NEXT-GENERATION ROBOTIC PLANETARY SURFACE/SUBSURFACE RECONNAISSANCE MISSIONS: A PARADIGM SHIFT.

W. Fink[1], J. Dohm[2], M. Tarbell[1], T. Hare[3], and V. Baker[2], [1]California Institute of Technology, *Visual and Autonomous Exploration Systems Research Group*, Mail Code 103-33, Pasadena, CA 91125, wfink@caltech.edu, [2]Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ, [3]United States Geologic Survey, Flagstaff, AZ.

Introduction: A fundamentally new scientific mission concept for remote planetary surface and subsurface reconnaissance will soon replace the engineering and safety constrained mission designs of the past, allowing for optimal acquisition of geologic, paleohydrologic, paleoclimatic, and possible astrobiologic information of Mars and other extraterrestrial targets. Traditional missions have performed local, ground-level reconnaissance through immobile landers and rovers, or global mapping performed by an orbiter. The former is safety and engineering constrained, affording limited detailed reconnaissance of a single site at the expense of a regional understanding, while the latter returns immense datasets, often overlooking detailed information of local and regional significance. A “tier-scalable” paradigm integrates multi-tier (orbit⇔atmosphere⇔ground) and multi-agent (orbiter⇔blimps⇔rovers) hierarchical mission architectures, not only introducing mission redundancy and safety, but enabling and optimizing intelligent, unconstrained, and distributed science-driven exploration of prime locations on Mars and elsewhere, allowing for increased science return, and paving the way towards fully autonomous robotic missions.

Scenarios for high-risk scientific exploration. Non-traditional autonomous missions to remote planetary bodies will be necessary [1], primarily to allow intelligent and unconstrained access to sites not currently feasible on Mars, including canyon systems, extremely ancient mountain ranges, sites of suspected magmatic-driven uplift and associated hydrothermal activity, regions that record ancient to recent aqueous activity, and polar caps and layered materials. These geologic terrains, including other regions of interest on other planetary bodies of the solar system, are particularly crucial for astrobiologic-oriented exploration in general, and sample return missions in particular. As such, a paradigm shift in future mission concepts for such planetary surface and subsurface exploration is not only overdue, but required.

Limitations of traditional scientific exploration. The traditional scientific mission of exploration utilizes a single, surface-based reconnaissance agent (e.g., a rover or lander) that is very sophisticated, has multiple sensors, and is dependent on Earth-based human control. Since this approach is expensive, both from the perspective of the capital cost to build and the resource cost to deploy and operate, typically only a single agent is deployed within an operational area. Thus, any operational area is constrained to an area no larger than what a single agent can explore. The agents are spatially constrained in that they can view only a small portion of an explored area at one time. Since most rovers are tracked or wheeled and surface-based, their elevation above the ground provides a very limited viewing range, making it likely to miss valuable information while en route. Therefore, it is difficult for such agents to view a large enough region to make an intelligent decision about what features in an operational area are worthy of scientific investigation. Also, the spatial constraint of an agent may cause difficulties in navigation when planning or optimizing a traverse. The agent may construct a locally optimal path through a limited operational area, but not a regionally and/or globally optimal path because of its limited field of view. Thus, previous robotic mission design has relied on Earth-based efforts, which include data processing by numerous technicians, data analysis by multiple scientists, and ultimately the planning of new traverses/observations collectively by both engineers and scientists using existing ground- and space-based information, all of which require tremendous effort, time, and cost.

Another significant concern in the use of only a few sophisticated, expensive, and multi-sensored agents is that the reconnaissance mission may be lost or adversely affected when even one of the agents is damaged or destroyed. Because of this lack of mission redundancy, there has been reluctance within the robotics community to give agents fully autonomous capabilities (e.g., for making independent decisions about where to go within an operational area or exploration space).

The often overstated term *autonomy* is defined here as the high-level automation of planetary reconnaissance missions, including automated data acquisition, data feature extraction, data analysis, identification of science targets, science goal prioritization, execution of science goals, navigation, and guidance. As such, most currently deployed agents are not truly autonomous, as they are mostly controlled via teleoperation by a human on Earth.

