On comparing the performance of robots and humans in planetary surface operations

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Abstract

Future operations on planetary surfaces will involve such tasks as exploration, location and retrieval of mineral samples and construction of habitats. In the long range, it is most likely that these activities will involve both humans and robots, although surface operations with humans have to date been focused on lunar exploration, whereas robots have explored Mars and many other planets in the solar system. This paper presents a methodology for analysis of both human and robot performance in such tasks, so that intelligent task allocation decisions can be made. The methodology consists of task decomposition into a set of primitive subtasks, each of which is largely independent of the others, and which are then classified by subtask complexity. Several examples involving exploration as well as a subtask involving primarily cognitive activities are discussed.

1. Introduction

Future planetary exploration and colonization will probably involve both robots and humans. Clearly, it is not possible for astronauts to perform all the required missions, not only because of the potential hazards but also because of cost considerations. The need to provide environments capable of sustaining human life makes such missions extremely expensive. On the other hand, even today's "intelligent robots" do not possess anywhere near the cognitive and adaptive abilities of humans. It is therefore clear that there are important roles for both humans and robots in space operations, and it is necessary to develop rational methods for proper partitioning and allocation of the mission tasks. Without such a methodology, it may not be possible to optimize the way humans and robots operate either together or independently, and thereby the opportunities to make such missions a reality may decrease. In order to allocate tasks intelligently to humans and robots it is necessary to develop metrics to quantify and evaluate performance. In other words, given a particular subtask, such as MOVE from point A to point B while avoiding obstacles, how can one map the task properties to the abilities of humans and robots so that the subtask assignment becomes clear? Other examples include identifying and retrieving a soil or rock sample containing a given chemical element, or assembling a structure out of prefabricated modules. In addition to evaluating and comparing performance for individual subtasks, there is a need to investigate the performance for entire mission scenarios, which involve the performance of many possibly correlated subtasks. In the following pages, we describe an approach to the development of such a methodology that encompasses within a unified framework the analysis of individual subtasks, such as that of traversing a specified distance, as well as accounting for several aggregated subtasks that together constitute a complete mission scenario.

It is also important to keep in mind that robots can be deployed in a number of different modalities, ranging from complete tele-operation to full autonomy. Tele-operation from earth involves long communication time delays and hence is not practical except for certain high-level commands (such as task command or reprogramming). Low-level control and moment-to-moment decisions will have to be made either using the robot's autonomous capabilities or tele-operation by humans sharing the same mission. The humans could be located either in a landing module, in a permanent habitat, or in a nearby planetary orbit. They could also be located on Earth, as in the case of a purely robotic mission, where it is only the robot that goes into space. The use of robots as assistants or partners to humans, with both of them operating at the remote planetary surface, is another possible mode of deployment.

In order to approach this process in a systematic way we have selected several sample scenarios, identified relevant mission functions that must be accomplished, and subdivided each mission function into simpler primitive subtasks. We then develop measures of subtask complexity, assign a value to each subtask and select a test for evaluating them. These metrics then make it possible to compute overall composite test scores for either humans or robots or robot-human teams. Ultimately we plan to perform both computer simulations and simple physical tests to validate the theory.

It should be noted that we have not restricted the analysis that follows to any particular robot configuration or platform. This means that our methods apply to a wide variety of robots, as well as unassisted or robot-assisted humans conducting surface operations. During the course of a specific mission design, there may be several options about how to do the surface operations that may be required. Our methods provide a means to evaluate and select among these options, using well-defined performance metrics for the tasks to be performed.

Humans and robots complement each other. However, we need to take into account activities in which each normally excels. Thus, we would expect to assign robots to tasks that are highly repetitive but may present low probability events to be discerned. Humans get bored with repetition, but respond well to surprises and unforeseen events. We would expect to assign humans to tasks that are not well defined in advance of the mission, and hence where frequent and rapid problem solving may be required.

2. Mission scenarios

The allocation of tasks to humans or robots may be scenario dependent, and there may not exist a single "optimum" allocation. For this reason, we have selected several mission scenarios with sufficient generality that they represent a wide spectrum of types of missions, and thereby allow for some extrapolation to other missions. The scenarios selected are:

- Surface Exploration Mission to explore a large area in search of interesting scientific samples, sedimentary rocks for example, using either robotic or human assets, or a suitable combination of the two.

- Set-Up Surface Infrastructure to deploy or assemble the habitats of other structures, as a precursor to human presence.

