AUTONOMOUS TIER-SCALABLE RECONNAISSANCE MISSIONS FOR REMOTE PLANETARY EXPLORATION

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ABSTRACT

A "tier-scalable" paradigm integrates multi-tier (orbit⇔atmosphere⇔surface/subsurface) and multi-agent (orbiter(s)⇔blimps⇔rovers, landers, drill rigs, sensor grids) hierarchical mission architectures [1-4], not only introducing mission redundancy and safety, but enabling and optimizing intelligent, unconstrained, and distributed science-driven exploration of prime locations on Venus, Mars, Europa, Ganymede, Titan, Enceladus, Triton, and elsewhere, allowing for increased science return, and paving the way towards fully autonomous robotic missions.

1. INTRODUCTION

A fundamentally new scientific mission concept for remote planetary surface and subsurface reconnaissance recently has been devised [1-4] that soon will replace the engineering and safety constrained mission designs of the past, allowing for optimal acquisition of geologic, paleohydrologic, paleoclimatic, and possible astrobiologic information of Venus, Mars, Europa, Ganymede, Titan, Enceladus, Triton, and other extraterrestrial targets [5, 6]. 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⇔surface/subsurface) and multi-agent (orbiter(s)⇔blimps⇔rovers, landers, drill rigs, sensor grids) hierarchical mission architectures [1-4], not only introducing mission redundancy and safety, but enabling and optimizing intelligent, unconstrained, and distributed science-driven exploration, allowing for increased science return and paving the way towards fully autonomous robotic missions [6].

In the highly automated scenario, the satellites command and control the airborne agents autonomously, and the airborne agents autonomously command and control the ground-tier reconnaissance agents (Fig. 1). This system integrates satellites with inexpensive balloons/blimps (airships) and ground-tier agents (rovers, fixed landers, e.g., Beagle 2, and sensors). The airborne and ground-tier agents can be inexpensive enough (in terms of capital cost and operational resources) to allow for the deployment of numerous agents that collectively can address specific science-driven questions. Multiple ground-tier and airborne agents collectively can explore the same science target with a complementary suite of instruments.

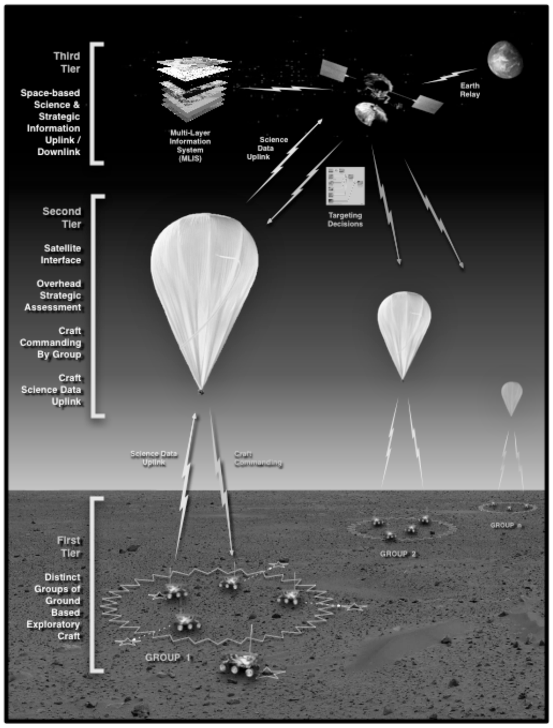

Fig. 1. Tri-level hierarchical multi-agent architecture for autonomous remote planetary exploration (from [1-4]).

To support such tier-scalable reconnaissance mission architectures, a high level of operation autonomy is required. Critical aspects of such operation autonomy are (1) to automatically map an operational area from different vantage points (i.e., space, air, surface/subsurface), (2) to automatically identify targets/regions of interest and to extract features of the identified targets/regions of interest within the mapped operational area [7], and (3) to automatically prioritize targets for close-up reexamination [7-11] (e.g., with ground-tier agents) based on preliminary (coarse) data, gathered (in transit) by, for example, space- and airborne sensor platforms, potentially coupled with existing information from previous missions.

Multiple prioritization scenarios can be conceived to evaluate the (scientific) importance of individual targets or combinations of targets to be further examined during reconnaissance missions (e.g., by a ground-tier agent such as a rover on Mars), which differ in their respective level of complexity. These scenarios can range from simple feature-based or feature-clustering-based prioritization (e.g., [12-14]) to prioritization via context-based clustering (e.g., [15]).

