MULTI-LAYER FUZZY LOGIC-BASED EXPERT SYSTEM FOR CONDUCTING TIER-SCALABLE PLANETARY RECONNAISSANCE

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Introduction: Even though orbiting spacecraft and ground-based landers and rovers have successfully collected significant data through instrument suites, working hypotheses are yet to be confirmed. For example, in the case of Mars, such hypotheses include whether the mountain ranges contain a greater diversity of rock types than just volcanic, sites of suspected hydrothermal activity are indeed hydrothermal environments, or prime candidate sites of potential life-containing habitability [1] actually contain life.

To effectively address this problem, a new scientific mission concept for remote planetary surface and subsurface reconnaissance recently has been devised [2]. The novel mission concept involves a paradigm shift from traditional missions, performing either local ground-level reconnaissance via rovers and immobile landers, or global mapping through orbiters, to what is termed “tier-scalable planetary reconnaissance”; the new paradigm integrates a multi-tier (orbit⇔atmosphere⇔ground) and multi-agent (orbiter⇔blimps⇔rovers/landers/sensors) hierarchical mission architecture to enable unconstrained, science-driven planetary exploration [2].

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. Such a system should (1) include software packages that enable fully automated and comprehensive characterization of an operational area (e.g., *Automated Geologic Field Analyzer (AGFA)* [3]) and (2) integrate existing information with such AGFA-acquired, “in transit” spatial and temporal sensor data, to automatically perform smart planetary reconnaissance, such as identifying and homing in on prime candidate sites for potentially life-containing habitats on Mars.

Methodology: Our goal is to define the framework for the design of an expert system (intelligent reconnaissance system) to be integrated into the tier-scalable mission architecture. Such a system is conceived to comprise two cascading subsystems capable of performing (1) and (2) respectively. Here we focus on defining an expert system capable of explicating functions as defined in (2). Since the tier-scalable approach is defined by the deployment of multiple agents in planetary environments to collect multiple layers of data at multiple scales as part of a *Multi-Layer Information System (MLIS)* [2] (both spatial and temporal), such an expert system should be able to ingest and elaborate on the stream of the “in transit” information in order to take appropriate steps to home in on locales where the potential of yielding significant scientific findings is the highest.

In general, the design of an expert system requires two basic ingredients: the knowledge base and the inference system. Both elements depend on the type of Artificial Intelligence (AI) scheme employed. Here, we focus on the problem of finding locales that yield the highest probability of detecting extant and/or fossilized life, addressed by proposing a fuzzy logic approach to design an expert system that can be used to autonomously operate the tier-scalable planetary deployment.

Fuzzy logic is very efficient in dealing with the vagueness typical of real life situations and allows the implementation of linguistic statements into a machine format [4]. The fuzzy logic framework, which includes concepts such as membership functions, fuzzification, and de-fuzzification, can be integrated with a set of IF-THEN rules (Mandami-type [5]) to infer new facts from the streaming data collected by the sensors. Most of the current effort is devoted to defining the appropriate set of rules that condenses a geologist’s approach of performing reconnaissance through spaceborne, airborne, and ground-based (tier-scalable) sensor observations, to synthesizing the spatio-temporal sensor information (e.g., stratigraphy, structure, topography, geomorphology, hydrology, and geophysical, geochemical, spectral, and elemental information), and formulating new working hypotheses and testing existing working hypotheses based on the tier-scalable information.

In the specific case of Mars, we define the environmental indicators to assess the potential for life-containing habitats using a tier-scalable deployment where the system is able to ingest in-transit multiple layers of data and perform synthesis of information (i.e., comparative analysis of the temporal and spatial information) in order to home in on selected, potentially life-containing, prime targets. The system will synthesize layers of information mimicking detective work to establish prime candidate sites. The premise is that water is key to life on Mars and therefore the system must follow the water. Energy is another crucial ingredient. Life, dormant in certain environments, might spring up once energy and nutrients are fed into the system [6]. Therefore, the system must follow energy sources as well.

Figure 1 shows a schematic of a multi-layer fuzzy logic-based expert system. First, raw data collected by the deployed sensors are pre-processed via embedded software (e.g., AGFA [3]) to determine the numerical values for the proper life indicators (e.g., amount of liquid water, water vapor, ice, sulfates). Then, the indicators are categorized according to the information they carry (e.g., spectral, geomorphological, topographical, thermal). Subsequently, the indicators are fed to four independent fuzzy logic systems where they are fuzzified and processed by a set of IF-THEN rules to determine the potential for past and present water, as well as the potential for past and present energy. The first-layer outputs are input to a second-layer fuzzy logic system that ingests the potential for past/present water/energy and uses a second set of rules to infer the potential of finding life.

