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From Mission Objectives to Design: An Efficient Framework for Downselection in Robotic Space Exploration

Jarret M. Lafleur*, Jonathan L. Sharma*, and Jillian Apa*
Georgia Institute of Technology, Atlanta, Georgia 30332

One of the most critical tasks in any design process is the initial conversion of mission or program objectives into a baseline system architecture. Approaches to this task commonly rely on qualitative assessments of design options and detailed sizing of a handful of potential point designs. Mission value is often difficult to compare among alternatives because it is often not captured quantitatively. The framework presented here is unique in its quick and thorough population of a Pareto front in the mission importance vs. cost domain, allowing early selection of non-dominated, Pareto-optimal designs. This is achieved via automated evaluation of thousands of potential candidate architecture and payload combinations. In an illustration of this method, 70,000 cases are sized for a robotic mission to the near-Earth asteroid 99942 Apophis. A design on the resulting Pareto front is chosen, and initial mass and cost estimates returned are accurate within 2-5% compared to the detailed final design. Despite some limitations, it is concluded that this framework is theoretically extensible to non-robotic, and perhaps even non-exploration, missions. It is believed that this framework is a valuable addition to the system engineer's toolbox and that it can allow the selection of higher-value, lower-cost solutions during preliminary design.

Nomenclature

AHP = Analytical Hierarchy Process
AO = Announcement of Opportunity
C3 = square of hyperbolic excess velocity
DDT&E = Design, Development, Test, and Evaluation
I2O = Instrument-to-Objective
IA&T = Integration, Assembly, and Test
I_{instr} = instrument importance
p_i = relative priority of a given objective
q_i = instrument correlation ranking for a given objective
QFD = Quality Function Deployment
RFP = Request for Proposals
SSDL = Georgia Tech Space Systems Design Lab
ΔV = equivalent zero-loss change in velocity

I. Introduction

ONE of the most critical tasks in the design of a complex engineering system is the initial conversion of mission or program objectives and requirements into a baseline system architecture. Moreover, a challenge exists to comprehensively explore the global design space while still leaving enough time and resources to decide upon the fine details of the selected point design. At one extreme, a comprehensive exploration of the global design space could be achieved with a monolithic vehicle or architecture model but could easily involve the unmanageability of hundreds of design variables and objectives. At the other extreme, a quick downselection based on engineering judgment is prone to reliance on historical experience and could easily produce suboptimal solutions for the problem at hand. The latter concern is particularly relevant for advanced systems and exploration applications where extrapolation based on historical designs is impossible due to new and unique requirements and environments. This

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[*] Student, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150, Student Member AIAA.

paper presents a superior compromise between these two extremes which is aimed at identifying Pareto-optimal designs which maximize mission importance and minimize mission cost.

The work presented by this paper originated in the design of a science and orbit determination mission to the near-Earth asteroid 99942 Apophis. The project required a framework which would allow a thorough evaluation of the global design space but which would also allow timely selection of a point design. For planetary robotic missions in particular, it was recognized that there are many options available to the designer in terms of (1) payload, which is the answer to "what should this system carry?" and (2) architecture, which is the answer to "how should this system carry it?". The separation of these two questions provides the foundation of this framework, since one quickly realizes that a large number of potential designs can be identified simply by mixing and matching candidate payloads with candidate architectures. Each of these mixed-and-matched possibilities is a unique design with a certain estimated cost and, due to its performance, a certain importance when evaluated against program and mission objectives. Plotting each design in this importance vs. cost objective space facilitates simultaneous selection of mission science (the "what") and the architecture to fulfill it (the "how").

II. Related Methodologies and Tools

A great deal is available in the literature on the topic of systems analysis for space vehicles and architectures, and the framework presented by this paper essentially utilizes a unique ordering of several commonly accepted systems analysis practices and tools.

Like the framework presented in this paper, the process defined by Wertz and Larson[1] includes elements of objectives and constraints definition, candidate mission architecture definition, and quantitative system performance characterization. Mission utility is also characterized by measures of effectiveness. Wertz and Larson present these and related steps in the context of an iterative loop and eventual convergence on a baseline mission concept.

