Low-Cost MEMs Robotics for Space Exploration: A Probabilistic Trade Space for Biomorphic Exploration Devices[1]

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Abstract— During the next decade, numerous in-situ sampling missions are planned to a variety of planets, moons, asteroids, and comets. A goal of these missions is to understand the origin and evolution of the planetary system and the physical and chemical processes that led to the evolution of life. Among the variety of new technologies needed for such exploration are small, highly mobile, autonomous and relatively inexpensive platforms known as Biomorphic explorers. These miniaturized robotic devices will be particularly valuable for study and exploration of the surfaces of planets, moons, and small bodies. Large numbers of small, dexterous explorers could seek out and deploy sensors in places not accessible by larger rover vehicles or landers. The low cost of such microdevices would also enable the exploration of heretofore high-risk and dangerous landing sites excluded by large, more expensive systems.

This paper addresses the problem of determining the tradeoff space between the likelihood of each device achieving its stated science goal and the number of units needed to obtain the minimum required mission probability of success. Probabilistically, to a first order, the paper addresses the question, "If the probability of a single unit achieving its goal is x%, what is the required number of units to achieve 95% probability of mission success?" The impacts of cost are discussed using a linear fixed and variable cost model to derive the optimum number of units for deployment.

The issues relevant to the analysis and deployment of multiple, low cost, microelectronic and electromechanical devices (MEMs) Biomorphic explorers and the corresponding risks are also presented. A simple decision tree is presented with a parametric cost model to illustrate the potential to address risk and cost trade-offs. Three-dimensional visualizations of the probabilistic trade space are presented to illustrate these issues.

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1. INTRODUCTION

Among the varied technology development strategies for in-situ sampling missions are Biomorphic exploration devices. The premise is to complement complex, high-cost, higher reliability exploration systems such as robotic rovers or landers with numerous low-cost, simple and expendable, lower reliability devices targeted at functions better suited to these highly mobile yet low-cost devices.

Biomorphic explorers are miniaturized systems that mimic the mobility of various biological systems spanning a range of functionality including, but not limited to, walking, crawling, flying, swimming, and jumping. Due to their simplicity and range of potential functions, Biomorphic explorers could be used to accomplish surface, subsurface, and atmospheric exploration [1].

A typical scenario would involve scattering a number of explorers in a target area to search for caves or undisturbed soil areas such as those sheltered by rocks and boulders. The objective of these simple explorers could be to locate such an area by random search. When one or more of the units detect the goal had been achieved, a transmitted tone would enable precise location of the site for further sampling or as a landing target.

A key issue, which this paper examines, is the trade-off between the probability of an individual explorer reaching its goal versus the number of required explorers needed to reach a pre-determined level of mission success probability.

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2. BIOMORPHICS AND CHANCE

Design of in-situ missions using Biomorphic explorers must address the question, "If the probability of a single explorer unit achieving its goal can be estimated as a probability, p, how many units are required to achieve the overall mission goal?" That is, at least one of the units reaches the goal so that mission success is achieved with some predefined probability (e.g., 95%).

One of the advantages of Biomorphic explorers is their low-cost that allows deployment of numerous units to increase the overall chance of achieving mission success. The lower the probability of an individual unit achieving its goal, logic dictates that more explorers would be required to guarantee mission success. Similarly, as the number of deployed explorers is increased, at some point, the value of adding yet another unit does not provide a corresponding increase in the probability of mission success proportional to the added cost. The aim of this paper was to characterize, to a first order, the trade-off between the probability of explorer success versus number of explorers to achieve mission success.

3. PROBABILISTIC TRADE-OFF MODEL

The event of interest, probability of mission success across all the Biomorphic explorers, can be viewed as the result of repeated trials of sub-events by a series of explorers. Each of these explorers can be assumed identical in behavior and structure (software and hardware) possessing a constant probability of successfully achieving their goal. Since the outcome of any particular explorer's attempt to reach its goal is success or failure, the governing probabilistic model is taken as a Bernoulli process.

