Economics of Automation in Space: Implications of Automated Versus Manned Operations on the High Cost of On-Orbit Assembly, Control and Servicing of Spacecraft

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Introduction

The continued high cost and risk of placing astronauts in space has placed considerable burden on NASA to cut costs and consider other means of achieving mission goals both effectively and safely, Additionally, future science missions which might place a tremendous burden on Shuttle availability, or require extended vehicle duty cycles on the Lunar surface and Mars surface, might preclude the presence of astronauts altogether. The solution to this dilemma involves recognizing the essential mission and cost parameters which must be controlled, and that determining which functions to leave to astronauts and which functions to automate is actually a complex resource allocation problem. A four tiered mathematical model has been designed, built, and tested on Space Station subsystems to assist the decision process associated with making human-machine tradeoffs. The model is composed of 1) a task decomposition step (involving both task time and safety elements as part of selecting the likely automation candidates), 2) development of conceptual designs and costs for the candidates, 3) cost and benefits assessment, and 4) optimization of automation candidates relative to a set of constraints. Although simple in concept, the actual process must consider many non-quantitative variables which must be merged with the quantitative factors in formulating the solution to the competing objectives and resources problem. Analytical advancements in the area of assessing human-machine tradeoffs are discussed in this chapter. Recent conclusions addressing likely near-term targets for robotics and automated systems on Space Station, based on human-machine tradeoff studies, are also described.

Background

Classical system resource allocation problems have employed time and motion studies, Project Evaluation and Review Techniques (PERT), linear regression analysis, and dynamic programming (Refs 1,2). These techniques are effective under two conditions: 1) the resource variables are well defined and an empirical database exists to quantify the variables, and 2) the relationships between variables are approximately linear. But these techniques have limitations because not all resource allocation problems have well defined variables, or can be uniquely configured with clean linear relationships between variables. These limitations became particularly apparent when JPL began developing new analytical techniques for making human-machine tradeoffs while injecting new, advanced automation technology into application designs.

The Jet Propulsion Laboratory (JPL), California Institute of Technology, has historically been one of the lead NASA centers for unmanned missions. Deep space probes such as Voyager, and more recently, Magellan and Galileo, are semi-autonomous vehicles. As such, JPL has been one of the leaders in autonomous system design and control for some time. In the nineteen seventies, JPL was involved in transferring expertise and technology for automated systems to the private sector through the Energy and Technology Applications Program. The first exposure to having to explore new ways of managing limitations of techniques such as mentioned above, came through an Advanced Underground Automated Mining project sponsored by the Department of Energy, Bureau of Mines in the late nineteen seventies. Although, on the surface, the insertion of automation into the mining process appeared to be a classical production optimization problem, upon further study it turned out to be a complex "interplay" of several factors. A means of assessing production impact considering limited workforce and dollar resources, variations in coal properties, mining techniques, and machine operator ability had to be developed. Not only production, but health, safety, system complexity, reliability, and technology variables had to be assessed in the final selection of the "best" human-machine combination. Although the coal mining industry had an extensive historical productivity and task work hour database, except for picking out obvious production stumbling blocks, the database was useless because the automated system performance required the model to "project" time, productivity, safety, and' cost impacts. Last, new technology was needed to replace old technology, and a new machine configuration needed to be conceptually generated to facilitate cost and benefit projections. Given all of the above analytical factors, it was clear that a new technique needed to be developed to combine the various quantitative and qualitative variables, and provide a solid means for choosing human-machine options. It was also clear that in this new realm of competing objectives and resource allocation, the idea of the "optimal solution" had to yield to a "best" or "reasonable" solution,

The problem was ultimately solved by building a model consisting of 1) a task network analysis (PERT) to drive out the major production barriers, 2) an interactive industry survey of potential quantitative impacts of automation on the major production stumbling blocks, 3) a technology assessment and conceptual design of the primary automation candidates, and 4) a cost and benefits analysis which included health and safety impacts analysis. The final results, which identified the highest payback design option, were presented as a multi-variable envelope consisting of cost, production impact, projected reduction in average yearly injuries, and reduction in exposure to coal dust. The modeling tool was eventually employed by the Utah Power and Light Company to automate one of their high-seam longwall mining operations (Ref 3).

The experience gained from the above initial modeling effort set the stage for the improved version(s) developed for Space Station. The newer versions of the human-machine tradeoff model, and associated supporting analytical processes, are discussed in the following sections.

The Problem of Limited On-Orbit Resources

One of the recurring problems which the NASA manned spacecraft community must constantly address is the availability of crew workhours. The Shuttle Mission Operations Directorate (MOD) at NASA JSC spends months meticulously planning each crew member's daily and hourly schedule. Typically, after subtracting out housekeeping activities, equipment monitoring, and anomaly/failure troubleshooting, an average on-orbit day only has three to five hours of productive time available for payload tending and science (Ref 4). It is clear, based on the Shuttle workload history, that crew availability is one of the most important resources to be managed. The recent Shuttle mission calling for retrieval and repair of the INTELSAT communication satellite (STS-49, May 14, 1992) is a good example of the importance of crew availability for contingency. What was originally planned for a two EVA crew and one IVA crew member, eventually required a three EVA crew and one IVA crew member after two unsuccessful tries to retrieve the satellite.

