Next-generation robotic planetary reconnaissance missions:  
A paradigm shift

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Abstract

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 rovers and immobile landers, 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/sensorwebs) 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.

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1. Scenarios for high-risk scientific exploration

Conventional robotic planetary exploration scenarios favor single lander/rover missions driven by safety and engineering constraints; mission redundancy and science return are deprecated (Reichhardt, 2004). The inner planets, Mercury, Venus, Earth, and Mars, exhibit very different atmospheres and surface temperatures, thereby challenging the landing of surface-exploring spacecraft. Furthermore, rovers are mobility constrained, unable to explore multiple non-adjacent sites on a planetary surface, and are safety constrained, unlikely to explore potentially hazardous, but scientifically interesting surface and subsurface terrains.

Non-traditional autonomous missions to remote planetary bodies will be necessary (Reichhardt, 2004), primarily to allow intelligent and unconstrained access to sites not currently feasible on Mars, including canyon systems (Scott and Tanaka, 1986; Carr, 1996), ancient mountain ranges (Dohm et al., 2001a, b), sites of suspected magmatic-driven uplift and associated hydrothermal activity (Dohm et al., 2001a, b; Chapman and Tanaka, 2002), regions that record ancient to recent aqueous activity (Dohm et al., 2004), and polar caps and layered materials (Tanaka and Scott, 1987; Tanaka et al., 2003). 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. In addition, in order to optimally harvest the information that awaits discovery at targets of special interest as noted above (including detecting and honing in on a unique rock or a transient process such as a water seep) or other extra-terrestrial targets (such as capturing volcanism on Io, hovering above the dissected terrain of Titan, or probing below the ice on Europa), limited bit-rate or a long communication time due to the great distance between roving spacecraft and Earth will require significant autonomy.

The often overstated term autonomy is defined in the context of this paper 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 (with the exception of very basic and local obstacle avoidance), as they are mostly controlled via teleoperation by a human on Earth.

2. 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-sensed 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).

3. The new paradigm

A paradigm shift is required to advance from Earth-based interaction to what is termed “tier-scalable” autonomy in scientific missions (Fink et al., 2005a, b). This is illustrated schematically in 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., low cost and expendable 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) (e.g., low-cost microspacecraft), 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.

Since the new paradigm strongly relies on the reliability of higher tier craft, redundancy is postulated at the ground-level tier, the airborne-level tier, and even the spaceborne-level tier, in addition to the fact that the spaceborne-level tier is less likely to be affected by adverse influences (e.g., wind).

This marks a radical departure from traditional approaches, as it allows for multiple exploration sites through multiple “drop zones” of expendable low-cost reconnaissance agents, and localized control of each site via abstracted tiers of autonomous operation.

4. Applications of the new paradigm

A typical operations scenario for a hierarchical multi-tier, multi-agent reconnaissance system is illustrated schematically in Fig. 2(1)–(17). While the multi-tiered, hierarchical, integrated mobile and/or immobile reconnais-
sance web allows for varying degrees of independence from human intervention, it also permits manual override at any level. A human operator may communicate to the satellites, as well as command the airborne units via the space-borne satellites (and thereby command the ground-level reconnaissance agents via the airborne units). Or, a highly automated operation mode may be used, enabling autonomous reconnaissance missions (necessary, e.g., on the rear side of the Moon).

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 air balloons or 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 to allow for the deployment of numerous agents that can collectively address a specific science-driven question. In terms of capital cost, they can be considered expendable due to increased mission redundancy. And in terms of operational resources, they allow for autonomous operation. 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 (Scott and Tanaka, 1986), 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 or help guide orbiter-based deployment.

Fig. 1. Tri-level hierarchical multi-agent architecture for autonomous remote planetary surface and subsurface exploration.
of ground agents to prime locations on the ground. To ensure success, the satellites can deploy both air and ground agents (sensors) to relay information such as current atmospheric conditions. Based on the deployment of these “scout” agents, information concerning present conditions inside and near the expansive canyon system can be gleaned from such forays. If, for example, the scouts highlight ample conditions in an operational area (e.g., low wind) or an interesting feature (e.g., unique rock) and/or a transient geologic (e.g., a giant landslide that initiates from the walls of Valles Marineris), a hydrologic (e.g., water seeps), and/or an atmospheric event (e.g., the retreat of the north polar ice cap) are detected, a major deployment may then occur.

Also, with balloon/blimp agents in Valles Marineris, the diversity of rock types can effectively be determined (see Fig. 3 for an example scenario). Airborne units can highlight anomalies bearing tremendous implications concerning the planetary evolutional history of Mars within their “unconstrained” field of view, 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.

