Aerial Explorers and Robotic Ecosystems

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ABSTRACT

A unique bio-inspired approach to autonomous aerial vehicle, a.k.a. aerial explorer technology is discussed. The work is focused on defining and studying aerial explorer mission concepts, both as an individual robotic system and as a member of a small robotic "ecosystem." Members of this robotic ecosystem include the aerial explorer, air-deployed sensors and robotic symbiotes, and other assets such as rovers, landers, and orbiters.

Keywords: UAV, Aerial Explorer, Robotic Ecosystem, Planetary Exploration, Autonomy

1. AERIAL EXPLORERS

A fascinating convergence of aeronautical engineering, information technologies, bio-inspiration, and planetary science is currently in progress. All of these disciplines are being exercised by a number of researchers to develop new generations of robotic explorers [1]. In particular, there is considerable potential for the development and use of aerial explorers: autonomous aerial vehicles designed to fly in the atmospheres of other planetary bodies [2-4].

Planetary aerial explorer concepts, and mission scenarios, embody technical challenges beyond their terrestrial brethren, the nowadays seemingly ubiquitous Unmanned Aerial Vehicles (UAVs). Unlike terrestrial UAVs which can be imbued with scalable-autonomy (i.e. varying levels of human operator monitoring and intervention), aerial explorers will have to be fully autonomous with high-levels of mission and contingency planning capability. Interplanetary communication time lag makes this an essential requirement for aerial explorers.

The focus of this paper is on the unique information technology and robotics issues underlying the development and use of aerial explorers and their host of robotic symbiotes that support their mission scenarios. This work can be applied to multiple types of aerial explorers (e.g. aerostat, fixed- and rotary-wing platforms), on several different planetary bodies in the solar system (e.g. Mars, Titan, and Venus). Most of the work summarized in this paper, though, is directed towards fixed-wing aerial vehicles for Mars exploration.

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, as these fixed-wing flyers cannot easily land and take off again.

The potential of aerial explorers for imaging surveys is obvious. However, imaging alone is not a strong enough mission requirement to drive the development of aerial planetary explorers. Additional justification, particularly an approach which embodies mission persistence beyond the duration of the flight, would increase the mission value of aerial explorers. A new approach shifts the paradigm of aerial explorers from simple imaging and remote sensing applications to a larger overall architecture. The flyer acts as a carrier or platform that can perhaps be best thought of as the ultimate manifestation of EDLS (Entry, Descent, and Landing System) technology. In this utility platform concept, the aerial explorer becomes one critical element in a system of sensors and robotic devices, both aerially deployed and otherwise. In effect, the mission architecture comprises a small but potent robotic ecosystem of heterogeneous robotic systems, both internal and external autonomous agents.

2. ROBOTIC COMMUNITIES

What is a robotic community? A robotic community takes its inspiration from biological communities as found in the study of ecology. A biological community is a collection of co-located organisms of different species. Interactions among members of a biological community focus on the exchange or flow of energy. A robotic community 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. Information and energy flow are the underpinnings of how a robotic community is actualized. The concept of a robotic community presupposes that the functional processes required to perform the mission and tasks can be broken into reasonably balanced discrete processes, subsystems, and systems (Fig. 1). For members of a robotic community, roles, motivation, and behaviors are ascribed so as to accomplish the goal of maximizing information. Maximum return of science information is paramount in robotic planetary exploration systems.

What is the purpose of a robotic community in the planetary exploration context? The task or mission of a robotic community comprising explorers – including aerial explorers in particular – is to maximize the information flow during exploration or scientific inquiry. The proposed aerial explorer ecological architecture employs a producer, consumer, and decomposer model borrowed from nature [5-8]. In the information-based community model, the producer provides input into the system in the form of observations and data measurements. 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. Similar to natural, energy-based communities, the processes form a repeating cycle.

The description of a biological community is based primarily on the flow of energy. For a bio-inspired community of autonomous vehicles an analogy of energy and information is assumed needed to successfully sustain vehicle operation and execution of the planned mission(s). The gathering of information may be regarded as the motivating purpose for sending autonomous vehicles to Mars. The role of information producer can be filled by instruments and probes, which collect information directly from the planetary surface or atmosphere. Information consumers take data from producers for processing and may release information in a different form to other information consumers. Decomposers take direction from consumers and make changes to the system, telemetry, and interact with the world. Multiple information processing roles may be implemented onboard the same hardware platform. Researchers on Earth are the ultimate information consumers. This information "food chain" provides a level of abstraction adequate for implementing multiple processes on a single robotic system element as well as a multiple system robotic ecosystem.