Similarly, current workload studies suggest the Space Station crew is going to be under equal pressure to maintain an extremely aggressive day-to-day work schedule with little time available for contingency (Refs 5, 6). Most importantly, the combined crew workload relative to EVA and IVA (Intravehicular Activities) tasks must not jeopardize astronaut, and overall system, safety. Concurrently, every effort must be exerted to meet mission objectives. This operational dilemma has historically placed significant strain on manned spacecraft systems. Whereas at one time astronauts felt strongly about exercising complete control over all spacecraft functions, the newer breed of astronaut (particularly mission specialists) recognizes the potential workload-mission conflict and welcomes assistance through robotic and automated systems (Ref 6).

Determination of Major Resource Variables

The key resource variables which consistently need to be balanced to solve the allocation puzzle, were determined by talking directly to the MOD at the Johnson Space Center (JSC) responsible for making crew/ system allocation decisions (Ref 7). The primary variables include, 1) system cost (initial investment and life cycle), 2) weight impact, 3) power consumption, 4) crew work hour impact, 5) reliability (impact on system mean time between failures), and 6) safety (reduction in hazard exposure hours). The secondary variables are associated with minimizing the technology developmental risk (i.e., making sure the necessary technology is developed at a timely rate which allows it be incorporated into the overall system by launch). These variables include 1) technology availability (both immediate and far-term), 2) retrofit amenability, and 3) technology importance to mission(s) completion. These last three variables do not normally have quantitative cost values, but they have major cost and schedule implications and are primarily used as “branching” or “bounding” decision factors in making human-machine design tradeoffs.

A branching or bounding decision factor means that the variable is used as a limiting or cutoff point. For example, a particular telerobotic design option might appear functionally sound, but might require technology which will not be available for several years past the intended launch date. Given a hard launch constraint, the only recourse is to branch to another design option. In this example, technology availability is used as a decision point to further limit the subsets of viable technology/design options.

Summary of Analytical Approaches

Several different types of modeling approaches have been used to develop a solid design tradeoff foundation for the manned spacecraft problem. Some of the approaches are based on well established operations research techniques; and, others are extensions or refinements of more recent decision making structures. It is not the purpose of this section to revisit and derive the host of analytical equations and examples leading up to the final human-machine tradeoff model. This information can be found in the several references cited in this chapter. Rather, this section provides the reader with insight into how the space station community is using techniques like this to select reasonable solutions to an extremely complex tradeoff problem; and, what those solutions are. Subsequently, a summary of the analytical techniques is provided here along with supporting references for the interested reader.

A. Guidelines for Automation

As a preface to the discussion of analytical approaches, it is important to recognize the basic human factors principles which provide a high level filter for the initial selection of task candidates which represent good targets for automation, This high level filter feeds the first step in the analytical process - the task network analysis. Accepted human engineering standards suggest that the following criteria be used for determining which functions to automate in complex manned systems. Designers should automate, in prioritized order, tasks which (Ref 8):

1. Endanger crew safety,
2. Cause perceptual saturation,
3. Must be completed on compressed timelines,
4. Exceed operator bandwidth limitations,
5. Are complex, or require quickened response,
6. Represent complex mathematical/logic problems,

7. Are time consuming, repetitive, sequential, require extensive memorization, or boring.

Criterion (1) is obvious since tasks which directly expose astronauts to hazards should be automated. The reader should note that their is an implied "acceptable" level of risk associated with this item. Clearly, sending astronauts into space is hazardous by itself. But given that NASA accepts this risk, then the implication here is that once on-orbit, we should look for ways to reduce exposure to hazards which both affect astronaut safety and mission safety.

Criteria (2)-(6) are all equally weighted in that they all address the problem of "errors." Errors caused by having to process considerable information and react quickly can not only result in component failures, but can have safety impacts as well. The last criterion is related to the above five in that the long term effects of tedious tasks can result in operational errors.

When the above criteria were applied to the Space Station system design and projected operations, the following functions became obvious robotic or automated system candidates (Ref 9):

1. EVA (assembly and long-term servicing of the station/payloads)
2. Subsystem monitoring
3. Subsystem state verification/calibration
4. Mission/operations planning
5. Subsystem state assessment/change

The candidate of greatest concern to NASA right now is, based on current EVA/IVA workload studies (see "problem of limited resources" above), the EVA function. Recent decisions on how NASA will proceed with the phased solution to this problem will be discussed after the summary of the supporting analytical techniques.

B. solution Structure

As stated earlier in the Introduction, the model developed for the Space " Station assessment was a four-tiered system which enabled a logical analysis, filtering, and grouping of data into the final cost-benefit and design tradeoff algorithms. That logical structure starts with a detailed task network analysis. This analysis identifies the obvious high workload, and potentially hazardous, task elements. The resulting "functional" and "time" (task and hazard exposure) data are stored for use in the conceptual design, cost-benefit, and tradeoff modules. The next component of the problem structure is the determination of how the functional candidate will be automated. This requires both a design and technology assessment. cost estimates are developed for the conceptual design using a "bottom-Up" component-by-component (hardware and software) approach. This step provides a solution to the "cost" side of the problem. The benefits side considers the task time, safety, and "other" potential benefits (e.g., reduction in number of launches) obtained by reducing the human involvement. Using constraints, or bounds, on the key resource variables (see above), the various robotic or automation design options are interactively assessed until the safest, lowest cost option(s) surface.

