

Aerial Explorers

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This paper presents recent results from a mission architecture study of planetary “aerial explorers”. In this study, several mission scenarios were developed in simulation and evaluated on success in meeting mission goals. This aerial explorer mission architecture study is unique in comparison with previous “Mars airplane” research activities. The study examines how aerial vehicles can find and gain access to otherwise inaccessible terrain features of interest. The aerial explorer also engages in a high-level of (indirect) surface interaction, despite not typically being able to take-off and land or to engage in multiple flights/sorties. To achieve this goal, a new mission paradigm is proposed: aerial explorers should be considered as an additional element in the overall Entry, Descent, Landing System (EDLS) process. Further, aerial vehicles should be considered primarily as carrier/utility platforms whose purpose is to deliver air-deployed sensors and robotic devices, or symbiotes, to those high-value terrain features of interest.

I. Introduction

The potential of planetary aerial explorers for imaging surveys is obvious. But aerial imaging is a necessary, but not necessarily sufficient, mission requirement for their development. Additional justification, particularly embodying mission persistence beyond the flight of the aerial vehicle, is required. This can be accomplished by shifting the paradigm of aerial explorers from simple imaging and remote-sensing applications to one of a utility/carrier platform that can perhaps be best thought of as the ultimate manifestation of EDLS (Entry, Descent, and Landing System) technology. Embracing this mission architecture concept, the aerial explorer becomes a critical element of a system of systems encompassing sensors and robotic devices, air-deployed and otherwise. In effect it comprises a small but potent robotic ecology of heterogeneous robotic systems (both internal and external autonomous agents). By embracing this paradigm shift, the flight duration of the aerial vehicle is of secondary importance to its ability to accurately identify terrain features of interest and precisely deploy sensors and devices that can make high-value science measurements at those surface locations. It is equally important that these sensors offer the quality of persistence by returning data well beyond the flight of the aerial explorer.

The objective of the research described in this paper is to craft a series of mission scenarios that embody this new Mars aerial explorer paradigm, develop and implement simulation tools and bio-inspired autonomy concepts to effect in simulation those identified mission scenarios, and, finally, to assess the simulation results in terms of the overall viability of the proposed aerial explorer mission architecture.

II. The Past Revisited

The literature is replete with a multitude of Mars airplane mission and conceptual design proposals. Table I summarizes a survey of the “Mars airplane” design/mission studies in the literature, dating back to the 1970’s. A common set of mission elements among all these “Mars airplane” studies is the emphasis on aerial imaging, remote-sensing of the Martian surface from the aerial vehicle, and atmospheric composition sampling/analysis.

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Table 1. Partial Survey of “Mars Airplane” Work

Author(s)	Vehicle Description	Mission Description
Butts and French ³⁵	Mars exploration program study effort; (15 hp) hydrazine engine driving a single propeller; with and without take-off/landing rockets; wing span = 21 m; range = 4800-6700 km; mass ~ 300 kg; cruise Mach # = 0.25 (near-empty) to 0.38 (full fuel load); 2m tractor propeller; six wing-folds, one tail-boom fold, and two tail-surface folds.	Multiple aerial vehicles released from orbit in Viking-type aeroshells from a spacecraft carrier platform. “High resolution” (0.5 m) aerial surveys, atmospheric measurements to 7.5 km altitude; deployment of network sensors, and site selection from Mars sample return missions. Each aerial vehicle would have a 40kg payload.
Calvin ¹	Glider and solid-rocket-glider configurations; wing span ~ 2m; flight duration = 20-60 minutes; range = 100-300km; cruise Mach # = 0.38-0.56.	Payload = 1-3kg, including possibly cameras, dust and cloud sensors, magnetometers, gas sampling and spectrometry; multiple vehicles released during entry.
Clarke, et al ²	Wing span =21m; wing area = 20 m ² ; flight duration 17-31 hours; max range 10,000 km; both electric and hydrazine engine propulsion studied driving single tractor propeller; cruise Mach # from 0.28 to 0.47; rockets for soft landing capability.	Mission study emphasized imaging, gamma-ray and IR spectroscopy, atmospheric composition and dynamics measurements, and gravity and magnetic field measurements. Payload from 40-100kg. Considerable discussion regarding Mission operations and systems.
Colozza ³	Solar powered, or radioisotope, long-endurance aircraft; wing aspect ratio = 19-40.5; wing span = 47.5-128.0m; flight duration > 1 year; electric propulsion (solar or radioisotope) with pusher propeller; mass = 438-1189kg (function of solar cell efficiency & latitude)	100 kg payload. Technology study.
French ⁴	Two vehicles studied: a “cruiser” and a “lander.” Wing aspect ratio = 22; wing span = 20 m; flight duration ranged from 7.5-31 hours depending on propulsion and payload assumed; range from 2000-10,000 km; single tractor propeller driven by either an Akkerman hydrazine reciprocating engine or electric propulsion; hydrazine rockets (Viking-lander derived) for landing; vehicle mass = 300kg.	Unmanned vehicle study. 40-100kg of payload. Design is to support human exploration of Mars; therefore the design is assembled by astronauts and ground-launched (catapult or rocket takeoff). Briefly touches upon issues related to a manned Mars airplane, though no design data was given.
Guynn, et al ⁵	ARES Mars Scout Proposal; wing aspect ratio = 5.58; wing span = 6.25m; max range = 500-600km; flight duration = 60-71 min; pulsed rocket propulsion; cruise Mach # = 0.65; maximum expected fueled mass = 149 kg.	Aerial imaging, atmospheric sampling, and residual surface magnetic field measurements.
Hall, et al ⁶	AME proposal; wing aspect ratio = 12.65; wing span = 12.45m; flight duration = 8.8 hours; range = 3500 km; cruise Mach # = 0.47; electric (fuel-cell) propulsion with 2m radius tractor propeller; mass = 204 kg.	Fly-over of Gusev Crater; 25 kg payload, including imaging cameras, mini-TES, robotic arm, Raman and APX spectrometers; proposed to survive landing and ideally take off again using rocket-power.
Hall, et al ⁷	Micro-mission proposal and “Kitty Hawk” prototype flight demos; wing span = 2.56m; flight duration = 1 hour; range = 291 km; cruise Mach # 0.57; tractor propeller; mass = 18kg.	Tech demo; high-altitude balloon-drop tests of unpowered glider versions of vehicle
Malin, et al ⁸	MAGE proposal; wing span = 9.75 m; hydrazine engine driving a pusher propeller; flight duration = 3 hours; range = 1800 km; mass = 135 kg.	Payload of gravimetric, magnetic, and electric field sensors, as well as infrared imaging spectrometer, laser altimeter, and imaging cameras for study of Valles Marineris.
Neunteufel ⁹	Three different vehicles studied (mass = 100, 120, and 300 kg) with two different propulsion options: electric-drive and hydrazine engine. Single 2m pusher propeller concentric with tail-boom/empennage of vehicle; wing span = 13.4m for 120 kg vehicle; Eppler E59 for the 100 and 120 kg vehicles and E61 for the larger vehicle; cruise Mach # for all vehicles ~ 0.39; range = 9171 km; no discussion of number of wing/tail-boom folds required.	Technology study. Long-range traverse: entry/deployment over Olympus Mons and traveling along the length of Valles Marineris. Aerial surveys with air-deployed penetrators and (pos-flight) ground released mini-balloons for meteorology. Final payload target of 47 kg for advanced electric propulsion configuration.
Raymer ¹⁰	Technology demonstrator; wing aspect ratio = 10; wing span = 9.75m; cruise Mach # = 0.2; electric (battery) propulsion with 1.22m radius propeller; mass=28 kg.	Flight hardware prototyping for proposed high-altitude (31.7 km) terrestrial balloon drop test.
Reed ³⁸	Mars study based on developed/demonstrated high-altitude remotely-piloted vehicle. Range of configurations considered. Wing span = 6, 9, and 12m; wing area = 4.2, 7.8, and 13.9m ² ; cruise mach # 0.5-0.6; range from 4800-9600 km; endurance 10-30 hours; total vehicle mass from 180-270 kg; hydrazine engine driving a single pusher propeller.	Extrapolation of prototype high-altitude aerial vehicle (“mini-sniffer”) characteristics to Mars operation. Air-deployment in Mars atmosphere. Low-altitude terrain-following mission briefly described. Payload ranged from 11 to 45kg.
Sivier & Lembeck ³⁶	Manned Mars airplane study; propellers with electric propulsion; rocket-based VTOL for take-off and landing; endurance of 8 hours.	Design intended to carry two space-suited astronauts.
Smith, et al ¹¹	“Mars Canyon-Flyer micro-mission” proposal; electric-propulsion (batteries) and hydrazine engine examined for a (four-bladed) 1.08m diameter single tractor propeller; wing span = 2.2m; flight duration 0.25 hours; range = 130 km; mass = 20kg; cruise Mach # = 0.55; two wing folds and one fuselage/tail-boom fold.	Aerial imaging survey of Valles Marineris. Payload = 8.7kg with electric propulsion and 11.5kg with hydrazine engine.

