Automated
Power Management and Control

Space Station Freedom

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ENGINEERING PROTOTYPE DEVELOPMENT FOR POWER MANAGEMENT AND CONTROL

A comprehensive automation design is being developed for Space Station Freedom's electric power system. A joint effort between NASA's Office of Aeronautics and Exploration Technology and NASA's Office of Space Station Freedom, it strives to increase station productivity by applying expert systems and conventional algorithms to automate power system operation. The initial station operation will use ground-based dispatchers to perform the necessary command and control tasks. These tasks constitute planning and decision-making activities that strive to eliminate unplanned outages. We perceive an opportunity to help these dispatchers make fast and consistent on-line decisions by automating three key tasks: failure detection and diagnosis, resource scheduling, and security analysis. Expert systems will be used for the diagnostics and for the security analysis; conventional algorithms will be used for the resource scheduling.

To demonstrate the benefits of automating these tasks we plan to operate the Space Station Freedom Power Test-Bed using our prototype automation technology in our Engineering Support Center (a mission control type of environment). In addition, we plan to demonstrate cooperative problem solving between this test-bed and the Common Module Power Distribution Test-Bed located at the Marshall Space Flight Center. These latter demonstrations will investigate using expert systems that cooperate to diagnose failures whose effects propagate across system boundaries and that cooperate to recover and restore the performance lost through such failures.

CONTROLLING SPACE POWER SYSTEMS

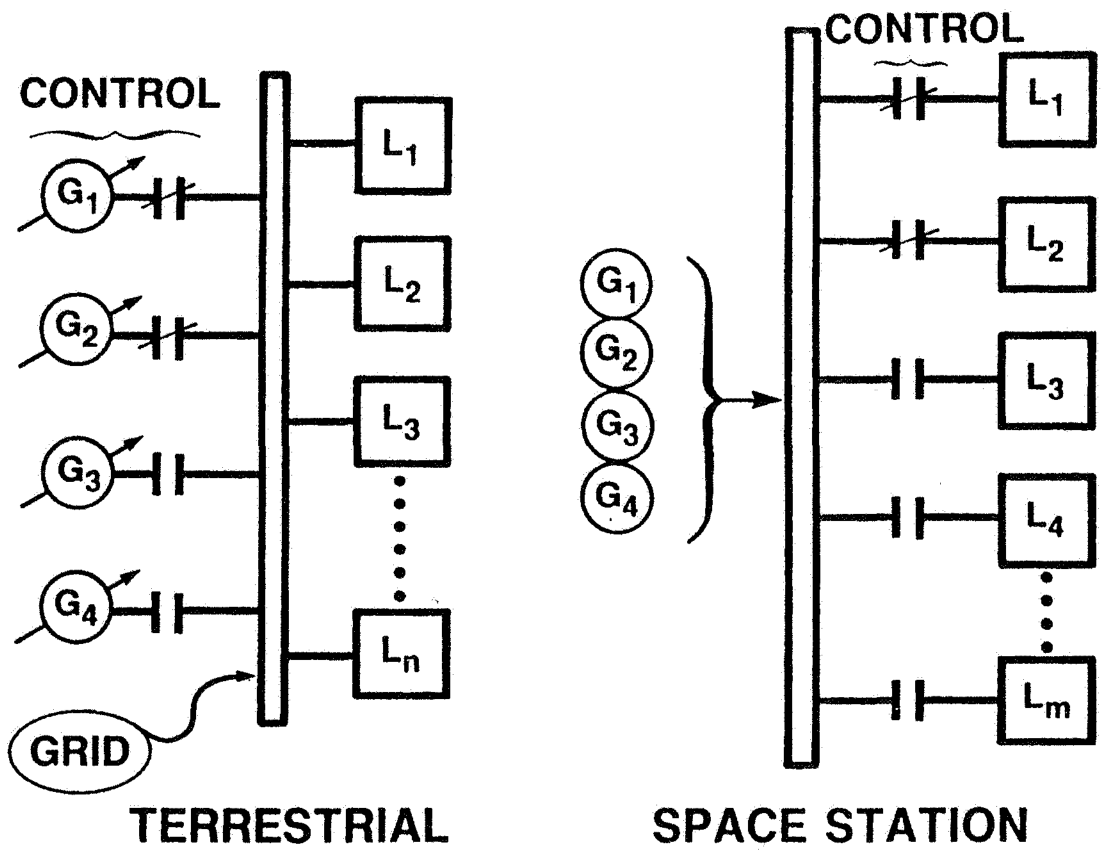
Many similarities between the space station's power system and terrestrial power utilities are apparent. Both systems incorporate generation, storage (usually a pumped water reservoir for the terrestrial -- batteries for us), transmission lines, circuit breakers, and power consumers. Both systems rely 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 load 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.

The space station's power system has no tie-line to a neighboring utility. Generation cannot be modulated to accommodate demand as in electric utility companies. The power aboard the spacecraft is produced by the solar energy conversion systems which are controlled to maximize energy production. With solar power systems producing only about 7 watts of power for every kilogram of equipment, Space Station Freedom will never grow to be a power rich environment. This makes space power an expensive, limited resource to be judiciously allocated among the on-board users to maximize payload productivity. Energy utilization is controlled by adding and deleting loads from the system. This 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 aboard complex spacecraft such as Space Station Freedom.

