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Abstract

Space Station Freedom's power system, along with the spacecraft's other subsystems, needs to carefully conserve its resources and yet strive to maximize overall Station productivity. Due to Freedom's distributed design, each subsystem must work cooperatively within the Station community. There is a need for a scheduling tool which will preserve this distributed structure, allow each subsystem the latitude to satisfy its own constraints, and preserve individual value systems while maintaining Station-wide integrity. The value-driven free-market economic model is such a tool.

1 Resource Allocation

1.1 The Need for Load Scheduling

Many similarities between Space Station Freedom's power system and terrestrial power utilities are apparent. Both systems incorporate generation, storage (usually a pumped water reservoir for the terrestrial—batteries for us), transmission lines, circuit breakers, and power consumers. Both systems rely heavily on human decision-making for safe, economic operation. But, the strategy that controls the operation of the two systems is fundamentally different. This difference arises at the power supply.

In terrestrial utilities, ample generation is usually available for the demanded loading; when it is not, power is purchased from the grid. The control strategy is to modulate generation capacity to match the demand's changes. Any shortage is covered by interchange with the grid. Every effort is made to meet the consumers' demands by managing the injection of power into the transmission network, controlling the loads themselves is reserved for extreme failures when there is no acceptable alternative.

Freedom has no tie-line to a neighboring utility. The control strategy is to maximize solar energy conversion with energy utilization controlled by adding and deleting loads from the system. This in turn requires that the load demand be as determinate as possible so that each watt can be allocated. Although this procedure maximizes payload productivity, it generates an extremely difficult scheduling problem [1].

Scheduling the electrical energy among the consumers is a resource allocation problem and would seem amenable to a host of mature operations research algorithms. However, Space Station Freedom's design is evolving as a confederation of separate agents (life support, communication, propulsion, payload 1, etc.), each with a responsibility to perform a unique function. Structuring the electrical resource allocation problem as a constrained maximization of some objective function oversimplifies the interactions with the rest of the infrastructure. The real issue is to maximize the collective welfare of the various functional agents. This implies bargaining among the power requesters and the power management agent to produce equitable allocations [2].

We note that managing the electrical loads is no different than managing loads applied to any subsystem aboard the station. If Space Station Freedom is to operate coherently as a confederacy of separate agents, some of the agents will necessarily have the authority to determine the behavior of others. For the present, who directs whom is contentious. We propose to define roles and responsibilities for participation in a distributed bargaining transaction that will yield a productive allocation of Freedom's resources through load scheduling.

1.2 A Cooperative Approach

1.2.1 The Project Management Paradigm

There is a strong parallel between managing the automatic operation of Freedom and managing complex projects involving human beings. The conventional wisdom for the latter uses a systems management approach to control and coordinate a project's activities. This contemporary theory of organization management uses a project manager to coordinate the entire operation. This manager's legitimate authority is based on participation and persuasion with the independent agents and is not based upon the unilateral exercising of power. In this context, the decisions are made by the individual functional agents and the overall success depends upon the integration of these decisions. The project manager basically monitors the interfaces, mediates conflicts, and negotiates equitable trade-offs among the various agents [3]. The basic behavioral recommendation in this philosophy is to establish cooperative alliances both among the individual agents and between an agent and the project manager. This conceptual framework for cooperative and hegemonic relationships is the basis of our proposal for automating the cooperative problem-solving among the Electric Power System, its consumers, and the the station's operations manager.

1.2.2 The Paradigm Applied

The various agents for Space Station Freedom can be organized into three categories: 1.) the operations management agent—OMS[1], 2.) resource managing agents—those which supply basic resources throughout the station, and 3.) resource requesting agents—those who plan to use the resources to perform other functions. Under the project management concept, each agent is allowed to make all the decisions about controlling any of the activities under his purview. Resource requesting agents will plan activities according to what is considered an acceptable discharge of their responsibilities. This action will request resources to be supplied by the resource managing agents who organize to support the desired activities.