The above discussions and sections provided a foundation for the reader to understand the primary tradeoff, or resource variables, the near-term automation candidates, and the solution structure. The next section provides a summary of the various solution techniques developed around the above foundation,

C Analytical Techniques

1. Task Network Analysis

The first component, task network analysis, is used uniformly in all of the analytical models which have evolved. The network analysis is a standard PERT type approach, exactly the same as presented in classical operations research textbooks. The two major departures from classical PERT analysis are derived from the recognition that human resources in space cannot be looked at the same way as in the private sector. The idea that "time is money" is not exactly correct. Although an approximate value of a "workhour in space" can be determined based on the cost of putting a human on-orbit, what is most important is how time is put to good use for science (the concept of quality-time). Therefore, the workhour time variable is analyzed by superimposing either EVA/IVA limits (based on overall schedule demands and life support constraints), and exposure time limits to hazards (based on pre-determined historical constraints (e.g., radiation, EVA life support system constraints)). When the schedule and hazard constraint template is placed over the projected task timelines, the high task time drivers exceeding the constraint template then represent the primary targets for telerobotic or automation augmentation (Refs 7, 10).

The second departure was more a matter of "foundation" than "process." It was recognized early in modeling stages that the task analysis was tedious and obviously could not draw on earth based industry experience. The PERT steps of the analysis, the process component, was straightforward. However, a detailed list of historical tasks in space had to be compiled to enable task sequence construction. This process was initiated by studies such as the Automation, Robotics, and Machine Intelligence Systems effort (Ref 11), and the McDonnell Douglas The Human Role in Space activity (Ref 12). Drawing on these data, the bank of Shuttle task data, and more recent contractor projections for work-load on Space Station, JPL developed a relational database which allows one to assemble any desired task sequence based on historical and projected task/time data using the Telerobot Joint Analysis System (Ref 13, 14). This tool supports the tasking analysis front-end to the human-machine tradeoff process,

2. Technology Assessment and Conceptual Design Generation

The technology assessment and conceptual design element of the human-machine tradeoff process has also been used uniformly throughout the evolution of the modeling effort. Similar to the earlier automated mining problem, the spacecraft problem requires the analyst to develop concepts which augment, or replace, the historical human function highlighted by the above task constraint template. This was done by pooling the results of NASA, national laboratory, industry, and university projections on technology needs/availability. The assembly of a conceptual design followed standard automated system design practice (see Fig. 1), namely (Ref 7, lo):

1) The telerobotic or automated system must have, at the lowest level, sensors to provide intelligence to the control system,
2) The system must have low level dedicated processors which provide reflex/safing control (e.g., shutting off fuel flow in the event of a leak),
3) Subsystem level processors must be present to manage incoming/outgoing command and status information and provide limited diagnostics/fault management for functions requiring rapid response,

4) System level processors must be included to provide an interface to the operator or fault manager, and contain sufficient memory and on-line analytical tools to enable supervision of control operations and full fault recovery.

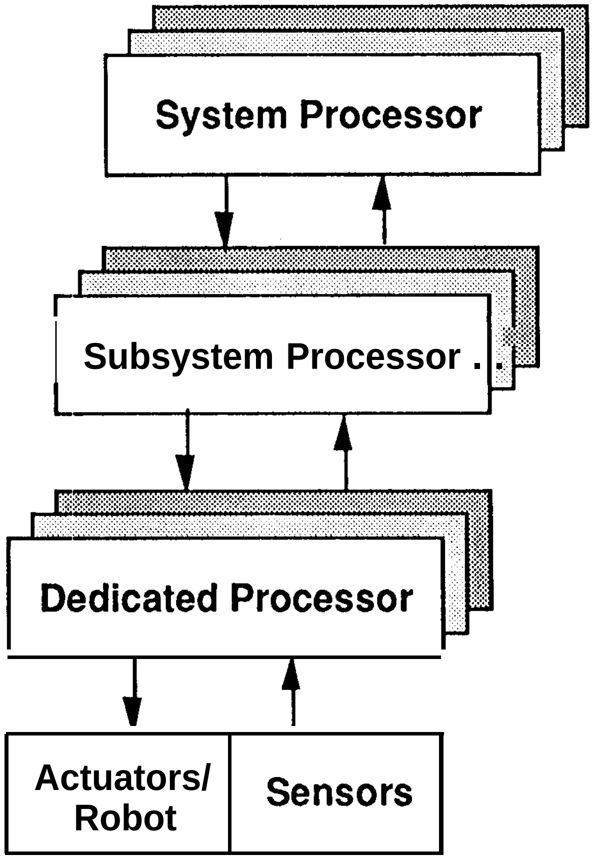

Figure 1. Standard Automated System Design

The network communication and actuator components exist whether the system is manually controlled or semi-autonomously controlled and, therefore, are not included as part of the system design. The two most important uses of the technology and conceptual design outputs are, 1) the technology assessment provides another screening variable relative to whether or not a needed piece of technology will be available on time, and 2) the conceptual design element feeds the cost-benefit assessment.