The goal of building a Space Station as an infrastructure for space research complicates the scheduling problems even further. Previous spacecraft have been dedicated to specific pre-determined experiments whose schedules are maximized before flight. A research environment requires the flexibility to generate detailed schedules throughout a thirty year span. Space Station Freedom must provide just such an environment and reap the concomitant development challenges.

CONTROL STRATEGY



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WHY ADVANCED DEVELOPMENT?

The Space Station prime program has many difficult problems to solve. The electric power system itself has endured the complications of a major component change from 20 kHz AC distribution to DC generation and distribution. Added to these problems are the more recent restructuring activities which emphasize ground control instead of flight control. All of these factors distract the prime program from addressing productivity. Overall, the major design objectives for SSF's electric power system are to build a fail-safe system, to operate within tolerances that provide the required amount of energy, and to create a power system that will be productive. The prime program must first focus on the safety and capacity objectives that create a working, robust flight power system. Unfortunately, the productivity issues do not receive the same attention. The advanced development program has the luxury of avoiding the direct developmental issues and can spend its resources on identifying and building products that will work with the flight power system to augment its capabilities and enhance its productivity for the long term.

Why Advanced Development?

Ranked prime program objectives:

1. Safety
2. Operation
3. Productivity

Advanced development = maximizing productivity

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MAJOR OBJECTIVE: MAXIMIZE PRODUCTIVITY

Our major objective is the maximization of productivity which manifests itself as efficient and effective operation of the Space Station. To accomplish this we consider two subobjectives of productivity: maximization of resource availability and minimization of operating costs. Maximization of power availability combines a maximization of usage and a minimization of restoration time. To maximize usage we consider load scheduling to be our primary strategy. With it we plan to devise a flexible tool which will be able to automatically schedule this scarce resource throughout the envelope of changing operational configurations. To minimize restoration time we are developing several diagnostic tools to investigate the merits of different approaches to determine failure causes. With strong diagnostic aids at hand, an operator will improve his abilities to respond to anomalies, whether he is ground-based or a member of the crew. To further augment the abilities of the operator we are developing replanning tools which will recommend possible remedial options after a fault has occurred or if a potential problem is brewing. Minimizing operating costs combines operating the power system as close to nominal as possible and minimizing the amount of involvement of the operator. Nominal operations may be traded for performance, especially in emergency situations involving crew. The major component of the power system that involves costly maintenance is the batteries. Optimizing battery usage will increase battery life and reduce the expenses involved in removal and installation of new batteries. Operators, whether ground based or flight crew, have significant duties to perform. We can minimize their involvement in routine power system operations by providing expert system consultation during reconfiguration and replanning.

ORIGINAL PAGE IS
OF POOR QUALITY

Maximize Productivity

- Maximize available power
  - Maximize usage
    - Resource scheduling
  - Minimize restoration time
    - Diagnosis
    - Replanning
- Minimize operating costs
  - Maximize battery life
  - Minimize operators' involvements

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POWER MANAGEMENT AND CONTROL AUTOMATION

In the fall of 1990, Congress mandated an eight billion dollar budget reduction for the Space Station Freedom Program. To meet this reduction, NASA has reduced the scope of the Space Station's objectives. One of the strategies was to move automation from aboard the space station to the ground control center. This new baseline design places the ground-based flight controllers as the principal decision-makers in the moment-to-moment operations. To make quality decisions, these flight controllers must have an acumen sharpened through years of experience. We believe that expert systems can capture much of this knowledge and help the flight controllers to make faster and more consistent decisions by reducing their cognitive workloads.

Power Management and Control Automation

- Baseline emphasizes ground operations

  — Intensive human involvement

  — Expertise

- Expert systems reduce cognitive workload

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POWER CONTROL CENTER CONCEPT

Our concept for ground-based control focuses on partitioning the control decisions for the electric power system into four decision-making entities. The first, the flight support system, is responsible for issuing the commands to the electric power system aboard the space station. It monitors the system's status and prompts the flight controller for appropriate responses. This is the fastest responding control system. When addressing failure events, this system must detect the failure and isolate affected systems so that the station's integrity is not jeopardized. In addition, the corresponding flight rules must be executed to minimize system degradation. Three other systems are used to aid the command and control activities of the flight support system. These systems are slower to respond than the flight support system and perform detailed event analyses (diagnosis and security analysis) and operations planning (scheduling). The diagnosis system uses available telemetry data to determine the most likely cause of a failure. The security analysis system conducts contingency ("What if...?") analyses to determine the risk of continued operation. The results of these event analyses alter the operating constraints and mission objectives which in turn require a revised operating plan. The scheduling system provides this plan by allocating resources according to the constraints identified by the event analysis systems. Human operators coordinate the exchange of information among these four systems.