- Asteroid Mining: to locate good site to drill, conduct the drilling operations to a sufficient depth, and retrieve sub-surface resources.

- Extreme Surface Exploration: to deploy and operate assets in high-risk areas, under severe environmental conditions such as extreme surface temperature and pressure.

In addition to these scenarios, our methods are intended to ultimately apply to free-flying Earth orbiting systems, requiring human and/or robot operations in a low-gravity environment. While our methods apply to this wide spectrum of missions, to simplify the discussion in this paper, our focus here is on mission types involving surface exploration of large areas. While we select this scenario to illustrate ideas, we keep in mind that the method is intended to apply as well to the other scenarios listed above.

3. Summary of Our Method

Once a scenario is selected our methodology consists of the following phases:

- **PHASE 1: Decomposition of the scenario into PRIMITIVE SUBTASKS.** These subtasks may appear in other scenarios as well, so that the decomposition may lead to some reusability. As will be shown below, these "primitives" may consist of subtasks such as reach, grasp, manipulate, drill (for the assembly task) or traverse, localize, detect specified rocks, etc. for the exploration task. Such a decomposition is analogous to the way in which Mataric breaks down behaviors (in behavior-based control of robots) into primitive *basis behaviors*, which are then used to create new complex behavior assemblages [see Mataric, 1999].

- **PHASE 2: Definition of a COMPLEXITY METRIC for each primitive.** We define these measures from the task and environment characteristics. Clearly, while there may be an inevitable subjective element in the mathematical definition of what constitutes a suitable metric for a given primitive subtask, once a metric is defined there is much less subjectivity. With a suitable metric, comparison of performance is reduced to a numerical comparison. Depending on the objectives of the comparison at hand, it may be necessary to define more than one measure for certain primitives. To arrive at the complexity metrics under development, we draw general inspiration from the goals of the body of knowledge emerging from the discipline of complexity theory [see Gell-Mann, 1995; Gregoire, 1989; Waldrop, 1992]. We also draw from celebrated Shannon information theory [Shannon, 1948], to arrive at mathematical formulas to measure the various degrees of complexity of the tasks being analyzed in this study.

- **PHASE 3: Conduct APTITUDE TESTS for each primitive subtask, to measure the performance of various subjects.** This phase of the method involves assigning or evaluating scores of human and/or robot subjects by means of thought experiments, simple models, and possibly inexpensive laboratory and field tests. The main motivation for keeping the experiments simple is that to characterize a complete mission, there may be a need to make a substantial number of performance measurements. Doing this collection of measurements as simply as possible, and with thought experiments alone if this proves to be feasible, reduces total cost and therefore makes application of the method affordable. The range of physical measurements also depends on the relative amount of complexity that is of interest in a given aptitude test, and this depends on the environmental characteristics, such as degree of terrain complexity, that must be understood for that test.

- **PHASE 4: Develop a COMPOSITION method to obtain total, composite values for complexity and scores for a task including two or more primitives.** Since the individual primitives are not orthogonal in a precise mathematical sense, the composition is not always a simple summation. In principle, it appears that a composite complexity could be smaller or larger than the arithmetic sum of the individual complexities. However, by introducing the notion of FUNCTIONAL ORTHOGONALITY among "basis" primitives, we select the primitive subtasks so that they are as independent from each other as possible, by having each of them exercise different cognitive, motive and sensory skills as those exercised by all of the other primitives. In addition, the composition method combines the results of analysis for each individual primitive into a combined assessment of multiple primitives, all of which must be executed in order to achieve a complete mission scenario. This part of the study is still in process.

4. The Concept of "Functionally Orthogonal" Primitives

The primitive subtasks are carefully chosen to be as independent from each other as possible, in the sense that they emphasize different aspect of cognitive, motor, and sensory skills. The notion of "functional orthogonality" is illustrated by the two distinct examples in the following table.