3. Cost and Benefit Projections

Two primary cost-benefit approaches were developed as part of the human-machine tradeoff process, namely: 1) incremental cost reduction, and 2) net cost savings (Ref 7, 10). Both of these approaches are summarized here. The "costing" approach for both techniques is provided first, followed by a separate section on "assessing tradeoffs" utilizing both techniques.

a. <u>Incremental Cost Reduction</u>

The incremental cost reduction technique provides a means of successively paring down automation options to eliminate the "low performers" before finally attempting to separate out the best set of automation candidates, Additionally, the approach utilizes a variable which measures the fractional increase/decrease in a particular cost variable as a result of automating a particular function(s). The process starts by taking the results of the task and conceptual design analyses and establishes an "efficient frontier" of viable options. Only the major variables of cost and productivity are used at this time. The cost of each telerobotic or automation design option is estimated using a "bottom-up" approach. The design is broken down into its hardware and software components (i.e., at the level of sensors, servos, actuators, processors, software module) and, using state-of-the-art industry historical costs, summed to obtain a implementation/delivery cost estimate. Spares are included and software is estimated using current versions of the COCOMO software costing model (Ref 15). If a component is not commercially available, current development costs and technology availability projections are used to project "time-of-availability" costs. The new technology cost projection can be computed by combining a historical percentage breakdown on first flight unit cost, as a function of total flight development cost.

The efficient frontier is established by plotting each candidate's relative projected impact on productivity as a function of relative cost. The candidates exhibiting the best productivity impact with the least cost are the winners. Equation (1) provides the mathematical representation of the decision process.

$$\underset{x}{Max} \sum_{i-1}^{n} P_i x_i \text{ , subject to} \qquad \text{(eq. 1)}$$

$$\sum_{i=1}^{n} c_i(x)x_i \le c \qquad \text{(eq.1.a)}$$

Where, P_i = incremental crew hours saved if function i is automated

x_i = automation decision variable; equal to 1 if automated, O if not

$c_i(x)$ = net incremental cost for automating function i

c = cost of most expensive man-machine alternative

The next step in the paring-down process is to take the above subset of viable candidates and determine the projected life cycle cost impact of inserting the technology into each respective subsystem. The mathematical representation of this next step is shown in equation (2).

$$\sum_{i=1}^{n}\left(C_{LC_i} - C_{LCB_i}\right)_{Pv} = \sum_{i=1}^{nn}\left[\sum_{jj=1}^{m}\left(1 \pm b_{LCVE_j}\right)C_{LCVE_{ji}}\right]_{i_{pv}} \qquad \text{(eq. 2)}$$

where,

C_{LC_i} = Life cycle cost of subsystem i

C_{LCB_i} = Life cycle cost benefit of automating subsystem *i*

b_{LCVE_j} = Fractional change in life cycle variable element *j* resulting from automation

C_{LCVE_j} = Life cycle cost variable element *j* (e.g., development, operations, maintenance, training, manpower)

Pv = Present value taken

The fractional increase/decrease in a particular cost variable was determined through three primary sources of historical data: 1) NASA/Department of Defense/aerospace industry data on automated spacecraft/aircraft/ship based systems; 2) Automobile industry (U. S., Japan); 3) Other industry (IBM, Honeywell, FMC Corporation). Where life cycle cost projections for Space Station components existed, they were used. Unknown cost variables were determined by using a historical "total percentage" breakdown for space based systems (e.g., Shuttle). By knowing one, or more, major cost component(s) (e. g., development/first unit cost), each of the other components can be represented as a function of the known variables. Each of the unknown variables are then projected as a fraction or multiple of the known cost components. Upon completion, a major piece of the tradeoff puzzle is available (example can be seen in Ref 16).

The third step in the paring process considers not only the now derived quantitative tradeoff factors (productivity, cost/savings), but incorporates other less quantitative factors as well. This total consideration of quantitative and non-quantitative factors is the list of resource variables described earlier in this chapter, This third step employs a well established decision analysis technique called multi-attribute decision analysis (MADA) to rank order the automation options across all tradeoff factors, or "attributes" (Ref 17,18), The objective/attribute hierarchy is shown in Figure (2). The technique basically calls for the analyst to establish measures for each attribute (i. e., cost-dollars, productivity-hrs saved, hazard exposure-hrs exposed, reliability- mean downtime or time between failures), technology availability- years to introduction). Approximate value ranges for each attribute are assembled based on the earlier analysis, historical data, and industry design projections, The analyst then carefully selects a group of experts in the field of automation/telerobotics and proceeds to interactively question them on their preferences for the different automation options within the range of the projected state values for each attribute. The expert is asked to globally examine the full range of state values, and, through a structured question and answer process, provide his assessment of candidate performance within the expected range of state values. The expert's projection of performance is equated to a "utility" value; and, once the utility values are known, the utility curve can be approximated. A utility value is selected within the range of O to 1; with O representing "low" performance, 1 representing "high" performance, and .5 representing average (or the point of indifference) performance. An "overall" utility value, for a particular option, is calculated by combining the various sub-utility values across all attributes. The outcome is a "weighted" product of the experts' responses.

The analyst now has a ranking of the best-to-worst telerobotic or automation options considering the host of tradeoff variables. The solution is not considered optimal, but reasonable, The last step, the system tradeoff and best-mix analysis, can now be performed using a much smaller subset of viable automation candidates. It should be