A quick review of Table 1 reveals a spectrum of vehicle configurations and mission capabilities. In general, the early Mars airplane studies tended to be quite ambitious in vehicle size, capabilities, and mission scope. Later studies, perhaps more pragmatic in nature, have tended toward much smaller vehicles – reflecting, in part, much more sensitivity to the practical considerations of the unfolding and mid-air deployment of the Mars airplane from the entry vehicle – with much more modest mission scope. (Mid-air-deployment from the entry vehicle aeroshell is the almost universally preferred approach for Mars airplane deployment. Ground launch is rarely advocated, except for vertical lift planetary aerial vehicle concepts.) With the exception of only a few proposals, most Mars airplanes are incapable of attempting soft landing. All Mars airplane proposals, but one, are robotic flyers; only one study investigated the possibility of a manned vehicle³⁷, with another briefly discussing the possibility⁴. In all the surveyed papers, only limited discussion touched upon (non-GPS) navigation and autonomous system technology issues for such vehicles. For the most part pre-programmed flight paths are assumed for these vehicles; there is no implicit intelligent search and find strategies being employed.

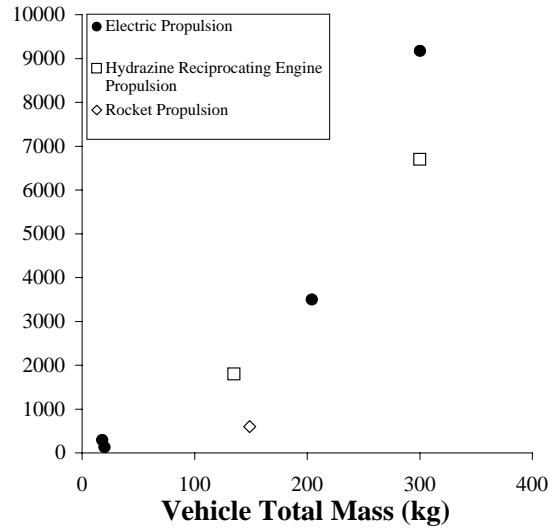


Figure 1. Past Mars Airplane Range versus Mass Trend

Figure 1 summarizes some of the range (km) and mass (kg) characteristics for these previously proposed Mars airplane concepts. In addition to the standard metrics for aerial vehicle performance, additional metrics must be defined and considered in the design of these vehicles. Among these new aerial explorer specific metrics are the following:

Deployed Wing Efficiency --

$$\eta_{DW} \equiv L/D(1 + N_{Wingfolds}) \quad (1)$$

The deployed wing efficiency parameter, Eq. (1), is simply the vehicle lift-to-drag ratio divided by the number of wing folds (plus one) the vehicle has to undergo during deployment. For all air-deployed (from the entry vehicle aeroshell) Mars airplane concepts, there is a clear design trade-off between vehicle lift-to-drag ratio and the number of wing folds necessary to accommodate the large wing span to achieve high L/D's. Therefore, it is not only necessary to optimize the wing design for aeroperformance but deployment simplicity (and risk mitigation) as well.

Volumetric Efficiency --

$$\eta_V = Sb/V_{Aeroshell} \quad (2)$$

Where S is the aerial explorer wing area, b is its wing span, and $V_{Aeroshell}$ is the available internal volume for the aerial vehicle to be stowed within the entry vehicle aeroshell. Though vehicle mass is an important consideration in transporting and delivering aerial explorers to other planetary bodies, volumetric considerations, Eq. (2), are of equal importance. Leveraging as much as possible heritage entry vehicle/aeroshell designs, there is only so much volumetric space available (which is not in a convenient form factor for aerial vehicles). The volumetric efficiency metric allows a quantitative comparison between aerial vehicle (or aeroshell) designs to find the optimal configuration for stowage and transport to other planetary bodies.

Mission Energy Efficiency --

$$\eta_{ME} = N_{Flights} \cdot W_{Payload} \cdot Range / E_{ExpendPerFlight} \quad (3)$$

Where N_{Flights} is the total number of flights for the entire mission for all vehicles, W_{Payload} is the weight of the payload (for a given planetary body), and $E_{\text{ExpendedPerFlight}}$ is the energy expended for a single nominal or representative flight during the mission. Equation (3) is purposely crafted to reflect total mission energy efficiency, and not just a metric for (necessarily) a single flight and a single vehicle. Thus this mission efficiency metric captures attributes of aerial explorer missions when there are multiple flights/sorties per vehicle and/or multiple vehicles per single mission.

Aerial Explorer Autonomy Level –

Drawing on inspiration from the Air Force Research Laboratory (AFRL) defined uninhabited aerial vehicle (UAV) autonomous control levels (ACL)³⁷, we propose a tailored set of autonomy levels for aerial explorers (Table 2). Aerial explorers are UAVs. Therefore, it is reasonable to start assessing their autonomous operational characteristics in the context of prior terrestrial UAV work. However, aerial explorers do have unique mission, operation, and environmental characteristics as compared to terrestrial UAVs – and therefore the AFRL ACL definitions are only inspirational and not directly applicable.

Table 2. Proposed Aerial Explorer Autonomy Levels

Level #	Level Description	Capability
10	Legacy/Legate	Human-surrogate capability to conduct long-term (perhaps years or decades) high-level exploration and scientific investigation.
9	Human Explorer Assistant	Limited human-level surrogate capability that works in close conjunction with human explorers and oftentimes acts as a liaison or intermediary for humans with other robotic systems
8	Integrated, Optimal Autonomy & Design	Autonomy considerations are implemented intrinsically in aerial explorer design and mission simulation. Additionally, for vehicles with “morphing,” hybrid, or adaptive capability, autonomous system characteristics are modified in accordance with revised vehicle characteristics (i.e. a simultaneous autonomous system and physical transmogification).
7	Robotic Ecosystem – Participant	Aerial explorer is part of a large and robust robotic ecosystem. All robotic systems part of this ecosystem must collaborate, and sometimes compete, for resources and other (oftentimes provided by human explorer) rewards. Such an ecosystem is only likely during and in support of human exploration campaigns. Missions being supported by such robotic ecosystems tend to be open-ended in terms of scope and duration.
6	Robotic Symbiosis – Leader/Co-Equal	Automation for extended missions (i.e. multiple flights with multiple automated cycles of vehicles servicing/recharging/refueling) is applied across multiple heterogeneous robotic systems, where the aerial explorer(s) take on leadership and or co-equal roles with other systems (necessitating robust “negotiation” for information and energy resources).
5	Robotic Symbiosis – Subordinate or Dependent	Automation for the mission is applied across multiple heterogeneous robotic systems, in addition to the aerial explorer, for the whole of the mission and not just the flight(s). Aerial explorer is primarily subordinate to some other robotic system, which provides guidance and support.
4	Opportunistic Self-Modifiable Goals and Lines of Investigation	Mission goals/objectives and approaches can be completely (autonomously) redefined as a consequence of information garnered during the course of the mission (i.e. things discovered and hypotheses disproved or revised). Sophisticated, intelligent sensors are employed on the aerial explorers. [§]
3	Search, Inquiry, and Decisions through “Discovery”	Aerial explorer implements flight behaviors, rather than flight/mission scripts. Heuristic and/or stochastic search and find methodology employed to find key terrain (atmospheric phenomena) features of interest. [†] Adaptive fault/anomaly logic implemented.
2	Changeable (though still scripted) Mission	Ability to enable scripted contingency plans based upon pre-defined (well-posed) conditional logic conditions. [*]
1	Execute Pre-Planned Missions	Can execute a scripted flight/mission plan without human intervention during flight; only limited contingency/fault capability. [*]

Notes:

*Navigation limited to simple sensors and Inertial Measurement Units (IMUs).

†Navigation based on sophisticated (non-GPS) sensors, including sun- or star-trackers, LIDAR, RADAR, etc.

§Navigation suite must include vision-based systems.

Autonomy and Intelligence in Aerial Vehicles

Most of the Mars airplane mission/vehicles summarized in Table 1 barely touch upon the autonomy issues of aerial vehicle flight control and navigation in the uncertain or unknown environments inherent in planetary exploration. At best, most of the mission scenarios included in the Table 1 studies would only be level 1 or 2 in the Table 2 hierarchy. The aerial explorer mission scenarios described later in this paper strive for much higher levels of autonomy.

