order to prepare for and serve long-duration space missions of humans on Mars or in other extraterrestrial environments. The emergence of this would necessarily expand the concept of the human factors. The human-human, human-technology, and human-environment human factors interfaces would be joined by the technology-technology, or machine-machine, interface, in the sense that machines would need to interact and cooperate for types of activities that, until now, would invariably involve humans.

In the complex interactions of perhaps even self-reproducing machines, where are the human factors? Neither a machine version of the current human factors interfaces, nor the classical human-technology interface quite captures the machine-machine interface as introduced by a robosphere. Throughout the history of automation, many examples demonstrate that machines have been programmed to work in tandem with other machines. Machines have been constructed to withstand environmental elements and to be useful to humans. Their human manufacturers built them for durability and utility. It is the issue of sustainability that makes all the difference. Machines that are complex enough to constitute a robosphere are endowed with the ability (and "duty") to take care of their own survival. In addition, their overall purpose is to sustain human life and its mission in extreme environments.

Several factors contribute to this issue of sustainability. Some examples would be machines that recognize faults in other machines and come to their rescue, alone, in collaboration with other machines, or in collaboration with humans. The same machine interface that serves a human may need to be able to serve another machine. This report discusses the conceptual challenges and ramifications of self-sustaining robotic ecologies to the human factors.

LONG-DURATION SPACE EXPLORATION AND SUSTAINABILITY

The proposition of long-duration space exploration brings humanity to the manifold issue of *sustainability.* Those agencies contemplating long-duration space exploration must wonder about the sustainability of financing and other resources needed to ensure the success of missions. In the early days of polar exploration, too often expeditions came to grief because of corner-cutting or withdrawn sponsorship from the explorers, even while they were in the field (Dudley-Rowley, 1999). This is one concern of those who contemplate the sustainability of long-duration space missions. Another concern is the issue of the robustness and functionality of equipment necessary to enable a long-term human expedition in an off-world environment for years on end – as would be in the case of a Mars mission.

Colombano has proposed an "infrastructure building" approach to planetary exploration in both the cases of advanced robotic exploration and robot-assisted human exploration (Colombano 2003). Special robotic explorers would enter the extreme off-world environment. These robots would have the capacity to be self-sustaining and self-repairing, and would even be able to make more hospitable a planetary base camp in advance of the arrival of human explorers. In the performance of their mission would emerge a kind of machine ecology that Colombano calls the "robosphere." Such a machine ecology would lower the preparation and risk threshold for the humans entering the off-world environment. The analogy to biology is strong in his concept. Robots in this machine ecology would have a degree of functional specialization and autonomy that might increase with mission needs, and the robosphere would evolve.

So, Colombano's concept is both ecological *and* evolutionary. It offers a "bootstrapping" and synergistic vision of robotic exploration as contrasted to the "one-shot" robots that perform today's long-duration space missions and then break down, run down, and, in effect, "die." He proposes sending in long-lasting teams of modular robots that repair individual members when they break down. Among the first facilities these robots would install would be power stations (variously fueled) that would allow the robots to recharge themselves. Another "first duty" would be to set up stores of parts and modules that robots could access for self-repair.

In his concept, Colombano asked the reader to imagine two "spider-like" robots built out of small modular snap-in pieces (Figures 1a-c).

