

# Instrumentation and Control Needs for Reliable Operation of Nuclear Propulsion Based Space Exploration Systems

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The President’s Vision for Space Exploration will, by its nature, push the boundaries of the state-of-the-art in nuclear propulsion system operation. Evolutions such as autonomous system startup /shutdown, load following, and maneuvering will require the application of advanced control and health management strategies with an emphasis on *robust, supervisory, coordinated* control of, for example, reactor, energy conversion plant (e.g., Brayton Energy Conversion units), and thruster components. Autonomous operation implies that, in addition to being capable of automatic response to disturbance input or load changes, the system is also capable of assessing the status of the integrated plant, determining the risk associated with the possible actions, and making a *decision* as to the action that optimizes system performance while minimizing risk to the mission. Adapting the control to deviations from design conditions and degradation due to component failures will be essential to ensure mission safety and success. The paradigm of having a “standing army” of people to monitor and control the system will need to be changed with greater emphasis on on-board diagnostics and autonomy because of the extensive communication delays. Indeed, it is conceivable that some mission evolutions will be undertaken in complete communication blackout lasting several days, in operating conditions that are not completely known. Intelligent decisions will have to be made to choose the right set of sensors to provide the data needed to do on-board condition monitoring and fault detection and isolation – because of weight and space limitations, it will not be possible to have an extensive set of instruments as used for land-based systems.

Advanced instrumentation and control technologies will be needed to enable this critical functionality of autonomous operation. Rather than taking the typical approach of developing instrumentation and control after a “configuration” has been designed, it will be imperative to consider instrumentation and control requirements in parallel so as to identify control-related, as well as integrated system-related, problem areas early to avoid potentially expensive “work-arounds”. This paper presents an overview of the enabling technologies necessary for the development of reliable, autonomous space nuclear propulsion systems – with an emphasis on system architectures and off-the-shelf algorithms rather than hardware. Autonomy needs are presented in the context of a hypothetical space nuclear electric propulsion system and may be extended to significantly different nuclear applications such as nuclear thermal rockets and surface power. The scenarios and applications presented are hypothetical in nature, based on information from open-literature sources, and only intended to provoke thought and provide motivation for the use of autonomous, intelligent control and diagnostics.

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## I. Introduction

To meet the goals of the President's vision for exploration of our solar system, several key enabling technologies need to be matured as quickly as possible<sup>1</sup>. Among them, space nuclear systems significantly more complicated than those which have been deployed on deep-space missions to date (i.e., radioisotope power sources)<sup>2</sup>. NASA and the Department of Energy are currently teaming to provide nuclear power sources to fulfill this need. Aggressive mission objectives and extended durations warrant the development of nuclear reactor-based power sources – many of those in the trade space being novel designs which have never been built or operated on earth. Indeed, the flagship mission for NASA's Project Prometheus, Prometheus 1 (the Jupiter Icy Moon Orbiter)<sup>3</sup>, may employ a completely new reactor design as well as other components that have been tested on significantly smaller scales than what the mission requires<sup>4</sup>. While each of the individual components may have their own, well known dynamic operating characteristics (at the present scales and state of the art), the characteristics of the integrated system with the component designs at the scale required by the Prometheus 1 mission (or future missions) are at present unknown. Also, feedback controllers designed for the individual components (again, at the current designs and sizes), may require significant redesign after integration of the component as part of the spacecraft's propulsion system – not necessarily for nominal operation but for off-nominal scenarios that may originate in other parts of the system. This suggests that an autonomous "supervisor", capable of rapidly assessing the state of each component and its effect on the performance of the overall plant, be employed. This function has, for the most part, been performed by employing the human-in-the-loop supervisory control paradigm. For example, space shuttle missions employ the so-called "standing army" of personnel at mission control who continuously monitor the status of key subsystems. The robotic mars exploration rovers required scores of support personal to monitor and control the mission. In the event of a component or system failure, it is assumed that a human being (or several human beings) will identify the problem and initiate a corrective action. However, for all but the more slowly varying operational evolutions, the requirements of unmanned deep-space exploration missions preclude the use of human beings as a practical means of propulsion plant supervisory control due to extensive communication delays, a 1 to 2 hour round-trip delay as in the case of Prometheus 1, and blackout periods<sup>5</sup>. Thus, the characteristic essential for success of these missions lies in the ability of the propulsion plant to make decisions and take actions on its own – in other words to operate autonomously. While terrestrial nuclear power plants and naval nuclear propulsion plants require a relatively small number of humans for operations (e.g., 10-40 on shift at a given time), truly autonomous plant operation has yet to be demonstrated for a system of this complexity with the proposed operational requirements. Among these, evolutions such as startup, power down/up, transitions to/from coast mode, and defense-in-depth malfunction recovery.