Under conditions which imply a sequence of Bernoulli trials, the probability distribution for the number of trials, x, required to reach the first success is a geometric probability distribution [2]:

$$p(x) = p\,(1 - p)^{x-1} \qquad x = 1, 2, \ldots$$

where "p" is the probability of success for each Bernoulli trial. The following interpretations are made:

1. p is the probability that an individual Biomorphic explorer achieves its goal.
2. x is the number of trials to reach a success (any one of the explorers reaching the goal). When any one of the explorers reaches its goal, the overall mission success of the explorers is achieved.
3. p(x) is the probability that the goal is reached (mission success) on the x^{th} trial where x = number of explorers used.
4. The operation of each explorer is assumed independent and no cooperation is assumed.

The geometric distribution can be extended to the cumulative distribution to answer the question, "What is the probability the first success will be achieved *by* the x^{th} trial.

$$P(x) = \sum_{j=1}^{x} p\,(1 - p)^{x-1}$$

Given this cumulative probability distribution, the trade-off between probability of success for a single Biomorphic explorer can be compared to the number of explorers required to reach a mission success probability requirement (such as 95%). The values of p and x were varied over a representative range of values to create a nomographic visualization of the probability trade-space.

Because cumulative geometric probabilities increase with number of units deployed, a decision framework was added to characterize the constraining influence of cost. The following fixed plus variable cost linear relationship was used:

$$\text{Cost} = ax + b$$

where a ≡ unit cost of a single explorer unit
x ≡ number of explorers
b ≡ fixed costs of explorer payload

(Note that different cost relationships can also be used without loss of generality if the first derivative exists.)

Figure 1 displays a simple decision tree for the choice facing the mission designer.

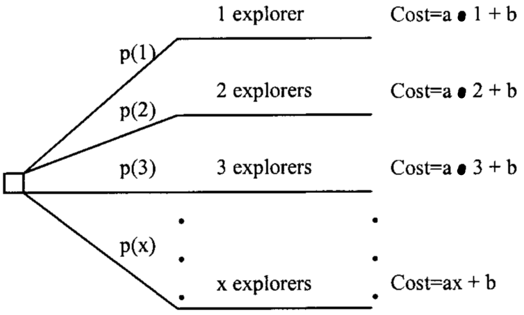

Figure 1 Decision Tree for Deployment Number of Biomorphic Explorers

Under this framework, the optimum number of units that minimizes expected cost can be derived from the convolution of probability and cost functions:

$$EC(x) = p(x)\,(ax+b)$$

where EC(x) ≡ expected cost of x explorers
p(x) ≡ Probability of success for x explorers

Setting the first derivative to zero and solving for the optimum number of units, the following relationship is obtained:

$$x^* = -\left(b/a + 1/(\log_e[1-p]) \right)$$

where $p \geq 1 - \exp^{-[a/b]}$

The value of x* yields the number of units required as a function of unit probability of success and cost equation parameters. Again, this result is presented to illustrate the potential use of the concepts presented herein.

4. RESULTS

For the probability trade-space, the resulting nomogram of unit probabilities, p, versus number of Biomorphic explorers, x, versus overall mission success, P(x), is presented in Figure 2. For example, if one Biomorphic explorer has a 10% chance of reaching its goal and the desired mission probability of success is 95%, approximately 27 units should be deployed. Similarly, if an acceptable mission probability of success is 75%, only 12 units are required.

From the cost perspective defined above, the ratio of fixed to unit costs coupled with the unit probability of success, p, determines the number of units which maximize mission probability of success while minimizing Biomorphic explorer costs.

5. DISCUSSION AND CONCLUSIONS

The relevance of Biomorphic explorers and technologies for in-situ sampling approaches is tied not only to cost considerations but also probabilistic factors that influence the quantity of deployed units necessary to achieve desired levels of mission success probability. The results presented in this paper are preliminary yet fundamental to the development of strategies for designing in-situ combinations of Biomorphic sampling technologies.

Additional work should be performed to understand the impacts on mission success probability for different Biomorphic explorer deployment approaches. For example:

- The effects of cooperative explorers working as a group toward a goal where information from other explorers is distributed and shared so the group can all move toward the goal instead of wandering randomly.

