Capability Investment Strategy to Enable JPL Future Space Missions

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Abstract

The Jet Propulsion Laboratory (JPL) formulates and conducts deep space missions for NASA (the National Aeronautics and Space Administration). The Chief Technologist of JPL has responsibility for strategic planning of the laboratory's advanced technology program to assure that the required technological capabilities to enable future missions are ready as needed. The responsibilities include development of a Strategic Plan (Antonsson, E., 2005). As part of the planning effort, a structured approach to technology prioritization, based upon the work of the START (Strategic Assessment of Risk and Technology) (Weisbin, C.R., 2004) team, was developed. The purpose of this paper is to describe this approach and present its current status relative to the JPL technology investment strategy.

The JPL Strategic Technology Plan divides the required technological capabilities into 13 themes. The results reported here represent the initial analysis of seven themes: In-situ Planetary Exploration Systems, Survivable Systems for Extreme Environments, Precision Flying Systems, Deep Space Communication, Planetary Protection Systems, Utilization of High Capability Computing, and Engineering Systems. The remaining six themes will be included in the study planned for FY '06.

Each theme is hierarchically decomposed into component capabilities, to a level where quantitative estimates can be ascribed. For example, in the In-Situ Exploration theme, the sub-theme of Mobility is broken down into Surface Mobility, which allows an estimate of the meters traversed per command, a specific and measurable quantity. This structure is repeated and data filled in for each mission.

All of this information is analyzed using an optimization technique (Martello, S., 1990) formulated to maximize total missions technologically enabled subject to overall cost constraints. Note that capabilities are given credit only if all capabilities needed to enable a particular mission are selected for funding. The recommended investments at each area of the capability hierarchy are plotted as a function of the total budget available to the sponsor.

The robustness of the investment strategy is quantitatively analyzed as a function of potential variation (the uncertainty) of the input data. In on-going work we are looking at measures for relative mission value, dependencies among missions and capability areas, and time profiles of the recommended investments.

Introduction

A capability hierarchy is created for each theme. Performance metrics are defined. Information is gathered on a mission-by-mission basis, and includes projected metric performance levels, their importance, estimated cost and development schedule, and likelihood of success if fully funded. (Recall that these are advanced research areas and not every effort is assured to succeed). Figure 1 shows a partial view of the capability hierarchy for Mars Sample Return.

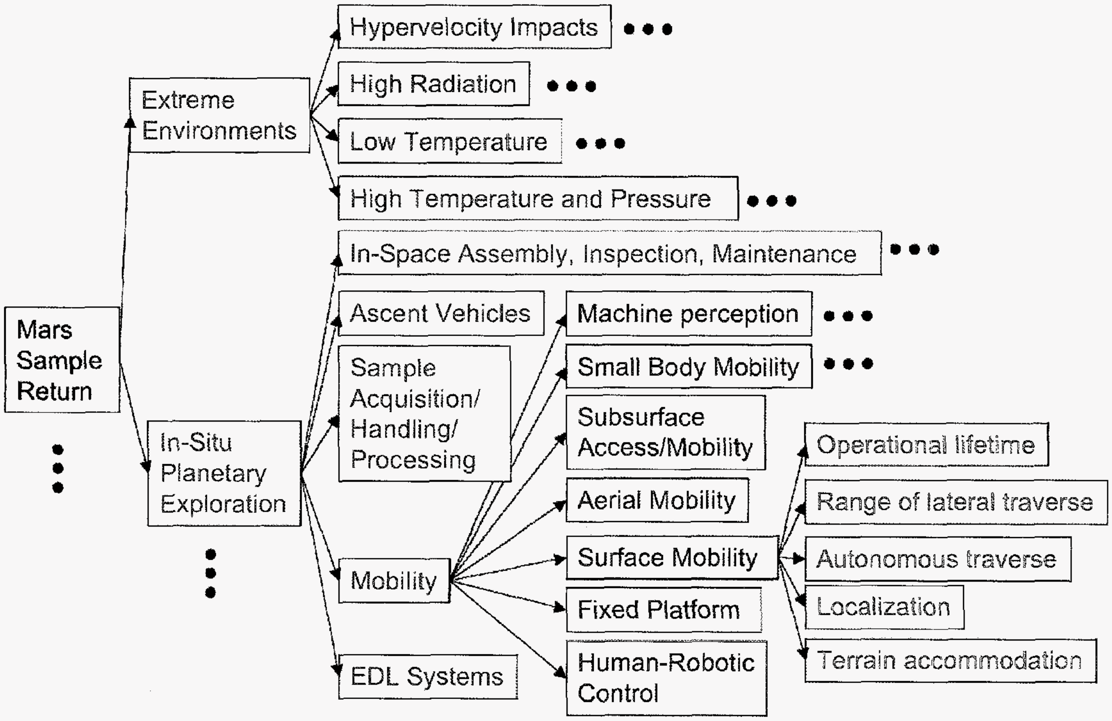

Figure 1. A partial view of the capability hierarchy for Mars Sample Return. Two themes are shown, Extreme Environments and In-Situ Planetary Exploration. Both themes are subdivided further. Metrics are placed at the lowest level. Metrics are shown for Surface Mobility.