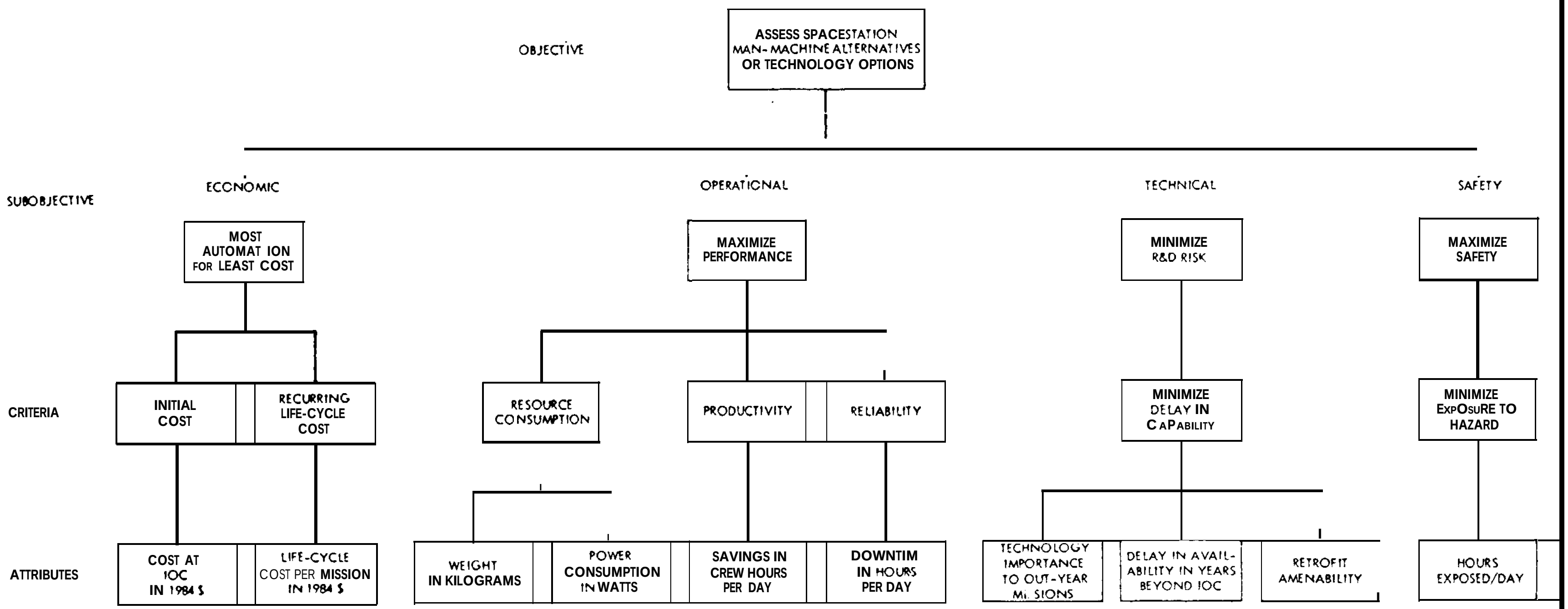

Figure 2. Hierarchy of Objectives, Criteria, and Attributes

noted that the simplifying assumption that only a given subsystem is affected by a particular automation option is conservative. Indeed, automation has a cross-correlation effect across subsystems (i.e., subsystems can share computing and diagnostic resources to meet redundancy needs).

b. Net Cost Savings

The net cost savings approach is more straightforward than the above incremental cost reduction technique, and was derived as an evolution of that model. All of the same sources of data/techniques are employed to determine the various development, flight unit, operating, and maintenance cost parameters. The difference revolves around the basic cost savings equation. Whereas the incremental approach uses a automation cost reduction factor (b), coupled with multi-attribute decision analysis for the harder to quantify design/cost attributes, the cost savings technique specifically concentrates on the cost-based variables and proceeds to calculate the net cost savings between the system without automation and the system with automation. The cos savings relationship is shown in equation (3).

$$TotO\&M_{PV}^{EVA+IVA} - TotO\&M_{PV}^{EVA+IVA+Auto} - CI_{PV} \geq 0, given \qquad \text{(eq. 3)}$$

$$CI_{PV} = \sum_{t=0}^{n} \left(DDTE_t + FLT_t + L_c \right)_{Pv} \qquad \text{(eq. 3a)}$$

where,

$TotO\&M^{EVA+IVA}$ = Total operations and maintenance cost without au oma ion

$TotO\&M^{EVA+IVA+Auto}$ = Total operations and maintenance cost with automation

CI = Development (DDT&E), flight unit (FLT), and launch costs (LC)

Pv = Present value taken

Upon completion of this step, the analyst has established a matrix with option cost along the horizontal, and cost savings along the vertical. Each of the automation candidates occupy their respective position within the matrix. As with the incremental cost reduction approach, the last step, the system tradeoff analysis, can now be performed using any one of the candidates in the matrix.

4. Design Tradeoff Analysis

The last analytical procedure calls for the analyst to iteratively sort through the telerobotic and automation design options and find the best overall system mix/design which meets the budget, productivity, and other attribute constraints. This last subsection completes the above cost-benefit discussion by addressing the two primary techniques for picking the best telerobotic or automation option(s).

a. Incremental Cost Reduction Optimization

It is now possible to impose some form of system optimization, having pared down the array of automation options to a subset which represents a reasonable solution pool. A standard linear regression technique was employed for the final tradeoff step (note- it is not necessary to assume linearity, but it appears to provide a reasonable solution given the uncertainty associated with the various attribute data). The 'solution of the problem calls for picking the best system-wide subset of automation options, across all subsystems, which satisfy all major constraints. Mathematically, the problem is stated as shown in equation (4).