Conflicts arise when more resources are requested than can be supplied. Rather than have the operations management agent decide directly which tasks will be performed and which will be curtailed, the resource managing agent with the conflicts should negotiate with the resource requesting agents to develop mutually acceptable allocations. The idea is to increase the *span of control* of the individual agents and to reduce the number of layers in the management hierarchy [3]. The elimination of intermediate hierarchies and direct micro-management should simplify automating resource allocation. Of course, to do all this, the participants will need some knowledge of what constitutes good and bad operation from the operations management agent's point of view, and the operations management agent will have to be concerned with issues of equity among the participants. This conceptualization requires:

1. *A two-level hierarchy.* Decision-making agents organized by function who either plan what is to be done or who manage the required resources constitute the bottom level. An operations management agent who integrates the decisions and resolves deadlocks constitutes the top level.

2. *Explicit value systems.* Decision-making agents use cardinal measures of preference for trade-offs among different resource consumption tasks to maximize station productivity and to preserve equity among the resource requesting agents.

3. *Local constraints.* Resource supplying agents schedule demands using only the constraints in their own subsystem. Resource requesting agents plan activities that do not violate any of their operating constraints.

In this type of operation, the resource requesting agents plan activities that require resources. The operations management agent polls the requestors and compiles integrated resource utilization schedules and sends them to the resource suppliers. In general, resource allocation is constrained by the amount of resource available at any instant, the time at which a resource is needed, and the priority of the need itself. Choosing a schedule of events that satisfies constraints implies the ability to use a value system to make the selections. The value system used rates these decisions according to their impacts upon overall station operation as well as preserves equity for the participants. These equity notions and preferences for overall station operation are determined by the operation management agent and communicated to resource requestors who eliminate resource conflicts by using this preference structure to revise their requests.

We use a free-market concept to organize the cooperative bidding for resources and to coordinate the

[1] OMS—the Space Station Freedom's Operating Management System—performs the automated coordination of systems and payloads