Weighing briefly into the autonomy versus intelligence debate, *autonomy* is defined for the purposes of this paper as the ability to independently perform without human intervention actions, tasks, or roles. *Intelligence* measures how well these actions, tasks or roles are performed under varying degrees of task and environmental complexity and other associated constraints and conditions. Further, *elegance* is the computational efficiency by which the autonomous vehicle *intelligence* is implemented. Therefore, it is wholly possible that two robotic systems can be at nominally equivalent autonomy levels but exhibit radically different levels of intelligence. For example, one robot could perhaps only perform its tasks in a simple invariant environment, whereas another robotic system could perform those nominally same tasks in a highly uncertain, unknown, or changing environment. The latter robotic system is clearly more intelligent than the robot that can only successfully operate in the simpler environment, though their autonomy level rating may be equivalent.

In a simplistic sense, these definitions for the aerial explorer application can be expounded upon by examining the following relationships, Eqs. (4a-b), for a given set autonomy level, as per Table 2:

$$Intelligence \equiv Mission\ Success \times \frac{Environmental\ \&\ Operational\ Complexity}{Number\ of\ Robots}$$

$$Elegance \equiv \frac{Intelligence}{Autonomous\ System\ Complexity \times Number\ of\ Robots}$$

(4a-b)

Where for aerial explorer autonomy levels 3-6, at least, where the principal bulk of the work by this paper's authors is currently being performed, the following holds true:

$$\begin{aligned} Environmental\ \&\ Operational\ Complexity \equiv & \\ & Robot\ Mobility\ Degrees\ of\ Freedom \\ & \times\ Number\ of\ Control\ Actuators \\ & \times\ Required\ Control\ Input\ Rate \\ & \times\ Number\ of\ Sensors \\ & \times\ Degree\ of\ Inaccessibility \\ & \times\ Degree\ of\ Resistance \\ & \times\ Degree\ of\ Interaction \\ & \times\ Inverse\ of\ Target\ Frequency \end{aligned}$$

$$\begin{aligned} Autonomous\ System\ Complexity \equiv & \\ & Lines\ of\ Software\ Code \\ & \times\ Number\ of\ State\ Space\ Variables \\ & \times\ Number\ of\ Robotic\ Behaviors \\ & \times\ Number\ of\ Conditional\ (Heuristic)\ Rules \\ & \times\ Number\ of\ Processors \\ & \times\ Size\ of\ System\ Dynamic\ Memory \\ & \times\ Mean\ Processor(s)\ Instruction\ or\ Operation\ Speed \end{aligned}$$

(5a-b)

Note that in the expression for “environmental and operational complexity” in Eq. (5a-b) that: 1. The “degree of inaccessibility” term for aerial explorers can encompass many things, but, in its simplest form, it is equivalent to terrain ruggedness, i.e. unity plus the variance of terrain elevation obscuring features of interest or impeding mobility; 2. The “degree of resistance” term can also encompass many things, but, again in its simplest form for aerial explorers, it is equivalent to atmospheric turbulence, i.e., unity plus the variance in wind magnitude and direction as affecting the ease of flight control; 3. The “degree of interaction” term encompasses the physical (manipulator or instrument) and informational interactions of the aerial explorer with objects/features of interest on the ground or interactions with external robotic symbiotes and/or other members of a robotic ecosystem, in its simplest form for aerial explorers it is unity plus the resultant of the number of probes and symbiotes released by the aerial vehicle *times* the post-flight “persistence” of those probes/symbiotes; and 4. The “inverse of target frequency” term, for discrete targets, is given by $\pi R_{max}^2 / N_{Actual}$, note that, though, alternate expressions are required for distributed and scarce targets. These aerial explorer environmental and operational complexity expressions have analogs with other robotic systems. For example, the “degree of inaccessibility” term for rovers would incorporate rock or grade-slope hazards to the rover mobility. Correspondingly, lack of traction for rover wheels (or relatively heavy object weight to be carried by the rover robotic arm) could contribute to the “degree of resistance” term for the rover. Finally, the difficulty of placement, and/or required fine control, of rover manipulators on external objects of interest would contribute to the degree of interaction term for rovers. As will be discussed later, “Mission Success” as related to the aerial explorer *intelligence* metric is directly proportional to the “discovery confidence” metric, D_C , for level 3-4 aerial explorers working in (robotic) isolation:

$$Intelligence \propto Mission\ Success \propto D_C \propto Targets\ Found\ Per\ Hour \quad (6)$$

Clearly alternate expressions and relationships could be proposed for defining aerial explorer (let alone other robotic systems) *autonomy*, *intelligence*, and *elegance*. The important consideration for all UAV and aerial explorer intelligent system researchers is to begin the process of defining quantifiable and testable metrics for these attributes. Inherent in this discussion of measuring aerial explorer autonomy is the key role of mission simulation in accomplishing this task. There will be very few opportunities for “do-overs” for planetary aerial vehicles; simulation work will be key to defining and validating mission architectures. Note that the number of robots required to effect a mission scenario is explicitly included in definitions of intelligence and elegance. More discussion is included in Ref. 33 regarding mission tradeoffs between the many simple small (MSS) versus the few complex large (FCL) robots used to achieve a planetary mission; this work can be extended to consider the unique relationship of aerial explorers and robotic symbiotes (autonomy level 5-6).

The contemplation of aerial explorer autonomy and intelligence is a key feature of this paper. We propose that: 1. a new compelling mission architectural approach for aerial explorers needs to be developed, and 2. a new approach to autonomy is also required to robustly implement this new aerial explorer architecture. We propose the application of bio-inspired autonomy and mission concepts to meet these requirements.

More than aerodynamics, making Mars airplanes a reality –

Despite years of study and mission advocacy, Mars airplanes – though they have come close a few times – have not been adopted by the NASA Mars Exploration Program. It is appropriate from a programmatic perspective to ask the question: *why not Mars airplanes?* The answer(s), it would seem, are in part because of actual or perceived risk and perceived low scientific return on investment. Most technical effort to date on Mars airplane concepts has focused on aerial vehicle design and aero-performance analysis. Although most Mars airplane advocates have taken some care to detail the science return of their notional vehicle missions, it is a difficult task to adequately address the return on investment question while focusing solely on aerial-survey-type missions. Significantly more aerial explorer mission capability than simple imaging and remote-sensing must be incorporated.

III. A New Paradigm for Aerial Explorers

One of the key challenges for promoting aerial explorer missions is to demonstrate how the scientific return on investment can be maximized. Inherently, fixed-wing aerial explorers will have limited endurance and will only be able to sustain one flight per vehicle per mission because of their inability to easily land and take-off again

(except for the VTOL concepts). This paper suggests a number of innovative mission architecture approaches that maximize aerial explorer return of investment.

Most of the work in the literature has focused on aircraft design issues related to the development of viable Mars airplane concepts. There has been some limited discussion and consideration of vehicle autonomy issues in regard to the development of these aerial vehicles, but for the most part there has been only cursory treatment of this important technical area. This paper intends to be a partial step forward in addressing this shortcoming. It is envisioned, though, that three aspects of the problem must be simultaneously advanced: mission concepts and overarching aerial explorer architecture, simulation tools and simplified vehicle and robotic symbiote representations, and bio-inspired autonomy concepts. Why bio-inspiration? Bio-inspiration is clearly not the only approach to take with UAV autonomy; many other autonomy concepts and software architectures have been or are being implemented for UAVs. However, a key supposition of the current work – see Ref. 12-21 – is that bio-inspiration can provide distinct advantages to the unique domain of planetary aerial vehicles.

Once the promise of planetary aerial vehicles is demonstrated – even with a very modest technology demonstration -- then it is anticipated that this technology will become an integral part of many future planetary science missions. The key – i.e. the critical challenge -- is to get the first mission underway.

Planning for planetary aerial vehicles should ideally move beyond the standard practice of proposal development and advocacy for individual planetary missions, one at a time. Instead, the development of these vehicles should be thought of in the context of developing a space science and exploration infrastructure. This is a question of both a programmatic and technical nature. To evolve a successful line of aerial vehicles to conduct planetary science campaigns, it is necessary to examine the vehicle design space and identify areas of commonality between individual technologies and vehicle configurations. The simulation and autonomy tools being developed as a part of this effort should aid in addressing some of the crucial challenges in developing a general class of aerial explorers that will find broad application to planetary science missions.

