A METHODOLOGY TO DETERMINE IMPACT OF ROBOTIC TECHNOLOGIES ON SPACE EXPLORATION MISSIONS

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ABSTRACT

This paper presents a new method for evaluating relative strengths and impact of robotic technologies utilized for space exploration missions. The method uses a three tiered process involving mission analysis, technology performance characterization, and technology influence models. Mission analysis focuses on determining the goals of the mission and evaluating the metrics that quantify those goals. Technology performance characterization allows the method to classify the capabilities of a diverse set of robotic technologies, in a systematic fashion, whereas the technology influence models allow understanding of the relationships between technology output and mission requirements. This three-tiered process is designed to provide a general framework for understanding the relative benefits of robotic technologies. Details on the method are provided in this paper and are illustrated on a representative Mars exploration mission.

I. INTRODUCTION

Future space exploration missions, proposed by NASA, involve satisfying an ambitious set of objectives, including Venus Exploration, the return of Martian samples to Earth, and the search for Earth-like planets that might harbor life [1]. Current technologies are not sufficient to meet the science demands of these missions, thus investments must be strategized to maximize the mission's achievable scientific yield [2,3]. To strategize investments, the relative benefits of robotic technologies on future science missions must be understood. Thus, a process that evaluates relative strengths of technologies and determines technology impact on a mission should be developed. To this effect, a framework is constructed that systematically relates technologies to mission goals in a structured fashion. This enables development of a methodology that allows robotic technologies to quantify the benefit they bring to a mission.

Previous work in assessment of robotic technologies has focused on different aspects of the problem. Through investigations, interviews, and surveys, the space robotics technology assessment study [4] analyzes the state-of-the-art (SOA) in robotic technologies. Functional lines subdivide the study into two categories: planetary surface exploration and in-space operations. The SOA is evaluated to understand the technology gaps that must be filled in order to enable the next generation of space missions. The Human-Robot Performance Analysis [5] focuses on analyzing the performance and trade-offs necessary for the development of integrated human-robot teams. The impact and benefits of cooperative human-robot teams is quantified as relates to a range of futuristic task operations, such as missions beyond low-Earth orbit. A case study to illustrate the new human-robot system architecture is presented for an in-space telescope

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assembly operation. In [2], the impact characteristics of rover autonomy technologies as applied to a future Mars mission are determined using utility functions, failure rates, and success probabilities derived from extensive available field data. Finally, a process that links robotic technologies to mission science goals through propagation of performance metrics through a technology hierarchy is presented in [3].

The methodology presented in this paper differs from these other approaches by providing a generalized framework that can encompass a wide range of uncorrelated robotic autonomy technologies, and can be applied to a large number of mission classes with minimum re-engineering effort. This is accomplished using a three-tiered process involving mission analysis, technology performance characterization, and technology influence models.

2. A GENERALIZED ASSESSMENT METHODOLOGY

The focus of our methodology is on robotic autonomy issues and how these technologies relate to satisfaction of mission objectives. The system analysis process is subdivided into three main steps, as shown in Figure 1:

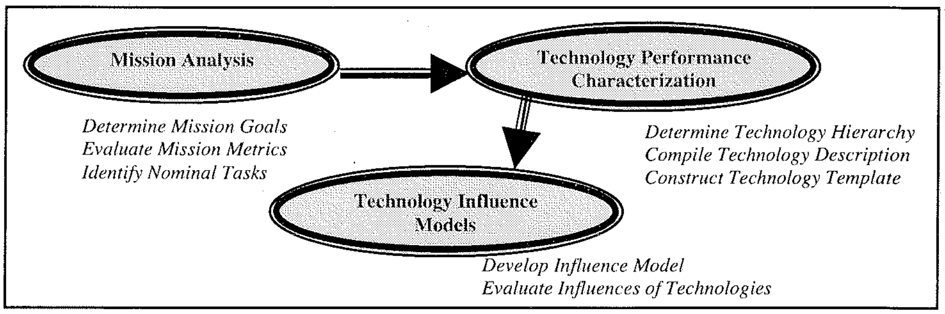

Figure 1: Assessment methodology to evaluate technology impact on a mission scenario

Missions analysis involves determining the goals of the mission, evaluating the metrics which quantify those goals, and identifying the nominal task scenario to satisfy those goals (such as minimum mission duration and surface traverse distance). The technology performance characterization phase involves assessing the diverse technology requirements needed to enable achievement of the mission goals and determining performance characteristics of relevant technology operations. The technology influence models phase involves developing influence diagrams for understanding the influence of technology on the mission and evaluating its impact as compared to baseline technologies. The following sections will discuss each phase in more detail.

3. MISSION ANALYSIS

The first stage in the assessment process is to determine the overarching objective of the mission and quantify those goals using identified metrics. This phase involves quantifying goals in terms of a physical parameter space. For example, the overall objective of a science exploration mission may be to search and locate scientific sites of interest in difficult-to-access terrain. For a robotic vehicle, one of the associated goals then becomes - navigate through a low traversability area of 100m x 200m within a minimum time of 1 sol. To evaluate for success, an associated metric can then be constructed that analyzes distance traveled per second in rough terrain.