The NASA Systems Engineering Handbook[2] recognizes and plots the notional trade between cost and effectiveness, noting the existence of a cost vs. effectiveness envelope defined by a set of nondominated points. Rodriguez and Weisbin[3] develop a method to quantitatively plot this same trade for multiple designs. The capability to accurately populate a plot of system cost vs. system importance is emphasized in – and is indeed one of the key results of – the framework presented in this paper. This capability, which effectively results in the generation of a Pareto front in the cost vs. system importance space, is largely enabled by the sizing and costing of thousands of unique potential designs. In contrast, the existing methods mentioned above are largely aimed at the generation of only a handful of point designs.

One process used directly in this paper's framework is the Analytical Hierarchy Process (AHP)[4] in order to prioritize objectives and compare potential solutions in terms of those objectives. Additionally, a variant of a Quality Function Deployment (QFD)[1] is used to quantitatively rate how well each candidate payload fulfills each objective for each candidate architecture. This paper assumes that the reader is already familiar with these tools and does not describe them in detail.

III. Framework Summary

The full downselection framework is summarized in Fig. 1. The process begins with the definition of objectives and ends at the initiation of detailed design and subsystem trades. Thus, the process starts with a global picture of the concept design space and intelligently narrows possibilities to the space surrounding a single point design. Key aspects are summarized below, and a more detailed summary is contained in the next section of this paper.

> ***Objectives Definition.*** The first step in this method is the clear and concise definition of those objectives for which the architecture selection will have a non-negligible impact. Often some of these objectives are clear from a Request for Proposals (RFP), Announcement of Opportunity (AO), or similar document.
>
> ***Prioritization Matrices***. Objective prioritization is divided into program and mission levels. The program level contains overriding programmatic concerns such as cost, risk, and schedule, while the mission level contains mission-specific objectives (e.g., science). An Analytical Hierarchy Process (AHP) prioritization matrix is used for each level to permit one-on-one evaluations of the priority of each objective compared to each other objective.
>
> ***Candidate Architecture Definitions.*** Next, all candidate architectures of interest are defined. This may include considerations such as constellation size, constellation configuration, whether a vehicle is a lander or an orbiter, and other considerations which would affect the rules used to size the vehicle system.

I2O Maps. For each candidate architecture, a Payload Instrument-to-Objective (I2O) map is created. The I2O map is modeled in the form of a Quality Function Deployment (QFD), but differs in that it maps mission-level objectives to the ability of candidate payloads to fulfill each objective. The bottom row of the I2O map thus indicates how important a given payload is to the overall mission.

Cost and Importance Estimation. Potential payloads from the I2O maps are next mixed-and-matched into thousands of cases for each of the candidate architectures (10,000 cases per candidate architecture are used for the *Pharos* evaluation illustrated next). For each individual case, which has a unique payload combination, mission importance is estimated as the sum of individual payloads' importances. Cost is estimated using a variety of first-order estimation tools, including a historical mass model, ΔV estimates, launch vehicle database, and cost estimation models.

Pareto Plot and Final Downselection. After cost and importance estimates are complete, results are plotted in the importance vs. cost objective space to observe the trade via a Pareto front. Several points are chosen along the front for further evaluation in the original program-level prioritization matrix and AHP. The results of this final AHP evaluation determine the final concept. From this point, the architecture and payloads are chosen and detailed subsystem sizing may follow.

A distinguishing feature of this overall process is its inclusion of an automated evaluation of the cost and mission importance of thousands of possible payload choices. The Pareto front that results clearly shows the frontier of achievable mission importance-to-cost ratios and in and of itself is a compelling illustration to show the Pareto optimality (or sub-optimality) of any design. A program-level AHP prioritization matrix evaluation follows selection to ensure consideration of non-cost and non-science factors.

It may also be helpful to consider this process "backwards": To plot a Pareto front in the mission importance vs. cost domain, estimates are required for both mission importance and mission cost for a large number of potential designs. Each potential design is defined by the payloads it carries and architecture it employs (meaning all payload and architecture candidates must be defined), so the cost of each potential design may be estimated using historical cost models, mass models, and basic orbital mechanics analyses. The importance of each design is estimated in terms of mission objectives (and their relative priorities) and a rating of how well the design fulfills each objective.