5. Implications of the new paradigm

Integrated multi-tier, multi-agent hierarchical mission architectures not only introduce redundancy, and thus unprecedented mission reliability and safety, they also enable spanning larger surface areas than previously possible—mimicking the way geologists explore regions on Earth—and therefore allow for increased science return. Several example scenarios are outlined below:

- Planetary bodies with atmospheres and non-extreme surface temperatures (e.g., Earth and Mars): Orbiter-guided deployment and control of balloon/blimp units, which in turn deploy or help guide orbiter-based deployment of both mobile and immobile ground-level agents (an example of which is the relatively inexpensive

![Fig. 3. 3-D oblique view, exemplifying an airborne agent (blimp) performing smart reconnaissance over Melas Chasma, the central part of the vast canyon system Valles Marineris on Mars. Part of the reconnaissance would include surveying the canyon walls, honing in on stratigraphic sequences, hovering above landslide and valley floor deposits, and identifying targets for subsequent deployment of ground-based agents. Target features of special scientific interest may include diversity of rock types, high heat flow, and/or surface/near-surface water, contributing to the success in identifying potential life-containing habitats. (Note that for visual purposes the blimp is not drawn to scale.)](image)

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**Fig. 2.** Tri-level Hierarchy Sequencing using Round-robin Sequential Commanding:
1. Tier 3 Satellite Orbiter instructs Tier 2 tethered Balloon and/or thrust-controlled Blimp (Airborne Unit) to destination site. Airborne Unit travels to and locates requested destination site.
2. Airborne Unit performs a craft-drop onto the surface via parachute/airbags/rockets, etc.
3. Tier 1 reconnaissance Agents deploy onto surface once they touch down.
4. Satellite Orbiter instructs Airborne Unit to scout out landing site for specific (science) targets (items or locations of interest) to be investigated by the Agents.
5. Airborne Unit identifies targets of interest, and assigns Agents to targets.
6. Airborne Unit performs Round-robin Sequential Commanding of Agents to their targets. The first Agent is commanded to move a small distance towards its target.
7. Airborne Unit commands Agent #2 to move towards its target.
8. Airborne Unit commands Agent #3 to move towards its target.
9. Likewise, Airborne Unit commands all of remaining Agents, in round-robin fashion, to move a short distance towards their designated targets.
10. When an Agent arrives at its designated target, it performs its reconnaissance function (spectral analysis, chemical analysis, photography, etc.). It then uplinks this information to the Airborne Unit in MLIS (Multi-Layer Information System)/GIS (Geographic Information System)-type datacube format.
11. In turn, Airborne Unit relays the uploaded MLIS/GIS science data to the Satellite Orbiter, which then processes it and/or relays it back to Earth for (further) analysis.
12. Airborne Unit then reassesses the position of each Agent. This is a feedback element for the Airborne Unit to appropriately calculate each Agent’s path based on its actual progress.
13. Airborne Unit redirects the Agent that arrived at its target to its next target.
14. Again, Airborne Unit performs round-robin sequential commanding of Agents to their targets. Agents are commanded to move towards their targets, etc.
15–17. The above subsequence (steps 10–17) repeats until there are no more targets to investigate. Satellite Orbiter then instructs Airborne Unit to move on to another target site. The entire sequence repeats at the new site.
Beagle 2 lander). The airborne units guide/control ground-level mobile agents, and establish communications with both mobile and immobile sensor webs.

- **Planetary bodies with atmospheres and extreme surface temperatures (e.g., Venus and Titan):** Orbiter-guided deployment of balloon/blimp units, which can cover larger surface areas through high-altitude reconnaissance such as in the case of Venus. The higher reaches of the Venusian atmosphere are the most Earth-like of any planet in the solar system, and thus may be explored for possible astrobiology (Schulze-Makuch and Irwin, 2002). Balloons high above the Venusian surface can perform reconnaissance and deploy short-lived (on the order of seconds) immobile sensors, since Venus has severe surface conditions, with temperatures of 735 K (which would melt lead, tin, and zinc), and hot spots in excess of 975 K (Landis, 2003).

- **Planetary bodies with no atmospheres and extreme surface conditions (e.g., Mercury, Moon, Europa, Io):** Orbiter-guided deployment of ground-level mobile agents and immobile sensor webs as well as communications with both mobile and immobile sensor webs. In addition, orbiters in (eccentric) low-altitude orbits guide and control the ground-level mobile agents by repeated overflights above the operational areas (for example, the Mars Global Surveyor has an approximately 48-h elliptical orbit to a 118-min circular orbit).

Since a detailed description of the many envisioned and possible mission scenarios is certainly beyond the scope of this paper, the reader may be referred to Schulze-Makuch et al. (2005) for a discussion of mission aspects for the astrobiological exploration of the inner solar system (Venus, Mars, Mercury, and Moon).

