TELEROBOTIC SPACE OPERATIONS

N90-29886

ESTABLISHING VIABLE TASK DOMAINS FOR TELEROBOT DEMONSTRATIONS

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Abstract

A suite of telerobotic tasks has been compiled and assessed for the purpose of selecting viable tasks for near and far term laboratory demonstrations. The primary intent of developing the task suite is to provide some technical guidelines, with supporting data, for focusing NASA laboratory demonstrations toward application domains that address a wide array of potential telerobot tasks and required technologies. This wide application would then result in a rich technology development environment to meet the broad task requirements of a system such as the Flight Telerobot Servicer (FTS).

This paper describes the methodology and results of the telerobot task assessment, including a ranking of the final select suite of major tasks. The study approach, database, and results of the task ranking computation are presented along with guidelines for both interpreting the task ranking results and setting programmatic objectives based on these results. The report also provides detailed data about the task candidates and their respective levels of complexity, task primitive actions, and the actual relative measures of task worth as associated with key tradeoff variables such as cost, available research resources, technology availability, and importance to the user community.

Introduction

The primary purpose of this task study was to compile a list of tasks that represented viable candidates for laboratory demonstrations, and satisfied two major constraints:

1. The tasks must clearly demonstrate application to a real-world user problem in the space environment, such as Space Station assembly or servicing.
2. Selection of the suite of tasks must reflect existing resource constraints within NASA telerobot research community.

In the process of structuring the task assessment and developing the suite of demonstration tasks, it became clear that the assessment contained additional information that could be useful to the telerobot research community:

1. The assessment, through its structure, provides a means of rationalizing the task selection process.
2. The assessment provides a traceable means for reasoning why one task tends to represent a better demonstration target than another.
3. The assessment, through its methodology and supporting task-related data (e.g., cost, technology contribution, resource availability, and user importance), provides a blueprint for mapping out near-term and long-range technology development and demonstration objectives as a function of varying task-complexity levels.

Approach

In order to develop the prioritized suite of tasks, we first wrote a straw-man report that included a preliminary list of tasks extracted from NASA documents, description of the multi-attribute decision-analysis method for ranking these tasks, tentative data (attribute weights and utility values) for computing the ranking, and preliminary task-ranking results. This report was distributed to several telerobot NASA Centers and contractors for review. We then visited the following NASA Centers and contractors:

NASA Goddard Space Flight Center
NASA Langley Research Center
General Electric RCA, Advanced Technology Laboratories
Massachusetts Institute of Technology (MIT), Aerospace Engineering Dept.
NASA Marshall Space Flight Center
NASA Johnson Space Center
Jet Propulsion Laboratory
NASA Ames Research Center

At each Center the straw-man report was presented, the findings were discussed and feedback was received from the Center's professional staff. The feedback from all of the Centers was used to adjust the results to reflect their respective resident experience.

One of the first steps in performing the task assessment was to compile a straw-man list of potential tasks. It was understood at the outset of this study that the deadline for completion of the assessment constrained the scope of the study. It was therefore decided to first develop broad potential categories of tasks, and then list tasks within each category. The major task categories, derived from existing NASA documents, were as follows:

1. Assembly - The process of physically connecting mechanical or electrical components.
2. Servicing - Various processes involving the removal and replacement, adjustment, refurbishment, or reconfiguration of spacecraft components.
3. Inspection - The process of using telerobotic sensing to determine the integrity of a spacecraft component.
4. Material Handling - The process of actively transporting and replacing supplies for performing assembly or servicing functions (e.g., pick-and-place supplies from the shuttle to an assembly site).
5. Manufacturing - The process of converting raw materials into finished products in the Space Station.

Tasks were selected drawing largely from documents describing the Robotic Assessment Test Sets (RATS)[1] and the Polar Platform Payload Servicing requirements [2]. We also examined Space-Station tasks and manifesting studies performed by the various work-package subcontractors [3,4,5]. One question that arose was the degree to which the suite of straw-man tasks comprehensively represented the total array of near-term tasks related to the Space Station. We examined two larger, more comprehensive task studies, the MIT ARAMIS and McDonnell Douglas THURIS studies [6,7], and compared them against our categories and the straw-man list. We found that, although they are more comprehensive in defining different tasks elements, both the ARAMIS and THURIS task listings could be represented as components of the straw-man suite of tasks we selected as demonstration candidates. Task comprehensiveness was also affected by inputs from the different NASA Centers we visited. During each session in which we discussed the straw-man task-ranking analysis with the respective Center's staff, we collected additional potential tasks. These tasks were then examined to determine whether they were different from the list already compiled, or whether they could be considered a subset of another task already on the list.