ORDINARY LIFE EXAMPLE	EXPLORATION MISSION EXAMPLE
Walk	Traverse
Chew Gum	Process Sample
Daydream	Plan Path
Smell Ocean Air	Sense Atmosphere Composition
Feel Breeze	Measure Atmosphere Pressure
Look for Seashells	Look for Interesting Samples
Flex Biceps	Relocate Robot Arm
Wiggle Finger	Grasp Sample
Blink	Blink (Camera Shutter)

Figure 1: Two Examples Illustrate the Concept of Orthogonal Primitives

The list on the left column contains primitives that would be of relevance in a highly idealized situation, someone engaged in the arduous activity of taking a leisurely walk along the beach, while simultaneously doing and thinking about several other things. Note that the primitives are generally independent, as can be verified by the relatively little effort that it takes to do them all, either one at a time or simultaneously. It is possible to do this because the primitives can be thought as being functionally independent. Each performs a unique function, and each requires a different emphasis on the use of cognitive, motive and sensory skills or behaviors. The list on the right represents a set of primitives that would be relevant to an exploration mission, a much more realistic situation than that illustrated on the left column. Note that the primitives on the right column also preserve in a general sense the feature of functional independence.

5. Major Tall Pole Primitives

Tall Pole Primitives vs Mission Types	Set-Up In-Space System	Mine Asteroid	Explore Large Area	Set-Up Surface System	Extreme Surface (Venus)
Traverse	Yes	Yes	Yes	Yes	Yes
Plan Path	Yes	Yes	Yes	Yes	Yes
Where am I?	Yes	Yes	Yes	Yes	Yes
Find Sample		Yes	Yes		Yes
Detect/Select Sample		Yes	Yes		Yes
Grasp & Handle		Yes	Yes		Yes
Analyze Sample		Yes	Yes		Yes
Be & Survive There	Yes	Yes	Yes	Yes	Yes
Get There	Yes	Yes	Yes	Yes	Yes
Lift & Unload	Yes	Yes		Yes	
Transport Load	Yes	Yes		Yes	
Recognize Object	Yes	Yes		Yes	
Grasp/Handle/Mate	Yes	Yes		Yes	
Localize Object	Yes	Yes		Yes	
Maintain & Repair	Yes	Yes		Yes	
Locate Good Site		Yes	Yes	Yes	
Set-Up Drill		Yes			
Drill Deep		Yes			
Extract Samples		Yes			

Primitives aim at measuring performance of salient active agent capabilities. For analysis of advanced mission concepts, of the type that this study is engaged in, the specific step-by-step design of all required mission sequence is not known in the early stages of system analysis. We simply do not know at this time, in the excruciating and necessary detail that would essential for executing a mission, the specific missions sequences that stipulate who does what, when and how. There will be a myriad of such detailed mission activities. The table shown immediately above lists a number of major primitives that would be relevant to a wide spectrum of mission types. While primitives are semi-independent or nearly "orthogonal" to each other in a conceptual sense, independence or "orthogonality" is only functional and not mathematically precise. The primitives are independent in that they can be executed either individually or all together. Analysis is easier if cross-primitive coupling is kept small. However, humans, and to a large extent robots, are holistic organisms, so that defining primitives with absolutely NO coupling may be impossible. For example, there may be inevitable coupling or resonance between the frequency at which the human jaws articulate while chewing, and the rate at which the legs move while walking. Independence means that primitives can be analyzed one at a time. While primitive independence is NOT ESSENTIAL to the proposed method, it attempts to avoid more elaborate multi-primitive tests. Avoiding multi-primitive tests is particularly useful to keep costs down. In addition, as the number of primitive tasks that must be performed increases, it becomes harder and more expensive to build robots with multi-primitive skills. Humans, on the other hand, can simply invoke similar, already natural, human skills to do several tasks at once, if these tasks fall within the restricted set of tasks that humans do well.

5. Example Scenario: Exploration of a Planetary Surface

The surface exploration scenario provides a good means to discuss the method under development. It consists of the search for interesting scientific samples, sedimentary rocks as examples that may be distributed over a large region. Important subtasks that must be performed in such a scenario include: 1) Traverse, requiring movement over varying terrain; 2) Navigate, involving localization and task planning; 3) Detect & identify sample materials (e.g. sedimentary rock); 4) Grasp & handle sample; 5) Analyze, store or discard sample; and 5) Survive the extreme temperature environment. As an illustration, we consider the Traverse Primitive in some detail.

The TRAVERSE primitive involves mobility of human and/or robot agents over a planetary surface terrain. The first issue that comes along with regard to this primitive is the substantial amount of uncertainty about the complexity inherent in this primitive. Traversing to a designated site in terrain of varying complexity, assuming the path to be traversed is provided from an analysis external to the primitive, involves various levels of complexity.