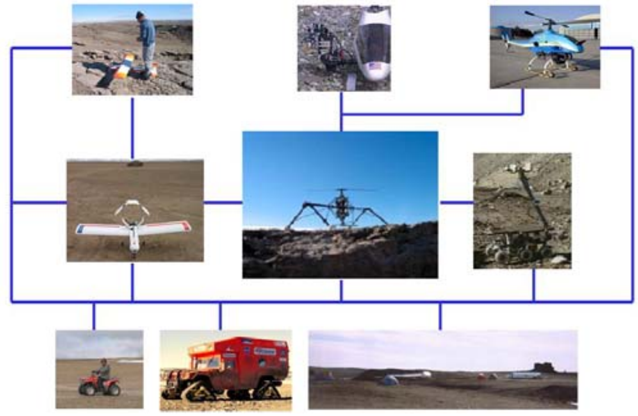


Fig. 1 – Example of a Robotic Field Assistant "Ecosystem" for Terrestrial Field Science

3. BIO-INSPIRED AUTONOMY FOR VEHICLE CONTROL

In order to realize the advantages of a robotic ecosystem, it's necessary to develop the individual members. Although the software architecture and components of these vehicles could be designed in many ways, one approach we are considering is to apply the producer, consumer, and decomposer paradigm to the implementation of these systems.

The concept of an aerial explorer personality was first discussed in [6]. A "personality", as used in this context is a system of agents that views and reacts to the world. It called a personality because it can be assembled to react in different ways based on the emotions and actions with which it is provided. A holon is a dualistic concept where a component can act both as an independent unit and also part of a larger encompassing whole. Emotional holons are used to describe the anxieties chosen for the system and how they specifically react to input. A general schema for implementing an aerial explorer "personality" is shown in figure 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 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 adjust.