Based on previously gathered, coarse feature/reconnaissance data that has been pre-clustered using general purpose clustering algorithms (e.g., [12-14]) or clustering algorithms associated with special-purpose models (e.g., [15]), more advanced prioritization frameworks recently have been devised [8] for (1) the selection of single or multiple targets, and (2) the selection of instruments used for the close-up reexamination of these targets in an operational area for potential "knowledge gain" about the operational area. These prioritization frameworks are based on the method of "hypothetical probing" [8] that exploits current data only to infer the probability for a particular target or combination of targets to contribute to the "knowledge gain" of an operational area if reexamined more closely.

In addition, the full-scale and optimal deployment of agents as part of a tier-scalable mission requires the design, implementation, and architecture integration of an intelligent reconnaissance system capable of integrating existing and acquired "in-transit" information to automatically perform smart planetary reconnaissance, such as homing in on prime candidate sites for potentially life-containing habitats on Mars [9-11]. To enable a higher level of on-board automation, a fuzzy-logic theoretical framework can be exploited [9-11] to design a fuzzy-based expert system capable of autonomously reasoning over multiple layers of information gathered while en-route and performing smart assessment of the observed areas to help deciding the most appropriate hardware deployment (i.e., deployment of agents and sensors). Fuzzy logic is efficient in dealing with uncertainty and vagueness typical of real life scenarios and may represent an ideal platform to define the basic components of such an expert system. The tier-scalable geological approach, which compiles, synthesizes, and analyzes layers of diverse information (e.g., *Multi-Layer Information System (MLIS)* [1-3]) to identify prime targets for continued exploration [16, 17], is implemented as a set of IF-THEN rules representative of the desired expert knowledge [9-11]. Such rules can be effectively used by a fuzzy inference system to reason over water and/or life indicators to extract parameters such as "potential for water/life-containing", indicating the confidence exhibited by the system to find water and/or life at the observed locales.

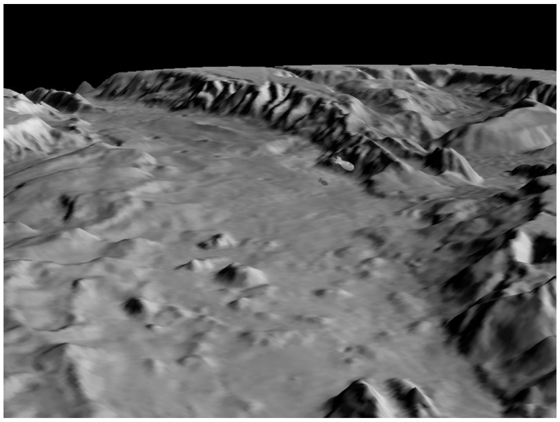

Fig. 2. 3-D oblique view, exemplifying an airborne agent (blimp/airship) performing intelligent reconnaissance over Melas Chasma (after [1]), the central part of the vast canyon system Valles Marineris on Mars. Part of the reconnaissance would include surveying the canyon walls, homing in on stratigraphic sequences, hovering above landslide and valley floor deposits, and identifying targets for subsequent deployment of ground-based agents such as miniature rovers and immobile sensors. Target features of special scientific interest may include: (1) geomorphic features and mineralogical/elemental signatures, indicative of past water activities; (2) diversity of rock types (e.g., site on Mars containing rocks that record the early, middle, and later parts of martian history); (3) elevated heat flow; (4) surface/near-surface water or moisture (including fog embankments); and (5) volatile plumes (e.g., methane). These target features contribute to the success in identifying potential life-containing habitats. (Note that for visual purposes the blimp/airship is not drawn to scale).