The number of levels in a capability hierarchy can vary with the fidelity of the subdivisions. The structure allows weighting within each branch, with weights normalized to sum to one within each sub-branch.

Metrics are organized under the lowest level of the capability hierarchy. Each metric in the database has a name, a physical unit, polarity, State-Of-the-Art (SOA) performance, and current maturity. Each mission has its own set of projected metric values, their importance to the mission, and probability of development success given the development cost and schedule. Development costs are to technology readiness level (TRL) 6.

This study used the mission set of interest to JPL shown in table 1.

Asteroid Sample Return
Mars Science Laboratory
Large Observatory Platform
Lunar Sample Return Lander
Comet Sample Return
Lunar Precursor Resource Survey
Venus Surface Sample Return
Mars Scout Line
Mars Sample Return
Astrobiology Field Lab
Europa Surface/Subsurface
Terrestrial Planet Finder - Interferometer
Titan Explorer

Table 1. Mission set used in the analysis.

Optimization

The optimization algorithm selects missions to enable by maximizing a benefit function subject to a budget constraint. A diagram of the optimization is shown in figure 2.

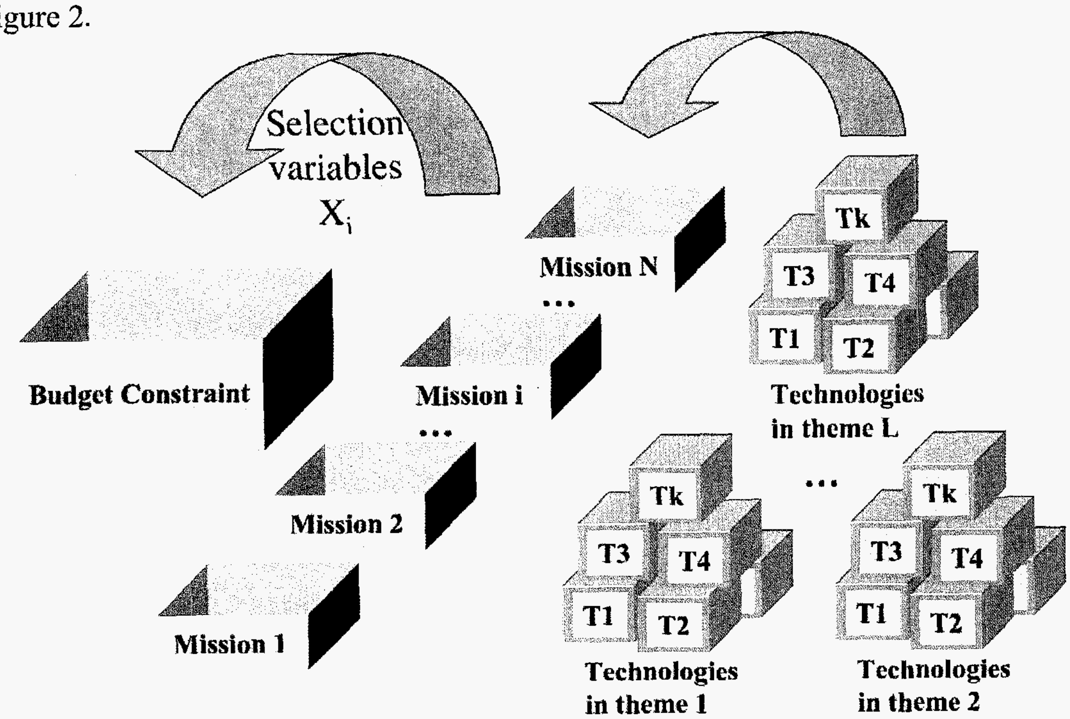

Figure 2. Missions use technologies from various themes. The set of missions that are enabled is constrained by the budget.