- 100 meter "dash" in flat terrain tests unidirectional horizontal mobility and speed
- 400 meter "dash" in mildly sloping terrain tests mobility, speed, and ability to go up and down
- 1500 meter traverse in natural rocky terrain tests ability to surmount or by-pass obstacles
- 10000 meter traverse in natural rocky terrain tests speed, endurance, and ability to surmount obstacles
- 42195 meter cross-country marathon tests endurance, speed, and ability to surmount obstacles
- 1000 meter climb to hill top tests strength and vertical mobility against gravity

The complexity of the primitive, for the subtasks defined above, increases with distance. However, there are several other physical parameters that tend to increase complexity. Note that the various levels depend only on the physical characteristics of the terrain itself, and do not depend on the characteristics of the agent (human or robot, or a hybrid of the two) that is executing the task. We continually strive to define complexity metrics that are INTRINSIC to the task itself, and not on the solution (which robot) to be evaluated. By deliberate choice, the distances involved have been selected to correspond to several of the track and field events that are traditionally performed at sanctioned athletic competitions. More on this topic will be discussed in a subsequent section.

One of the important topics under investigation is how to quantify complexity. Clearly, for a horizontally flat terrain, a reasonable measure is the path length, the distance of the traverse. A marathon-distance involving more than 40 km is much more complex than a "simple" 100 meter traverse. One could use distance as a measure of complexity. However, here we prefer to use the logarithm (to the base 2) of the distance, not only to honor the eternal spirit embodied in information theory, but because the use of such a logarithmic metric proves itself quite general in combining the effects of complexity from other sources besides distance. In particular, the effect of slopes, curvature, and roughness are easily accounted for using this metric, and this metric also generalizes to many of the other primitives under analysis. The logarithmic metric from information theory also provides us with a standard and well-understood unit (the BIT) with which to measure complexity. The following table shows the logarithmic complexity for the various distances involved in the traverse primitive. Note that since the logarithmic function can be inverted, it is easy to go back and forth between the complexity metric and the corresponding distance, for this example. This property is however only true when there is only one source of complexity, in this case the distance involved in the traverse. In more general cases, in which there are several sources of complexity, one cannot in general recover the physical parameters from the value of the complexity metric.

Distance (Meters)	Binary Complexity (Bits)
100	6.64
400	8.64
1000	9.97
1500	10.55
3000	11.55
10000	13.29
42195	15.36

Figure 3: Complexity Value for Various Distances

The base-2 logarithmic or binary complexity for a given distance can be thought of as the shortest binary word, consisting of a string of 1's and 0's, that is needed to code the distance in binary code. For example, the binary word needed to code the 100-meter distance is the word 110010. Similar binary words, with a larger number of bits, can be determined for each of the other distances listed in the table. The use of a binary system to quantify complexity also provides a means to code the complexity value, in terms of widely understood ideas and concepts, such as the binary bit.

The various levels of complexity reflect the uncertainty that may exist in the early understanding of mission goals and needs. In futuristic mission studies, that analyze missions far into the future, one simply does not know what the specific traverse requirements may be. Will it be "only" 100 meters, as in the 1997 Sojourner rover mission [see Sojourner, 1997], or will they be at the other extreme involving tens and even hundreds of kilometers. Another source of uncertainty is that, even when the mission is already under way, there may be a need to traverse over distances that have not been planned for. There always will be the natural temptation to go over the visible horizon, to answer the question: what is on the other side of that hill there? In this manner, it is possible for the traverse requirements to grow during conduct of the mission itself, far beyond what was anticipated at the beginning of the mission.

Other sources of complexity besides distance are terrain slopes, curvature and roughness. The approach to quantify complexity just outlined can be extended with relative ease to analyze more complex terrain. Such analysis, as applied to Mars topographical data [see Smith, 1999] returned by the Mars Global Surveyor mission, is being documented and will be published elsewhere by the authors.

6. Measuring Performance for the Traverse Primitive

We have shown how to quantify the degree of complexity involved in a typical primitive, that of traversing a distance over natural terrain. The next step in the method is to measure the performance for candidate agents (humans, robots, or a combination) that may be under evaluation to execute this primitive. The following "scoring" method is under investigation

For each level of complexity, the time T that a participating agent, a competitor in an athletic competition, takes to complete the corresponding event is recorded. An event (100m, 400m, etc.) is associated with each complexity level.