2. PRIME CANDIDATES FOR HIGH-RISK SCIENTIFIC EXPLORATION

Non-traditional autonomous missions to remote planetary bodies will be necessary [1-4, 6] primarily to allow intelligent and unconstrained access to scientifically interesting terrains on planetary bodies of the Solar System, not currently feasible with conventional mission designs, including: (1) canyons (e.g., Valles Marineris on Mars, or Devana Chasma, a big rift valley on Venus), (2) mountain ranges (e.g., Thaumasia highlands on Mars, Isthar Terra on Venus), (3) sites of suspected magmatic-driven uplift and associated tectonism and possible hydrothermal activity (e.g., plume-related activity such as hypothesized for the central part of Valles Marineris and the Warrego Valles rise on Mars [17-19], and Maxwell Montes on Venus), (4) polar ice caps (e.g., Mars), (5) suspected ice deposits within impact basins (e.g., Mercury and Moon) (e.g., [6]), (6) volcanoes of diverse sizes and shapes (e.g., Venus and Mars), (7) putative ancient accreted terrains and associated volcanism (e.g., Mars), (8) regions indicating potential recent hydrologic or hydrocarbon activities such as spring-fed seeps (e.g., Mars, Titan), (9) chaotic terrain (e.g., source areas of the circum-Chryse outflow channel system on Mars, Conamara Chaos on Europa), (10) liquid pools of ammonia-water mixtures associated with cryovolcanism or a recent impact cratering event (e.g., Titan, Triton, Enceladus), and (11) liquid hydrocarbon accumulation on the surface (e.g., Titan). All of these geologic terrains, including many other regions of interest on the planetary bodies of the Solar System, are particularly crucial for astrobiologic-oriented exploration in general, and sample return missions in particular [5, 6, 20].

3. APPLICATIONS OF TIER-SCALABLE MISSION ARCHITECTURES

A multi-tier, hierarchical mission architecture would overcome the inherent challenge of traditional geologic planetary surface exploration [1-3]: airborne agents (orbiters in conjunction with balloons/blimps) possess overhead perspectives at different length scales/resolutions, which could provide guidance to ground-based agents (e.g., mobile rover units).

In case of the central part of Valles Marineris: Melas Chasma (Fig. 2), the following deployment and reconnaissance sequence of such a reconnaissance mission is envisioned (see [1, 2, 6, 21-23] for further detail): Orbiter(s) with an embedded existing knowledge base (e.g., *Multi-Layer Information System (MLIS)* [1-3]) scout areas of scientific interest at a global scale, i.e., within Valles Marineris and subsequently Melas Chasma. They subsequently deploy airborne agents such as balloons, blimps, or airships, which deploy in mid-air above Melas Chasma for further scouting and testing of hypothesized conditions. If one (or more) of the airborne agents were to detect scientifically interesting features, such as volatile releases (methane plume or water vapor) and/or elevated heat flow, or transient geologic events (e.g., a giant landslide that initiates on the walls of Valles Marineris), hydrologic events (e.g., water seeps), atmospheric events (e.g., reoccurring fog embankment in a specific part of the canyon system), and/or unique rock assemblages (other than the typically reported basaltic/basaltic-andesite, sulfates, and hematite, e.g., [24, 25]), this airborne agent(s) would then attempt to map out, for example, methane concentration profiles and acquire terrain images of the locales of ancient and extant hydrothermal or gas release activity (i.e., potential source regions).

The information acquired from the airborne vantage would subsequently be processed through automated feature-extraction algorithms such as with the *Automated Geologic Field Analyzer (AGFA)* [7]. The feature data would be autonomously/automatically analyzed by science prioritization algorithms while en route (e.g., [7-11]). This includes coupling existing information with the newly acquired information for comparative analysis (e.g., using a fuzzy-based expert system), to choose potential targets for in-situ investigation and sampling by subsequently deployed ground-tier agents (small rovers, drill rigs, networks of sensors, etc.) and for determining safe passages to their respective designated targets within the prime sites, as identified from the airborne vantage. At the respective targets, the ground-tier agents would conduct in-situ science experiments and thereby gather data that complement the remote sensing data obtained by the airborne agents. For example, the ground-tier agents would help identify, characterize, and map out sources of the volatile plumes (e.g., potential sites of extant hydrothermal activity). In addition, such a system could help direct ground-tier agents, potentially equipped with drills, to a locale of extant hydrothermal activity that records distinct elevated heat flow, mineral assemblages, near surface groundwater, volatile seepage such as water and methane vapors, etc., thereby paving the way for future sample return missions [6, 20].

4. IMPLICATIONS

Multi-tier multi-agent autonomous robotic planetary surface/subsurface reconnaissance will lead to an improved understanding of the various histories (e.g., geologic, geomorphic, pedologic, aqueous, climatic, and possible biologic) of Mars and other extraterrestrial targets, through the tier-scalable geologic approach. Importantly, this new paradigm in planetary reconnaissance will integrate disciplines such as geology, biology, chemistry, physics, mathematics, and engineering, allowing for optimal reconnaissance and testing of overarching theories [26]. This includes confirming working hypotheses such as in the case of Mars, whether (a) the mountain ranges contain a greater diversity of rock types than just volcanic; (b) sites of suspected hydrothermal activity are indeed hydrothermal environments; (c) prime candidate sites of potential life-containing habitability actually contain extant or fossil life or life forms [16, 27, 28]; or (d) close examination of surface/buried soils with sensors suitable for microscopic observation and chemical analysis of coatings on weathered sands might reveal important data on possible soil microenvironments, live microbes, or fossil forms (e.g., [28, 29]). Moreover, tier-scalable autonomous reconnaissance missions afford a first-of-a-kind opportunity to scout, discover, and characterize potential habitats and possible life [6, 20].