$$\max_{A,a} \sum_{k=1}^{n}\sum_{t=1}^{m} B_{kt}(a_{kt}) \text{ subject to,} \qquad \text{(eq. 4)}$$

$$\sum_{k=1}^{n}\sum_{t=1}^{m} (C_{kt} - B_{kt})(a_{kt}) \le C_t \qquad \text{(eq. 4a)}$$

$$\sum_{k=1}^{n}\sum_{t=1}^{m} W_{kt}(a_{kt}) \le W_t \qquad \text{(eq. 4.b)}$$

$$\sum_{k=1}^{n}\sum_{t=1}^{m} P_{kt}(a_{kt}) \le P_t \qquad \text{(eq. 4.c)}$$

$$\sum_{k=1}^{n}\sum_{t=1}^{m} H_{kt}(a_{kt}) = 0 \qquad \text{(eq. 4.d)}$$

where,

$\sum_{t=1}^{n} a_{kt} = 1, k = 1 \ldots n, t = 1 \ldots n, a_{kt} \geq 0$ for all k, all m

A = subset of viable man-machine alternatives composed of a_{kt}

B_{kt} = net benefit from automating subsystem, k, with alternative, t. This net benefit is made up of the benefit from manhours saved, M_{kt}, and other incremental net dollar benefits, ckt, [i.e., B_{kt} is $(M_{kt} + c_{kt})$]

C_{kt} = net subsystem, k, cost not considering the benefit of automating alternative, t

C_t = cost target for the total system

W_{kt} = incremental weight impact of automating subsystem, k, with alternative, t

P_{kt} = incremental power impact of automating subsystem, k, with alternative, t

W_t = system-level weight constraint

P_t = system-level power constraint

Hkt = incremental hazard exposure time reduction due to automating subsystem, k, with alternative, t

a_{kt} = identified man-machine alternative, t, for a given subsystem, k

The branch and bound technique is the preferred method of solution and is a standard operations research optimization process. The technique begins by obtaining a bound on ‘the objective function (i.e., maximize productivity hours/value) by suppressing the dependencies at the system level. This is done by fixing the values in the above equations at their upper values and solving the resultant integer linear program. Next, the branch and bound method requires that the set of all feasible solutions (i.e., the telerobotic and automation candidates selected, by subsystem, using the previous paring down process) first be partitioned into subsets. This means that we start by picking one candidate from each subsystem and form a single system solution subset. This process continues until all candidates are partitioned into subsets. Because the objective function requires that we maximize available on-orbit workhours and net benefits, without exceeding a cost ceiling, any solution subset which surpasses the cost ceiling is excluded. The remaining subsets are partitioned further and examined in the same manner. This process is repeated until a feasible solution is found which satisfies the objective function. It is possible that no solution subset meets the objective function. In this event, the next step is to select the subsets that "minimize" the difference between the cost target and upper bound on each of the solution subsets.

b. Net Cost Savings Optimization

The net cost savings optimization process aims at establishing an envelope of acceptable telerobotic or automation solutions. In the process of performing the cost savings calculation, the high cost operations and maintenance drivers become apparent. If a telerobotic/automated system is going to be cost effective, it must offset these high cost drivers. The ability of a given design option to effect these high costs is determined by plotting cost savings as a function investment cost; and, then parametrically varying the major operating cost drivers. By doing this, the analyst can see how much, and how quickly, changes in the major cost drivers effect the net cost savings. As with the incremental cost reduction approach, the final "best" design may only offer a reasonable payback.

The application domain for this technique was the Space Station Flight Telerobot Servicer (FTS)(Ref 10). The problem was to find an FTS configuration which could provide enough functionality to reduce EVA hours sufficiently to allow the station to be assembled in the prescribed number of flights (i.e., early workload studies showed that insufficient EVA astronaut hours were available to assemble/ maintain the station in the first several years of operation). Figure (3) displays a graph of required EVA assembly hours, versus the EVA budget (driven by constraints of the EVA life support system and fatigue). As can be seen, the addition of the FTS allowed the budget to be met. When the cost savings analysis was done it was discovered that even with the highest estimated dollar value of an EVA hour, the real cost driver was the flight manifesting and launch costs. This variable was critical because if assembly or maintenance on-orbit is not completed on schedule, then additional Shuttle flights must be scheduled and payloads must be remanifested to meet both weight and workload constraints. This remanifesting effort is done at great expense. Therefore, by varying launch costs one could see the allowable FTS investment cost range that would still allow the system to breakeven or save money. A set of graphical plots showing an envelope bounded by cost savings and an FTS cost investment range were generated by parametrically varying Shuttle launch costs. An example of one of these plots is shown in Figure (4). Other cost saving envelopes were generated using other drivers such as EVA hours, discount rate, and combinations (e.g., EVA hours and Shuttle manifesting) to obtain a clear picture of the FTS design configuration offering the best impact on meeting the EVA hour budget, while still offering a savings given current/projected Shuttle launch costs.

Implications of Telerobotics and Automation for Space Station

The above discussion provided the reader with an understanding of some of the current modeling techniques being employed to weigh the human versus machine partitioning problem. With the opportunity to perform more unmanned and manned missions in space, coupled with the growing availability of advanced telerobotic and automation technology, it is clear that for safety, efficiency, and cost reasons we must develop a clearer understanding of how to resolve this extremely complex problem. We cannot take a standard "human capital" approach to this tradeoff problem (i.e., replace human beings with machines when the net cost/profit of the machine exceeds the benefits offered by humans). In the space environment, there are many functions better performed by astronauts than machines. For example, the tending of science payloads often require the performance of off-normal anomaly troubleshooting tasks. Data collection and reduction often requires complex on-line analysis. Finding the right mix-and-match of human/machine skills requires an understanding of non-cost related variables such as these. This last section explores NASA's current thoughts and plans relative to introducing telerobotic and automation technology into the manned space arena.