Finally, there are several planetary bodies in our solar system where it might make sense to use planetary aerial vehicles to conduct scientific investigations. These range from Mars, Titan, and Venus where a high degree of surface interaction can be anticipated. It also includes the outer gas giants such as Jupiter, Uranus, and Neptune, where investigations would focus primarily on the qualities of the local atmosphere through which the vehicle might fly. Many of the aerial mission architecture issues being examined in this study will be applicable to multiple vehicle types and planetary environments.

IV. Search and Find Strategies and Bio-inspired Autonomy

Over the past three years a modest amount of work has been conducted at NASA Ames examining the feasibility of bio-inspired approaches to defining new types of search and find strategies, mission concepts, and overall aerial vehicle autonomy.

The general schema for implementing an aerial explorer “personality” and “emotional holons,” or rather anxieties, is shown in Fig. 2. Information about the system and the outside world enters the system primarily through the observer agent. The observer monitors data such as instrumentation and data from sensors and provides its results to the emotional holons. The emotional holons evaluate and translate this data into concern levels in the form of several anxieties. These levels are passed on to the vehicle personality module, which tempers these results based on the personality traits chosen for this explorer. Note that over time or, based on the situation, these personality weights can be adjusted.

Data can also enter the system via sensors that translate this data into discrete events. The Decision Making (Consumer) reacts to these events based on the personality filtered anxiety state of the system. It chooses behaviors appropriate for that state using heuristic rules and predictive sampling theory. The chosen behaviors and changes to the system are implemented by the Action (Decomposer) agent, which modifies the goals and state of the explorer. These changes are observed by the Producer and the cycle repeats.

This overall bio-inspired autonomy approach is discussed further in Ref. 19 and an alternate implementation in Ref. 36. Additional details as to the definition of aerial explorer flight behaviors are noted in Refs. 14 and 18.

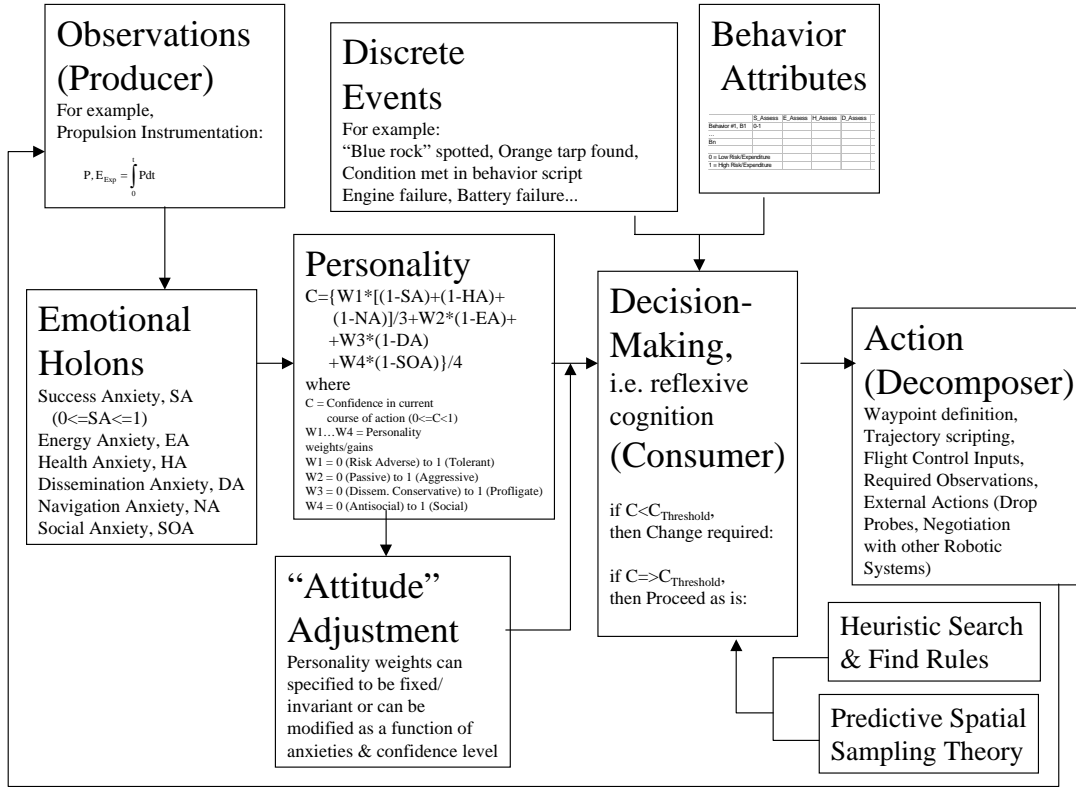


Figure 2. Aerial explorer emotional holon and behavioral model

V. Mission Scenarios, Robotic Elements, and Overall Architecture

In order to successfully execute the envisioned mission scenarios in the aerial explorer mission architecture, it is necessary to define a small, but potent, "robotic ecology" to distribute tasks and roles and maximize information flow. Previous work in this area is reported in Refs. 16, 17 and 19.

A robotic ecology is defined, for the purposes of this paper, as a combined collection of "external" robotic systems and "internal" software agents or processes that collectively interact to maximize information flow during a mission or task. It presupposes that the functional processes required to perform the mission and tasks can be broken into reasonably balanced discrete processes, systems, and subsystems. As a member of this robotic ecology, roles, motivation, and behaviors are ascribed so as to accomplish this goal of maximizing information. Information and energy flow are the underpinnings of how a robotic ecology is actualized.

The proposed aerial explorer ecology architecture employs a producer, consumer and decomposer model borrowed from nature^{16, 17, 19, 20}. Where, in this model, the producer provides input (observations) into the system, the consumer evaluates the data and makes decisions about the input and the current state of the machine, and the decomposer translates those decisions into selections of actions that are applied to the world.

Figure 3 represents one limited implementation of an aerial explorer “robotic ecology” as envisioned for the mission architecture simulation study. Note that the “ground scientist” element for various possible mission scenarios can either be “mission control” on Earth, astronauts at a base camp on Mars, or field scientists at a terrestrial extreme environment and/or Mars-analog site interacting with a surrogate UAV²¹⁻²³.

The aerial vehicle element of the robotic ecology to date only has a simplified representation as to performance and flight dynamics in the simulation study. The aerial vehicle is an approximate composite of many of the vehicle characteristics noted previously in Table 1. The emphasis in the simulation will be in the details of the mission execution (search and find strategy and deployment of robotic devices or symbiotes) and the bio-inspired autonomy aspects.

The same suite of aerial explorer mission architecture simulation tools (Fig. 4) developed for this work is also generally applicable to modeling aerial robotic field assistants for terrestrial field scientists. This should help enable the safe and efficient conduct of science at Mars-analog sites using aerial robots.

VI. Aerial Explorer Mission Scenarios

Two fundamental mission architecture questions are posed and examined in the following defined mission scenarios as well as the simulation work performed: first, how to incorporate high-levels of vehicle autonomy to best effect search and find of high-value terrain features of interest, and, secondly, show whereby surface investigations/interactions can be (indirectly) effected in aerial explorer missions through use of the aerial vehicle as a carrier/utility platform delivering probes and robotic devices to those same high-value terrain features of interest which are assume to be in hard to access surface locations.

The current mission simulations do not account for the launch, entry, and vehicle-deployment phase of the aerial explorer flight; i.e. at time $t=0$ the aerial explorer is assumed to be in powered level flight at a prescribed altitude. A single mission-scenario test case is presented in this paper. Additional mission scenarios are also briefly outlined, though simulation results are not presented.

Metrics have been defined to assess mission success as influenced by various parametric permutations of the aerial explorer simulation. In particular this work, and the corresponding metrics, will show when and how bio-inspired strategies can be more efficient and robust than classic exhaustive search methods. Among these classic search strategies are: grid-pattern, spiral, and “Zamboni” [24].