Table 1 lists 23 tasks considered unique from the standpoint of representing different size and scale of objects, different types of manipulation, and different kinds of technologies. Among the 23 tasks in Table 1, only the first 18 tasks were ranked because the details of the remaining ones were insufficient. Having selected this set of candidate tasks, the next step was to rank them in the order of their utility ("worth" or suitability) as domains for demonstration of telerobotic techniques. These techniques may be applicable to future NASA missions, in particular to those associated with the Space Station. A variety of factors were listed, called attributes, that have a direct effect on the task ranking. We then used the Multi-Attribute Decision Analysis (MADA)[8] method to rank the candidate tasks on the basis of the effect of each attribute on the suitability of each task as a domain for telerobotics R&D. MADA provides a decision structure with which to rank several task options based on an aggregate value of the net worth measured across several attributes. The following discussion defines the MADA technique and explains how it was applied to the task ranking.

Capabilities of Multi-Attribute Decision Analysis (MADA)

Task ranking based on a set of different attributes may pose some problems. The original guidelines under which the task assessment was initiated indicated that we had to compile a suite of tasks that was appealing to the user community and that could be developed and demonstrated in the laboratory within limited resources. These guidelines may lead to conflicting results, because tasks that possess attributes important to NASA's user community may require more laboratory and professional resources than the NASA Centers have. Further, some attributes, such as "Importance to User" or "Technological Contributions," are more easily measured qualitatively than quantitatively.

Multi-attribute decision analysis facilitates decision-making in the presence of conflicting attributes, measured either qualitatively or quantitatively. MADA is based on the premise that individuals knowledgeable in the area of interest (in this case, task demonstration designers) can express their preferences among different options if provided with an appropriate decision structure that enables them to make comparisons and quantify their responses.

The quantification of their responses is in the form of a so-called utility value - a metric that measures the net worth, or effectiveness, of a given option to the group of knowledgeable individuals. The quantification process draws on well-developed and tested methods of decision analysis [8,9,10].

Selection of Attributes

To be able to apply MADA to the task ranking, the following seven attributes were selected:

- Cost - The approximate design, development, test, and evaluation (DDT&E) cost of the hardware and software required to demonstrate a task.
- Technology Demonstration/Development Schedule - The time required to acquire and/or develop the technologies, hardware, and software required for a task, design and integrate the system, and demonstrate the task to a specified level of robustness.
- Importance to User - The degree to which a task can be applied to real world problems, meets the requirements of the user community, utilizes a domain the user community feels is important, and, if done successfully, enables completion of other similar tasks.
- Productivity/Safety Impact - The potential for a telerobotic task to increase the productivity of an astronaut and reduce his/her adverse risk. Aspects of productivity include reduction in EVA time and the amount of time an astronaut or ground crew is freed to do other tasks. Safety is primarily related to reduction in hazard exposure, whose two main factors are the hazard severity and exposure time.
- Center Resources - The degree to which the hardware and software and the technical personnel required by a task are available in any of the various NASA Centers.
- Technological Contributions - Contributions to advancing the state of the art of the technology elements required to perform a task.
- Possible Near-Term Demonstration Success - The estimated confidence that a laboratory demonstration of a given task will succeed.

