SEARCHING FOR LIFE ON EXTRATERRESTRIAL BODIES: FUZZY AUTONOMOUS SYSTEMS FOR PLANETARY RECONNAISSANCE

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Introduction: Autonomy will play a critical role in future science-driven, tier-scalable robotic planetary reconnaissance [1] of extremely challenging planetary locales. A full-scale, optimal deployment of agents employed by tier-scalable architectures [1] to explore for extraterrestrial life, habitats and life's precursors requires the design, implementation, and integration of an intelligent reconnaissance system [2]. Such a system should enable fully automated and comprehensive characterization of an operational area; to integrate existing information with "in transit" real-time spatial/temporal sensor data; and to identify and home in on prime candidate locales having the greatest potential of containing life.

To aid the discovery of locales with the highest *Potential for Life Habitability (PLH)* on Mars, we designed a two-layer fuzzy-based system [3] capable of autonomously assessing PLH (defined as an index ranging between 0 (min) and 100 (max). This system assumes that life is tied to water and energy availability; it operates (1) by ingesting appropriate past and present water/energy indicators while the tier-scalable mission architecture is deployed (1st layer), and (2) by evaluating life habitability through a specialized fuzzy knowledge-base of water and energy information (2nd layer) acquired through (1) and existing multi-layered information (see [1]) based on past missions.

Why fuzzy logic? Except for the Moon, planetary exploration has thus far been the investigation of planetary bodies through remote reconnaissance, either by orbiting spacecraft or field-based (lander/rover) platforms. New discoveries are made coupling newly acquired data with existing information to test working hypotheses and formulate new hypotheses. For example, diverse evidence points to regions on Mars that could yield significant geologic, paleoclimatic, and possible exobiologic information (e.g., [1,4-6]). Fuzzy logic provides an ideal framework in the search for prime locales of elevated life-containing habitability (the greater amount of identifiers of extant/ancient water/energy, the greater the potential of life), as it can deal with independent layers of diverse spatial and temporal information of varying degrees of confidence (e.g., elevated hydrogen content, low sulfate level, medium number of sapping channels, etc.). The absolute values of the input data can be transformed into fuzzy values and incorporated into rules that deal with concepts/working hypotheses of varying degrees of confidence (depending on the layers of information deemed consistent with the respective hypothesis).

Fuzzy System Design Process: The design of an expert system requires the selection of the appropriate knowledge-base and inference system. The fuzzy logic framework, which includes concepts such as membership function, fuzzification, and de-fuzzification schemes, can be integrated with a set of IF-THEN rules (Mandami-type [7]) to infer new facts given the streaming of spatio-temporal data collected by the sensors. The selected Fuzzy Artificial Intelligent Scheme (FAIS) is embedded in a two-layer system specifically designed to link water and energy to life habitability. The first-layer is comprised of four independent fuzzy systems (present water, past water, present energy, past energy), each devoted to determine the water/energy potential depending on its own specialization. Each knowledge-base is constructed according to linguistic rules connecting life indicators to water/energy content. After these data, collected by the deployed sensors, coupled with existing information (e.g., [1-4]), are pre-processed via embedded software (e.g., *Automated Geologic Field Analyzer (AGFA)* [8]) to determine the numerical values for the proper life indicators (e.g., amount of liquid water, water vapor, ice, sulfates), the first-layer fuzzy systems are activated to determine the potentials for (1) past and present water and (2) past and present energy. The first-layer outputs are input to a second-layer system that ingests the past/present water/energy potentials and uses a second set of rules to infer the potential for life habitability. Details for one of the first-layer fuzzy system are presented next.

Fuzzy System for Water Potential: The first fuzzy system is designed to ingest indicators of present water at a locale under investigation as signs for potential life. The first fuzzy system evaluates the presence of water, yielding a parameter (PrW) between 0 and 100. Table 1 shows a set of water indicators relevant to the potential for life. We consider water in all forms (solid ice and hydrates, liquid, and vapor), occurring in the subsurface, on the surface, and in the atmosphere. The mixture of salt and water is also considered (e.g., brines). The confidence factor is descriptive of the importance of the indicators relative to each other. For example, when combined with other indicators, atmospheric moisture embankment is critical to identifying potential life-containing locales based on work in the extremely arid Atacama Desert (e.g., [9]). The associated rules are shown in Table 2. The set of IF-THEN Mandami-type rules are organized to show the impact of the indication of present water potential on life. In the semantic description of the rules, “H”,”M”,”L” stand for high, medium, and low. The rules have been organized in two sets where the indicators have the same confidence factor. The confidence factor weights the importance of the rules associated with the corresponding indicators and defines a lower limit. For example, the locale under observation might show high liquid water content but low solid and atmospheric water. In this situation, the locale still exhibits an elevated presence of water. To adapt the rule to this circumstance, the AND connector is utilized for low content, i.e., “present water” is low only if all indicators are low (Table 2).