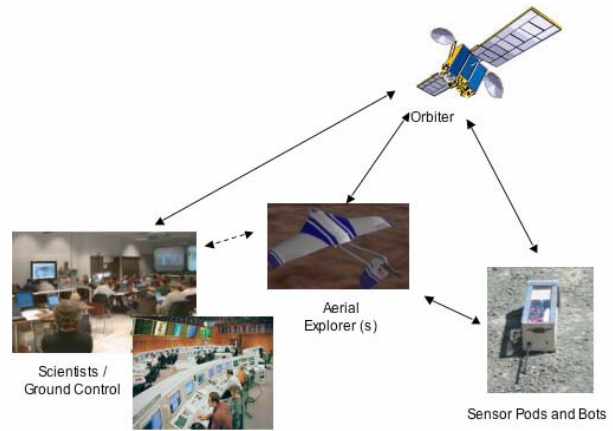
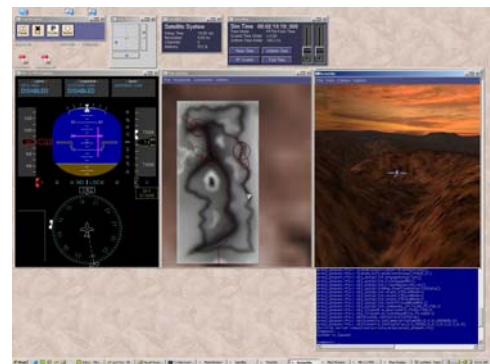
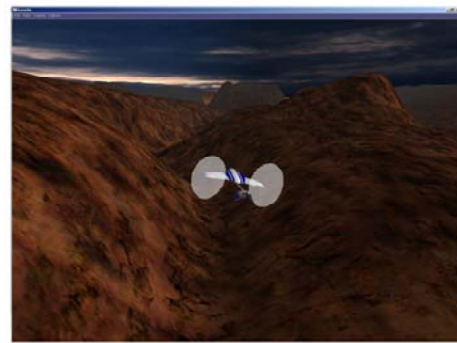


Figure 3. Illustrative Aerial Explorer “Robotic Ecology” Network



(a)



(b)

Figure 4. Screenshot of “Reflection” UAV Simulation Environment: (a) generic display and (b) close-up of a Mars “aerial explorer”

Figure 5 is a first-order graphic presentation of search and find mission metrics. The metrics are: the actual achieved scouting range radius, R ; the ratio of the survey area to the circumscribed area, πR^2 (i.e. this can be thought of as a measure of how exhaustive a particular search is); the search and find discovery confidence, D_C .

The discovery confidence metric, D_C , is derived and based on the assumption that stationary, randomly placed targets are sought for in a maximum bound area of πR_{\max}^2 , where R_{\max} is the best straight-and-level range predicted for the aerial explorer. The discovery confidence metric must take into account three considerations: first, the ability to correctly identify a terrain feature of interest (a.k.a target); second, given possible multiple targets or a continuously varying distribution of features of interest, find the “best” target by some prescribed criteria; and, third, penalize for the misidentification of terrain features of interest.

The expression for estimating the search and find discovery confidence, D_C , is given by:

$$D_C = \frac{1}{2} \left((N_{\text{Found}} - N_{\text{MisIdent}}) / N_{\text{Actual}} + (R / R_{\max})^2 \right) \quad (7)$$

Where N_{Actual} is the number of targets seeded in the mission simulations, R is the radius circumscribing the actual area surveyed by the aerial explorer, N_{Found} is the number of targets found in a given mission simulation run, and N_{MisIdent} are the number of target “false positives” in the simulation. Note that negative values of DC are possible if large numbers of target “false positives” occur.

If “perfect knowledge” regarding the target and vehicle location were known at time equal to zero (post entry and deployment; i.e., the effective beginning of powered level flight) and the target could be over-flown within the maximum vehicle range, then $D_C = 1$. The emphasis of the simulation work is to evaluate the relative success of bio-inspired search and find strategies in conducting planetary science. Conventional spiral and grid-pattern searches were run against the bio-inspired high-level autonomy missions and will be discussed later in the paper.

A. Search and Find: Finding “Blue Rocks” – i.e. discrete terrain features of interest

A generic low-fidelity aerial explorer model is used in the simulation. It is not meant to represent any one given aerial vehicle concept, though it has attributes similar to some of the Mars airplanes proposed in the past - - for example, it could be thought of as a hybrid design of Refs. 5 and 8. But the emphasis of the illustrated simulation work, at this point of the study, is not on the aerial vehicle itself, but rather on the potential bio-inspired autonomy and mission characteristics of aerial explorers in general.

The simulation snapshot shown in Fig. 6 illustrates in more detail the search and find behaviors implemented by the aerial explorer in the “blue rock” scenario (i.e. searching to find discrete high-value terrain features of interest). In this particular case, the aerial explorer is primarily engaged in a “fox and mouse” behavior^{14,18} (following along the terrain gradient in the

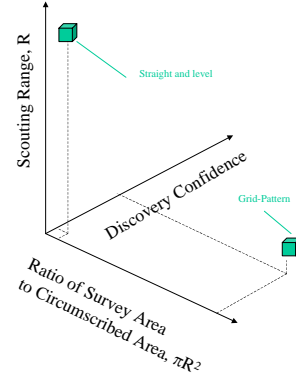


Figure 5. Search and Find Metrics

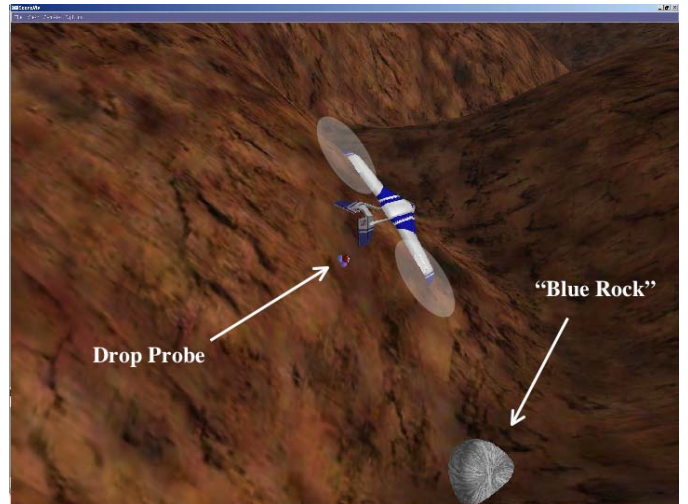


Figure 6. Post- Search and Find: Aerial explorers as carrier/utility platforms for drop probes and robotic symbiotes

small canyon network mapped in the simulation). The aerial-deployed drop probe can have various different capabilities (both in terms of sensors and robotic manipulation/mobility). These “robotic symbiotes” of the aerial explorer are discussed in detail in Refs. 16, 19, and 20. To summarize the flight behaviors exhibited in the simulation introduced in Fig. 6: 1. the aerial explorer performs an intelligent random walk prior to discovery of and entry into the canyon network, 2. once above the canyon the aerial explorer performs a follow the terrain gradient (a.k.a “fox and mouse”) flight behavior (ideally flying over the lowest portion of the canyon floor), 3. throughout the flight the explorer is “searching” for terrain features of interest (in this case “blue rocks”), 4. as the aerial explorer finds “blue rocks” it backtracks, circles, and deploys drop probes (Fig. 7) over them, and 5. after completing the drop and circling once over each “blue rock” found the explorer resumes its “fox and mouse” terrain following behavior. In Figure 7 the aerial explorer is the white triangle, the “blue rocks” of interest are shown as red dots, the flight path is shown as a red curvilinear line, and the box canyon floor is shown as a dark grey-scale image.

The search and find scenario as presented is very complementary to earlier experimental work using small fixed-wing UAVs at NASA Ames and at Devon Island in the high-arctic of Canada¹⁸. This is actually a very important point to consider. A significant amount of complementary experimental and simulation work can be performed to develop aerial vehicle mission scenarios and autonomous system technology, in lieu of actually flying Mars-airplane-representative demonstration vehicles at high altitudes (>100kft or 30km) on Earth. Such mission/autonomy demonstrations can instead be more fruitfully conducted at low-altitude near geologic and biologic terrain features of interest at representative Mars-analog sites, such as Devon Island.

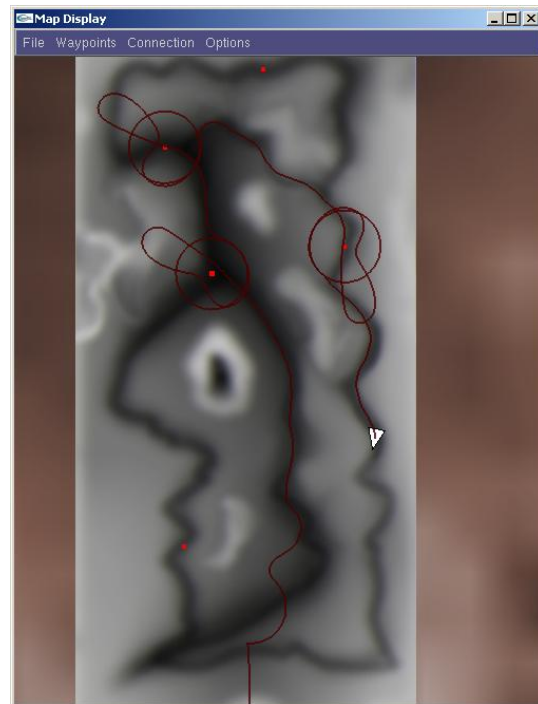


Figure 7. “Fox and Mouse: aerial explorer search and find behavior (looking for “blue rocks”)

B. Search and Find: Ancient River Beds, Outflow Sedimentary Deposits, and/or Gullies

Mission Scenario:

An aerial explorer is deployed from an entry vehicle aeroshell, pulls out and achieves level powered-flight from its ballistic drop, and begins a high-level search at an altitude of ~1.5km. It gathers a panoramic image and long range sensing data of the area around it (terrain, spectroscopy) by using both controlled camera pointing and a vehicle spiral maneuver. Using onboard analysis, areas of interest are prioritized (flat areas with nearby hills, areas showing better spectral results) and the aerial explorer heads in the direction of the most promising sectors.