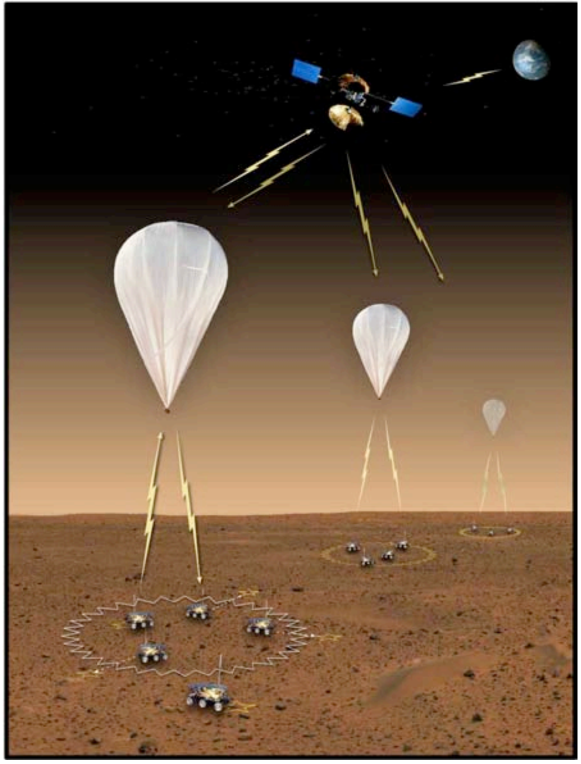

Fig. 1. Tri-level hierarchical multi-agent architecture for autonomous remote planetary exploration.

The new paradigm. A paradigm shift is required to advance from Earth-based interaction to what is termed "tier-scalable" autonomy in scientific missions [2-4] (Fig. 1). Each tier, or layer, is a hierarchical abstraction of the tier beneath it. There may be as many or as few tiers as are required for a particular mission.

A *ground-level tier* typically comprises the deployed reconnaissance agents. The deployed agents may be low cost and expendable, each having only a few scientific instruments aboard. The ground-level tier is organized into drop-zones (one for each site of scientific interest). Each drop-zone contains one or more agents (Fig. 1), and/or web of sensors.

An *airborne-level tier* (e.g., balloons or blimps) is utilized in environments containing a sufficiently dense atmosphere. Its purpose is to control and command the ground-level tiers in their operations. This level also receives the science data uplink from the deployed ground-level agents.

A *spaceborne-level tier* is generally implemented as orbiter(s), which overfly the operational areas. This tier commands the airborne-level tiers, and receives the science data uplink that the airborne-level tiers receive from their ground-level tiers, or directly from the ground-level tiers if there is insufficient atmosphere. The science datasets are forwarded back to Earth. The spaceborne-level tier is the tier with which Earth-based operations interact.

Applications of the new paradigm. In the highly automated scenario, the satellites command and control the airborne units automatically, and the airborne units automatically command and control the ground-level reconnaissance agents. This system integrates satellites with inexpensive balloons/blimps and ground-level agents (rovers, fixed landers, e.g., Beagle 2, and sensors). The airborne units and ground-level agents can be inexpensive enough (in terms of capital cost and operational resources) to allow for the deployment of numerous agents that can collectively address a specific science-driven question(s). Multiple ground-level agents in conjunction with airborne units can collectively explore the same science target with a complementary suite of instruments.

The multi-tier system can be applied to locations that are dangerous for conventional missions, but have great scientific interest, such as the Valles Marineris region, a vast canyon system that would stretch across the United States. The satellites may intelligently deploy airborne units at will, which in turn intelligently deploy ground agents to prime locations on the ground. The airborne units can highlight anomalies - interesting features or transient geologic events (e.g., a giant landslide that initiate on the walls of Valles Marineris), hydrologic events (e.g., water seeps) and/or atmospheric events (e.g., the retreat of the north polar ice cap) - bearing tremendous implications concerning the planetary evolutional history of Mars within their "unconstrained" airborne field of view, which is far superior to the limited horizontal view of a traditional ground agent. The airborne units then communicate and direct the ground agents to the desired targets. If some of the agents are lost during the reconnaissance mission, those that remain can still identify, map out, and transmit back significant information, thus rendering the overall mission a success.

References: [1] Reichhardt T. (2004) *Nature* 428, 888-890. [2] Fink W. et al. (2004) "Next-Generation Robotic Planetary Reconnaissance Missions: A Paradigm Shift", submitted to *Planetary and Space Science*. [3] Fink W. et al. (2004) "Multiple-agent air/ground autonomous exploration systems", *NASA Techbrief*, in press. [4] Schulze-Makuch D. et al. (2004) "Comparative Planetology of the Inner Planets of the Solar System: Geologic Setting, Astrobiological Assessment and Implications for Mission Design", *Journal Astrobiology* in press.