Fuzzy Simulation and Testing: The overall two-layer system was simulated on a hypothesized martian scenario to test its predictive consistency. A tier-scalable deployment was assumed to collect a set of water and energy indicators for an area, which was rated by field experts and the four first-layer fuzzy systems to exhibit medium present water but high past water and present/past energy. Figure 1 shows the inference process performed by the second layer. The first-layer outputs are fuzzified and processed by 13 rules fired concurrently. The fuzzy inference process yields a composite fuzzy PLH, which is de-fuzzified using a centroid method [7]. The system rates the area’s PLH = 81.2. Since the area is rated high, such information is passed by the Fuzzy AI system to a lower-level agent/sensor control system, which orders relocation or further deployment of agents/sensors for closer, more detailed observations that might yield conclusive evidence for life or its precursors or fossils.

Implications and Future Work: Ultimately such a two-layer fuzzy expert system must be integrated with a tier-scalable planetary life reconnaissance architecture [1]. The approach must incorporate an updated expert system through future interdisciplinary scientific collaboration among geologists, biologists, hydrologists, geochemists, geophysicists, engineers, and roboticists to design optimal systems. We anticipate the development of systems tailored to find life, its fossils, or its precursors on Mars, Titan, Enceladus, Europa, and beyond.

References: [1] Fink, W., et al. (2005) *Planet. Space Sci.*, 53, 1419-1426. [2] Furfaro, R., et al. (2006) *AIAA SpaceOps Conf.*, Rome .[3] Furfaro, R., et al. (2006) PSS- in review [4] Dohm, J.M., et al., *Planet. Space Sci*., 52, 189-198, 2004. [5] Schulze-Makuch, D. et al. (2005) *Astrobiology* 5, 778-795. [6] Schulze-Makuch, D. et al. 37th Lunar Planet Sci. Conf . [7] Ross, T. J., (2004), Fuzzy Logic with Eng. Appl., Wiley Publ. [8] Fink, W., et al. (2005) *Geochimica et Cosmochimica Acta*, Volume 69, Number 10S, A535. [9] Dohm et al. [2005] 36th Lunar Planet Sci. Conf., Abstract #1579.

Table 1. Indicators for the Present-Water fuzzy system

Category	*Indicators*	*Confidence Factor*
Elemental/Spectral	Surface Liquid Water (SLW)	1
Elemental/Spectral	Surface Solid Water (SSW)	0.9
Elemental/Spectral	Surface Brine (SB)	1
Elemental/Spectral	Subsurface Brine (SSB)	1
Elemental/Spectral	Subsurface Liquid Water (SSLW)	1
Elemental/Spectral	Subsurface Solid Water (SSSW)	0.9
Atmospheric	Atmospheric Moisture (AM)	0.9
Atmospheric/Spectral	Soil Moisture (SM)	0.9
Atmospheric/Geomorphology	Embankments Moisture (EM)	0.9

Table 2. IF-THEN rules for the Present-Water fuzzy system.

Indicator and Confidence Factor	*Rules*
SLW, CF =1	IF SLW is H THEN PrW is H IF SLW is M THEN PrW is M
SSLW, CF = 1	IF SSLW is H THEN PrW is H IF SSLW is M THEN PrW is M
SB, CF = 1	IF SB is H THEN PrW is H IF SB is M THEN PrW is M
SSB ,CF = 1	IF SSB is H THEN PrW is H IF SSB is M THEN PrW is M
Low-rule , CF = 1	IF SLW is L AND SSLW is L AND SB is L AND SSB is L THEN PrW is L
SSW, CF = 0.9	IF SLW is H THEN PrW is H IF SLW is M THEN PrW is M
SSSW, CF = 0.9	IF SSW is H THEN PrW is H IF SSW is M THEN PrW is M
AM, CF=0.9	IF SLW is H THEN PrW is H IF SLW is M THEN PrW is M
SM, CF = 0.9	IF SLW is H THEN PrW is H IF SLW is M THEN PrW is M
EM, CF = 0.9	IF SLW is H THEN PrW is H IF SLW is M THEN PrW is M
Low-rule, CF = 0.9	IF SSW is L AND SSSW is L AND AM is L AND SM is L AND EM is L THEN PrW is L

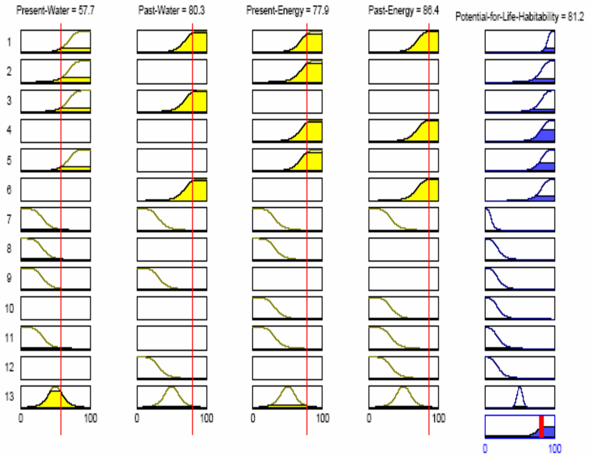

Figure 1. *Fuzzy rules interpretation process for second-layer fuzzy system (first-layer) as applied to the hypothesized region. Each row represents one rule. The values for the input parameters are reported at the top of each column. After inference and de-fuzzification, the hypothesized locale exhibits a high potential for life habitability.*