As the explorer descends to an intermediate analysis altitude (~600 meters) it begins a random behavioral search of the first area, looking for image (image recognition, rock distribution) and spectral (soil and rock composition) evidence of riverbeds. The explorer continually monitors resource constraints, (fuel, power and time) and decides whether to prolong a search in a particular sector or direction, based on the state of the science return.

Upon sensing high evidence of ancient river outflows, the explorer would commit to an area and descend to a low sensing altitude (~150 meters). It would then use a combination of data sources (slope following, rock dispersal distributions, linear feature following) to lead the explorer toward the potential source of the outflow. The outflow area would be imaged in detail through circling maneuvers and direct over-flights at various altitudes and trajectories. Upon completion of the primary mission and near exhaustion of fuel and/or propulsion system power the vehicle would then enter the terminus phase of the flight and attempt a survivable crash landing (putting the vehicle in a deep stall and attempting to bleed off as much forward momentum as possible) so as to have a measure of “persistence” beyond the flight as a data archive/transmitter and limited-sensor ground station.

An initial flight behavior script that is modified, as necessary, by a bio-inspired decision-making module, governs this simulation mission scenario. (Refer again to Fig. 2 and Refs. 19-20). Preliminary discussion related to aerial imaging surveys of the type required by this mission scenario are detailed in Refs. 25 and 34. The main objective of this mission scenario is to demonstrate flexible but robust search and find strategies to identify terrain features of interest in potentially an unknown or uncertain environment. Additionally, it should be noted (as described in detail in Ref. 32) that these bio-inspired autonomy approaches apply not only to aerial explorer flight-path control but to camera-pointing as well (Fig. 8).

C. Access to Cliff Faces and Canyon Walls

Mission Scenario:

An aerial explorer that has the payload capacity to act as a cargo/utility platform, is released from the EDLS aeroshell and completes its deployment and high-speed and altitude dive/pullout maneuver to achieve powered level flight²⁶. The aerial explorer orients itself and then flies toward a range of mountains identified by Mission Scientists as an area of interest. This determination was made through a fusion of data gathered from directed orbiter imaging and prior explorer flights. The terrain includes steep hillsides that show evidence of change from season to season. Because of terrain considerations, this area is considered inaccessible by rovers, and analysis of alluvial fan material would not reveal the active processes that might be going on in the hillside.

As it identifies the terrain, it descends then follows the ridgeline of the hills identified for the study. Based on sensor input, the aerial explorer locates a cliff face with potential sedimentary layering, and maneuvers to make a perpendicular pass across the hillside toward the layered cliff face. Compensating for altitude and local wind component, the aerial explorer drops a tetherbot that unreels in flight and catches on the hillside (Fig. 9). A combination of parachute, flat-plate stabilizers, and rocket braking/steering will be need to brake the high forward velocity, control the vertical descent rate, and steer the drop-probe/tetherbot package to the cliff face. The explorer continues on, dispensing multiple tetherbots over promising sites. Each Tetherbot makes contact with an orbiter and begins to uplink data on the state of its local hillside. Mission scientists utilize a two-way link to control the tetherbots for an extended period (several dozen Sols as a minimum), viewing close up details of 50 meters span of the rock faces.

A tetherbot is an instrumented robot that locomotes along an attached cable. The tetherbot in its pre-deployed (stowed) state is in a compact package form.

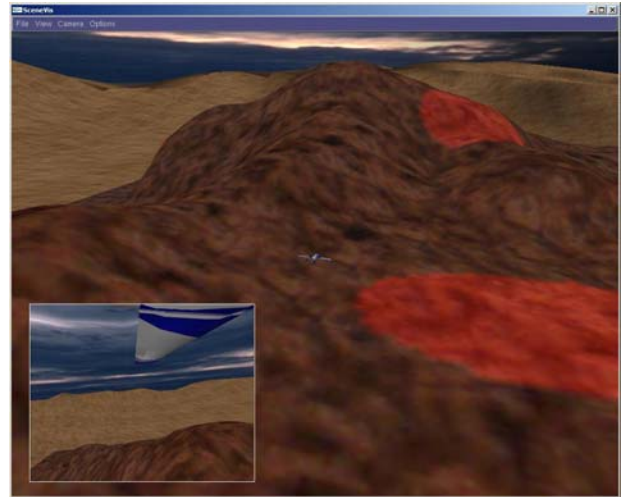


Figure 8. Searching for features of interest – both flight-path and camera-pointing control

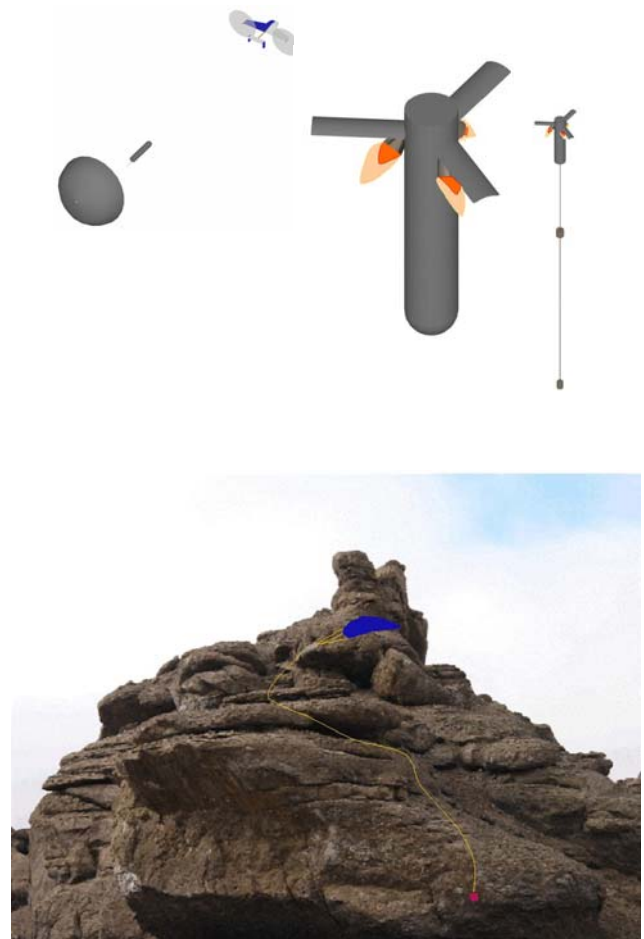


Figure 9. Notional Deployment and Operation of a Tetherbot

Upon release from the aerial vehicle, and descent via parachute and rockets, a reel-mechanism lets out a monofilament tether, separating the tetherbot into two discrete mechanical sub-assemblies.

A notional deployment sequence of the tetherbot is shown in Fig. 9. Upon aerial release and reel-out of the tether, momentum from the drop and natural air currents near steep terrain slopes, in particular cliff faces and canyon walls, will tend to draw the tetherbot to them. A steerable rocket assembly could also be implemented. The tetherbot, upon descent and contact with the ground, will drape across a given terrain feature of interest. The main (upper) body of the tetherbot is the “anchor” and will consist of the parachute, grappling hook, and communications antenna. A first generation device would simply reel up (unidirectional) the “plumb bob” lower element. A “micro-imager” (with some pan/tilt/zoom capability) could be mounted to the “plumb bob.” Figure 10 shows an early prototype of the tetherbot as deployed on the Ames Marscape terrain.



Figure 10. Early prototype tetherbot

D. Exploring Volcanic Remnants

There are several particularly impressive examples of ancient volcanic action on Mars – with the Olympus Mons, the solar system’s tallest volcano, being the most noteworthy. Currently, these magnificent examples of Martian terrain are inaccessible, except by means of orbiter imaging.