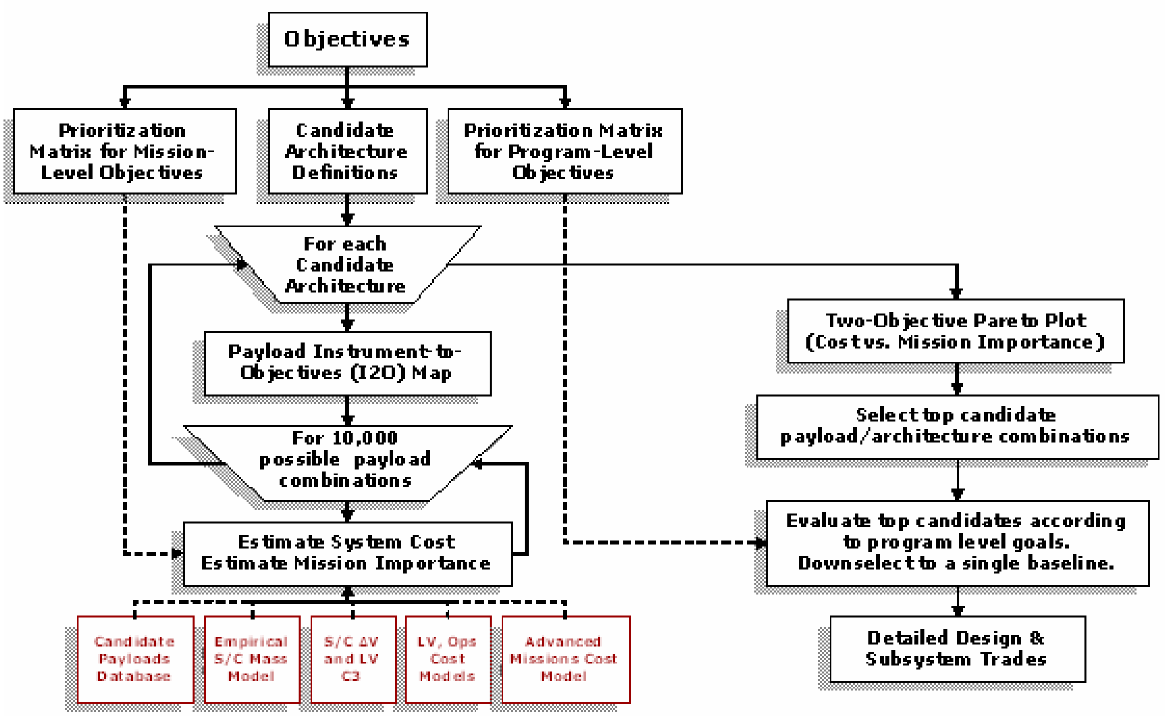


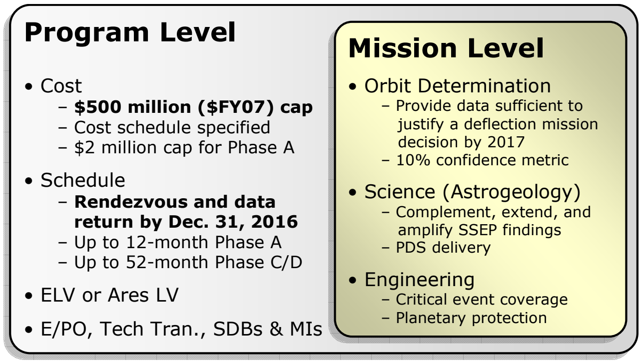
Figure 1. Downselection framework summary.

IV. Framework Illustration

As mentioned earlier, the work presented by this paper originated in the design of a science and orbit determination mission to the near-Earth asteroid 99942 Apophis. The design team was given considerable freedom in determining the mission and architecture provided that a $500 million (FY07) cost cap (as well as annual spending limits and a completion date requirement) was met. The vehicle finally selected as a result of this process, named *Pharos*, was a 721-kg orbiter-class vehicle with four science instruments (a multi-spectral imager, infrared spectrometer, laser rangefinder, and magnetometer) and four small probes[5] which would impact the surface of Apophis to return deceleration and temperature profile data to the main *Pharos* spacecraft. Illustrated here is the *Pharos* design team's implementation of the downselection framework described above.

A. Objectives Definition

The beginning of the design process is marked by recognition and documentation of formal requirements from the given AO. These requirements are summarized in Fig. 2. Note that the requirements are divided into both the program and mission levels, where the program level consists of aspects such as cost and schedule and the mission level consists of specific technical mission requirements.