Prioritization frameworks for single and multiple (science) targets such as introduced in [8] may be useful for autonomously operating computer-based planning systems (e.g., onboard science craft such as satellite platforms, spacecraft, planetary orbiters, landers, rovers, etc.) to decide which previously detected and coarsely examined target or set of targets harbor the greatest potential for an overall "knowledge gain" about an operational area if revisited or examined more closely. In addition, prioritization frameworks for (science) instrument usage such as introduced in [8] may provide guidance as to which instrument out of a suite of available instruments onboard a science platform has the largest potential to contribute to the above "knowledge gain" if used on these targets. Since instruments may differ in power consumption, time of data acquisition (including total time to take measurements), and distance from the object to be examined (i.e., spatial association between instrument and target), etc., a planning system can take into account these constraints together with the prioritization probabilities and may come up with optimized "target-to-reexamine" and "instrument-to-use-for-reexamination" scenarios, thereby paving the way to more autonomous reconnaissance missions.

5. DISCUSSION & OUTLOOK

Following the published works by Fink et al. [1-3], NASA is now soliciting proposals calling for technology development of *"Sensor webs of the future [that] may include space-based, airborne, and in-situ sensors, all working together in a semi-closed loop system in which "smart" sensors sense what is happening per their designed sensing capabilities and feed that information into a control system. Based on the sensor inputs, the control system then modifies the environment (instrument pointing, data collection on or off, etc.) and causes the sensors to take in and provide new information to the control system."* (excerpt from Science Mission Directorate NASA Research

Announcement "Advanced Information Systems Technology" Solicitation: NNH05ZDA001N-AIST). Moreover, in testimony to Congress in May 2005, NASA Administrator Michael Griffin included the following statement: *"In the future, NASA plans to develop a "sensor web" to provide timely, on-demand data and analysis to users who can enable practical benefits for scientific research, national policymaking, economic growth, natural hazard mitigation, and the exploration of other planets in this solar system and beyond."* This followed the release of the February 2005 publication *The New Age of Exploration: NASA's Direction for 2005 and Beyond* that stated: *"NASA will develop new space-based technology to monitor the major interactions of the land, oceans, atmosphere, ice, and life that comprise the Earth system. In the years ahead, NASA's fleet will evolve into human made constellations of smart satellites that can be reconfigured based on the changing needs of science and technology. From there, researchers envision an intelligent and integrated observation network comprised of sensors deployed to vantage points from the Earth's subsurface to deep space. This "sensor web" will provide timely, on-demand data and analysis to users who can enable practical benefits for scientific research, national policymaking, economic growth, natural hazard mitigation, and the exploration of other planets in this solar system and beyond."*

There are individual components of the tier-scalable mission architecture proposed by Fink et al. [1-3, 21], which are either under development or have already been tested and proven in the "field". These include orbiters, balloons/blimps/airships (although not tested in a space environment so far), and ground-based agents such as rovers and landers as well as immobile sensor webs. The biggest challenge, however, appears to be not so much the hardware but the "intelligent" software that would enable all the components of a multi-tier multi-agent mission to be integrated and function autonomously. Some of the authors of this contribution are developing software (e.g., [7-11]) that would allow the orbiters, blimps, and rovers both to communicate with one another and to navigate and explore the planetary terrain with greatly reduced (and ultimately without) help from mission control on Earth, thus affording more mission autonomy/flexibility and increased science return.

We believe that it is possible to develop, test, and have ready multi-tier multi-agent hierarchical mission architectures within a 10-15 year timeframe to home in on prime targets such as potential volatile-enriched targets (e.g., water and methane sources), which include candidate sites of endogenic-driven hydrothermal activity on Mars. Integrated orbiter-airship missions, especially suitable for the exploration of Mars, Venus, and Titan, are envisioned to be feasible within a decade from now. Subsequent science-driven robotic exploration will couple this new paradigm in planetary reconnaissance with astronautic exploration and research.

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