The benefit function emphasizes performance improvement for metrics required for a mission. Equation 1 gives the metric gain, which measures the projected improvement of a metric over state of art. The metric's polarity indicates whether improvement is measured by reduction or increase; it is equal to -1 for metrics where a reduction in the metric's value is improvement; otherwise it is equal to 1. A total gain value of 1 means the projected level is 100% improvement of state of art.

$$gain_{metric} = polarity_{metric} * \log_2\left(\frac{Projected\ level_{metric}}{State\ of\ Art_{metric}}\right) \quad (1)$$

Each metric gain has a probability of development success to reach the projected performance level based on cost and schedule. Equation 2 shows the calculation of the expected gain.

$$expected\ gain_{metric} = probability\ of\ development\ success_{metric} * gain_{metric} \quad (2)$$

Mission gain is the weighted sum over all the required metrics' gains in the capability hierarchy for the mission.

$$mission\ gain = \sum_{themes} w_{theme} \sum_{areas} w_{area} \sum_{technologies} w_{technology} \sum_{metrics} w_{metric} * expected\ gain_{metric} \quad (3)$$

Where w_{theme}, w_{area}, $w_{technology}$ and w_{metric} are weights at the different levels of the capability hierarchy.

The total cost for the technology development of the mission is the sum of the cost for each of the required gains.

$$mission\ technology\ development\ cost = \sum_{themes} \sum_{areas} \sum_{technologies} \sum_{metrics} cost\ for\ gain_{metric} \quad (4)$$

The optimization is:

$$\text{maximize} \sum_{i=1,N_{missions}} X_i * mission\ gain_i \quad (5)$$

$$subject\ to \sum_{i=1,N_{missions}} X_i * development\ cost_i \le Budget \quad (6)$$

Selection variables, $X_i = \{0,1\}$, are associated with each mission. A selection variable, X_i, equals 1 when all the required metric improvements are funded for the mission. If X_i equals 0 then none of the metric improvements are funded for that mission. Note that a technology development in a capability area is selected for funding only if all technologies needed to enable a particular mission of interest are selected for funding.

Projected metric levels for a mission have an importance weight. Higher weights correspond to metrics more important to the mission. At the extreme high end of the scale are the required metrics. A two-step process is used. First, the optimization uses only the metric levels that are required by the missions. Figure 3 shows the technology investment by theme that resulted from the first stage optimization. Plots of investment at other levels of the capability hierarchy were also made.

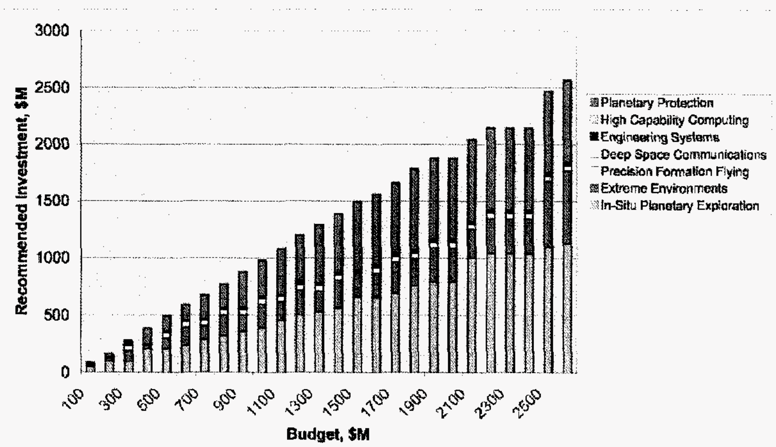

Figure 3. Recommended technology investment for required metrics by theme for different budget levels. Budget covers a period of roughly 15 years.

The second step identifies metrics that are not required but have high gain-to-cost ratios for the missions that are enabled in the first step. Figure 4 shows the investment by theme for the second step.

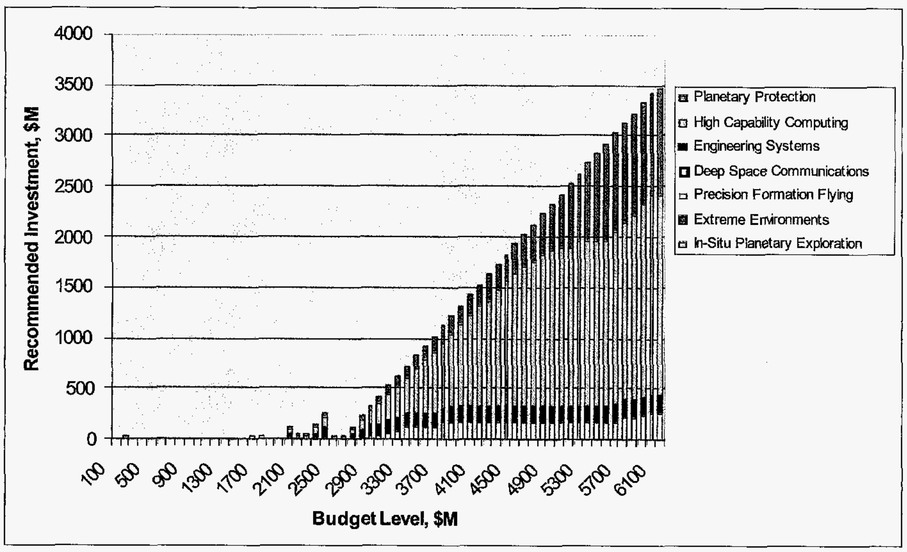

Figure 4. Recommended technology investment for metrics with high gain-to-cost ratios by theme for different budget levels. Budget covers a period of roughly 15 years.