Program Level

- Cost
  - **$500 million ($FY07) cap**
  - Cost schedule specified
  - $2 million cap for Phase A
- Schedule
  - **Rendezvous and data return by Dec. 31, 2016**
  - Up to 12-month Phase A
  - Up to 52-month Phase C/D
- ELV or Ares LV
- E/PO, Tech Tran., SDBs & MIs

Mission Level

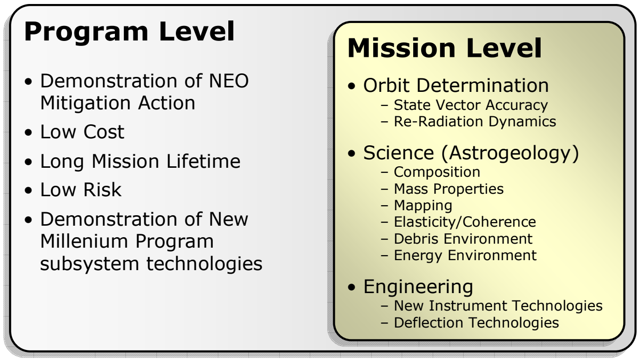
- Orbit Determination
  - Provide data sufficient to justify a deflection mission decision by 2017
  - 10% confidence metric
- Science (Astrogeology)
  - Complement, extend, and amplify SSEP findings
  - PDS delivery
- Engineering
  - Critical event coverage
  - Planetary protection

Figure 2. The *Pharos* design is driven at the highest level by AO requirements.

B. Prioritization Matrices

The program and mission level requirements given by the AO are next translated into a number of objectives for the *Pharos* mission which are prioritized in two matrices. As shown in Fig. 3, program-level objectives include aspects of cost, risk, schedule, and public demonstration of action regarding deep space technologies and near-Earth objects. Mission-level objectives are a subset of the program-level objectives and include orbit determination, science, and engineering objectives of interest.

The full prioritization matrices are shown in Fig. 4. Given the focus of the AO, it is not surprising that highest priority is placed on precise determination of Apophis' state vector. The second priority of the mission is determination of the composition of Apophis.



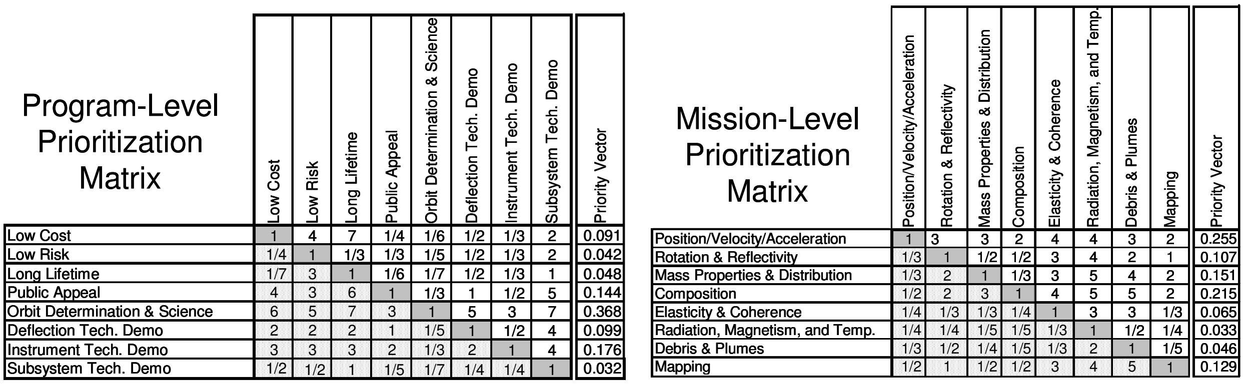
Program Level

- Demonstration of NEO Mitigation Action
- Low Cost
- Long Mission Lifetime
- Low Risk
- Demonstration of New Millenium Program subsystem technologies

Mission Level

- Orbit Determination
  - State Vector Accuracy
  - Re-Radiation Dynamics
- Science (Astrogeology)
  - Composition
  - Mass Properties
  - Mapping
  - Elasticity/Coherence
  - Debris Environment
  - Energy Environment
- Engineering
  - New Instrument Technologies
  - Deflection Technologies

Figure 3. *Pharos* program and mission goals.