FREEDOM

SSF POWER AUTOMATION

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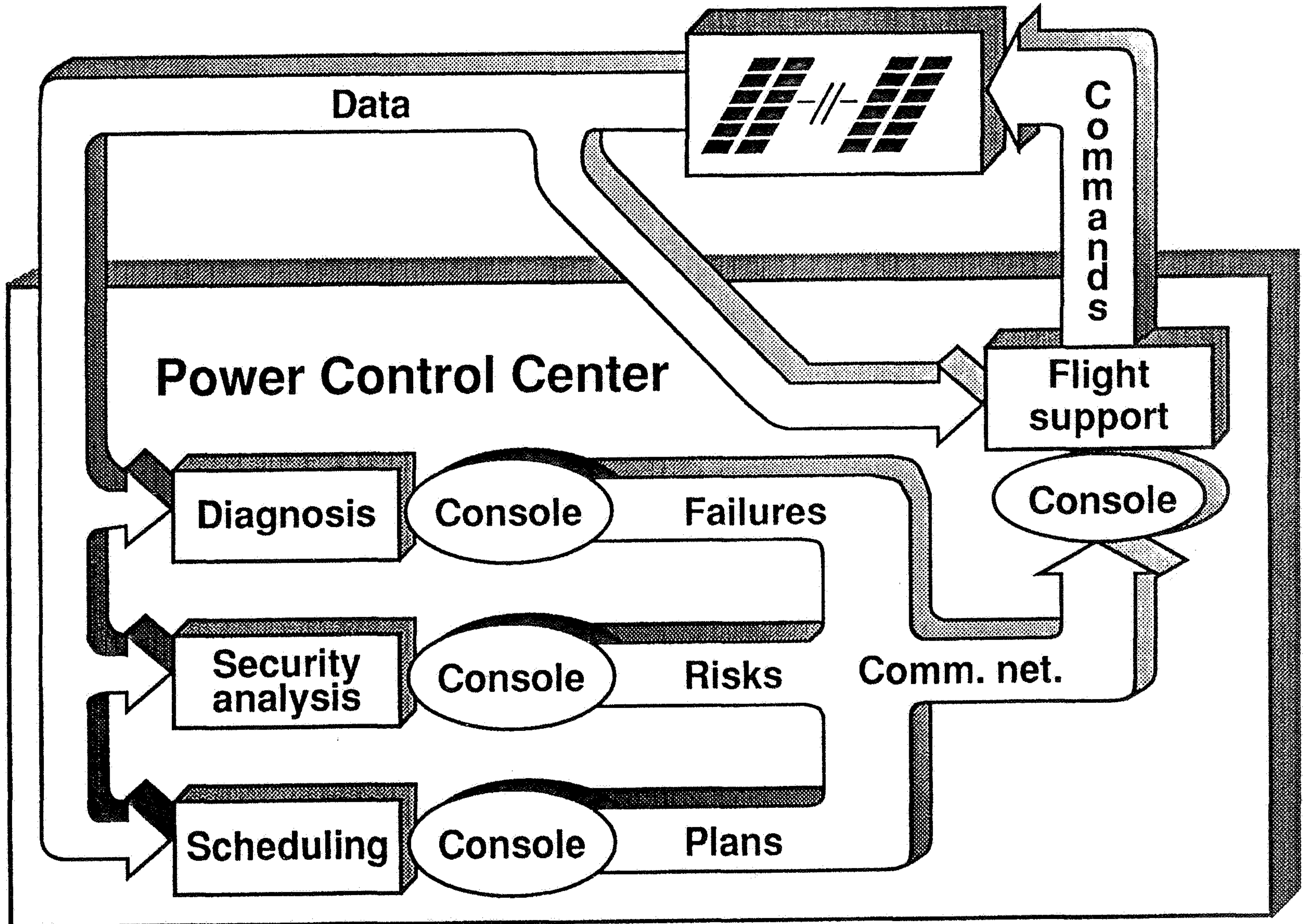

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PRODUCTION SYSTEMS FOR DIAGNOSIS

The diagnostic system is an expert system that uses set-covering rather than a series of if-then rules to encode the failure knowledge. In this software, a data base linking all known system failures to their known symptoms is built and searched to generate the failure cause hypotheses for observed symptoms. Antecedent driven rules control hypothesis generation and determine the most likely cause. Nonmonatonic inference is implemented using reasoned assumptions and rule conflicts are identified and resolved using Petri net transitions. The failure knowledge, however, is stored as data and is easily maintained. This diagnostic system uses a standard reliability analysis tool -- the failure modes and effects analysis -- to produce the symptom and failure data base. Symptoms are detected using rule-based classifiers which process the telemetered measurements.