Robustness of Portfolio

The recommendations for technology investments are subsequently qualified in post-optimality analysis by using two complementary methods: parametric sensitivity analysis and k-best sets analysis. At a given budget level, the parametric sensitivity analysis consists of incrementing/decrementing the nominal values of cost and gain - one variable at a time, for each mission - until a change in the resulting portfolio is observed. This approach yields the range within which the portfolio selections are invariant to change in the specific value of a particular cost or gain for the given budget. The change events are recorded and cumulated over the entire parametric screening. The elements in the portfolio with the highest cumulated activity form the trade-off set, while the rest is separated in persistent selected and non-selected sets, respectively.

The complementary k-best sets approach offers “k” alternative portfolios close to the optimal recommendation for a given budget level. Based on the k-best sets the decision-maker could take into account aspects of the problem that are not easily modeled quantitatively. By finding the k-best sets of technologies with the base-case input parameters, and then comparing the values of these sets over the entire range of possible values for the input parameters, one can identify competitor portfolios. The intersection of the k-best sets with the optimal set produces a set of mission selections deemed as “robust.” Although the two approaches are complementary, their results are consistent, in that the persistent set is similar in composition to the robust set.

Figure 5 illustrates the 5-best portfolio analysis at a $2B budget level using only the enhancing technologies. Although at this budget level only four out of seven selected missions can be considered as robust choices, the decision maker has enough supplementary information to accept with confidence two or even three alternatives to the recommendation based on the optimal solution.

Mission	Opt	KB1	KB2	KB3	KB4	KB5	Overall
Asteroid Sample Return	1	1	1	1	1	1	100.00%
Comet Sample Return	1	1	1	1	1	1	100.00%
TPF- Interferometer	1	1	1	1	1	1	100.00%
Lunar Sample Return Lander	1	1	1	0	1	0	66.67%
Europa Surface/Subsurface	1	1	1	1	1	1	100.00%
Large Observatory Platform	0	1	1	1	1	1	83.33%
Titan Explorer	1	1	0	1	0	1	66.67%
Mars Science Laboratory	1	0	0	1	0	0	33.33%
Astrobiology Field Lab	0	0	0	0	0	1	16.67%
Mars Scout Line	0	0	1	0	0	0	16.67%
Mars Sample Return	0	0	0	0	1	0	16.67%
Lunar Precursor Resource Survey	0	0	0	0	0	0	0.00%
Venus Surface Sample Return	0	0	0	0	0	0	0.00%

Figure 5. The 5-best portfolios at the $2B budget level. The green background denotes “selected,” the red “non-selected” and the orange “trade-off.” The overall presence in all 6 portfolios is expressed as percentages.

Conclusions

The START team developed a structured approach to technology prioritization. Our approach and its current status relative to the JPL technology investment strategy have been demonstrated. Results reported here represent the initial analysis of seven themes.

The results are based on the input data. The data needs to be independently reviewed by technologists and mission architects, before the process outlined in this paper is used to aid decision makers

In particular, the designation of a metric level as required is critical since required metrics have priority over other metrics. By definition, if it were clear which metrics were necessary to mission success, the problem of selecting capabilities would already be solved. But in order to compare metric gains, the requirements must be known; for many future missions the system architecture is not completely defined and thus the requirements are not firm.

Changes in the mission set used for the analysis will also results in different recommended portfolios. For example, additional missions beyond TPF that use capabilities in Precision Formation Flying will raise the forecasted investments in that theme. The current data is for a single mission, TPF.

The post-optimality analysis qualifies the recommendation obtained from the optimal solution and offers the decision-maker with an array of viable alternatives.

Because the near-term missions are close to their technology freeze dates, there is no temporal component in the analysis. It is assumed there are current developments to reach the projected metric levels for those missions. We have extended the analysis for temporal scheduling and constraints for missions with a later freeze date; this will be reported elsewhere.

Future work includes establishing mission value, adding the remaining themes to the analysis, and determining importance of metric levels for missions.

Acknowledgements

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