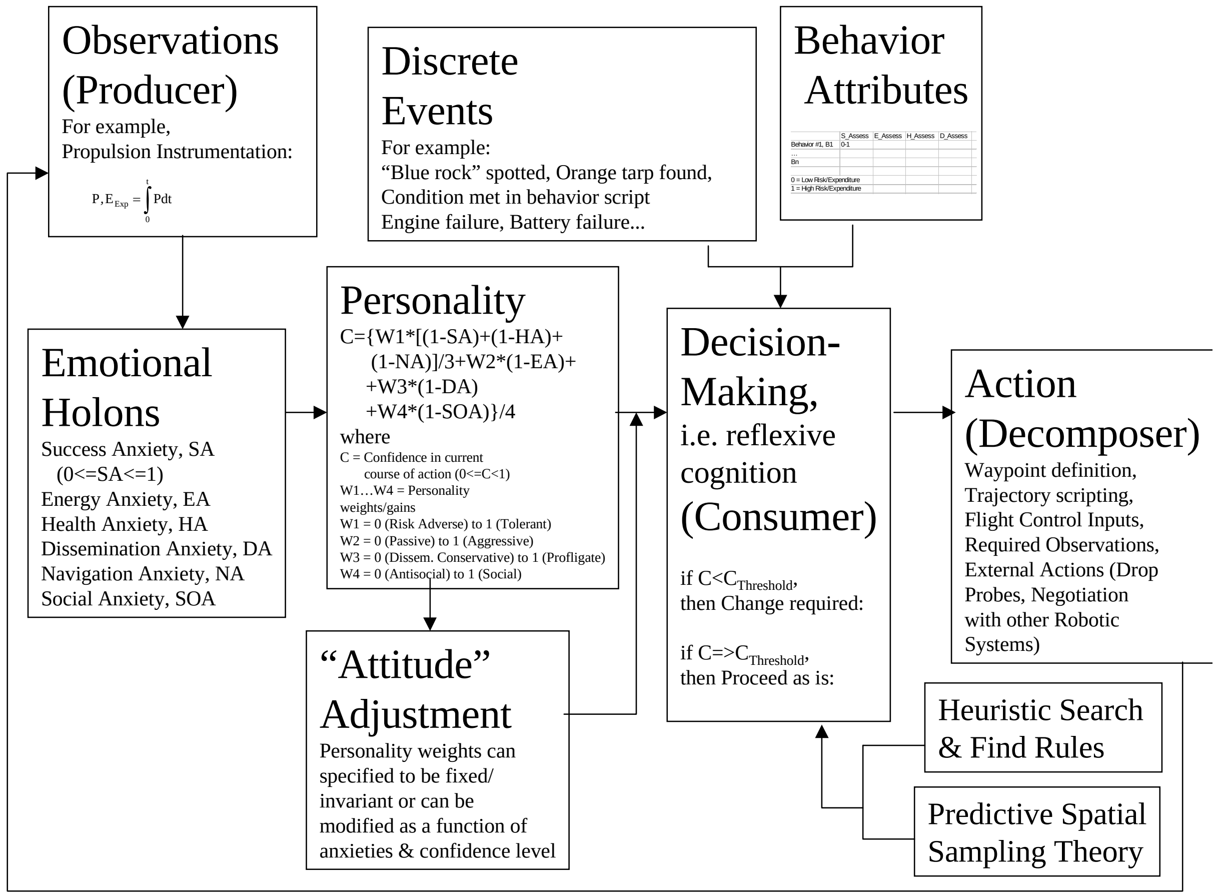


Fig. 2 – Aerial Explorer Emotional Holon and Behavioral Model

Data can also enter the system via sensors that translate this data into discrete events. The Decision Making agent (Consumer) reacts to these events based on the personality filtered anxiety state (anxieties) 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... The Producer agent observes these changes and the cycle repeats.

Aerial Explorer Personalities

The aerial explorer "personality" module (Fig. 2) can be thought of as a set of fixed, or adjustable, "gain" settings applied to "anxiety" level input from the emotional holon module, i.e. W1, W2, etc. In turn, the personality module would provide a single scalar estimate of current confidence, C_i, in the mission approach, particularly as affected by the flight behavior currently being implemented by the aerial explorer. Different sets of personality gains might be applied to different vehicle types and missions. (For example, a long endurance flyer might have a fairly low W2 gain, directly influencing the confidence metric, C_i, as it is affected by the energy anxiety, EA.)

In addition to the personality module is a complementary "attitude adjustment" module. The personality weights (gains) can either be fixed or flagged as adjustable and would therefore update with time.

Slowly with time, the personality weights could be allowed to update as two conditions are met: 1. there is a protracted change in confidence levels and 2. there is a significant change in the relative proportional ratio between the aerial explorer anxieties. Thus, for example, if mission confidence is progressively decreasing, and the anxiety related to energy expenditure is the key driver underlying that shift in confidence, then the weight W2 is adjusted downward. Subsequently, the aerial explorer becomes somewhat more "passive," i.e. more conservative in the types of flight behaviors that are subsequently implemented, as reflected by their pre-mission attribute assessments as to relative energy expenditures.

A critical consideration in this proposed approach is the definition and implementation of the emotional holon module such that the anxiety states of the aerial explorer are robustly modeled. Six aerial explorer anxieties have been defined: success, energy, health, navigation, social, and dissemination anxieties. The dissemination anxiety will be discussed in some detail as it directly touches upon discussion later in the paper on mission scenarios and the deployment of robotic symbiotes. Additional details can be found in [5-8].

Dissemination Anxiety

Anxieties are the key element in the system that is used to translate a large amount of data into levels of concern that will affect the personality. As an example, the proposed general functional form of aerial explorer dissemination anxiety is dependent upon four key parameters:

$$\mathrm{DA} = g(\mathrm{t},\mathrm{NP},\mathrm{SA},\mathrm{x}) \qquad (1)$$

Where in the case of the aerial explorer drop probe sensor dissemination anxiety, DA, functionality: t is time; NP, is number of drop probes left to be deployed; SA is the success anxiety, which also drives the dissemination anxiety; and, finally, a provision is also provided for discrete trigger events, x (true/false), for deployment (i.e. do I see the orange tarp on the ground? [5, 7]). When DA>1, then a sensor, drop probe, or other robotic symbiote is air-deployed. An infinite variety of functional forms could be devised for DA – as well as the other anxiety functions – but a reasonable one in terms of simplicity and, yet, overall potentiality is

$$\mathrm{DA} = \mathit{if}(\mathrm{x} = \mathit{true}, 1, \mathrm{Y}) \qquad (2a)$$