All of the advances in understanding the natural world that geology and the other Earth sciences have achieved stem from inferences. These inferences are never made from a single piece of evidence, but from the different and unique layers of information that often have to be gathered from multiple, potentially distant, field sites. Multi-tier, multi-agent hierarchical mission architectures overcome this inherent challenge of geologic planetary surface exploration.

Airborne units (orbiters in conjunction with balloons/blimps) possess overhead perspectives at different length scales and resolutions that enable them to characterize and classify geologic field sites, and to provide guidance to ground-level agents. The lack of vegetation on planets such as Mars makes this feature especially feasible. Scientifically interesting (terrain) features, hazards, or obstacles, obstructed from the view of ground-level agents (e.g., by an intervening mountain), can be observed by an airborne unit and subsequently communicated back to the ground-level agents for effective, ground-level navigation and investigation. The airborne units then acquire images of the operational area that can subsequently be image-processed and analyzed by automated feature-extraction algorithms, provided by software packages such as the Automated Geologic Field Analyzer (AGFA) (Fink et al., 2005c), developed by several of the authors. Analysis packages such as AGFA are generally useful for any kind of robotic planetary exploration mission. They are of particular importance to the proposed multi-tier, multi-agent hierarchical mission architectures as they can (a) improve the ratio between transmitted amount of science data and data transmission rate, and (b) further render autonomous the individual tiers and agents thereof. The feature data is used by science prioritization algorithms to choose potential targets for close examination by the agents and for determining safe passage of the agents across the terrain to their designated targets (e.g., detection of a unique rock such as a tabular white sedimentary rock among mostly black vesicular basaltic rocks of varying sizes and shapes and determination of the optimal path to get to the detected unique rock). At their respective targets, each agent conducts in-situ science experiments and thereby gathers data that complement the remote sensing data obtained by the airborne units, resulting in a much more complete picture of the planetary surface under examination.

In order to make science craft more autonomous and productive, acting as a mechanized field geologist, the multi-agent autonomous system can include a Multi-Layer Information System (MLIS), akin to a Geographic Information System (GIS) (Fig. 4), which is an effective software package that allows the storage, retrieval, manipulation, analysis, display, and inference of spatially registered information over a large range of length scales (e.g., data at orbiter, airborne, and ground-level resolution; Hare et al., 2003; Hare and Tanaka, 2001; Fisher, 1995; Bonham-Carter, 1994; Fotheringham and Rogerson, 1994). Such a system affords the ability to smartly perform reconnaissance of the region of interest (Fig. 5).

![Subset of layers, in part delivered by, e.g., the Automated Geologic Field Analyzer (AGFA), that make up the Multi-Layer Information System (MLIS).](image-url)
Such future mission concepts are already in the test bed stage (developed by the authors), allowing for testing advanced hardware and software designs, and will one day have great potential to harvest significant geologic, climatologic, hydrologic, and possible astrobiologic information from the terrestrial and extraterrestrial planetary bodies.

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Appendix

Technical description of multi-tier, multi-agent autonomous reconnaissance system

A multi-tier, multi-agent, autonomous system for exploration of hazardous or inaccessible locations includes simple ground-level agents (e.g., mobile rovers, stationary landers/sensors) controlled by local airborne units that have onboard airborne tracking and command systems.

The tracking and command system may be supported by lighter-than-air or heavier-than-air aircraft. The lighter-than-air aircraft may be a tethered balloon or thrust-generating blimp (airborne units). To control a ground-level agent within an operational area, the tracking and command system of an airborne unit includes a transceiver and an instrument suite used to identify the agents, targets for exploration, and obstacles in the operational area. With a wide field of view, the tracking and command system optimally determines paths for the ground-level agents, identifies interesting science targets and obstacles, and subsequently commands the agents using simple movement commands to move through the operational area to the targets while avoiding the identified obstacles. Each ground-level agent includes its own instrument suite to collect surface and subsurface information about the operational area, which is transmitted back to the tracking and command system. The tracking and command system may further be coupled to a satellite system to provide additional (image) information about the operational area, and provide operational and locational commands to the tracking and command system.

Algorithms for determining paths for a robot in an accurately characterized environment are well known in the design of robotics. Using these conventional means, the issue of simultaneously commanding even a few deployed reconnaissance agents to their designated targets becomes exceedingly complex. Each additional simultaneously moving agent increases geometrically the chances of collisions as well as the processing power required for computing and managing the agent trajectories.

In contrast, the overhead perspective greatly simplifies the path-planning effort within the multi-tier, multi-agent autonomous system: the order of complexity of path-planning can be reduced to linear terms by adopting a round-robin sequential commanding scheme (Fig. 2(1)–(17)), as each agent is commanded in turn, instead of all being commanded simultaneously.

References