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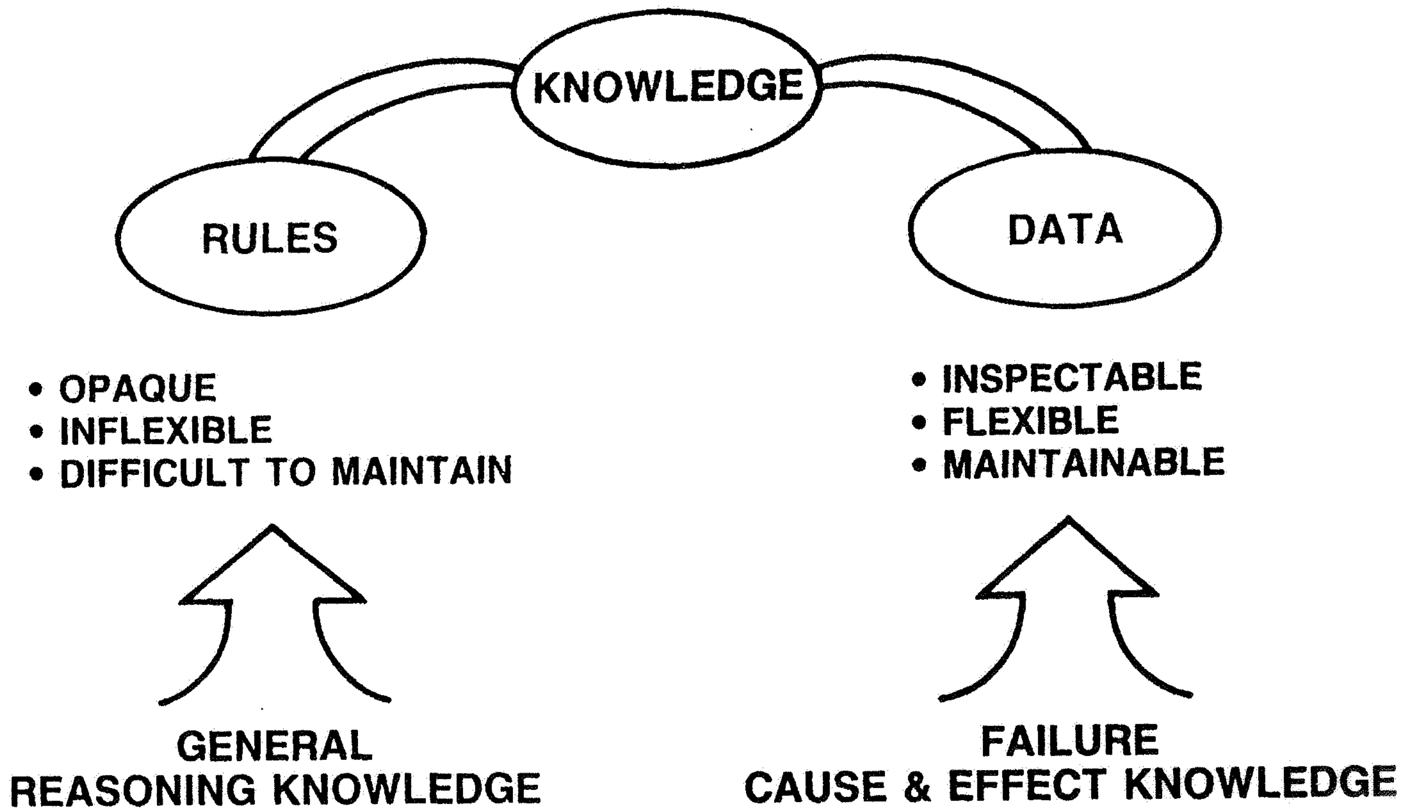
PRODUCTION SYSTEM



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SECURITY ANALYSIS

System security analysis is a risk assessment. It examines the liabilities of continued operation by identifying contingencies and estimating their consequences. The contingencies are either sudden disturbances or gradual performance degradations that could lead to overloads, voltage degradation, source shutdown, or load shedding. If the risk of continued operation is judged acceptable, the system is classified "secure" and system operation proceeds according to the current plan. If there are risky contingencies, the system is judged "insecure" and preventive control strategies are recommended.

Three distinct activities are required to analyze system security:

1. Generate and test contingencies: Worrisome failures that are present under all operating conditions as well as operating-state dependent failures such as transmission outages are compiled and submitted for analysis. The analysis calculates the operating margins for each of these failures.

2. Project trends: Incipient failures such as gradual degradation in battery storage capacity or inconsistencies between proposed consumption and production are detected by specialized software. The anomalies are forecasted and added to the list of contingencies to be analyzed at that time.

3. Judge security: A "system" is secure if there are no contingencies that result in an emergency state. If the operating margins calculated in the analysis are insufficient, the system is judged "insecure" and control actions are recommended that will attain an acceptable operating risk.