Figure 2 shows details of the fuzzy logic rules proposed for the second-layer fuzzy logic system. The rules are organized to highlight the impact of energy and water on the potential life-containing habitability. We consider six levels in which the impact is rated from Very Low (VL) to Very High (VH). Highest potential for life is given to locales exhibiting high indication of past/present water and energy, i.e., if spectral, geomorphologic, stratigraphic, topographic, elemental, and thermal indicators yield high values (first-layer) for all possible water/energy potentials. The other levels are ordered according to the scheme shown in Figure 2.

Implications and Future Work: The proposed multi-layer fuzzy logic-based expert system has been conceived to define an intelligent reconnaissance system to be integrated into the tier-scalable mission architecture. The current conceptual design has been developed using Mars as a case study, though it could be tailored for tier-scalable missions to other planetary bodies (e.g., Titan). Future work will include the full-scale implementation and testing of the system on existing Mars data (e.g., geologic, paleohydrologic, spectral, elemental, geophysical, etc.) to identify potentially life-containing prime targets.

References: [1] Dohm, J.M., et al. (2004) *Planet. Space Sci.*, 52, 189-198. [2] Fink, W., et al. (2005) *Planet. Space Sci.*, 53, 1419-1426. [3] Fink, W., et al. (2005) In *Abstracts of the 15th Annual V.M. Goldschmidt Conference, Moscow, Idaho. Geochimica et Cosmochimica Acta*, Volume 69, Number 10S, A535. [4] Zadeh, L.A. (1988) *Computer*, Vol. 1, No. 4, pp. 83-93. [5] Mandami, E.H. (1977) *IEEE Transactions on Computers*, 26, 12, pp. 1182-1191. [6] Schulze-Makuch et al. (2005) *JGR-Planets*, 110, E12S23.

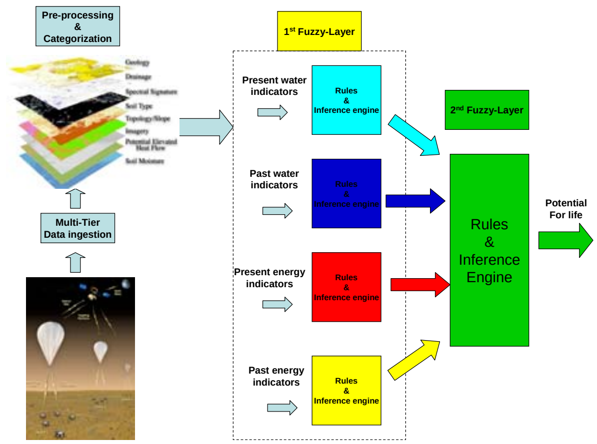

Fig. 1. Schematic of the multi-layer fuzzy logic-based expert system for the tier-scalable mission architecture [2]. The schematic diagram illustrates the sequence of operation during deployment. The mission agents/sensors are deployed to collect multi-scale multi-sensor data, which are subsequently processed to extract the appropriate indicator values. The indicators are fed to two layers of fuzzy logic systems, which use Mandami-type rules [5] and inference mechanisms to identify, characterize, and subsequently home in on candidate life-containing locales. Depending on the assessment result, the system might order further deployment to the locale (e.g., drill rig that is optimally placed to sample identified near-surface groundwater in a locale of elevated heat flow).

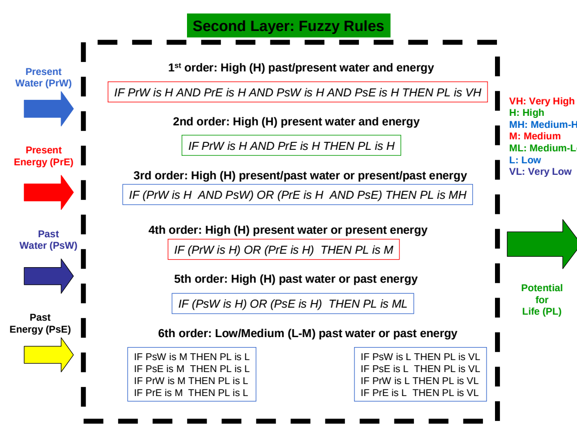

Fig.2. Second-layer fuzzy logic system. While the first layer processes various layers of indicators to yield potential for past/present water and energy, the second layer uses this information to identify, characterize, and subsequently home in on candidate life-containing locales. The rules, which form the knowledge base of the system, are highlighted to show the internal structure of the expert system. After fuzzification, the rules are fired at the same time to assess the life-containing habitability of the observed locale. The rules are organized in six prioritized levels.