The ratio (SR/T) of a standard record (SR) to the measured time (T) is computed. The standard record is a recognized standard, that has been verified as having been accomplished, and that can be used as a factor to normalize the measured time (T) of the given participant. In athletics competitions, such standard times are readily available as the world record times for the given track and field events. In fact, for athletic events such records are not only verified, but they have been sanctioned by international organizations [see Wallechinsky, 2000]. However, it is recognized in our formulation of the method that similar standards may not be available as easily for other primitives. However, in all of the primitives that we have analyzed to date, it has been possible to define a standard with respect to which performance can be compared. The score (S), the total number of points credited to a participant is computed by multiplying the ratio (SR/T) by 1000. This computation results in a numerical score for each participant, and this score represents the degree of aptitude that the participant displayed in executing the given primitive. The score is similar in spirit to that used in evaluating the decathlon event in athletic competitions [see Zarnowski, 1996]. However, it is streamlined in the sense that the numerical score here is computed from a simple arithmetical ratio, whereas decathlon scoring uses a set of look-up tables to compute scores from measured performance.

Distance	Complex -ity (Bits)	Standard Perform	Agent Perform	Agent Score (Points)
100	6.64	9.8 seconds	100	97.9
400	8.64	43.2	400	86.4
1500	10.55	206.0	1600	128.8
3000	11.55	486.1	3500	138.9
10000	13.29	1583.2	12000	131.9
42195	15.36	7610.0	24000	181.2

Figure 4: Scoring Table to Compare Performance

The standard performance quantities, listed in the central column correspond to the times recorded by the current athletic track and field record holders at the various distances. The columns labeled "Agent Performance" and "Agent Score" contain hypothetical data, used primarily to illustrate the proposed scoring method. Work in progress over the next few months will lead to experimental and computer-simulated data, to enable a comparative evaluation of specific robot and human agents, with respect to the standard performance.

Use of these officially sanctioned records is convenient, but not essential. Their use provides an easily and widely accessible standard from which to measure the performance of every other subject or agent, whether a robot, a human, or a hybrid combination of the two. This analogy to athletic events is only possible for a few primitives, such as the traverse primitive, and does not apply to other primitives. In those other primitives, there is a need to define what a standard performance is, in a manner that may not be as widely disseminated as the records for athletic events are. However, while it does require some thought, the definition of a standard from which to measure performance in each primitive is possible, based on a detailed understanding of the primitive and its related complexity.

The Versatility Factor

The versatility factor defined below is a very useful parameter to compare the performance of any given agent, across a number of levels of complexity. The versatility factor is defined as the total performance score that a given subject achieves in a set of events, in an imaginary competition against the "best" in each of the events. For the example in Fig. 4, the versatility factor is computed by summing all of the point scores in the extreme right column, to obtain the total score of 765 points, and then dividing this total by 6000, which is the maximum number of points that could be scored. In doing this computation, one imagines the "thought" experiment, in which a single agent competes against a team of 6 other agents, each of which is the best at that event.

When there is uncertainty about the task to be done in a given mission, length and type of traverse for example, agents (robots or humans) with a high versatility factor are needed. A high versatility factor is also needed when a single agent (human or robot) must do many different tasks of various types. Humans are supremely versatile when doing tasks that fall within their physical constraints. The versatility factor measures the degree of versatility WITH RESPECT to a set of specific tasks. A subject that is quite versatile in one set of tasks may lack versatility in another set. No subject, human or robot, is universally versatile. It is extremely challenging to achieve a high versatility factor with current robot technology; in contrast, it is easier to achieve very good robot performance with specialized robots for specific tasks.

Multiple Performance Measurements

Measurement of the total amount of time, as in the previous section, may be extended to measure a complete time profile needed to get to various intermediate points along the way. A "power meter" to monitor energy usage during the test provides another important measurement. A measurement of the mass of the subject, both before and after execution of the test, provides a means for further comparison; and could be used to do mass or weight classification into various categories (heavy, middle, welter, light, bantam, etc.), as in boxing and other athletic competitions. The degree of system autonomy can also be measured, by determining the number of interventions required in doing the primitive.

7. Summary of Other Primitives

The traverse primitive just discussed provides a good example to illustrate the basic ideas of the comparison method under development, because there is a substantial amount of physical intuition involved, and the analogy to athletic events helps to explain relatively abstract concepts, such as the versatility factor, with concrete examples. However, the traverse primitive is only one of many. Here, we focus on summarizing briefly the salient issues in several other primitives.