Where

$$\mathrm{Y} = \kappa \cdot \mathrm{NP} \cdot (1 - \mathrm{SA}) \cdot (\mathrm{t} - \Delta\mathrm{t}) \qquad (2b)$$

And

$$\Delta\mathrm{t} = \mathit{if}(\mathrm{DA} > 1, \mathrm{t}, \tau) \qquad (2c)$$

Where

$$\tau = \left(\mathrm{T} \Big/ \sum_{n=1}^{\mathrm{NP0}} 1/n \right) \cdot \sum_{k=1}^{\mathrm{NP0}-\mathrm{NP}} \frac{1}{(\mathrm{NP} + 1 - k)} \qquad (2d)$$

Note that κ is a user-prescribed constant, T is the total estimated flight duration of the aerial explorer mission, and NP0 is the original number of drop probes onboard the aerial explorer, prior to deployment. The relationship between NP and t in defining the dissemination anxiety is a particularly noteworthy one (Fig. 3). The function is piecewise linear (a "saw-tooth" function with an arithmetically-increasing period). This could almost be considered a "dynastic" approach to drop probe deployment, i.e. the first drop probe (offspring) ideally has to come quickly in the mission (reign), whereas subsequent drop probes sensors (if any) can be released at ever more leisurely paces.

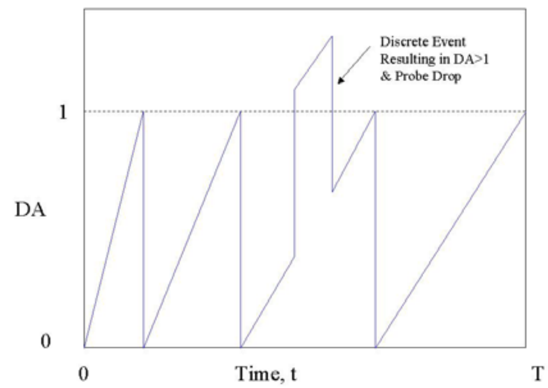


Fig. 3 – Dissemination Anxiety Functionality

Note that when the success anxiety, SA is low, i.e. terrain features of interest are being identified by onboard instrumentation, the dissemination anxiety is high and sensors probes are more likely to be deployed.

Reflexive Cognition

The above aerial explorer implementation of a set of personality attributes coupled with a simple, but robust, set of emotional holon anxieties yields a powerful set of tools to effect "decision-making" with respect to implementing flight behaviors. (C)

The confidence metric estimates (Fig. 2) – owing, in part, to the definition of the aerial explorer personality weights and emotional holon anxiety updates – drives determines the need for change in the prescribed set of flight behaviors being implemented in the explorer mission flight plan. If the confidence metric is below a critical prescribed confidence threshold value, then change will occur and the flight behavior will be modified. How they're modified, and the decision-making process used to define and implement the changes, will now be discussed.

A matrix formulation for flight behavior qualitative attributes needs to be defined (Eq. 3). This attribute matrix is instrumental in implementing a "reflexive cognition" decision-making methodology.

$$
\mathbf{M} = \begin{bmatrix}
 & \begin{matrix}\textit{Behavior Complexity}\\ \textit{Assessment}\end{matrix} & \begin{matrix}\textit{Energy Expenditure}\\ \textit{Assessment}\end{matrix} & \begin{matrix}\textit{Fecundity}\\ \textit{Potential}\end{matrix} & \begin{matrix}\textit{System Stress/Strain}\\ \textit{Assessment}\end{matrix} & \begin{matrix}\textit{Reckoning}\\ \textit{Robustness}\end{matrix} & \begin{matrix}\textit{Communication}\\ \textit{Potential}\end{matrix} \\
\textit{Behavior \# 1} & \begin{matrix}0(\textit{simple})\\ -1(\textit{complex})\end{matrix} & \begin{matrix}0(\textit{low expenditure})\\ -1(\textit{high})\end{matrix} & \begin{matrix}0(\textit{high data return})\\ -1(\textit{low return})\end{matrix} & \begin{matrix}0(\textit{low loading})\\ -1(\textit{high})\end{matrix} & \begin{matrix}0(\textit{reliable})\\ -1(\textit{easily lost})\end{matrix} & \begin{matrix}0(\textit{little opportunity})\\ -1(\textit{high})\end{matrix} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots \\
\textit{Behavior \# N} & - & - & - & - & - & -
\end{bmatrix} \qquad (3)
$$