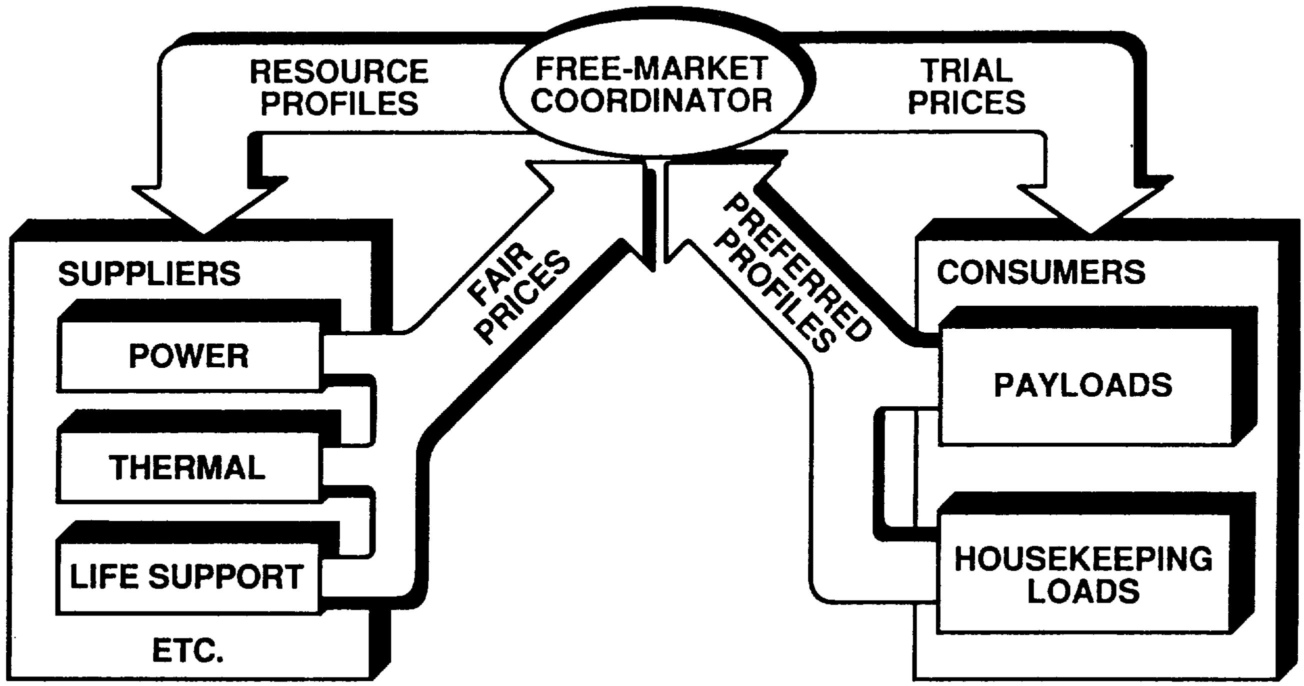

Figure 1: Free-Market Transaction Cycle

convergence upon an equitable allocation. Using a free market for the exchange of goods and services provides a natural and easily comprehended environment for experimenting with supply and demand.

1.2.3 Free-Market Economic Model

The transactions among our functional agents are coordinated with the familiar concept of a free-market economy. Shown in Figure 1, the operations management agent, the OMS, acts as a free-market coordinator to mediate conflicts and to provide a top-level value system. The resource management agents—the suppliers, are concerned with maximizing the use of their resource without violating any of their operating constraints. The resource requesting agents—the consumers, are concerned with generating sets of preferred operating profiles for their desired tasks. Each of these participants coordinates his actions as if operating in a free-market economy. The free-market coordinator sets initial trial prices for all the resources over the planning horizon. The consumers then generate their preferred usage profiles incorporating their own value systems, the top-level priorities and the resource costs. The suppliers, using their system-level constraints, evaluate the resource profiles and set fair prices for each resource throughout the planning horizon. This exchange continues until the fair prices quoted for each resource equal the trial prices used by the consumers. This partitioning of constraints and value systems preserves the notion that each agent is most interested in and most knowledgeable about his own part of station operation. An additional advantage of this approach is that it solves one of the most difficult scheduling problems, inter-system scheduling requests. Realistically, most consumers will demand several resources for each operation (any request for power will contain the hidden request for heat rejection). Most resource schedulers generate solutions for a single resource and hope to partition the problem among different schedulers. To us the cooperative approach is more appealing.

2 A Value-Driven Approach

2.1 Generalized Lagrange Multipliers

The theory behind the free-market economic approach is the Generalized Lagrange Multiplier technique [4]. Everett showed that Lagrange multipliers can be used to solve maximization problems with many variables without any restrictions on continuity or differentiability of the function being maximized [5]. While traditional Lagrange multipliers deal with equality constraints and handle inequality constraints with slack variables, Everett's GLM techniques do not use slack variables. The goal of GLM is "maximization" rather than the location of "stationary points" as with traditional Lagrange multipliers. The following is a simplified discussion rather than a rigorous mathematical description. For such information refer to [5] and [6].

Our approach is to perform an unconstrained maximization of the following Lagrangian:

$$L(x) = \sum_i \sum_j \left[V_i v_{ij} x_{ij} - \sum_k \lambda_k \phi_k x_{ij} \right]$$

where:

V_i = overall value of the i^{th} project

v_{ij} = relative value of the j^{th} mode of the i^{th} project

$x_{ij} = 1$ if project i is performed in mode j

$x_{ij} = 0$ otherwise

and subject to the constraint

$$\sum_i \sum_j \phi_k(x_{ij}) \leq C_k$$

where $\phi_k(x_{ij})$ = the amount of resource consumed by mode j of project i

and C_k = the total amount of resource k available

The V_i values are determined by the operations management agent—the OMS, and are used to incorporate top-level, station-wide preferences among the various projects. The v_{ij} are the preferences determined by the consumers for each operating option that they might choose to have scheduled. The key to solving this problem is *choosing* the Lagrange multiplier. Instead of solving sets of simultaneous equations to find λ_k at a stationary point, we choose an initial value for each λ_k. This choice corresponds to the trial prices set by the free-market coordinator. Finding the maximum of the Lagrangian using these assigned values for λ_k will optimize *some* problem. The issues are to find what problem was optimized and to adjust λ_k to optimize the problem at hand. Finding a maximum requires that the objective function be concave[2] around the solution point or else the algorithm will skip solutions [5]. Fortunately, most real-world problems either have an objective function that is concave or can be made concave in the area of interest.

Our application of the GLM technique follows the transaction cycle depicted in Figure 1. The consumers evaluate their options using the trial prices, λ_k. They will choose the option with the greatest overall value ($V_i v_{ij} - \sum_k \lambda_k \phi_k$). The free-market coordinator aggregates each consumer's profile by resource, i.e. all the power requests over the planning horizon are added together, all the thermal, etc. These aggregated resource profiles are then sent to the resource suppliers.

The suppliers have their own system level constraints that must not be violated. Some of these are *hard* constraints, constraints that *must* be met or there is no feasible solution. The total amount of power available is a hard constraint. Some are *soft* constraints, constraints that *may* be violated, reducing payoff but not producing an infeasible solution. An optimum battery charging profile that preserves battery life is a soft constraint. For hard constraints, the resource demands would be added over the planning horizon; and if there were an excess, the fair price would be lowered—λ_k would decrease. Correspondingly if there were a shortage of a resource, the fair price—and λ_k, would be increased. Most power system constraints will be soft constraints dependent upon time-varying factors. Soft constraints are evaluated using penalty functions (Section 2.2). With either type of constraint, the resource suppliers generate a set of fair prices over the planning horizon.

The fair prices for each resource return to the free-market coordinator who uses them to modify his next set of trial prices. He compares the fair price and the trial price at each time interval and adjusts his trial price proportionally and according to the sign of the difference. Since the objective function is concave around the solution point, such an incremental adjustment of λ_k will avoid large oscillations during convergence.

Another important consideration for optimization techniques is their ability to handle large problems without suffering from combinatorial explosion. The separability of the Lagrangians makes the GLM technique's solution time vary proportional to $pq\log(q)$, where p is the number of variables and q is the number of constraints, whereas, standard linear and non-linear

[2] A function is concave at a point if all values of the function are less than the values of a line tangent to the function at that point.