This paper presents an overview of the enabling technologies necessary for the development of reliable, autonomous space nuclear propulsion systems – with an emphasis on system architectures and off-the-shelf algorithms rather than hardware. It is acknowledged that each topic presented represents a significant research effort in its own right, with the ultimate control and diagnostic solutions dependent on the final design. Emphasis is placed on the proposed near-term missions (through the year 2020) which are not intended to be basic research endeavors from the propulsion system perspective, with aggressive milestones and schedules that need to be met with *engineering solutions* to the challenges that arise.

There are literally scores of potential control and diagnostic solutions available. However, it is the opinion of the authors that, given the proposed schedules (e.g., a 2015 launch date for Prometheus 1), a prudent down-selection needs to be performed as early as possible concurrent with the design of the propulsion plant, rather than in the final stages of design where sensing or control requirements may not be achievable with the assigned sensor locations or computational capabilities. This paper is intended to provide a conceptual basis for such a down-selection. Autonomy needs are presented in the context of a hypothetical space nuclear electric propulsion system and may be extended to significantly different nuclear applications such as nuclear thermal rockets and surface power. The scenarios and applications presented are hypothetical in nature, based on information from open-literature sources, and are intended only to provoke thought and provide motivation for the use of autonomous, intelligent control and diagnostics.

## II. A Hypothetical Space Nuclear Propulsion System

There are several nuclear propulsion options in the trade-space for space exploration in the 21<sup>st</sup> century. Some of the more common system features include ion thrusters for primary propulsion, a nuclear heat source (either reactor or radioisotope type), an energy conversion unit used to convert heat produced in the nuclear reactor to electrical power, and a power management and distribution (PMAD) system used to route power from the energy conversion system to the primary propulsion units and science payloads. For the present study, a configuration similar to that

being considered for Prometheus 1 will be employed to provide a specific context for discussion. Figure 1 presents a possible propulsion system configuration consisting of a nuclear reactor, redundant Brayton cycle-based power conversion systems (PCS), waste heat radiators (WHR), power management and distribution (PMAD) systems, parasitic load resistors (PLR), power processing units (PPU), and ion thrusters<sup>3</sup>. As shown in figure 1 via the bidirectional arrows, it is anticipated that there will be dynamic interaction between those systems that have a direct interface e.g., the nuclear reactor -Brayton unit interface, as well as indirect effects that propagate through several different subsystems and affect the component of interest. The exact nature and magnitude of these interactions is, of course, dependent on the final design of the components. For the hypothetical propulsion plant provided, PCS load changes result in varying amounts of heat transferred from the reactor primary system to the Brayton working fluid (e.g., He-Xe) through an intermediate heat exchanger. The reactor, employing a negative temperature feedback characteristic, would naturally follow Brayton unit load transients. However, normal operation has the reactor (and Brayton unit) power constant over the majority of the mission, with load transients accommodated by diverting excess power to the PLR and radiating the heat produced into space. This load accommodating technique has been successfully demonstrated during ion thruster recycle transients at NASA Glenn using a 2 kW Brayton turbo alternator supplying thruster power via a PMAD.<sup>4</sup> As mentioned previously, normal operation (as well as anticipated, high probability component malfunctions - accommodated via redundancy) does not necessarily justify the need for autonomous, intelligent, supervisory control. The need for autonomy arises when the propulsion system encounters off-normal situations that may result in a variety of outcomes, depending on the actions taken by the supervisor, that require a *decision* to be made in *real-time*.