Program-Level Prioritization Matrix

	Low Cost	Low Risk	Long Lifetime	Public Appeal	Orbit Determination & Science	Deflection Tech. Demo	Instrument Tech. Demo	Subsystem Tech. Demo	Priority Vector
Low Cost	1	4	7	1/4	1/6	1/2	1/3	2	0.091
Low Risk	1/4	1	1/3	1/3	1/5	1/2	1/3	2	0.042
Long Lifetime	1/7	3	1	1/6	1/7	1/2	1/3	1	0.048
Public Appeal	4	3	6	1	1/3	1	1/2	5	0.144
Orbit Determination & Science	6	5	7	3	1	5	3	7	0.368
Deflection Tech. Demo	2	2	2	1	1/5	1	1/2	4	0.099
Instrument Tech. Demo	3	3	3	2	1/3	2	1	4	0.176
Subsystem Tech. Demo	1/2	1/2	1	1/5	1/7	1/4	1/4	1	0.032

Mission-Level Prioritization Matrix

	Position/Velocity/Acceleration	Rotation & Reflectivity	Mass Properties & Distribution	Composition	Elasticity & Coherence	Radiation, Magnetism, and Temp.	Debris & Plumes	Mapping	Priority Vector
Position/Velocity/Acceleration	1	3	3	2	4	4	3	2	0.255
Rotation & Reflectivity	1/3	1	1/2	1/2	3	4	2	1	0.107
Mass Properties & Distribution	1/3	2	1	1/3	3	5	4	2	0.151
Composition	1/2	2	3	1	4	5	5	2	0.215
Elasticity & Coherence	1/4	1/3	1/3	1/4	1	3	3	1/3	0.065
Radiation, Magnetism, and Temp.	1/4	1/4	1/5	1/5	1/3	1	1/2	1/4	0.033
Debris & Plumes	1/3	1/2	1/4	1/5	1/3	2	1	1/5	0.046
Mapping	1/2	1	1/2	1/2	3	4	5	1	0.129

Figure 4. *Pharos* objectives are divided into program and mission level prioritization matrices.

C. Candidate Architecture Definitions

The next step in the downselection process is the definition of candidate mission architectures. Four core architectures are chosen for evaluation, although two additional architectural options (a sample return system and distributed sensor system) are also considered and modeled as payloads. The first candidate architecture is dubbed a two-phase orbiter/lander in which an orbiter operates in proximity to Apophis and has the capability to land and return data at end of life. The second option is a lander only, for which all instrumentation is geared toward surface activity. The third option is an orbiter only, for which all instrumentation is geared toward remote sensing. Finally, the fourth candidate architecture involves a separate orbiter and lander strategy in which an orbiting mother ship launches a lander to conduct surface operations. Three additional candidate architectures are defined which are identical to the first three but which consist of twin vehicles instead of a single one.

D. Instrument-to-Objective Maps

The final step required to enable the automated analysis of thousands of potential vehicle designs is the definition of an instrument-to-objective (I2O) map for each candidate architecture. A sample I2O map is shown in Fig. 5. Modeled in the form of a QFD, the left two columns contain mission-level priorities from the associated prioritization matrix. The top two rows contain all payloads under consideration as well as their masses for reference. In the remaining rows and columns, each potential payload is ranked as a 1, 3, or 9 in terms of how well it fulfills the corresponding objective. The bottom row indicates each instrument's overall importance score, which is calculated from Eq. (1). In Eq. (1), q_i is a given instrument's correlation ranking (1, 3, or 9) for a given objective i, and p_i is the priority of that objective (from the mission-level prioritization matrix in Fig. 4).