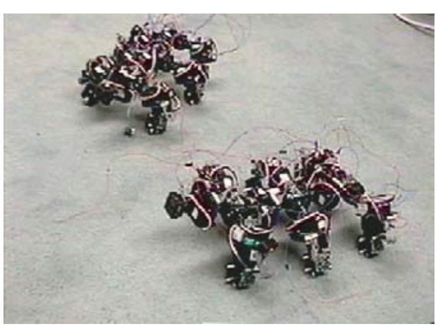


Figure 1a: CONRO modules in spider configuration. http://www.isi.edu/conro

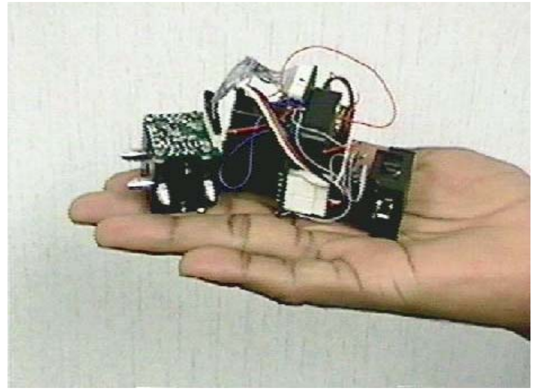


Figure 1b: The CONRO self-reconfigurable system.

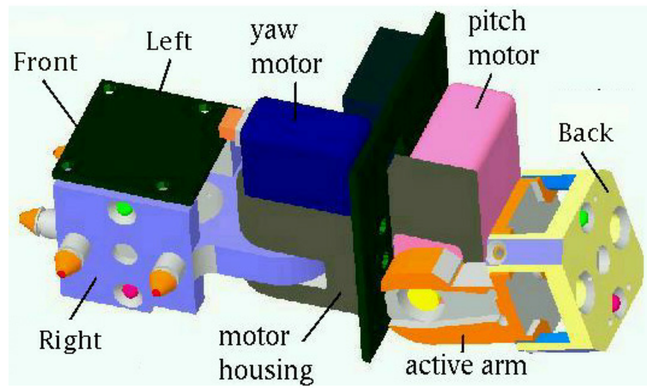


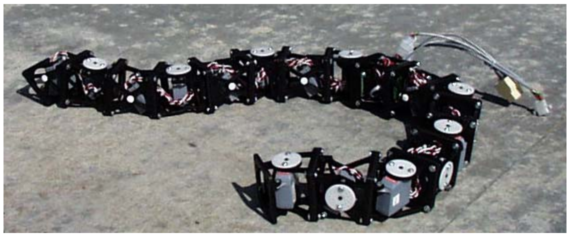
Figure 1c: Schematic of CONRO system.

In this scenario, one of the spiders breaks down – one of its modules needs to be replaced. The second spider rescues the first one by replacing the broken module. Colombano's point is that no robotic mission need come to an end as parts fail. Modular parts could be augmented by re-supply from Earth. Should re-supply not arrive on time, broken modules might be repaired by some of the robotic explorers who have been programmed with a special mechanic function (Trebi-Ollennu *et al.,* 2002).

Not only would small robotic teams be capable of mutual repair, but robots would be self-reconfigurable. The spider configuration could be re-worked into a "snake" configuration (Figure 2). Neither of these abilities has yet been developed, but these are the next steps in robotics that are expected in the near future (Shen and Will 2001).

At the core of Colombano's robosphere are *four necessities* that he envisions as being met by a "robotic outpost," that would be the fundamental unit for sustained planetary exploration.

Figure 2: CONRO modules in snake configuration.



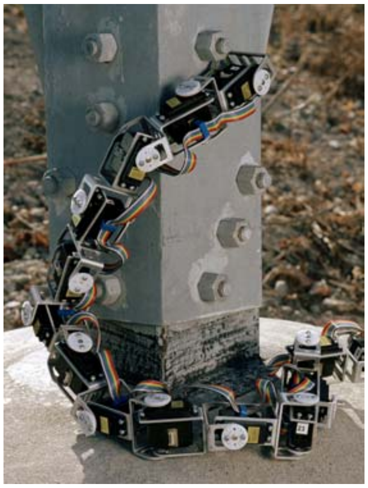


Figure 3: Work at NASA Ames Research Center. Lighter snakebot modules (Gary Heith) based on Mark Yim's polybot modules (Yim *et al.,* 2001). Also see Howe 1997.

Those four necessities are:

- 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 (Figure 3).