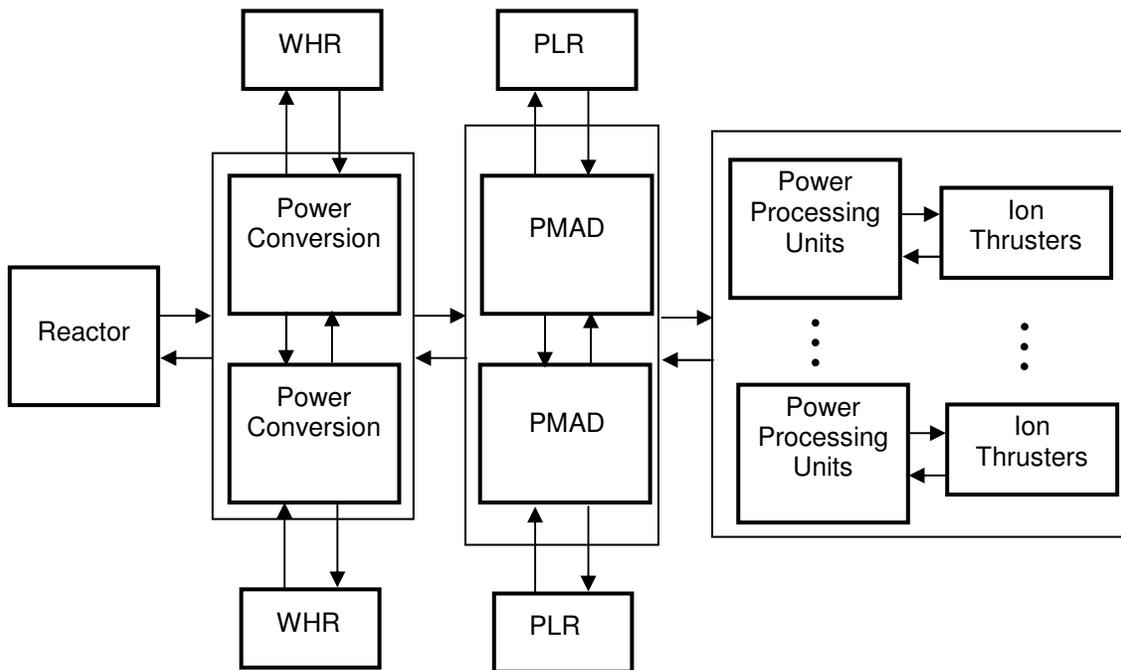


Figure 1. Hypothetical spacecraft nuclear propulsion system

### III. Motivating Scenarios for Autonomous Space Nuclear Propulsion

Consider as a motivating example the hypothetical scenario where the switching circuitry that directs power flow to the PLR suffers a malfunction. A large, rapid loss of load occurs (perhaps due to loss of one or more PPU), and excess power that would normally be radiated out into space via the PLR gets diverted to a second, redundant PLR. The situation deteriorates further with the redundant PLR's circuitry also failing due to some common mode event, causing the Brayton Unit's alternator to overspeed and consequently trip off line, resulting in significantly less heat being transferred from the reactor coolant to the Brayton's working fluid in the intermediate heat exchanger. The temperature of the coolant flowing back to the reactor rises, with the inherent negative temperature feedback effect driving the reactor power down. Since the Brayton unit has tripped off line, power that would normally be supplied

to the reactor coolant pumps and control drive mechanisms is no longer available, resulting in a reactor shutdown. During the initial stages of this loss of load transient an autonomous system's supervisor could *anticipate* this possible fault scenario and *decide* to initiate an alternate control strategy to minimize the risk to the system and mission e.g., performing a limited runback of the entire system, thus preventing a turbo alternator trip due to a double PLR loss. The extent of the runback would be determined by the evolution of the malfunction i.e., as the situation deteriorates the likelihood of a mission failure increases, resulting in more drastic measures being taken on the part of the supervisor. Thus, the autonomous system will preserve the mission at the cost of, perhaps, mission schedule and has also provided a more *reliable* system in general via a *defense-in-depth* strategy.