In this paper, we select a future Mars science mission as our real-world application. The overarching objective of the mission is to conduct a Mars habitability investigation, aimed toward achieving a breakthrough in astrobiological sciences [6]. Habitability is defined as the potential of a given environment to support life at some time. Scientific measurements for this mission include examining sedimentary deposits, ancient highlands, and hydrothermal alteration zones. The associated goals for this mission therefore become 1) perform a daily traverse of about 50 meters/sol to reach a designated site, 2) perform a site reconnaissance to locate an interesting target, 3) approach the identified target, and 4) gather scientific data at the target location. These goals are then mapped into the metrics for determining success as shown in Table I.

Mission Metrics	Example Robotic Metrics
Sols required to traverse to each site	Meters traveled per sol
Sols required for site reconnaissance	Natural images processed per sol
Sols required to approach sample	Localization errors per meter traveled
Number of samples gathered per site	Accuracy of end-effector positioning
Sols required for science measurement	Science analysis processing per sol

Table I: Mission metrics associated with mission goals and associated robotic technology metrics

Once derived, these metrics are used to assess the diverse technology requirements needed to enable achievement of the mission goals and determine performance characteristics of relevant technologies.

4. TECHNOLOGY PERFORMANCE CHARACTERIZATION

Robotic technologies fall into a wide span of diverse technology interests – from vision to manipulation to mobility. To manage the extent of the robotics field, technologies can be classified based on common research objectives into seven technology areas, namely: Sample Handling, Mobility, Validation/Verification, Approach/Instrument Placement, Fault Management, Human-Robot Interaction, and Architectures/Computation.

These seven technologies areas can be mapped directly into mission goals. For example, improvement in the accuracy of an approach/instrument placement robotic technology can increased the number of samples gathered per site. A fault tolerance software module that monitors for robotic hardware faults can decrease the sols required to traverse to a site by identifying and recovering from a fault without Earth intervention.

To understand the impact of a technology on mission goals, we further classify the technologies into a technology hierarchy. At the first level of the hierarchy are operations technologies. These include technologies that affect all components of a system, such as a sequence generation task that determines the operational steps necessary to achieve mission goals, irrespective of existing technologies. At the second level are the system technologies that allow achievement of mission goals based on existing technology. For example, a software architecture task allows development of integrated algorithms that possess various operational functions to work together. The third level of the hierarchy is represented by subsystem technologies. Technologies at this level address specific functions needed to ensure mission success. Examples include instrument placement for extracting science measurements, mobility for reaching interesting science sites, and contingency planning for deciding what to do if a step in the on-surface system sequence is unachievable. At the last level are component technologies that assist in the completion of a subsystem task. As an example, long-range mobility involves a large sequence of steps necessary to complete its goals. In this application, a localization technology that is resident at the component level is needed to ensure that the long-range mobility functions are successful. Figure 3 shows the hierarchy format.

Performance metrics are defined to capture important attributes of each technology. The performance metrics are characteristic of how the technology impacts the mission goals and how the technology compares to current State-of-the-Art research efforts. For example, a *mobility* technology, which is resident at the subsystem level, may have performance metrics that relate to distance traveled per sol, whereas a *localization* technology, which is located at the component level, may have performance metrics that relates accuracy to distance traveled. Additionally, the performance parameters of a technology may differ from other technologies in the same level. For example, a performance metric for a *science planning* technology (resident at the component level) is related to science volume. On the other hand, the performance metric for a *localization* technology (also resident at the component level) is related to accuracy. To enable reasonable comparison of different technologies, a unified template that characterizes technologies in terms of three factors is utilized. The three factors segment the performance parameters into classes that represent the task dependencies (inputs), the task results (outputs), and the relevant mission constraints (environment and resources). Figure 4 depicts the technology template for an example robotic manipulation task.

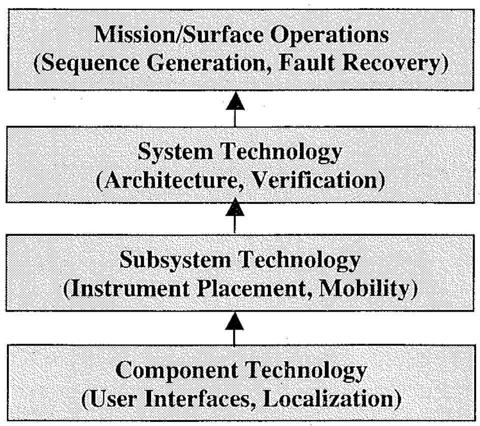

Figure 3. Technology Heirarchy

PERFORMANCE METRICS	units	SOA value	Targeted Performance (for mission scenario) value	stdv
Inputs				
No. Placements in 1 sol	unitless	1	4	0
Outputs				
Placement Accuracy	mm	cm	mm	0.1 mm
Mission Constraints				
Number of science sites	unitless	8	4	1
Number of samples per site	unitless	1	7	2

Figure 4. Example technology template for documenting performance metrics

Once determined, these performance parameters are used in the technology influence models, as explained in the next section.