Further, let the anxiety vector be defined as

$$
\mathbf{A} = \begin{bmatrix} SA/C \\ EA/C \\ DA/C \\ HA/C \\ NA/C \\ SOA/C \end{bmatrix} \qquad (4)
$$

Where, in the anxiety vector, **A**, the individual normalized (with respect to the current confidence metric) anxieties form the elements of the array.

A flight behavior modification "decision" can be "made" by the simple linear algebra operation

$$
\textit{New Behavior} \Rightarrow \textit{minloc}(\mathbf{R}) \qquad (5a)
$$

Note that the function *minloc* returns the indices corresponding to the array element having the minimum value in the array. Further, the vector **R** is the product of the matrix and vector **M** and **A**, i.e.

$$
\mathbf{R} = \mathbf{MA} \qquad (5b)
$$

The "new" flight behavior to be adopted corresponds to the i^{th} array element, as identified by the *minloc* function, that has the minimum value of all array elements formed by the product of the attribute matrix and the normalized anxiety vector. Note that there is a matching attribute column for the matrix, **M**, for each anxiety vector, **A**, element. The **R** vector can be thought of as the relative strength of each candidate flight behavior for possible implementation given its prescribed perceived attributes and flight experience in the form of current confidence and relative anxieties. For example, if a flight behavior has a high complexity attribute, while at the same time there is high success anxiety, then the i^{th} element of the matrix multiplication product, **R** – all other attributes and anxieties considered equal -- will have a higher numeric value than another flight behavior with a lower assigned complexity attribute value; consequently, the second behavior will be implemented over the first. Therefore, "high-level" mission planning can be affected by a fairly simple "reflexive cognition" approach. Assignment of assessment values in the flight behavior "attribute" matrix, **M**, can be accomplished by any variety of means: engineering judgement, high-fidelity simulation, flight test of surrogate vehicles and/or prototype test articles, etc.

Among the many flight behaviors that could be applied by an aerial explorer [5, 7, 8], there are two key behaviors that will now be discussed: "terminus" and the air-deployment of robotic symbiotes.

4. DESIGN CONSIDERATIONS

In addition to examining how the ecosystem as a whole and how the internal workings of the members might be implemented, we are also interested in the way in which explorer missions are designed, and the components that will comprise the ecosystem in achieving that mission.

One design consideration is that all components in the system be used as efficiently as possible. An aerial vehicle that can only perform imaging before crash landing limits the science return of the mission. Components should be designed using a holistic view of the mission to provide data beyond their primary focus.

Another consideration is in the design of components that can extend the scientific reach of the aerial vehicle, and the reach of the mission itself. In addition to exploration missions, an aerial vehicle can also tasked to place specialized robotic components (via drop pods) in terrain where conventional robotic systems cannot reach.

Terminus

The cliché, "What goes up, must come down," is especially true for aerial explorer concepts. Most estimates of "Mars airplane" explorer endurance range from a few minutes to a couple of hours [4]. It is essential to the development of successful aerial explorer mission architectures to consider ways to build in mission "persistence" beyond the flight of the vehicle itself. One approach is the incorporation of aerially deployed robotic symbiotes into the explorer mission. A crucial capability for these symbiotes is communication with the aerial explorer, among themselves, and with other assets as well, such as orbiters, rovers, and landers.

Another way to build in mission persistence is to address means by which the mission elements might survive a high-speed crash landing on the planet's surface upon termination of the flight, or "terminus." Elements that might need a strategy for terminus include the aerial explorer or a core payload system that was jettisoned and crash protected. Such a core package might then act post-flight as a remote surface station. Flight data could be sent back to Earth either directly or via an orbiter at a reasonable bandwidth from a stationary system. An additional advantage is that new data from the surface could continue to be acquired. The post-flight module might also act a relay for telemetry from robotic symbiotes deployed in the immediate area.