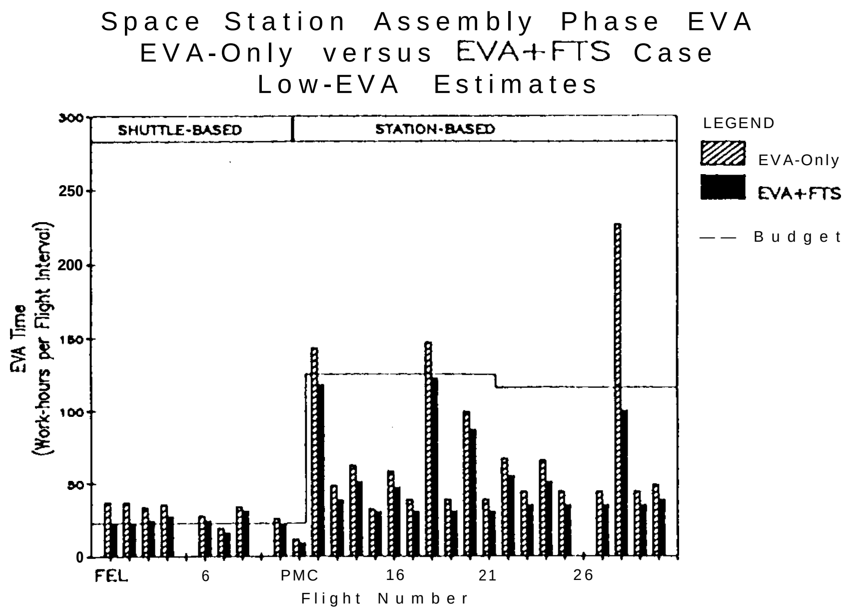

Figure 3. Low-Range EVA Estimates for EVA-Only Versus EVA+FTS Cases

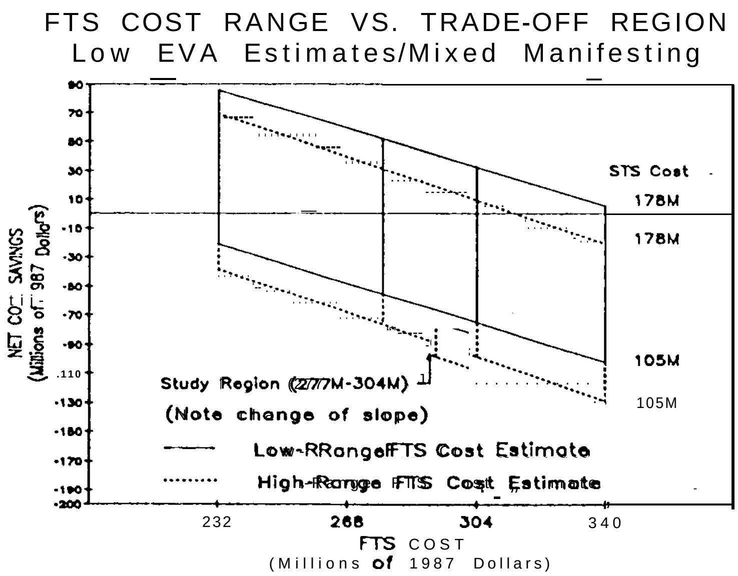

Figure 4. High-Range Versus Low-Range FTS Cost

There are many factors to consider in injecting more telerobotic and automation technology into an environment classically dominated by human operators. Earlier in this chapter reference was made to the realization of the new "wave" of astronauts for greater augmentation by automated systems. Several "risk" factors have affected the development and injection process. The Challenger disaster placed NASA's leadership role in cutting-edge science and technology development at risk. Numerous questions have been raised about the true need to continue to place humans at risk in the space environment at great cost. At the same time, the research and development budgets within NASA have been tightly constrained over the last several years by a squeezed national economy. This condition has required several station redesigns and made it difficult for the technology to keep pace with flight program requirements and demands. Therefore, NASA currently is taking a very cautious approach to having astronauts and machines concurrently controlling functions or telerobotic devices.

In the previous section the primary automation candidates were listed. Although the EVA function was part of that list, distinct tasks were not included, A more complete list of planned automation and telerobotic functions which resulted from the tradeoff studies is provided here:

1. Subsystem state monitoring
2. Subsystem state verification/calibration
3. Subsystem state assessment/change
4. Fault diagnostics/recovery
5. Mission operations/planning
6. Station module placement on-orbit
7. Module assembly
8. Inspection
   - Pre-assembly
   - Post-assembly
   - Work cell preparation
   - Scheduled/unscheduled maintenance
9. Work cell setup/teardown
10. Station/payload servicing (Orbital Replacement Unit (ORU) level)

11. Logistics support to EVA
    - Pallet handling
    - EVA tool/component holding
      Holding/jigging components being worked on by EVA astronauts

Items (1) through (5) are more automation oriented, while items (6) through (11) are telerobotic functions. In the automation area, expert systems are being built to monitor sensed subsystem state data, simulate subsystem performance, and determine whether a state change must be initiated, The target subsystems include almost all of the station subsystems, such as power, life support, thermal, navigation/control, and data management. Much of this work is being done within the NASA centers for eventual transfer to the primary ground operations control center, Johnson Space Center. Before any of the expert system software will be allowed to migrate to on-orbit systems, it will be used in the ground operations monitoring facility. The automated control software will actually operate simultaneously with the more manual on-orbit subsystem, but in simulation mode. Anomalies and faults will be simulated and diagnosed in the ground version using the actual on-orbit sensing data, The ground version will initially provide support to the ground operations crew. As the ground based automated systems get debugged and confidence is established, the expert systems will be moved on-orbit. Several of the ground based automated tools for mission planning, state assessment/change, and fault diagnostics are already in use for unmanned spacecraft such as Voyager, Magellan, and Galileo.