Security Analysis

Security is freedom from risk

1. Known contingencies
2. Incipient failures

Analysis yields a risk judgement

1. Generate & test
2. Project trends
3. Evaluate consequences & judge risk

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NIH2 BATTERY HEALTH MONITORING SYSTEM

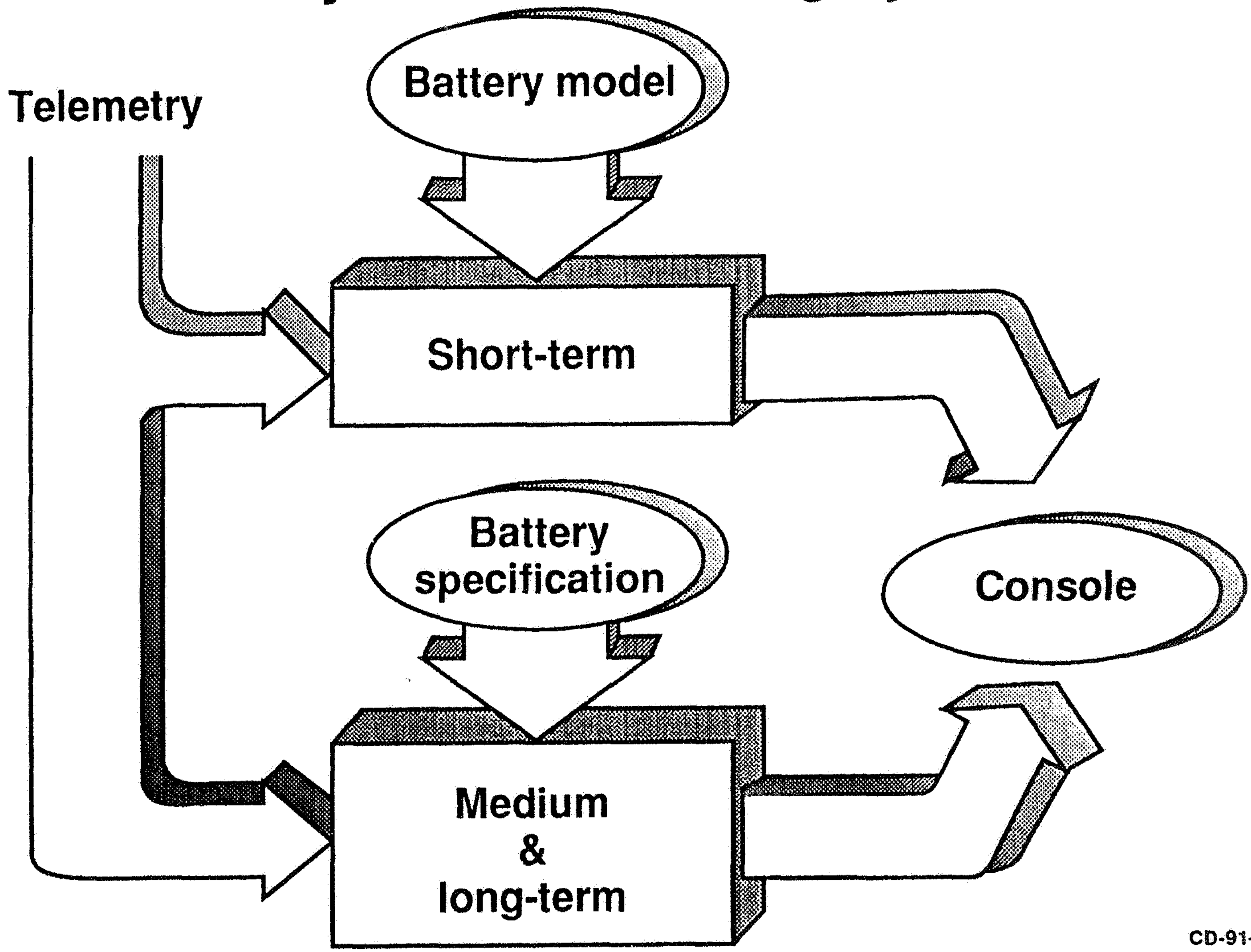
A significant part of the security analysis problem is monitoring the health of the battery system and projecting any loss of capability. A battery health monitoring system is being developed that detects anomalies in the batteries, provides problem diagnosis, and projects expected life estimates. This system uses a combination of analytic models and tabulated aging characteristics to identify incipient failures. Three trends are maintained: short-term, medium-term, and long-term.

The short-term trend data (3 orbits) address battery current and voltage, cell pressure and temperature, and depth of discharge. The data are smoothed. Trends are identified and compared with results from an empirical analytic model of the battery. Deviations are used to detect events such as sensor failure, cell short circuit, and cell rupture.

Medium-term (100 orbits) and long-term (3000 orbits) data address cell pressures and voltages at the end of the charging period and at the end of the discharging period, recharging ratio, Watt-hour efficiency, depth of discharge, and cell temperatures. These data are smoothed and trends are identified and compared with the batteries' expected aging characteristics. The comparisons detect the anomalies that develop over many orbits such as: cell soft short, slow cell leak, high internal resistance, internal corrosion, excessive overcharge, abnormally high operating temperature, and gradual loss of charge carrying capacity.

The system displays these health trends and alerts the system operator should there be any deviations from the expected.

Battery Health Monitoring System



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SYSTEM MANAGEMENT AND SPACE STATION FREEDOM AUTOMATION

One of the key concepts in our automation scheme parallels the systems management approach to project management and design. This approach is utilized in our scheduling tool by incorporating a two-level hierarchy for distributing the computational requirements and the regions of responsibility. The hierarchical design resembles the manager and subordinate with respect to their roles and responsibilities. This system is based on the concept of participative management where the manager describes the work to be done and then leaves the subordinate alone while the work progresses. Communication between the levels is minimized. Detailed information resides with the person who will be using it. In this fashion we build a computer system that can be distributed across different machines reducing computational overload and minimizing data passing.