From a mechanical design perspective, development of such a crash protected and/or jettisoned core system would not be an easy task. However, such a capability is perhaps essential to maximize the scientific return on investment of data acquired in-flight and post-flight. As a adjunct to the mechanical design challenges, though, are significant information technology issues: unique flight control problems for effecting the minimum impact energy during the crash landing, controls for core system jettisoning (if the preferred approach), and, not least of all, the autonomous decision-making approach for determining the timing, location, and overall circumstances of the "terminus" aerial explorer behavior.

Ground-Truth from Imaging Drop Probes

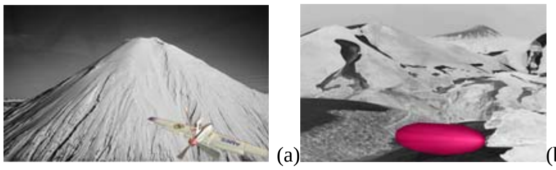
In addition to providing enhanced mission persistence, air-deployed robotic symbiotes provide fixed-wing aerial explorer vehicle configurations a means of gaining access to surface sites of high scientific value that would otherwise be inaccessible by rover and landers. (Alternate vehicle configurations such as rotorcraft or VTOL platforms should also be capable of gaining access to such sites with and without symbiotes and, further, can acquire and return samples.) It is this capacity of surface "interaction" provided by air-deployed robotic symbiotes carried and delivered by, and working in conjunction with, aerial explorers that provides full scientific return on investment. Being able to reach out, sample, and make decisions about the world provides the aerial explorer with most of the ability of planetary rovers with a much larger range. A number of examples will now be presented as to leveraged mission scenarios and specific robotic symbiote concepts for Mars aerial exploration.

The NASA Global Surveyor orbiter, as well as earlier observations, has clearly shown large-scale signs of past water flow on the surface of Mars. Among this imaging and remote-sensing evidence are images of gullies on hillsides and crater rims and layered or striated canyon walls of ancient water channels. Aerial explorers would, as a minimum, be able to get higher resolution images than an orbiter could, but more importantly if imaging drop probes were also released onto these terrain features of interest a tremendous opportunity to gain an element of "ground truth" of these areas would be achieved. Orbital, low altitude and ground truth data could be fused to provide a much more detailed view of the world. Figure 4 shows a simple imaging drop probe developed and tested in flight demonstrations at a Mars-analog site [7]. Future designs could include additional sensors, such as contact (moisture, mineral contact), weather, or microscopic imagers. They could also include the capability of two way communications and control similar to that of rovers, allowing scientists to interact and reprogram data gathering capabilities. With the inclusion of long duration power and environmental considerations, a probe or series of distributed probes could persist for multiple seasons to ascertain whether or not, and how, periodic water surface seepage might still exist on Mars along and in these gullies.

Fig. 4 – Simple Imaging Drop Probe

Bumble bots to navigate steep hillsides

There are many very large-scale geologic features on Mars that are likely to be inaccessible to conventional landers or rovers. Among these potential sites are the ancient remnants of volcano such as the Olympus Mons. The steep and relatively smooth slopes of the outer cones of these volcano remnants are suggestive of the potential of relying on gravity to provide the impetus for long duration ground mobility. A challenge is in determining how to get safe access to these sites, while also providing mobility in a highly reliable system? The proven success of inflatable structures for Mars EDLS (air-bags) used for the NASA Pathfinder and MER missions is well known. Similar technology might be employed to develop an air-deployed robotic symbiote that could self-inflate while being dropped from an aerial explorer. The final ellipsoidal inflatable system could then roll down the volcanic cone or other steeply sloped areas. A simple pumping system could be devised to periodically deflate and re-inflate the inflatable rover to pause its descent and take stationary measurements. A simple device interior to the ellipsoid could shift its lateral center of gravity and, thereby, modestly turn the inflatable rover. Cameras mounted on the ellipsoid could take panoramic images throughout the whole descent. Figure 5 are images of such a notional mission scenario and inflatable robotic symbiote.