An aerial explorer could be used to access these areas. The mission profile for aerial exploration of ancient volcanic regions on Mars would include an imaging survey as well as air-deploy an inflatable robotic symbiote – a “Bumblebot” – to roll down the outer cone of a volcanic remnant.

Upon deployment of the aerial explorer, an initial panoramic elevation map would be generated. Based on terrain data of interesting sites and priorities uploaded prior to deployment, the UAV would compare the data to in-flight measurements and fly toward the most promising mountain. When positioned over the mountain, the UAV would deploy the Bumblebot, which would inflate in the air. Once on the ground and established on the hillside and moving downward, the Bumblebot would use differential inflation to along with internal gyros to control its path and speed. Contact sensors built into the outer covering and imaging sensors in the central core would gather data about the changing states and materials along the hillsides. Once at the bottom, or when no movement is sensed within a period of time, the Bumblebot would upload data to mission control via a satellite link.

The “tumbleweed rover” concept was first discussed in the 1990’s²⁷. The key difference between the two ideas is that the tumbleweed relies primarily on the (semi-unpredictable) wind for passive mobility, the bumblebot would instead rely on gravity and generally predictable surface slope gradients for a semi-active mobility.

Initial development work continues to be conducted in this area through simple prototyping and simulation efforts (Fig. 12). Simulations of the bumblebot were conducted in the Mission Simulation Facility using the Open Dynamic Environment set of dynamic simulation tools. Physical models of different designs were developed and tested on a laboratory slope table and on the Ames MarsScape (Fig. 12b). A tetherbot technology testbed was also developed as shown in Fig. 12c.

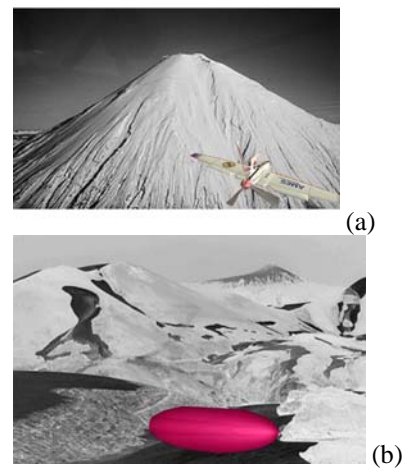


Figure 11. (a) Aerial explorer approach and (b) Bumblebot traverse down-slope (MAGE Image Courtesy of the Space Projects Division, NASA Ames)

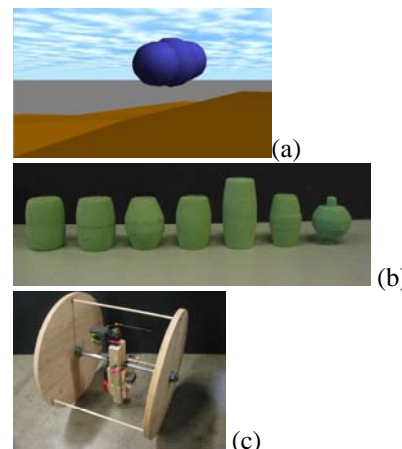


Figure 12. (a) dynamic simulation, (b) small-scale rolling stability tests, and (c) camera imaging tests

E. Polar Ice Studies

Another application of robotic symbiotes would be the air-deployment of ice penetrators to distribute a network of sensors for polar “ice” studies (Fig. 13). From altitude, weighted penetrators could be deployed over regions thought to contain ice or active ice flows. Penetrators could be used to pass through an upper crust of rock and soil to bring sensors to bear on the ice or melting ice below. A series of penetrators could also be designed to remain active for several seasons and report their movement in position, due to possible glacier shift in relation to other penetrators. Data regarding the extreme change in volatiles (especially near the outer boundary of the polar caps) through the Martian seasons would provide invaluable information about the atmospheric dynamics of Mars as well as its climatology. Such Martian polar studies could have profound implications for possible human exploration of the red planet.

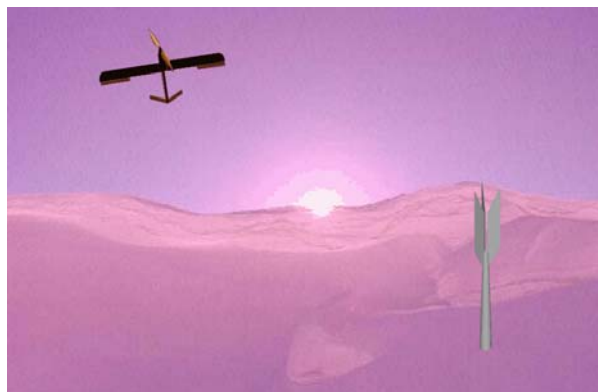


Figure 13. Ground Penetrators

VII. Preliminary Simulation Results

To this point, we have discussed mission, behavioral, and technical concepts in support of aerial explorers. We continue to use simulation as a way to evaluate potential concepts as a precursor to flight implementation. In this section, we evaluate the use of biologically inspired behaviors for a search and find task both individually and also through an intelligent Cognitive architecture.

In the following simulation experiments, the computer-generated environment used consists of a largely featureless terrain with the exception of a large gully running randomly through it (refer to Fig. 14). The entire search area is 466,000 square kilometers, with 75 targets randomly distributed in the environment based on three distribution strategies: (i) 1/3 of the targets are randomly distributed over the entire search area, (ii) 1/3 of the targets are randomly distributed but concentrated near the gully based on a Gaussian distribution, and (iii) 1/3 of the targets are distributed based on a random blend between (i) and (ii).

We simulated an aerial explorer cruising at Mach 0.7 in the Martian atmosphere at an altitude of 1.5 km, with a total search time of one hour (which is optimistic given estimates in the literature). The aircraft was provided with five search strategies as described below. Each strategy has an advantage to its application over the others, depending on the actual distribution of the data.

Behavior

Grid Search
Spiral Search
Terrain Following
Random Walk
CEL

Heuristic

Targets concentrated in an area (directionally)
Targets concentrated in an area (non-directionally)
Targets are concentrated in the dried riverbed
Targets are uniformly distributed over entire area
Combines random-walk and terrain-following, with neither being favored.

The last behavior uses a CEL (Cognitive Emotion Layer) reinforcement learning network to combine or choose between different behaviors. The CEL software architecture is discussed in detail in Ref. 32; the CEL network is an alternate behavioral/emotional autonomous system implementation from Ref. 19. Desire nodes in the network will combine the random-walk and the terrain-following heuristics and rely on the reinforcement networks to determine which strategy to favor, based on continuous stimulus from the environment. This would be useful, for instance, in a case where many different heuristics are suspected to be employed in aerial explorer search and find

missions, with no one heuristic dominating the other (a dominant heuristic function is one that is less 'optimistic' in its evaluation of a search path, resulting in more accurate appraisals of different possible search directions that lead to better decision making by a search algorithm).

A total of 645 simulation runs were performed, 129 for each strategy, with targets randomly distributed in each run. The results, in terms of numbers of targets found per hour, are described in Table 3. Note that the metric "average targets per hour" found is to the first order directly proportional to the "discovery confidence," D_C , metric discussed earlier in the paper.

Although the CEL architecture enters the test not favoring any of the strategies it is given, it will choose to emphasize one over the other (or a mix) based on a continuous search success metric (targets observed per minute). Given the random target distribution strategy applied in these tests, the CEL network almost always chose to heavily favor the slope-following behavior over the random walk. The average time it took to reach a point where 75% of total behavior is determined by slope-following behavior was, on average, 36.8 minutes (standard deviation of 8.5 minutes). The desire to favor slope-following peaked, on average, at 89.7% (standard deviation of 8.5%). The peak desire was greater than 85% in approximately 76% of the 129 experimental runs that used the CEL networks.

A possible weakness of the simulation results is in the target distribution strategy that was applied. Despite randomness in the distribution, the slope-following heuristic dominated. A typical sample distribution is shown in Fig. 14 (the target areas are highlighted with oval boxes); obviously a slope following algorithm will be very successful in this case. A follow up to this experiment would be to apply other strategies for distributing the targets or to also randomize the size and shape of the riverbed.

However, because of its flexibility, we would expect the CEL to do much better in this case. In a purely random distribution the slope-following heuristic should perform as poorly as a random-walk; if the targets were concentrated around a particular location, the slope-following may perform very poorly indeed. The CEL network is able to adapt to the most optimal conditions, as this simulation suggests. The CEL network could be expanded with the behaviors and heuristics needed to implement the spiral search and the grid search behaviors as well other flight behaviors noted in Ref. 14.