TABLE 1: List of Candidate Telerobotic Tasks

ASSEMBLY TASKS

1. Truss Assembly
2. Utility Tray Deployment and Pop-Up Connector Utility Line Installation
3. Station Interface Adapter (SIA) to Truss Connection
4. Payload Interface Adapter (PIA) to Station Interface Adapter (SIA) Connection
5. Solar Dynamic Array (SDA) Radiator Assembly and Deployment

SERVICING TASKS

6. Solar Power Converter Orbital Replacement Unit (ORU) Changeout
7. High Resolution Solar Observatory (HRSO) Film Canister Changeout
8. Hubble Space Telescope (HST) Axial Instrument Changeout
9. Hubble Space Telescope (HST) Reaction Wheel Assembly (RWA) Changeout
10. Gamma Ray Observatory (GRO) Refueling
11. Earth Observatory System (EOS) Instrument/Orbital Replacement Unit (ORU) Changeout
12. Solar Maximum Mission (SMM) Main Electronics Box (MEB) Replacement
13. Earth Observatory System (EOS) Instrument Reconfiguration
14. Earth Observatory System (EOS) Instrument Recalibration/Adjustment
15. Extra Vehicular Activity (EVA) Retriever
16. Telerobotic Docking

INSPECTION TASKS

17. Electrical Connector Removal/Inspection
18. Clean/Inspect Surface (Solar Cell Cleaning)

TASKS CONSIDERED UNIQUE BUT NOT RANKED BECAUSE OF INSUFFICIENT INFORMATION

19. Position/Push RCS Thruster
20. Alpha Joint Position/Installation
21. Antenna Position/Installation
22. Repair Manipulator Arm on Platform
23. Specific Failure Recovery Schemes

The importance of each of the above seven attributes relative to each other depends on the main drivers behind the development of telerobotic techniques and task demonstrations. We represent the relative importance of each attribute by an attribute weighting factor, called attribute weight, whose value varies between 0 and 1. During our visits to the various Centers we were urged to consider two different sets of attributes, user attributes and research attributes. As a result, we established the two attribute lists shown in Table 2.

TABLE 2: Attributes Important to User and Research Communities

User Attributes	Research Attributes
a. Cost	a. Cost
b. Technology/Demo Development Schedule	b. Technology Demo Development Schedule
c. Importance to User	c. Importance to User
d. Productivity/Safety Impact	d. Center Resources
	e. Technological Contribution
	f. Possible Near-Term Demo Success

Our visits made clear the need for a new attribute called "Demo Fidelity" or "Demo Realism." Changes in dynamics due to scale, inertial characteristics, lighting, or weightlessness definitely alter the usefulness of the results. This attribute was incorporated into the attribute "Importance to User." Therefore, the more closely a laboratory demonstration approaches the real on-orbit task, the higher its utility to the user.

The agreed-upon approach for handling the two sets of attributes was realized by applying different weights to the attributes, depending on whether the task ranking was being done for the user community or the research community. Those tasks that ranked equally high for both communities would then make up the desired task suite. The other major distinguishing factor for segregating the desired task suite from the rest of the tasks was whether the tasks that had high ranking in the research community had application to the high-ranking (but different) tasks in the user community. This would mean that, indeed, the final suite of tasks had importance to the user community as a whole.

Utility Values

Using MADA, once the attributes and their relative importance weights are established, the next step is to develop measures by which to determine the utility (the net worth) of a given candidate task in relation to each attribute. The measure of worth of a given task candidate is the utility value of that particular task. For example, the cost attribute, measured in 1988 dollars, reflects the rough cost of constructing the required hardware/software testbed in the laboratory to perform a given task. Tasks that could be done within the budget constraint have high utility values for that attribute; conversely, tasks that exceeded the budget constraint have low utility values. Similarly, different utility values correspond to each task for each of the other attributes. The measures used to estimate each of these utility values are described in Reference [11]. It is important to recognize that derivation of actual utility measures, using empirical data, provides the most accurate ranking outcome. The data presented in Reference [11] reflects an attempt to use as much empirical data as possible.

Classically, MADA requires that utility values range between 0 and 1. To facilitate the assignment of utility values, we classified the utility of each attribute relative to any task into three levels: Low utility (0.0 to 0.3), medium utility (0.3 to 0.6), and high utility (0.6 to 1.0). These ranges are shown in Table 3.