THE ROBOTIC OUTPOST: THE FUNDAMENTAL UNIT FOR SUSTAINED PLANETARY EXPLORATION

The outpost would rely on regular shipments of parts and modules from Earth, while energy and sheltering would rely on *in situ* resources (Schenker *et al.,* 2000). Except for detailed, low-level actions like module swapping, that would be hindered by the transmission time delay between Earth and Mars (about 20 minutes), more complex robotic functions and activity planning could be controlled from Earth. Diagnosis and repair initiation could still be controlled from Earth if necessary.

The level of autonomy of the outpost might grow in time and functional specialization might increase, but the speed of that "evolution" would depend on

- Availability of local resources,
- Scientific and/or economic drive for exploration or exploitation,
- Costs of autonomy *vs.* human control, and, most importantly,
- The point were humans would be introduced into the robosphere.†

The functions of energy production and shelter construction would be transferable to the human situation, provided units could be reprogrammed to meet the needs of human infrastructure (Kaplan *et al.,*1999). Human presence could be accommodated as a natural co-evolutionary process of the robotic infrastructure. Colombano has argued that if a long-term commitment were made to implement this ecological and evolutionary robotic enterprise, that it would be a time-tested stable infrastructure by the time humans came on the scene, which would go far in making the human presence sustainable. Then, with humans on the scene, a testbed would then be available to see if human life and robotic functionality would be enhanced as an emergent property of their synergy

†From these potential conditions, a series of laboratory-testable hypotheses might be posed for future research.

in the extreme environment. With robotic ecologies leading the way, the human ecology can expand into the Cosmos, to explore distant planets, to exploit asteroid resources, etc.

ROBOTIC EVOLUTION

However, in so doing, we might expect the field of robotics to advance. Though in the here-and-now, humans use robots in industry and hazardous environments, and robots rely on humans to keep them operating, more sophisticated forms of synergy might be expected to evolve as robots and humans enter environments that increase in the variety of their extremity. Colombano envisions robotics at multiple scale levels. At one level are robots only a bit more sophisticated than those with which we are familiar today – *macrobots* that are capable of complex tasks, of cooperating on a single task, that can repair and reconfigure themselves and other macrobots, and need no human supervision. At the other end of the scale are *nanobots* that can construct other nanobots and organize themselves into macrobots, much like cells of a multicellular organism forming the larger entity. At this level of sophistication the robot might be self-reproducing. We can also expect the nanobot to make easier the intersection of the human and the machine. One immediate use of nanobot innovation is that molecular-sized machines could be introduced into the human body to make repairs without external incisions and to make repairs at cellular and genetic levels. But, they might also be designed to augment human perception, cognition, and other abilities (Figure 4).

Colombano's vision of an evolutionary robotic ecology provides us glimpses from many windows. On one hand, we see the practicality of an "infrastructure building" approach to planetary exploration, sending simple, but robust, robots into an extreme exploration environment to pave the way for the humans who come along later. On the other hand, we see the vast panorama of what is possible as conjoined robotic and human ecologies engage variously different extreme environments and co-evolve over time.

EXPANSION OF THE HUMAN FACTORS

The emergence and evolution of these technologies would necessarily expand the concept of the human factors. The human-technology, human-environment, and human-human interfaces comprise the most comprehensive vision of the human factors (Dudley-Rowley and Bishop, 2002). The concept of a machine ecology that paves the way for a human ecology and that interacts with that ecology invites a conceptual expansion of the human factors. Bringing a robosphere on line means that there would be a technology-technology (i.e., machine-machine) interface that is different than anything seen before. This would be no mere mechanical interface, for we are speaking of machines that need to interact and cooperate for types of activities that, until now, would invariably involve humans. But, in the complex interactions of perhaps even self-reproducing machines (Chirikjian, Zhou, and Suthakorn, 2002), where are the *human* factors?

The classical human-technology interface that occupies so much of today's human factors work does not quite embrace the machine that purposely engages other machines for their survival in Colombano's robosphere concept. Neither does a simple machine version of the human factors interfaces do the job. And, that is because at some point, the analog would break down. That point would be precisely when humans would enter the robosphere and start interacting with the machine ecology.