The above is an example of functional redundancy (the autonomous control system deciding to initiate a system runback) providing support to hardware-based block redundancy (the two PLRs). The Cassini-Huygens mission system architecture<sup>6</sup> provides an example of a similar defense-in-depth strategy. For terrestrial nuclear systems, functional redundancy is often provided by plant operators. However the entire sequence of events described could occur over a period of several seconds, precluding possible human intervention (recall the 1 to 2 hour round-trip communication delay). Thus, illustrating the essential need for autonomy in systems where fault conditions have the potential to deteriorate rapidly and result in mission failures.

Other, relatively routine operating evolutions would also benefit from an autonomous supervisory control system with varying degrees of intelligence. For operation involving automated up-power from extended coast periods and maneuvering transients, a candidate controller algorithm would be optimized feedforward-robust feedback control. This technique uses optimized actuator commands computed in advance (possibly using a genetic algorithm-based optimization scheme), with robust feedback controllers to accommodate system uncertainties and real-world effects such as actuator saturation (it is prudent to assume that due to the aggressive schedules presented, a "perfect" integrated system model will most likely not exist at the time of launch). If a significant decrease in power of the entire system is implemented, the subsequent startup sequence is crucial not only from the perspective of mission goals, but also from the perspective of operability e.g., the reactor and Brayton system components require the appropriate time to heat-soak their internals prior to initiating the next phase of startup. A potential concern regarding reactor startup involves brittle fracture of the reactor vessel - heat up and pressurization must be coordinated in order to maintain reactor vessel integrity. The propulsion plant supervisor might employ Multiple Input Multiple Output-type (MIMO) subsystem controllers to effectively coordinate the operation of multiple Brayton units, thrusters, etc., while accommodating uncertainties in the models used to synthesize the controllers. As well, supervisory algorithms could be developed to address issues such as optimal load distribution during maneuvering transients. Once again, due to the interaction of several subsystems, each with their own dynamic (feedback) characteristics, precise coordination of the integrated system is essential. Autonomy during well-planned, perfectly understood, operating scenarios may still be thought of as unnecessary. However, to accommodate *unanticipated* events, a supervisor, continuously monitoring the progress of each subsystem, additionally determines alternate minimum-risk control strategies to use in the event of off-normal occurrences or malfunctions.

#### **IV. A Supervisory Control Architecture for Autonomous Space Nuclear Propulsion**

The exploration of space has associated with it many sources of uncertainty e.g., long communication delays, system degradation, and rare (but possible) events such as meteoroid impact. These need to be accommodated by a supervisory control structure that integrates controls, diagnostics and decision making ability for the entire system. Autonomous operation can be achieved by applying a high-level supervisory architecture, such as the hierarchical discrete event supervisory (DES) control structure presented in Yasar et al<sup>8</sup>. This type of architecture would enable different degrees of system autonomy at various hierarchical levels, while giving Mission Control mission level system control. Mission planners maintain control over the overall mission goals and objectives while yielding subsystem and component level control to the hierarchical DES system.

External commands from the on-board flight control system are communicated directly to the top level DES, the *Integrated Propulsion System Supervisor* (IPSS). The commands then propagate through the system via the DES hierarchy. Each hierarchical level performs the commands and controls the levels below it. For example, figure 2 presents an architecture with the various subsystems of the integrated propulsion plant, each with their own *component supervisor*, control, and diagnostic systems, interacting with an integrated propulsion plant supervisor. Highlighted in the figure is the Brayton power conversion system interacting with its own DES, or component supervisor. The IPSS informs the other component supervisors to perform the commands to meet the highest level commands, typically from the flight controller. This hierarchical architecture results in a low level of autonomy for the highest hierarchical level, the IPSS; a high level of autonomy for the lowest hierarchical level, the component supervisors, thereby giving subsystem and component level control to the designer. As additional hierarchical levels

are added, the component supervisors will have more autonomy, because they will become further removed from direct IPSS command. In certain situations, mission planners may need direct control of the component, which can be achieved by designing a DES override.