TABLE 3: Utility Value Ranges

Attributes	Low Utility (0.0-0.3)	Medium Utility (0.3-0.6)	High Utility (0.6-1.0)
Cost	High Cost	Medium Cost	Low Cost
Technology/Demo Development Sch.	Far Term	Medium Term	Near Term
Importance to User	Low	Medium	High
Productivity/Safety Impact	Low	Medium	High
Center Resources	Absent	In Process	Existing
Technological Contributions	Low	Medium	High
Possible Near-Term Demo Success	Low	Medium	High

Detailed utility values were calculated by using the measures defined above. Applying the ranges indicated in Table 3 allowed Center participants to understand what was meant by a task having low, medium, or high utility value. During the Center visits, we received feedback regarding the attribute weights, the utility values, and the ranking results.

Utility Functions

Following the assignment of the attribute weights and the utility values, the final step in the MADA process uses these numbers to calculate the value of an overall task utility of each task candidate. Once the calculations are completed, the candidate tasks can be ranked in the order of highest to lowest overall task utility.

The overall task utility is computed by means of a utility function - a function of the attribute weights and the utility values. There are two forms of the MADA utility function: the additive form and the multiplicative form.

Although the additive form, or weighted sum, is more intuitive in its design, it is restricted to being applied only when the various attributes (as measured by the utility values) are independent of one another, i.e., the utility value obtained for one attribute should not change if the utility values of other attributes are adjusted. This condition can be difficult to meet because attribute utility independence is rare in the real world. However, if the attribute weights are not normalized and the above condition is not met, then use of the additive form can result in an incorrect ranking.

The attribute utility independence condition discussed above is the major complication in using the additive form. To resolve the potential problem of ranking errors, the multiplicative form of MADA was developed. The multiplicative form, although more complex than the additive form, is more rigorous because it does not require utility independence (i.e., changes in the utility values for one attribute can be traded off pairwise against the utility value of another attribute). Reference [8] provides a detailed derivation of the multiplicative form of the utility function, which is as follows:

$$U(x) = \frac{1}{K} \{\Pi_{i=1}^{n} [1 + Kk_i u_i(x)] - 1\} , \qquad (1)$$

where $U(x)$, k_i, n, and $u_i(x)$ are defined above and K is a master scaling constant, which is inserted into the function to ensure that $U(x)$ falls between 0 and 1, as required by the definition of a utility value. The value of K is derived by setting $U(x) = u(x) = 1$ in the above equation and numerically solving the following nth order polynomial for K:

$$1 + K = \Pi_{i=1}^{n} (1 + Kk_i) . \qquad (2)$$

Among the different real values of K, the single value satisfying $-1<K<0$ should be chosen [8]. Once K is calculated, $U(x)$ can be determined discretely for each task option through the multiplicative combination of all the attribute utility values for a given task.

Task Complexity

The scope of this study precluded the generation of detailed specifications for each task. A wide disparity was found in the levels of detail to which the tasks were described in the literature. In addition, different levels of telerobotic technology advancement were required by different tasks. For these reasons, we introduced the notion of task-complexity levels.

We analyzed each task from the point of view of demonstrating, in the laboratory, the technologies necessary to perform that task. Rather than selecting a single task demonstration scenario, we postulated several scenarios, at increasing levels of complexity, for each task: Level A was the most complex, Level B the second most complex, Level C the third most complex, and Level D the least complex. For each task, we specified scenarios for these three or four complexity levels. We set the levels so that there would be a high confidence of success if task scenarios of low complexity level (Level C or D) were to be demonstrated today, while those of the highest complexity level (Level A) would have a low confidence of success (the Level A demonstration represents the task as it would be performed in the real application environment). See Reference [11] for specific examples of different levels of task complexity.

We considered only task complexity and made no assumptions about how a given task-complexity level should be implemented (i.e., by teleoperation or automatically). Additionally, we made no attempt to correlate the complexity levels across different tasks; for example, Level C of one task could be more complex than Level B of another.

Task breakdowns and task rankings performed in this study were done assuming Level-A complexity for all tasks. The task complexity levels are useful because they provide (1) a progression of increasingly complex demonstrations as a means for measuring R&D progress toward the ultimate (Level A) objective, and (2) a fallback implementation; if a given complexity level cannot be achieved within budget and schedule constraints, a lower level may be attainable. Each set of task levels, therefore, provides only a progressive set of objectives.