- The impact of different probabilities of success implied for a mission with a combination of different explorers (e.g., land walkers coupled with crawlers). In this case the question would be, "If one class of explorer has a lower probability of success than another class, under what conditions would a mixed strategy be appropriate?" What does a mixture of devices with different success probabilities imply for the deployment strategy?

- Alternative models of cost and their implications on the decision to deploy x units. There are conditions under which additional units are deployed to compensate for uncertainties in the unit probability of reaching the goal or other mission uncertainties.

These and other issues can be quantified using the expected cost versus risk approach outlined herein to assess starting design points for future space missions contemplating the use of Biomorphic explorer and MEM's robotics.

During the course of this study a number of conclusions were drawn:

1. Given a single class of Biomorphic explorers, the trade-off space between 1 explorer probability of success, the mission probability of success, and the number of units required can be characterized to a first order using the geometric probability distribution.
2. In general, approximately 30 units are sufficient to produce high mission success probabilities (90%+ range) for unit probability of success in the 10% range. Lower unit probabilities of success increase this number geometrically.
3. If the unit probability of success is at least 20-50%, the number of explorers drops rapidly to the neighborhood of 5-10 while maintaining a high mission success probability (75% and above)
4. The number of required units drops below 5 as the unit probability increases to 50% and above while retaining mission success probabilities in the 85% and above range.
5. If a linear, fixed plus variable cost relationship is used, the number of units which minimize the cost and risk relationship is a function of the ratio of fixed to unit costs and the unit probability of success:

$$x^* = -\left(b/a + 1/(\log_e[1-p]) \right)$$

ACKNOWLEDGEMENTS

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6. REFERENCES

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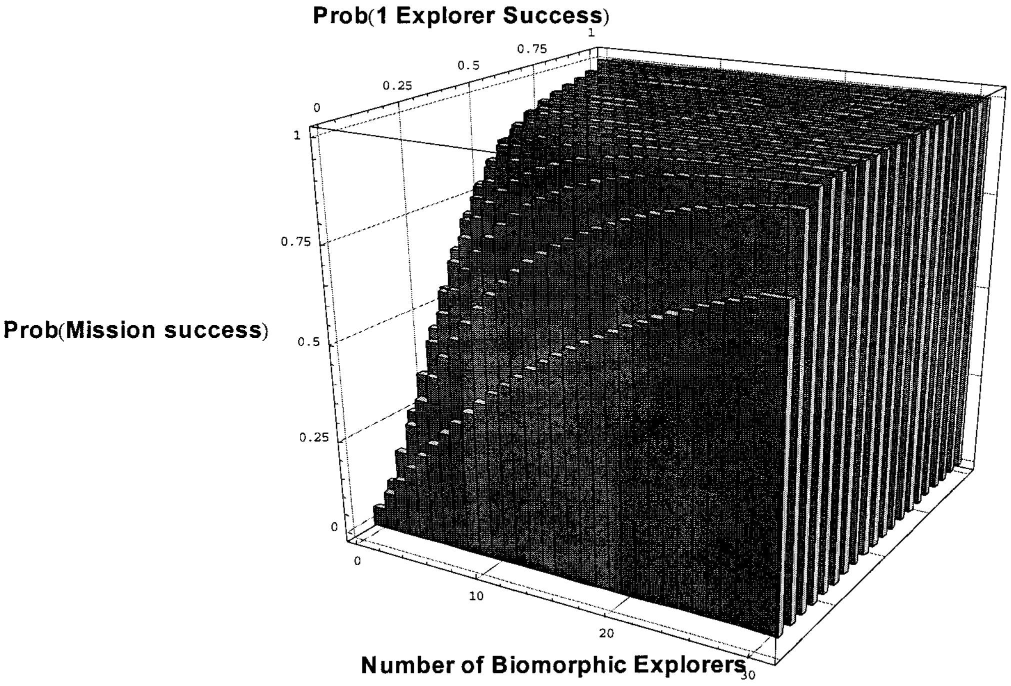

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