Along with distributing our scheduling process, we are defining an explicit value system to be used in evaluating the proposed schedules. Maintaining the separation of responsibility each subordinate system will maintain and define its value for a specific schedule which can be interpreted on the higher level. Each subsystem will maintain its own system integrity and evaluate schedules with respect to its own system level constraints. These evaluations will be passed up to the higher level where they will be interpreted within the context of the entire system rather than the local point of view.

SYSTEMS MANAGEMENT & SPACE STATION FREEDOM AUTOMATION

REQUIREMENTS:

1. TWO-LEVEL HIERARCHY
2. EXPLICIT VALUE-SYSTEMS
3. LOCAL CONSTRAINTS

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FREE MARKET ECONOMY MODEL FOR SCHEDULING RESOURCES

Using the systems management approach we have developed a value-driven distributed scheduler that models a free market economy. This scheduling technique is based upon three agents, resource suppliers, resource consumers and an overall market coordinator. The resource suppliers are the various subsystems on the Space Station. They maintain their local systems and evaluate proposed schedules based upon usage of their resource. Consumers are the payloads and various housekeeping tasks aboard the Space Station. Each consumer describes the various options for each desired activity along with defining a specific numeric value for each of these options. The schedule is determined by setting initial prices for each resource throughout the scheduling horizon which are sent to each of the consumers. The consumers evaluate how much each of their options would cost and choose the one with the highest net benefit where net benefit is the difference between the value of the option minus the cost of the resources used. The selected options are aggregated by the market coordinator who sends the appropriate total usage profile to the resource supplier. Each supplier looks at the proposed schedule of usage and compares it to what he knows he can supply throughout the orbit. He will then send a set of price adjustments to the market coordinator to drive usage to his specific abilities. His goal is to maximize usage of his resource, operating neither in a deficit nor in a surplus condition. The market coordinator continues this iterative process until the prices converge and the schedule options are stable.

One of the benefits of this approach is that the explicit value system can be used to identify how good the proposed schedule is before the solution has converged. Consumers and suppliers define utility functions that are used to evaluate the proposed operating condition generated by each proposed schedule. The utility functions are sent to the market coordinator who can evaluate the entire state of the Space Station operation and decide whether or not to continue iterating. Scheduling needs to be responsive to different operating states of the Space Station. Some schedules will be routine, others will be emergency schedules needed very quickly to return to a sensible operating condition. Using explicit values and utility functions allows us the flexibility to provide for many different operational scenarios.

FREEDOM

SPACE STATION FREEDOM

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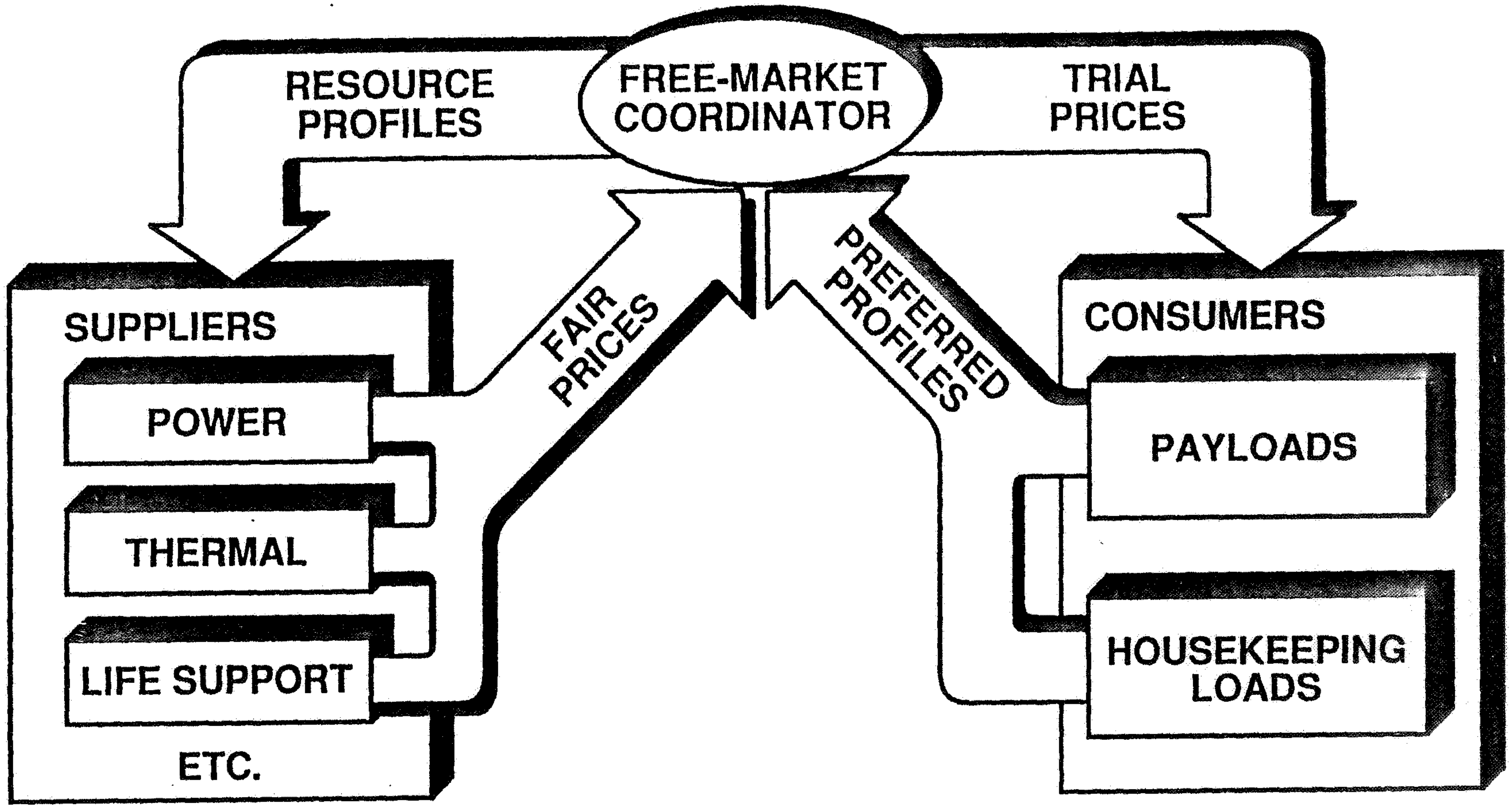