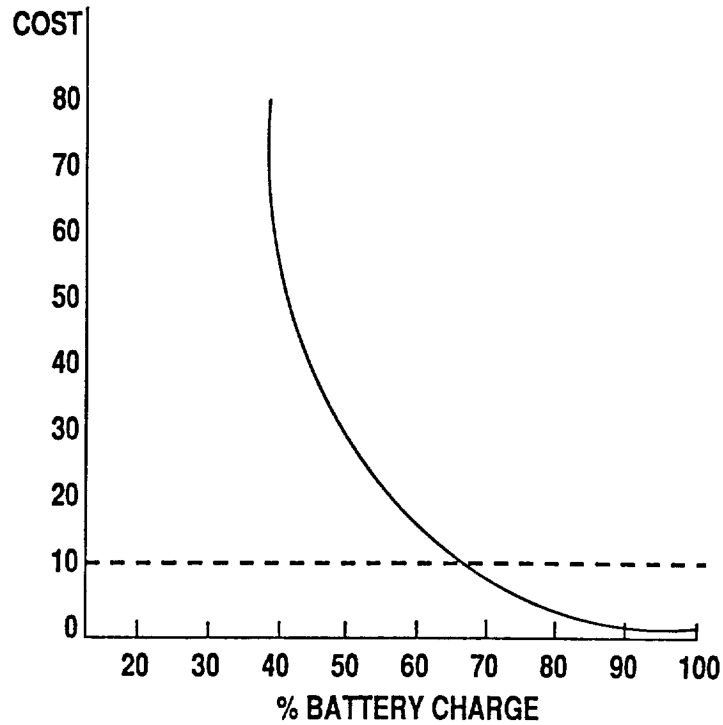

Figure 2: Cost Function

techniques vary porportional to p^2q [4]. For large applications such as Space Station Freedom, this is an important advantage.

2.2 Penalty Function

For soft constraints we modify the Lagrangian in Section 2.1. Instead of having resources that are strictly available or unavailable, we have resources whose price increases with scarcity and decreases with abundance. We control the usage of such a resource with a penalty function so that we avoid operating at extreme supply levels. This leads to the following equation:

$$L(x) = \left(\sum_i \sum_j V_i v_{ij} x_{ij} \right) - \sum_j \int_0^{y_j(x)} P_j(y)dy$$

where $y_j(x) = \sum_i \phi_j(x_i)$

$y_j(x)$—the amount of resource j used

The penalty function, $P_j(y)$, is a non-linear function. Integrating $P_j(y)$ over resource consumption y_i generates a cost function such as shown in Figure 2 for battery charge. This cost function is used to generate the fair price quoted to consumers—prices which will coerce the consumers into changing their preferred project profiles.

Each soft constraint will be represented by its own penalty function and cost function. Figure 2 depicts percent of battery charge as the constrained resource. For this particular case, there are appropriate intervals where the battery state-of-charge is known and can be compared to desired values. At the end of the orbit's sunlight portion the battery should be fully charged. To determine the cost of power for a given sunlight portion, the energy demand is calculated and used to determine the battery state of charge. The cost function supplies a fair price for power usage during that sunlight portion. Correspondingly, at the end of the orbit's eclipse portion the battery depth of discharge should not exceed 35%. After calculating the energy demand over the eclipse portion and determining the battery depth of discharge, the cost function will supply a fair price for power for that eclipse portion.

2.3 Value Functions

For this scheduling algorithm to satisfactorily allocate resources among consumers, the values V_i and v_{ij} must simulate the human managers' preferences for choices among alternatives. As previously discussed, the station-wide values (V_i) are passed to the consumers and used in their deliberations. The station-wide importance of an option can be made a function of time and used to represent urgency.

Project managers have two basic types of criteria for judging when to schedule a project; the relative *importance* of that project and the *urgency* of project completion. The relative importance would most likely be a numerical value, whereas the urgency would be more like a rate. The value function might be represented mathematically as follows:

$$V(t) = V_0 \cdot e^{\alpha t}$$

where V_0 represents the importance factor and α represents the urgency factor.

The placement of a project in the schedule would depend on both its importance and relative urgency for the time periods in question. The value function could be used to indicate the urgency of continuing a relatively low-importance experiment that is very near the completion of a several day operation. The concept of urgency being applicable for specific time periods in an orbit or mission is something intuitably obvious but not necessarily easy to implement. In the GLM technique additional equations representing time-dependent value functions do not complicate the solution because of the separabilty of the Lagrangians. Each consumer will still evaluate his project's options, choosing the one with the greatest overall value, only his method of calculating that value will include time-dependent factors rather than a single value for the entire project.

3 Goals

A design prototype will be available in the summer of 1990. This prototype, using a 386 machine, OS/2 and Presentation Manager, will depict these concepts for Freedom's electric power system and a few representative consumers. We will use this prototype to solicit evaluations of our approach from the Space Station Freedom community. Our long term goal is to incorporate a more detailed version of this software into the Space Station Power System Test-bed. This test-bed work will provide a foundation for Space Station Freedom's operation as a distributed yet cooperating collection of entities.

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