5. TECHNOLOGY INFLUENCE MODEL

An influence diagram provides an intuitive way to identify and display the essential elements of a decision problem. By representing the structure of a problem and the relationships among inputs and outputs, influence models provide a simple tool for decision analysis [7]. In our approach, a technology influence model is used to understand the impact of a technology on a science exploration mission.

The technology influence model decomposes the mission goals in terms of mission metrics. The influence diagram is composed of performance variables and mission constraints, such as the number of samples per site, number of sites, distance between sites and the nominal mission length in units of sols. A technology may impact one or more of the performance variables. The impact of a technology on the mission is computed by propagating the effect a technology has on the performance variable through to the output of the influence model. Figure 5a shows an example influence diagram for a future Mars exploration mission.

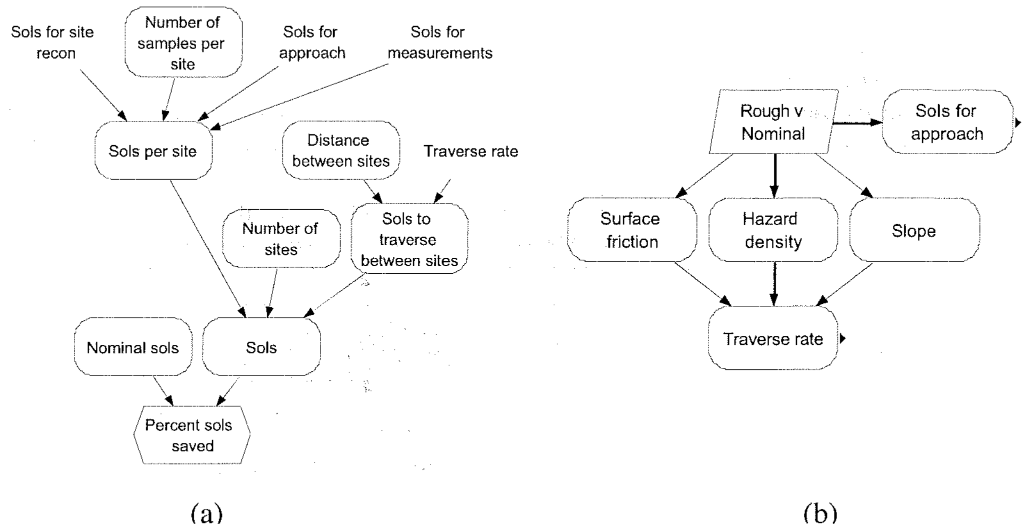

Figure 5. (a) Technology influence model, (b) Influence diagram of enhance mobility capability

The influence model computes *Sols per site* using equation 1 by adding the time for site reconnaissance ($Sols_{siterecon}$), the time to approach a site ($Sols_{approach}$), and the time required to measure all the samples at the site ($Sols_{measurements}$). The *Sols per site* is computed as:

$$\text{Sols per site} = Sols_{siterecon} + \text{Number of samples per site} * (Sols_{approach} + Sols_{measurements}) \quad (1)$$

The time required to traverse between sols is given by:

$$\text{Sols to traverse between sites} = \text{Distance between sites} * \text{Traverse rate} \quad (2)$$

The time needed to complete all mission goals is then calculated as:

$$\text{Sols} = \text{Sols per site} * \text{Number of sites} + \text{Sols to traverse between sites} * (\text{Number of sites} - 1) \quad (3)$$

The output of the influence model is represented by the value of *Percent sols saved*, such that:

$$\text{Percent sols saved} = 100 * (\text{Nominal sols} - \text{Sols}) / \text{Nominal sols} \quad (4)$$

where *Nominal sols* are calculated as the time required to achieve all mission goals using technology with state-of-the-art performance. To facilitate ranking of dissimilar tasks, it is necessary to select common units upon which to determine technology impact. Mission time is a convenient choice, thus the calculated parameter *Percent sols saved* is used as an approximation to the increased impact of the technology on the mission.

A technology may impact one of more of the nodes in the technology influence model. For example, an enhanced mobility technology may impact the traverse rate and the sols needed for approach. Figure 5b shows the influence diagram for such a mobility task. Table II gives an example comparison of this enhanced mobility technology over state-of-the-art mobility technology.

Performance in Rough Terrain	Sols per Approach	Traverse Rate (sol/m)
Nominal Technology	5	.06
Enhanced Mobility Technology	3	.02

Table II. Performance comparison of nominal technology versus enhance mobility technology

Using equations 1-4, the *Percent sols saved* for this example is calculated as approximately 46%. Thus, the impact of this mobility technology on the mission goals is 46% greater than current technology capability.

Through this process of mapping mission goals to mission metrics, quantifying the technology through performance parameters, and propagating the performance metrics through a technology influence model allows the development of a generalized process for evaluating the impact of technology on space exploration missions.

6. CONCLUSIONS

The analysis process presented in this paper represents a framework for determining impact of technologies on future missions. The framework developed provides a general system analysis process for understanding technology impact. The process can incorporate a diverse set of technologies in a globally unified process. Future work entails expanding the general framework and applying it to a wider range of mission classes.

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