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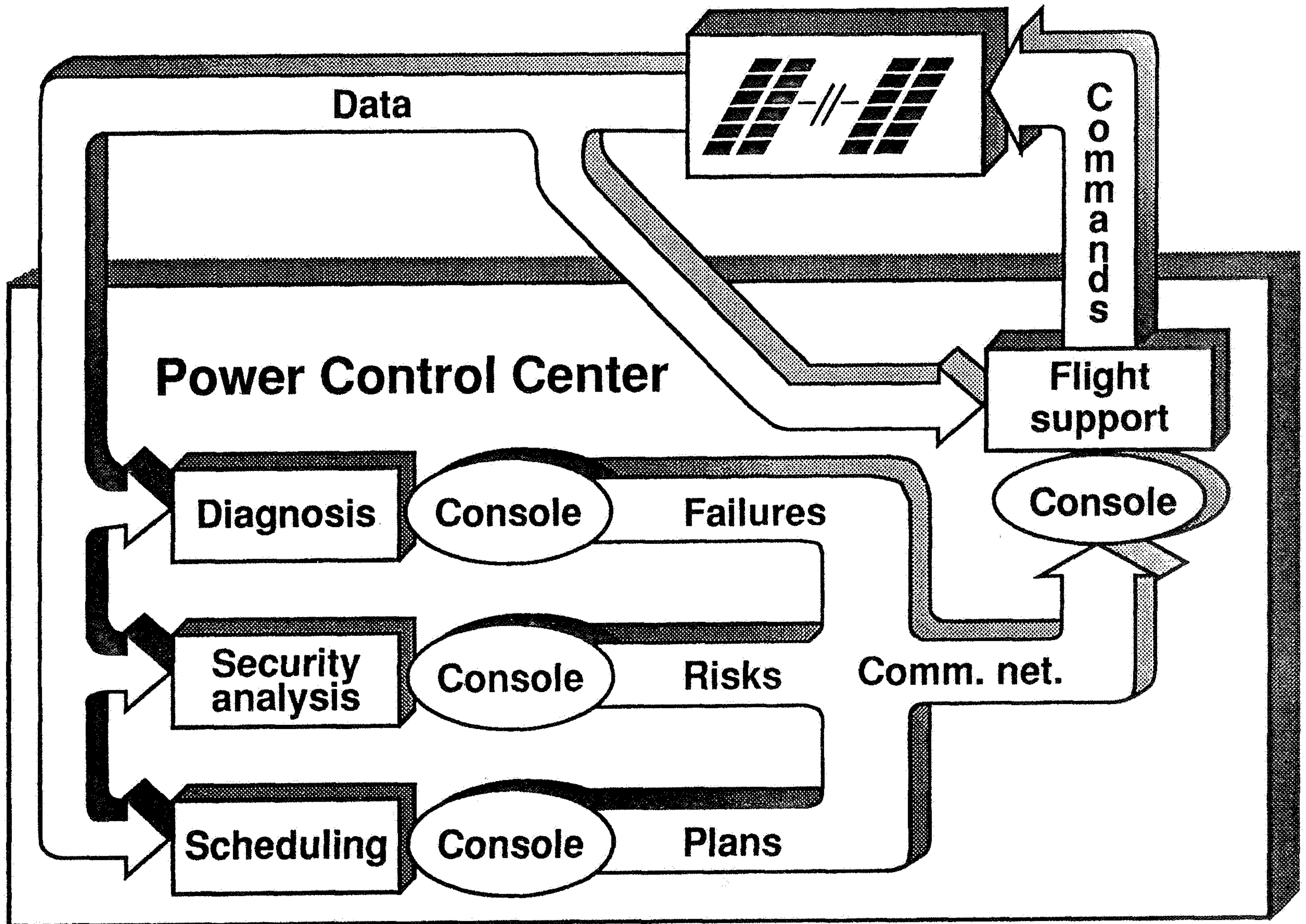
POWER CONTROL CENTER CONCEPT - REVISITED

To revisit the motives behind our program, we have responded to the Space Station restructuring effort by focussing our products as ground-based tools for operators. We see the use of our intelligent decision-making aids as improving the overall Station productivity by enabling decisions to be made faster and more accurately.