Task Breakdowns

Some of the attributes used in the task ranking depend on the technology required to perform a given task [12,13]. Progressive, hierarchical task breakdowns to the task-primitive level are intended to provide the means for identifying the underlying task technologies. The low-level breakdowns can be viewed as generating pseudo-code subroutines for performing tasks. It is at the primitive level of the task breakdowns that the required technologies become apparent. Several studies have drawn upon task-breakdown analysis for deriving the required technology elements [12,13,14,15,16].

Task breakdowns are used only to define the required task technologies; they are not intended to specify the approach for implementing a task demonstration, although they may serve as a good starting point. The breakdowns have been done from a telerobotic perspective because the demonstrations are intended to be performed by a telerobotic system. Care has been taken to ensure that the telerobotic actions are generic enough to be accomplished autonomously, by teleoperation, or by a mixture of both. For instance, a common function is to determine the location of a part. This function could be performed automatically by a vision system; it could also be performed in a mixed mode by having the system display a processed image of the scene, which helps the teleoperator determine the part's location.

Ideally, a task breakdown would be performed for each of the tasks considered (see Table 1). However, to make the most of the limited time of this study, we decided to break down only three tasks, one from each of the three task categories (assembly, servicing, and inspection). We assume that tasks within a given category will require similar technologies so that it should be possible to find a representative task. The following tasks were selected for breakdown:

- Assembly: Truss Assembly
- Servicing: Solar Maximum Mission MEB Changeout
- Inspection: Solar-Cell Cleaning/Inspection

A typical breakdown of one of these tasks is given in Reference [11].

Results

The multiplicative-form ranking method described earlier was applied to rank the first 18 tasks listed in Table 1 on the basis of the initial (straw-man) attribute weights and utility values. These initial weights and values were later modified based on inputs from NASA Center participants, and the ranking was subsequently recalculated.

Attribute Weights and Utility Values

In our discussions with the NASA Centers it became clear that the research community views the relative importance of the attributes differently than the user community (see Table 2). For this reason we performed the task ranking for two sets of attribute weights, one representing the research community, and the other representing the user community. Table 4 presents the attribute weights for the two cases. Feedback from the Centers also indicated that some attributes are not significant in ranking the tasks for one community or the other; in this case, these attributes are not used in the ranking and do not have a weight (see Table 4).

TABLE 4: Attribute Weights (k_i)

Attributes	User Community	Research Community
Cost	0.5	0.9
Technology/Demo Development Schedule	0.75	0.7
Importance to User	0.95	0.6
Productivity/Safety Impact	0.95	–
Center Resources	–	0.7
Technological Contributions	–	0.95
Possible Near-Term Demo Success	–	0.7

The utility values for each task, assuming Level-A complexity, are listed in Table 5.

TABLE 5: Task Utility Values $u_i(x)$

	Attributes								
	Cost		Tech./Demo Development Schedule	Importance to User	Productivity/Safety Impact	Center Resources	Technological Contribution	Possible Near-Term Demo Success	
Tasks	Tel.	Aut.						Tel.	Aut.
Truss Assembly	0.9	0.5	0.5	0.8	1.0	0.8	0.8	0.7	0.4
Utility Tray Deployment ...	1.0	0.9	0.7	0.7	0.4	0.6	0.4	0.7	0.7
SIA to Truss Connection	0.8	0.0	0.4	0.8	0.3	0.2	0.6	0.4	0.1
PIA to SIA Connection	1.0	1.0	0.9	0.4	0.2	0.9	0.3	0.9	0.8
SDA Radiator Assembly & Deployment	0.8	0.0	0.1	0.7	0.4	0.2	0.8	0.3	0.1
Solar Power Converter ORU Changeout	1.0	1.0	0.9	0.4	0.2	1.0	0.2	1.0	0.9
HRSO Film Canister Changeout	1.0	0.8	0.4	0.7	0.4	0.5	0.6	0.5	0.3
HST Axial Instrument Changeout	0.9	0.6	0.4	0.8	0.5	0.3	0.8	0.5	0.1
HST RWA Changeout	1.0	0.8	0.4	0.6	0.2	0.5	0.5	0.5	0.3
GRO Refueling	0.9	0.6	0.4	0.7	0.9	0.6	0.7	0.7	0.2
EOS Instrument/ORU Changeout	0.9	0.9	0.8	0.7	0.6	0.8	0.5	0.9	0.7
SMM MEB Replacement	1.0	0.4	0.6	0.9	0.4	0.7	0.9	0.7	0.2
EOS Instrument Reconfiguration	0.8	0.3	0.3	0.7	0.6	0.4	0.8	0.3	0.1
EOS Instrument Recalibration/Adjustment	1.0	0.8	0.5	0.6	0.6	0.7	0.4	0.8	0.7
EVA Retriever	0.8	0.0	0.6	0.8	0.9	0.7	1.0	0.7	0.0
Telerobotic Docking	0.6	0.0	0.3	0.7	0.7	0.6	0.7	0.7	0.0
Electrical Connector Removal/Inspection	1.0	0.6	0.2	0.7	0.5	0.5	0.8	0.4	0.1
Clean/Inspect Surface (Solar-Cell Cleaning)	0.9	0.4	0.1	0.7	0.6	0.3	0.8	0.6	0.1