- **Plan Path Primitive:** The main issue in this primitive involves planning a path to a designated site, given a topographic map of a region. This can be viewed as a primarily cognitive or "thinking" primitive, in the sense that the agent need not move while executing the primitive. It need only stay there and "think", at least in the version of the primitive that mimics the process of path planning required prior to actually moving along the path.

- **Where am I? Primitive:** The human or robot test subject is asked to determine its location on a planet's surface; increasing accuracy leads to increasing levels of complexity. The complexity is the base-2 logarithm function Log(N), where N is the number of subdivisions of the sphere. In this primitive, a hand-held GPS unit can be used as the standard, and the performance this standard can be used to measure the performance achieved by other means more typical of the technologies that will be available on other planetary surfaces besides Earth.

- **The "Get There" and "Be There" Primitives:** These primitives respond to the need to assess the likelihood that a given human (or robot) mission involving extensive surface operations can be made to happen in the foreseeable future. The Get There primitive encompasses the complexity involved in getting from Earth to the desired planetary destination, Venus or Mars as examples. The complexity involved in this is dependent not only on the distance to the planet, but also on many other parameters. Closely related to the Get There primitive is the Be There primitive, which reflects the ability to survive and operate on a designated surface, in order to do the other task primitives such as traverse.

The complexity in these primitives depends on many parameters, including atmospheric composition of the designated "There", the intended location where surface operations are to take place. Other parameters that add to complexity are the relative strength of the gravity field, surface temperature and pressure, solar radiation, and such orbital parameters as rate of rotation about the sun and about the planetary axis. As anticipated, the binary complexity metric, derived from information theory and measured in bits, provides an overarching means to combine the complexity due to all of these parameters into a composite value. A more detailed description of such a complexity analysis will be published elsewhere by the authors.

8. Concluding Remarks

We are in the formulation and initial analysis stage of a proposed method to compare the relative performance of a variety of agents, either robots or humans or a combination of the two. This paper focuses summarizing the basic concepts, and illustrating ideas with simple examples. More extensive documentation of the method is under development. The method is based substantially on decomposing a given task, into a number of functionally orthogonal subtasks or primitives. Each primitives exercises different a different aspect of the cognitive, motive, and sensory skills from those required by all of the other primitives. The primitives are not orthogonal in a precise mathematical sense, but they do retain a certain amount of independence, if chosen carefully for any given situation. They allow affordable analysis of complex tasks, by decomposing them into several primitives, each of which can be analyzed and evaluated independently. A complexity metric, based on the Shannon theory of information, is used as a means to measure the degree of complexity in each primitive. For each primitive, there is a corresponding complexity metric defined, based on a physical model of the primitive at hand. The complexity metric is then used to define a set of challenges of increasing complexity, and the challenges are then presented as tests where the aptitude of various subjects can be evaluated. A scoring method is presented to evaluate relative performance quantitatively. The formulation of the method is currently exercised with the analysis of many primitives typical in a wide variety of space operations. Current emphasis is on working additional examples and on gathering experimental data of the performance of various agents for these primitives.

9. References

[1] Mataric, M. J., "Behavior-Based Robotics", in the MIT Encyclopedia of Cognitive Sciences, Robert A. Wilson and Frank C. Keil, eds., MIT Press, April 1999, 74-77.

[2] Gell-Mann, Murray, ``What is Complexity," Complexity, Wiley Interscience Journal, Vol. 1, No. 1, 1995

[3] Gregoire Nicolis, G. Nocolis, With Ilya Prigogine, Exploring Complexity: An Introduction, W. H. Freeman Company, October 1989.

[4] Waldrop, M. Mitchell, Complexity: The Emerging Science at the Edge of Order and Chaos, Simon & Schuster, 1992.

[5] Shannon, C. E., ``A Mathematical Theory of Communication," Bell System Technical Journal, vol. 27, pp. 379-423 and 623-656, July and October, 1948.

[6] Sojourner Web-Site:
http://mars.jpl.nasa.gov/MPF/sitemap/sitemap.html

[7] Smith, D.E., et al, "The Global Topography of Mars and Implications for Surface Evolution," Science, 284, 1495-1503, 1999.

[8] Wallechinsky, David, The Complete Book of the Summer Olympics, The Overlook Press, Woodstock & New York, 2000 Edition.

[9] Zarnowski, Frank, A Basic Guide to Decathlon, An Official United States Olympic Committee Sports Series, Griffin Publishing, 1996.