$$I_{instr} = \sum_i q_i p_i \tag{1}$$

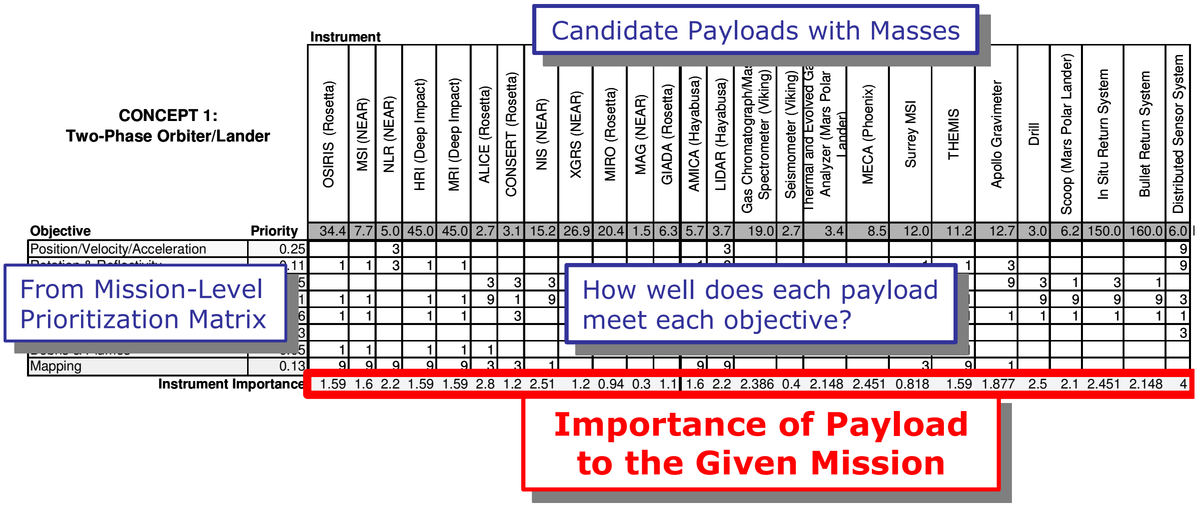


Figure 5. A sample Instrument-to-Objective (I2O) Map indicates the relative importance of all potential payloads to each *Pharos* candidate architecture.

E. Automated Cost and Importance Estimation

Automated cost and importance estimation is performed using a short MATLAB code which takes the I2O payload masses and importances, generates a series of potential payload combinations (in this case, 10,000 combinations were chosen per candidate architecture), and evaluates each payload combination to determine mission cost and mass. For a given payload combination, the evaluation takes several steps:

1. ***Mission ΔV and C3 Definition.*** Outputs from a separate cost-based launch opportunity selection process produce approximate launch vehicle C3 and arrival ΔV values. Maintenance ΔV requirements are also estimated.

2. ***Spacecraft Dry Mass Estimation.*** Spacecraft dry mass is estimated via a historical curve fit from the total payload mass based on seven similar past missions. This is effectively a rough sizing of all spacecraft subsystems and support hardware.

3. ***Spacecraft Gross Mass Estimation.*** Spacecraft gross mass is estimated via application of the rocket equation using the estimated dry mass and the arrival and maintenance ΔV numbers from previous steps. A hypergolic engine specific impulse of 300 s is assumed.

4. ***Launch Vehicle Selection.*** With spacecraft gross (launch) mass known, a launch vehicle is selected from an in-house Georgia Tech Space Systems Design Laboratory (SSDL) launch vehicle database. The lowest-cost American launch vehicle which can lift the spacecraft to the specified C3 is automatically selected.

5. ***DDT&E Cost Estimation.*** Design, Development, Test, and Evaluation (DDT&E) cost is estimated using an Advanced Missions Cost Model which has been scaled to produce correct DDT&E costs for the NEAR-Shoemaker mission to the asteroid Eros.

6. ***Ancillary Cost Estimation.*** Integration, Assembly, and Test (IA&T), program management, ground equipment, operations, and software costs are estimated using methods from Larson and Wertz[1].

From the information generated by these six steps, the total cost estimate is known, and the total mission importance is taken as the sum of the individual instrument importances.

F. Pareto Plot

From the 70,000 point designs generated by the automated cost and importance evaluation, a plot can be made representing the inherent trade between cost and attainable mission importance. This plot is shown in Fig. 6. Some important characteristics to note are the large vertical white spaces near $350M and $425M, discontinuities which are the result of jumps in launch vehicle. It can also be seen that all "A" concepts, or two-vehicle variants of the four core concepts, lie away from the well-populated Pareto front which forms the border between the white and populated space on the graph. This Pareto front represents the set of non-dominated solutions, or the set of solutions for which no same-cost mission has higher importance or for which no same-importance mission has lower cost. Ideally, the chosen design (at least from a cost and mission importance standpoint) will lie on the Pareto front.