Top Ranked Task Candidates

One of our primary objectives was to compile a suite of tasks that both researchers and users would find useful. We noted that five tasks appeared among the top eight tasks in the rankings, regardless of whether the ranking was performed for the user or research community, and regardless of whether the task was to be mostly automated or mostly teleoperated. All of these tasks were basically equal and are discussed briefly as follows:

- The EVA Retriever task has an extremely high technical contribution rating because it requires the combination of challenging levels of most technologies, including manipulation, mobility, sensing and perception, reasoning, and communication. This task also has a high rating for the attribute "Productivity and Safety."
- The SMM MEB Replacement task also requires multiple technologies, and has a high "Importance to User" rating because the actions required to perform the task are highly generalizable to other tasks.
- The Truss Assembly task currently would require the highest amount of astronaut EVA time, so it has the highest "Productivity and Safety" rating; in addition, it requires significant perception, reasoning, and manipulation technologies, yielding a high "Technical Contribution" score; and since some centers are already working on this task, the "Center Resources" rating is high.
- The EOS Instrument/ORU Changeout task is relatively inexpensive, requiring only a medium-size mock-up and a single arm; it has a high "Importance to User" rating because there are about 50 different kinds of instruments on the EOS; in addition, it receives a high "Center Resources" score.
- The HST Axial Instrument Changeout task is included because of its important technological contributions to the handling of large and massive objects and the use of flexible arms.

The subsequent technologies required to implement the tasks are shown in Reference [11]. Note that two utility values associated with the attributes "Cost" and "Possible Near-Term Demo Success" are given for each task, one (marked by "Tel") assuming that the task will be controlled mostly by teleoperation and the other (marked by "Aut") assuming that the task will be mostly automated. The rationale for the selection of the utility values in Table 5 is also given in Reference [11].

Decision Framework for Determining Task Objectives

The results of the task ranking can help develop a program plan for both the near-term and far-term research and demonstration objectives. While carrying the task breakdown analysis down to the task-primitive action level, we became aware that the selection of tasks is highly dependent on technology availability. It became clear that the task demonstration selected by a research Center should support that Center's technology research goals. Taken one step further, selecting technology research goals within an application environment implies meeting cost, resource, and schedule constraints. Therefore, the decisions about what to pursue in terms of a task demonstration objective require an iterative process of selecting a task, comparing it with given technology objectives, and verifying that the schedule and resources limits are not exceeded. The decision framework shown in Figure 1 illustrates the process of using the task-ranking results, task complexity, and supporting task-utility data to formulate program plan objectives. The JPL $3M limit was used as the budget ceiling for example purposes. The 1-2 year demonstration cycle is the present preferred time-frame for exhibiting technologies because it is essential to show "progress" as a means of substantiating the associated yearly funding support.