(a) (b)

Fig. 5 – (a) Approaching Ancient Volcano and (b) Symbiote Rolling Down Slope (MAGE Image Courtesy of Space Projects Division, NASA Ames)

Ground Penetrators for Polar Regions

Telescopic and orbital evidence has already determined that both Mars' polar regions contain water ice (as well as "dry ice"). The Mars Orbiter and the European Mars Express have sensed the spectral signature of ice over large areas that scientists theorize could be in the form of moving glaciers. Every solar year for Mars results in large changes to the expanse of the polar regions, as well as substantial (~37% mean pressure) changes in the Mars' atmosphere as condensation or sublimation of volatiles occurs in those regions. The ill-fated Mars Polar Lander will be succeeded in 2007 by its near-twin the Mars Scout Phoenix Lander, which will visit these polar regions and get a first hand set of surface measurements. Such orbital and lander measurements could be greatly enhanced by aerial explorer enabled air-deployment of ice ground penetrators to distribute a network of sensors for polar "ice" studies. Figure 6 is an image of such a notional mission scenario.

The aerial explorer could be instrumental in targeting and implanting the penetrators in selective ice formations and surfaces, such that the seasonal evolution of polar and other regions could be comprehensively quantified.

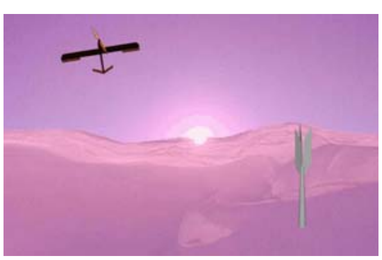


Fig. 6 – Ground Penetrators (Mars airplane image courtesy of NASA Ames Center for Mars Exploration)

Tetherbots for access to rocky hillsides

There is considerable interest [9-12] in developing robots that have the ability to scale steep terrain slopes on the Martian surface. Despite a catalog of innovative concepts that might allow for such traverses to be made, it is also quite clear that such a task will be a tremendous technical challenge to try to achieve. The overall problem can be considerably simplified if an aerial deployment is used to place the robotic device on the slope. For example, the difficult task of transiting to the cliff face, or canyon wall, of interest is obviated through the use of air-deployment.

The "tetherbot" concept is a uniquely tailored robotic device for scaling steep slopes or surfaces. From one perspective the tetherbot represents an entirely new level of drop probe sophistication; from another it is a natural marriage of ground and aerial robotic devices.

A tetherbot is an instrumented robot that locomotes along an attached cable. The tetherbot in its pre-deployed (stowed) state looks very similar to other previously tested drop probes (Fig. 4). Upon release from the aerial vehicle, and descent via parachute, a reel-mechanism lets out a monofilament tether, separating the tetherbot into two discrete mechanical sub-assemblies or elements.

A notional deployment sequence of the tetherbot is shown in Fig. 7. Upon aerial release and deployment 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 parachute 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 (Fig. 8). A "micro-imager" (with some pan/tilt/zoom capability) could be mounted to the "plumb bob."

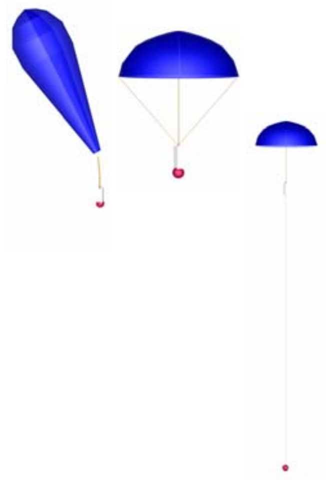


Fig. 7 – Deployment and Operation of a Tetherbot

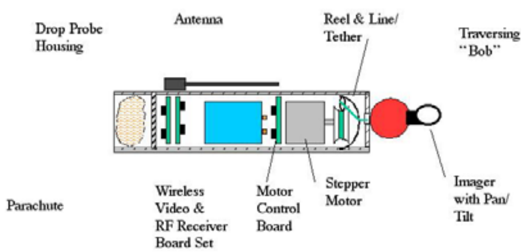


Fig. 8 – System Elements of a Tetherbot

5. CONCLUDING REMARKS

Aerial explorers for planetary science missions present considerable challenges for state-of-the-art information, communication and control technologies. Nonetheless, the potential for aerial explorers, and their robotic symbiotes, is tremendous. This paper outlined some of the ongoing research as to aerial explorer bio-inspired autonomy, robotic symbiote conceptual design, and mission scenario development.

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