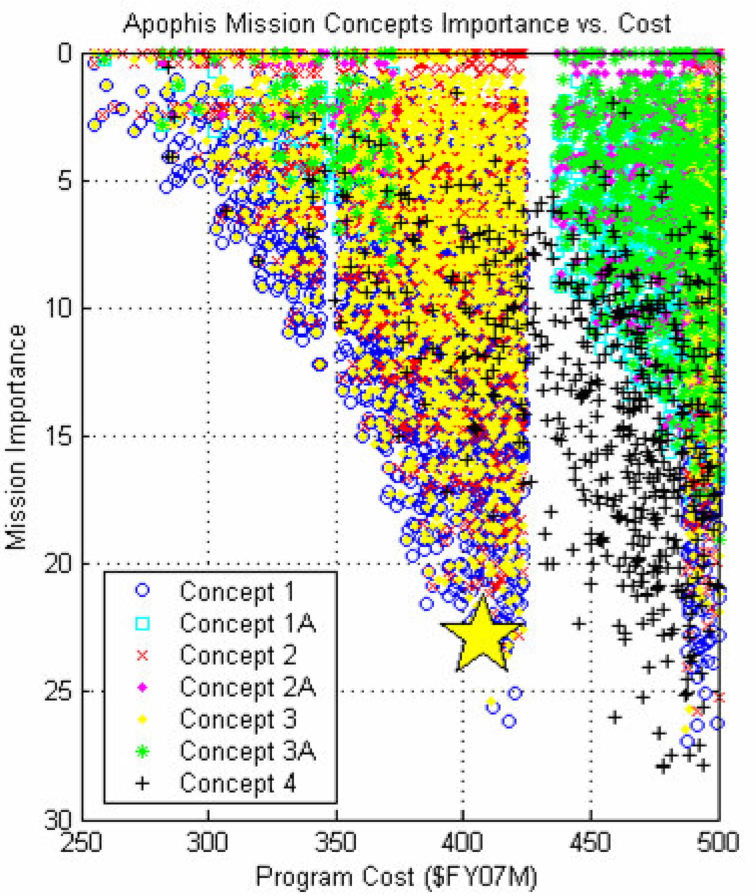


Figure 6. Resulting costs and importances of thousands of potential missions to Apophis. The final *Pharos* design selection lies at the yellow star on the Pareto front.

G. Final Candidate Architecture and Payload Selections

To continue to the final downselection of a point design, several points are selected for detailed examination from the Pareto front that was identified in the previous step. By examining each of these points, the design team is able to learn common characteristics of the most efficient designs. One of the lowest-cost solutions on the Pareto front, for example, uses only a spectrometer from the European Rosetta mission at a cost of just $250 million. Higher-cost solutions utilize multiple distributed sensors (modeled after the 1999 Mars Microprobes) plus a suite of instruments, which allows the team to realize that the advantage of designing for a larger payload not only allows more scientific return but also more scientific return per dollar. Furthermore, the team notices that most mid- and high-range Pareto-optimal solutions utilize one or more distributed sensors.

With this insight in mind, the team chooses four designs to evaluate in the final program-level prioritization matrix. The first is a two-phase orbiter/lander concept with an imager, laser rangefinder, magnetometer, mass spectrometer, and four distributed probes. The second is a variant of this concept which utilizes two orbiters, each carrying half the instruments listed above. While this second option is not on the original Pareto front, it is decided to examine it since it may have benefits of lower risk, a characteristic which is not captured on the importance-cost Pareto plot but which can be captured through the program-level AHP selection. The third candidate is similar to the $250 million concept mentioned earlier, an orbiter with only a single instrument. The fourth is a large lander like one of those seen in Fig. 6 as the black crosses in the $450M - $500M range with high (25-30) importances.

H. Final Downselection

As indicated by Fig. 1, final downselection is conducted by evaluating the four final candidate designs via an AHP based on the program-level prioritization matrix. The results of this evaluation are shown in Table 1. Note that compared to the baseline Pareto-optimal two-phase orbiter/lander design mentioned above, the two-vehicle solution scores higher but is not selected because of concerns that the budget would not allow (the baseline concept is already at $410 million). The minimal-instrumentation orbiter scores the lowest of all because of the heavy weighting that orbit determination and science have in the program-level priorities. The Pareto-optimal lander scores close to the baseline design, but it is also discarded due to cost concerns since it lay so close to the cost cap.

Table 1. Final scores of candidate designs justify the choice for the baseline Pareto-optimal two-phase orbiter/lander. Note that while the twin vehicle concept scored slightly higher, cost concerns kept it from further consideration.