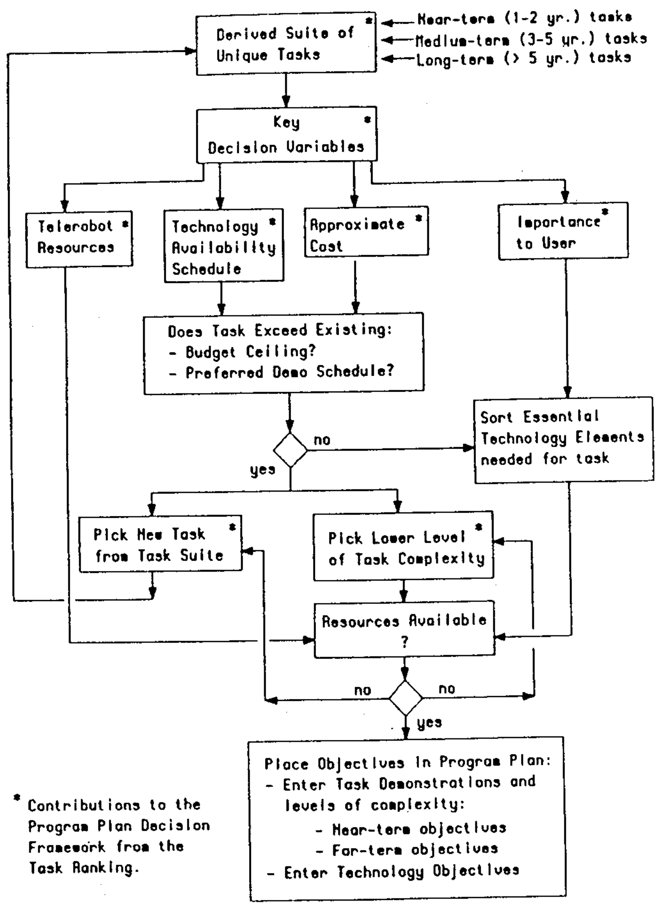

Figure 1: Decision Framework for Establishing Objectives

The decision framework starts with the suite of tasks composed of the highest ranked tasks. The key tradeoff variables are available resources, technology availability and schedule, cost, and importance to user. A task objective is selected from the suite of tasks and evaluated initially as a function of the cost ceiling and as to whether the technology and task domain can be successfully demonstrated in the near term. The next step is to pick the key technology elements essential to the user community and determine whether the existing testbed and workforce resources can complete and demonstrate the technology and the task. If the cost ceiling and schedule constraints are exceeded, then either a new task that is lower on the ranking list or a lower level complexity of the same task is examined. The process is repeated until task objectives that reasonably meet the programmatic constraints have been established. This process can be applied to setting both near-term and far-term task objectives.

Conclusions

Based on the preceding analysis, it would seem feasible to give priority to the development and demonstration of the five tasks listed in Table 6, each at the complexity level outlined in that table.

TABLE 6: Recommended Tasks and Their Complexity Levels

Task	Complexity Level
EVA Retriever	Level C
SMM MEB Replacement	Level C-B
Truss Assembly	Level C-B
EOS Instrument/ORU Changeout	Level A
HST Axial Instrument Changeout	Level C

- EVA Retriever: Obstacles, moving targets, natural lighting, and testing the system in a 3-D environment require a significant amount of software and hardware development, which is probably an unrealistic goal for a two-year time frame. Hence, we recommend a demonstration task at Level C complexity.
- SMM MEB: Portions of Levels B and C have been demonstrated for this task. However, manipulation of flexible materials, such as thermal blankets and cables, will require significant development time. For this reason a Level C-B demonstration is a reasonable goal in the near term.
- Truss Assembly: This task has been demonstrated at Level D in the laboratory, both under teleoperation and automatically. A similar truss assembly task has been demonstrated at Level B purely teleoperation control. We therefore recommend a Level C-B demonstration in the laboratory with the emphasis on automatic operation.
- EOS Instrument/ORU Changeout: This task has been demonstrated in the laboratory at a Level B complexity. Several Centers have mock-ups of EOS or EOS-type ORUs. Thus, there is little impact on cost and schedule from having to develop mock-up equipment. For these reasons we recommend a Level A demonstration in the near term.
- HST Axial Instrument Changeout: A Level C complexity is recommended for the following reasons: Significant time and money are required to develop the mock-ups needed for a full-scale demonstration. In addition, we anticipate that a significant amount of R&D is needed to handle the large payloads entailed in this task in constrained areas by means of large flexible arms.

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