Perhaps a clue to the answer to this question lies in human prehistory, in the interplay of time, environment, and natural selection, and the role of tool use by proto-Hominids. When the organisms that would become human became fully bi-pedal, their hands were freed. They employed these hands to make tools. Tool-making increased hand-eye coordination. The interplay between tool-making and attendant activities and the organism responding to the challenges of its environment with its tools, resulted in time in Hominids with larger cerebral cortices, brain sizes that enabled language and other abilities that we ascribe to humans today. This is a rather shorthand way of telling the human story as it is rather more complicated than all of that. However, it will serve to make our point.

As modern humans face ever more extreme environments, we find ourselves not only making tools (i.e., machines, robots) that use tools and make tools, but that we seek to imbue with genetic algorithms and other programming so that they can think, learn, and make their own innovations. When our tools can invent their own tools to ensure their own survival and continued functioning, then we have something more than mere technology. Is it conscious, and in that respect, human or "like-human?" How can we say? Science has not yet quantitatively defined human consciousness.[‡] But, it would not be untoward to ascribe some sort of rising consciousness to this new category of tool-makers, a consciousness that can be expected to become more mature. This requires a conceptual expansion of the human factors frontier (Figure 5).

Now, it may be argued that the human analogy may lead to false expectations. After all, chimpanzees are tool-makers and they have not gotten very far. About the most complicated tool that a chimp in the wild has been observed to make is stripping a twig to ram down a termite hole to fish for edible insects.

Figure 6: Chimpanzee parent teaching its child to fish for termites.

http://www.discoverchimpanzees.org/become/child_termites.php

However, there would be a couple of things wrong with presuming that chimps are not capable of developing greater tool use and increased consciousness. Chimpanzees have not been observed scientifically in the wild over a long enough period of time to know how they are developing. Perhaps had they been left alone in an environment for long enough time, on the scale of thousands and millions of years, that was various and vigorous enough to challenge them, but not destructive to them all, then they might be further along. As it was, in the human story, it took early human groups many hundreds to thousands of years to alter simple toolkits. But, being left alone for long spans of time has not been the case for chimpanzees. Their ancestors and they have had to compete with the whole of the Hominid line. They have been in competition with human groups since the dawn of humanity and have often been hunted to near-extinction at times.

Not so the case of the smart machine. From its infancy, it develops in cooperation with humanity, cultivated by its inventors to be ever more like humans and other organisms and even better. Because of the nature of the machine, it has the capacity to evolve quickly. It evolves rapidly enough with human help, especially where it manifests as a marketable product, as in the case of desk-top computers. However, once the machine is capable of making its own innovations, the frequency of that innovation may exceed any assistance that humans can render. It is the *angst* of our imagining this moment that has given us such fictional works as *The Forbin Project* and the *Terminator* movies.

Here, again, another issue of sustainability raises its head. Can humanity sustain itself in the advance of the machine? Can the machine sustain itself without human experience, without the template that biology can provide? To guarantee a positive outcome, it is incumbent upon humanity not to be negligent, as the parent of this technology that is becoming ever more than a tool kit. Part of not being negligent as a parent is recognizing the need for autonomy of the child, and at the same time, providing a place for that child in human society. Humans need to ensure that the robot and the human, though different from the outset, remain two co-evolutionary lineages that will blur in their distinction over time as humans expand their ecology to seek direct experience with the Cosmos.

[‡]Roger Penrose forcefully makes the case that consciousness does not arise from computational sophistication alone, but requires physical activity at the quantum-classical borderline as may occur in sub-levels of human neurons (Penrose 1994).

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Simple automation   Self-repairing macrobots   Nanobots   Self-reproducing macrobots   Intersection of human and machine

Figure 4: Scale of robotic evolution

	Robot		**Human**
Human→	**Technology**	**Robot-→**	**Technology**
	Environment		**Environment**

Figure 5: The Human Factors Interfaces Modified to Account for Tool-Making Robots

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