Candidate Design	Final Score
Baseline Pareto-Optimal Two-Phase Orbiter/Lander	0.290
Twin Two-Phase Orbiter/Landers	0.317
Minimal-Instrumentation Pareto-Optimal Orbiter	0.114
Pareto-Optimal Lander	0.279

Thus, the final selection for *Pharos* is the baseline two-phase orbiter/lander described above. Note that due to the payload choices for the vehicle, this is nearly an orbiter solution since end-of-life landing on an asteroid can be accomplished with little or no dedicated landing gear. Perhaps the most powerful aspect of this analysis method is that it can show that this final design lies squarely on the Pareto front of the mission importance vs. cost objective space as shown by the yellow star in Fig. 6. The initial mass and cost estimate is 706 kg and $410 million (FY07 dollars), respectively. Notably, when compared to the final mass and cost estimates which result from later detailed sizing and costing analysis (721 kg and $430 million), this initial estimate is found to be 2-5% accurate.

V. Framework Applicability, Extensibility, and Limitations

As mentioned earlier, the framework presented here has been applied to a case of a robotic mission to the asteroid 99942 Apophis. It is considered quite generalizable to any robotic planetary exploration design or any design which can be characterized by multiple payload options and multiple architecture options. This framework is particularly useful if the payload and architecture options are independent of each other, although this does not need to be the case[†]. It is easy to see this method (and certainly many of the underlying principles) being extended to other mission types as well, such as human missions or unmanned Earth orbital missions.

[†] In fact, this was not the case for the example mission here. Unique I2O maps were created for each architecture, allowing, for example, lander instruments like scoops and drills to have zero importance on an orbiter mission.

One limit to this framework is its treatment of non-cost, program-level objectives such as risk. These objectives are indeed accounted for in the late stages of the downselection process, but ideally they would also form dimensions of the Pareto front. For example, if a third "risk" axis were added to Fig. 6, a Pareto surface would be formed. Of course, by extension, ideally all objectives would be shown as dimensions on the Pareto front, but this would easily become unwieldy and difficult to visualize. The framework presented in this paper has chosen to limit the Pareto front to a two-dimensional plot for this reason and for the reason that risk and other performance parameters are particularly difficult to quantify accurately at the very beginning of the design process.

Another limit to this framework is its treatment of instrument importances as linearly additive, which is not necessarily true. For example, a vehicle with two identical spectrometers is likely not twice as important as the same vehicle with only one spectrometer since the two instruments will return identical information. Additional redundancy might add some value, but it is likely not as high as a factor of two in importance. Thus, an improved method might incorporate a model of diminishing return. In the *Pharos* example, redundant instruments were excluded from consideration and this was not an issue except for deciding the limit to place upon the number of probes.

VI. Concluding Remarks

The downselection framework presented here is meant as an efficient method of evaluating a global space of potential vehicle designs for a given set of requirements. It allows thorough search of all identified options for a relatively quick (and intelligent) selection of a baseline point design. Elements of standard systems engineering tools are heavily relied upon, and key elements include objective prioritization matrices, instrument-to-objective maps, and the final identification of a Pareto front in the importance vs. cost objective space. Quantitative mass data is key to estimating costs, and qualitative evaluations of the relevance of instruments and the overall architecture to mission objectives are converted to numerical importance ratings.

It should be noted that while accurate mass and cost models are preferable for the implementation of this framework, they are not necessarily required. As long as the mass and cost models chosen for a particular problem are relatively correct and self-consistent, the points which show up on the Pareto front of importance vs. cost will be the same (i.e. model errors might only result in offsets or gains on the cost axis). Furthermore, even if a final design is chosen which is not originally evaluated quantitatively (for example, if a team member brainstorms an entirely new architecture not originally considered), this process is still valuable since any competing designs can be plotted as a point on the importance vs. cost space to show their degree of Pareto optimality (or suboptimality).

One final note on the advantage of this framework is that it effectively allows simultaneous selection of mission science and the architecture to fulfill it. This capability may be quite useful since these are normally highly coupled: Delving into detailed spacecraft design under the assumption of overambitious science requirements is likely to place a project over its budget. Similarly, designing a low-cost spacecraft well within the budget may easily result in a mission return not worth the time or investment. The compromise between these extremes is an iterative process which is often long and painstaking; use of the framework presented here may help mitigate this and foreseeably save both time and money in the design process.

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