The results of these simulations require a few interpretive observations. As with any case involving a large search space where exhaustive coverage of the area is not feasible, informed and efficient heuristics will allow efficient pruning of the area to eliminate large swaths and make the search problem more reasonable. In this experiment we cover around 6% of the search area, so in a purely random distribution we would statistically expect only to identify 4.5 targets. Our experiment applied a pattern to the randomness, accumulating more nodes near the riverbed gully. The random search did better than the 4.5 expected, as did the spiral search, partially because most of the time the circle and the random search crossed paths with the canyon area, which is where most of the identifications occurred, and the spiral's search area typically intersected the gully. The CEL combination of slope-follow and random walk performed the best on average, but had the highest standard-deviation. An interesting observation that can be seen in Fig. 14 is that the aircraft will miss a few points that are located away from the gully unless randomness is introduced to allow the aircraft to meander back and forth. This typically accounted for the better average identification rate for the CEL network.

If the environment is such that a single dominant heuristic exists, based on the probability distribution of targets in the search area, there is no need for an adaptive reinforcement learning network like CEL. However, we

Table 3. Simulation Statistics

Search Pattern	Grid	Spiral	Slope Follow	Random Walk	CEL
Average Targets Per Hour	3.8	5.9	24.6	5.7	29.4
Standard Deviation	1.7	2.3	3.8	2.3	11.5

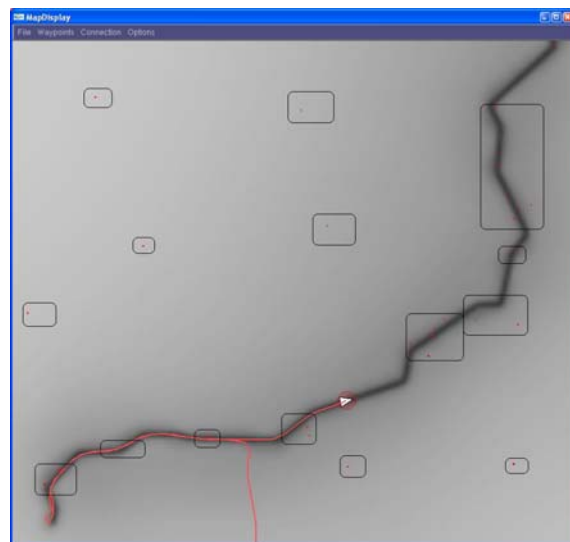


Figure 14. Simulation Environment with Target Seeding Highlighted

suggest that the most appropriate application of CEL is where there is a high degree of uncertainty, a large number of possible heuristics, or where one heuristic does not dominate. Given a number of search heuristics in a highly uncertain distribution, the CEL network will adapt aerial explorer behavior towards the apparent most-successful strategy. In other words, the strategy that will have a high degree of success given limited information previously gathered about the environment. Therefore, the CEL network can make decisions that are most appropriate for the environment, where search times are small and a limited amount of information is available. If scientists have an initial guess as to the distribution of the data (affecting the successfulness of different heuristics/behaviors), these can be seeded into the CEL networks by providing an initial desire ratio that integrates this knowledge.

There is a danger, however, that the adaptive strategy, given limited information, can make wrong decisions. Although the CEL performed better on average, the standard deviation for the number of targets found using the adaptive CEL network was several times larger than the other non-adaptive strategies. Part of this is because of the dominance of the slope-following heuristic; the network sometimes favored the random search approach over the slope-following based on a few initial inputs that were not indicative of the larger search space. The larger danger, however, is applying non-adaptive search heuristics where the assumptions about target distribution are incorrect. In the simulation experiments we ran, the grid search strategy was the most inappropriate; however, should the targets have been concentrated around a single location, the grid search could perform quite well (should the search pattern intersect with the concentration of targets). Using an adaptive CEL network increases the probability of success for aerial exploration given this uncertainty.

VIII. Mars Airplanes: a modest plan of action

Returning for the moment to the essential question of what it takes to enable a robust program of aerial explorers to support NASA planetary science missions, it is important to consider aerial explorers in the context of developing a technology infrastructure and not just a single mission opportunity. Only by this means can the full potential of aerial explorers be realized.

Therefore, in the spirit of trying to make aerial explorers a reality, irrespective of the particular vehicle and mission concept and sponsoring organization, we propose the following modest suggestions:

- Emphasize the multi-mission and multi-science-objective payoff of the aerial explorer technological investment
- Embrace flight/mission demos at Mars-analog sites using surrogate aerial vehicles
- Continue emphasizing the cross-enterprise opportunities of aerial explorer technology to NASA and the nation
- Use the multi-disciplinary nature of the aerial explorer development and demonstration to foster early cross enterprise collaboration and teaming

IX. Other Aerial Explorer Vehicle Configurations

Many of the bio-inspired autonomy concepts being developed at NASA Ames can be applied to other aerial explorer configurations besides those of fixed-wing aircraft. Any aerial platform that has an element of active control (discounting, for instance, pure balloons and aerostats) can potentially accommodate some of the bio-inspired search and find strategies.

One vehicle configuration that has undergone a modest amount of study at Ames is the Mars rotorcraft (Fig.15). Additionally, other planetary aerial vehicles (vertical lift, and otherwise) for other planetary bodies are also being studied²⁸⁻³⁰ (Figs. 16-18).



Figure 15. Mars Rotorcraft

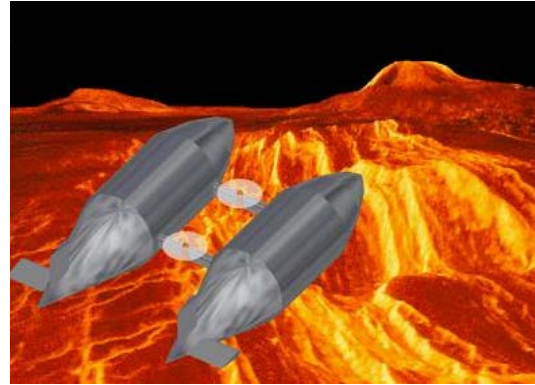


Figure 17. Venus Hybrid Airships



Figure 16. Titan VTOL

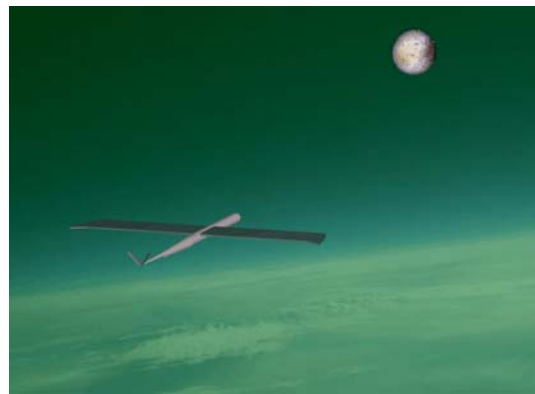


Figure 18. Outer Planet Robotic Gliders

X. Future Work

The mission architecture simulation study will be expanded beyond the test case mission scenario detailed in this paper and will encompass the wide range of scientifically valuable missions that are impossible to achieve by any means other than aerial exploration.

Aerial deployed robotic device/drop-probe proof-of-concept work continues at Ames both in simulation and actual flight demonstrations. Flight demonstrations using surrogate aerial vehicles testing mission concepts and bio-inspired search and find strategies will soon resume (Fig. 19-20). This is an important element of an overall strategy to lay the information technology groundwork to one day enable successful aerial explorer planetary missions.

A decided side benefit of the ongoing aerial explorer work is the development of bio-inspired autonomy concepts. This bio-inspired autonomy work is beginning to be applied to a number of non-aerial-explorer application robotics and autonomous system efforts at NASA Ames Research Center.



Figure 19. Smart Rotorcraft Field Assistants



Figure 20. Fixed-Wing Field Assistants

XI. Concluding Remarks

A new aerial explorer mission paradigm has been advanced wherein the aerial vehicle is one additional element in the entry, descent, and landing approach for a planetary mission. Using the aerial explorer as the primary means by which high value science targets are identified, and deploying “persistent” sensors and robotic devices to sites inaccessible by any other means, is a promising way that the science return on investment of fixed-wing planetary aerial vehicle missions can be maximized. This has led to the development of a number of mission architecture concepts that are being studied in simulation. This work complements earlier and ongoing work in the areas of bio-inspired search and find strategies and overall autonomy. It also complements the development and demonstration of auxiliary robotic devices/drop-probes that can be aurally deployed to enhance aerial explorer missions. Though the focus of the current work is on fixed-wing vehicles for Mars planetary science missions, the work can be extended to aerial explorers for other planetary bodies, as well as potentially contributing to an overall strategy of human/robotic exploration for future manned Mars missions.

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