We have been investigating the Engineering Support Center at LeRC as our potential site for the power control center. Using the ESC we will be able to communicate directly to the LeRC Power Management testbed, as well as receive actual telemetry when appropriate. In this environment we will also be able to link to the MSFC payload operations center and exchange data necessary to diagnose and recover from power system failures that propagate from the primary system into the secondary.

SSF POWER AUTOMATION



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MSFC -- LERC COLLABORATION

Development of different expert systems for the power system on board the Space Station has been a direct response to the programmatic partitioning of the primary power system generation and storage and distribution from the secondary power distribution network. This partitioning has provided a manageable subset of the system for each of the developers. However, certain failures will propagate across these system boundaries and it is necessary to begin investigation of these effects.

A data link between testbeds at NASA-LeRC and NASA-MSFC has provided information to begin these investigations. This link has been used to demonstrate cooperating expert systems during this past year. The demonstration addressed a power generation failure that required the secondary system to perform intelligent load shedding at the module level. We are planning to continue this effort by investigating failures that ripple through the secondary distribution and whose recovery requires cooperation between both systems. In the context of the control center environment we are not planning any direct testbed links for the coming year. We want to study how to coordinate the entire power system operation using the control center environment. This will prepare us for real operational scenarios.

MSFC – – LeRC Collaboration

Cooperating expert systems

- Diagnosis
- Recovery

Effects that propagate across system boundaries

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LeRC POWER MANAGEMENT AUTOMATION EVOLUTION

When the Space Station program began, the electric power system was a 20kHz AC distribution system. Pioneering work had been done at LeRC in development of this technology. Many power system experts were available to provide the information required for intelligent control and diagnostic tools. Our program took advantage of these factors and developed a diagnostic tool in KEE for 20kHz switchgear which communicated with a scheduler for replanning usage after a system failure. These tools also communicated directly to prototype Ada flight code controlling 20 kHz switchgear. Development of these products and their integration has provided us with valuable insight into the problems that can occur. This work culminated in an integrated demonstration with a MSFC testbed over a long distance communication network. The products from this work are being modified to apply to the DC testbed configuration and will also be integrated into the power control center.

Parallel efforts began when the Space Station program switched from 20kHz AC to DC distribution. A diagnostic product using ART was developed along with a value-driven scheduler and the beginnings of the security analysis system. These products had been targeted for integration with the DC testbed directly as a demonstration of their potential use as flight decision-making aids. Due to the restructuring efforts and the current emphasis on ground-based control, we have reevaluated the thrust of our program. We are, however, continuing with integration of our products and the DC testbed directly. This serves as a preliminary step before integrating with the LeRC engineering support center, the ESC. We are developing the interfaces required to make an initial communication path between our advanced development machines and the testbed control computer using its current operator interface system protocol. Testbed work is very intense at the moment and this approach creates minimum impact on their efforts. We are also investigating the interfaces required for integration of the power system testbed and the ESC. The ESC will provide our advanced development products a rich environment of processed data and graphics interfaces. Our initial design features the advanced development machines communicating on a subnetwork and using one of the ESC machines for passing the data to and from our products. This minimizes the impacts on both the ESC and our program. After this interface has been developed and used to investigate testbed and automation product performances, we plan to generate specific application programs that would dirctly reside on the ESC processors.

Evolution

20 KHz AC System 1988-1991

- Scheduler
- Diagnostic
- Integrate with testbed
- Cooperative demo with MSFC testbed

DC System 1990-1992

- Scheduler
- Diagnostics
- Security analysis
- Integrate with testbed using OIS
- Integrate with testbed using ESC
- Link ESC with MSFC testbed
- Develop products as ESC application

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IN A NUTSHELL

In the ever changing environment of the Space Station program, power system management and control continue to be critical development items. Our advanced development program is focussed on developing decision-making aids for operators, either ground-based or flight-based. In the efforts to fully utilize electric power at all times, we need much automation. We are striving to provide automation tools which will allow the Station to flexibly and productively manage of one of its critical resources, energy.

We are targeting our products for the ground-based control centers knowing that this is where they are needed initially. Operating a Space Station will be a monumental effort and products to reduce the workload will prove themselves well worth their development cost. As Space Station develops, the need for these products will be onboard. We are prepared to continue our efforts and provide flight-quality products.

In a Nutshell

Productivity

Control center environment

Flight potential

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