The telerobotic functions will primarily be performed using teleoperation from the Shuttle and/or Space Station operator control stations (i.e., basically real time). Current autonomous control augmentations to manual teleoperation will initially take the form of proximity position accommodation, joint limit monitoring, manipulator pose monitoring, or force threshold monitoring and control. As with the automated systems, all telerobotic technology will be exercised in a ground based task verification environment before being migrated on-orbit. The ground based environment will operate primarily in a support mode for the on-orbit IVA teleoperator. As the technology establishes a confidence base, more functions will be offloaded to the autonomous control system. This process will be necessary in the early phases of operation of the Space Station because of on-board computational constraints. On the ground, task sequences will be built, partitioned between operator and autonomous control, and simulated/tested before being telemetered up to the station operator control station (Ref 19).

In addition to the migration of technology on-orbit, NASA is also developing the technology base necessary to allow ground-remote operation of telerobotic systems. When implemented, the technology will initially be used for inspect on (non-contact) type tasks until a strong confidence base is built. Again, each inspection task will be simulated and verified on the grc und before a command sequence is telemetered to the robot controller(s) (Ref 19).

Conclusions

In conclusion, the author has endeavored to expose the reader to some of the key issues and variables which drive the human-machine partitioning of functions in space, along with a summary of some of the analytical techniques used in the tradeoff process, and last, provide an indication of the direction NASA is moving in getting the applications and technologies offering the most immediate cost and functionality payback implemented. This tradeoff process is being executed in a rapidly changing design and economic environment which has effected the rate at which needed technologies are being developed. This environment may impact the readiness of the various emerging technologies. The reader will be exposed to many of these emerging technologies and their use in subsequent chapters of this book.

REFERENCES

1. Ackoff, R., Sasieni, M., **Fundamentals of Operations Research,** John Wiley and Sons, Inc., New York, N. Y., 1968.

2. Miller, D., Starr, M., **Executive Decisions and Operations Research,** Prentice Hall, Inc., New Jersey, 1969.

3. Zimmerman, W., Aster, R., Harris, J., High, J., "Automation of the Longwall Mining System," JPL Publication 82-99, November, 1982.

4. Freeman, D., "STS Work Day Handbook," Johnson Space Center, Operations Planning Section, February 1980.

5. Fisher, W., Price, C., "Space Station Freedom External Maintenance Task Team Final Report," Volumes 1 and 2, NASA, Johnson Space Center, July, 1990.

6. Weeks, D., Zimmerman, W., Swietek, G., "Space Station Freedom Automation and Robotics: An Assessment of the Potential for Increased Productivity," NASA/MITRE Corp., December, 1989.

7. Zimmerman, W., Bard, J., Feinberg, A., "Space Station Man-Machine Automation Trade-off Analysis," JPL Publication 85-13, February, 1985.

8. Von-Tiesenhaussen, G., "An Approach Toward Function Allocation Between Humans and Machines in Space Station Activities," NASA, Marshall Space Flight Center, NASA Report TM-8251 O, November, 1982.

9. Advanced Technology Advisory Committee (ATAC), "Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy," NASA, NASA Technical Memorandum 87566, Volume II, March 1985.

10. Smith, J., Gyamfi, M., Volkmer, K., Zimmerman, W., "The Space Station Assembly Phase: Flight Telerobotic Servicer Feasibility, Volume 2- Methodology and Case Study," JPL Publication 87-42, September 1987.

11. Miller, R., Minsky, M., Smith, D., Akin, D., "Space Applications of Automation, Robotics, and Machine Intelligence Systems (ARAMIS)," MIT, NASA, Marshall Space Flight Center, August 1982.

12. McDonnell Douglas Corporation, "The Human Role in Space (THURIS)," sponsored by NASA, Marshall Space Flight Center, 1984.

13. Smith, J., Drews, M., "Generic Extravehicular (EVA) and Telerobot Task Primitives for Analysis, Design, and Integration," JPL Publication 90-10, March, 1990.

14. Drews, M., "Telerobotics/EVA Joint Analysis System (TEJAS), Version 1.0 User's Guide," JPL Publication 90-11, March, 1990.

15. Boehm, B., **Software Engineering Economics,** Prentice Hall Inc., New Jersey, 1981.
16. Zimmerman, W., "Closeout of FY90 Space Exploration Initiative Surface Transport Vehicles/Human, Automation, Robotic Tradeoff Deliverables," JPL IOM 3475-90-66, November 7, 1990 (Informal Document).
17. Kenney, R., Raiffa, H., **Decisions with Multiple Objectives: Preferences and Value Trade-offs,** John Wiley, New York, 1976.
18. Tarvainen, K., Haimes, Y., "Coordination of Hierarchical Multi-objective Systems: Theory and Methodology," IEEE Trans. Systems, Man, and Cybernetics, Vol. SMC-12, no. 6, 1982.
19. Zimmerman, W., "Supervisory Autonomous Local-Remote Control System Design: Near-Term and Far-Term Applications," NASA/ Airforce, SOAR, August, 1992,