Using this architecture, Yasar et al<sup>8</sup> have shown an increased mission success rate during off-nominal flight of aircraft. The adaptation of hierarchical DES to space nuclear systems would involve identifying uncertainties and accommodating them in the DES design. Figure 3 presents an overview of the diagnostics and prognostics portion of the component supervisor. Success of the hierarchical strategy presented is heavily dependent on the effectiveness of the on-board diagnostics and prognostics system. Optimal sensor selection and placement, which is accomplished early in the design of each subsystem, is essential for successful diagnostics and prognostics.

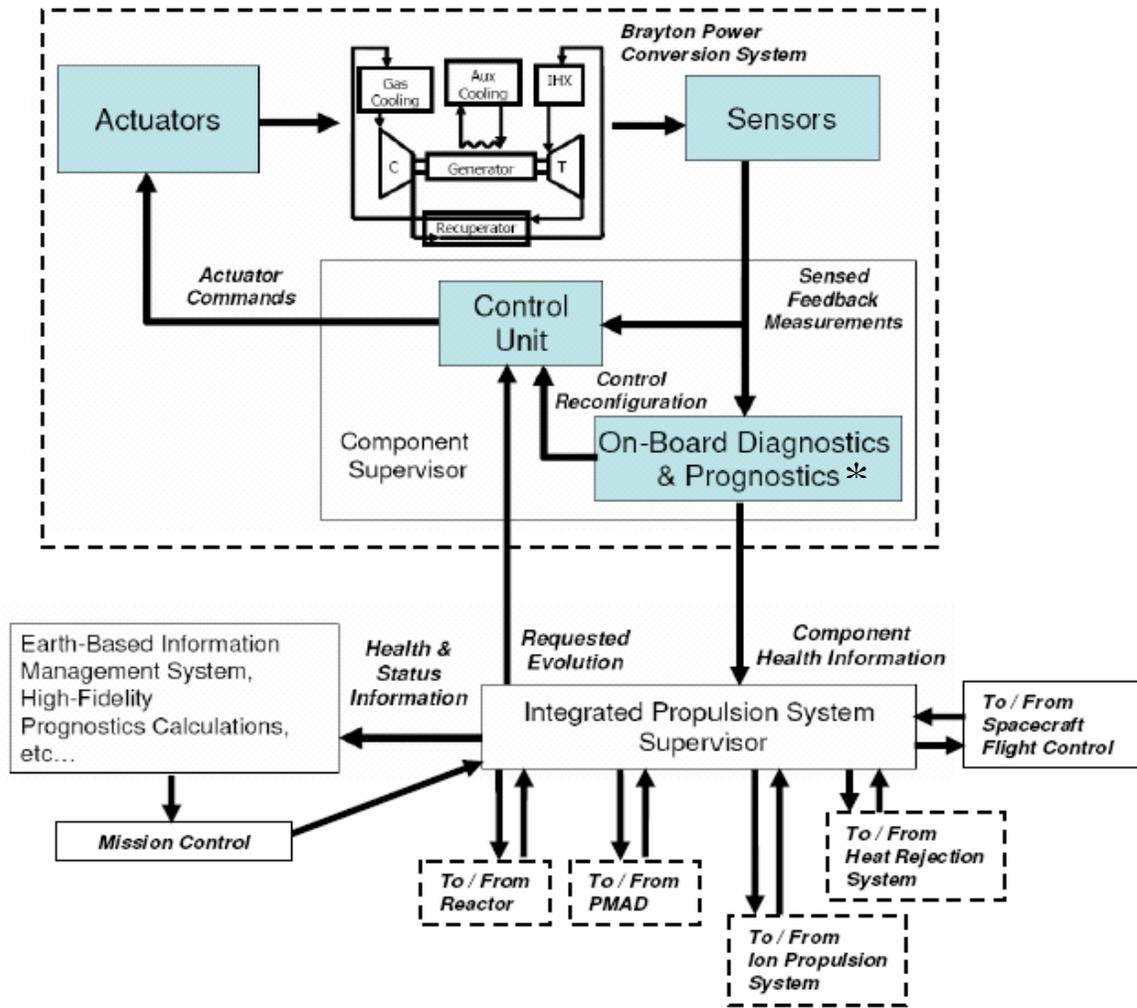


Figure 2. An example supervisory control architecture for autonomous space nuclear propulsion.

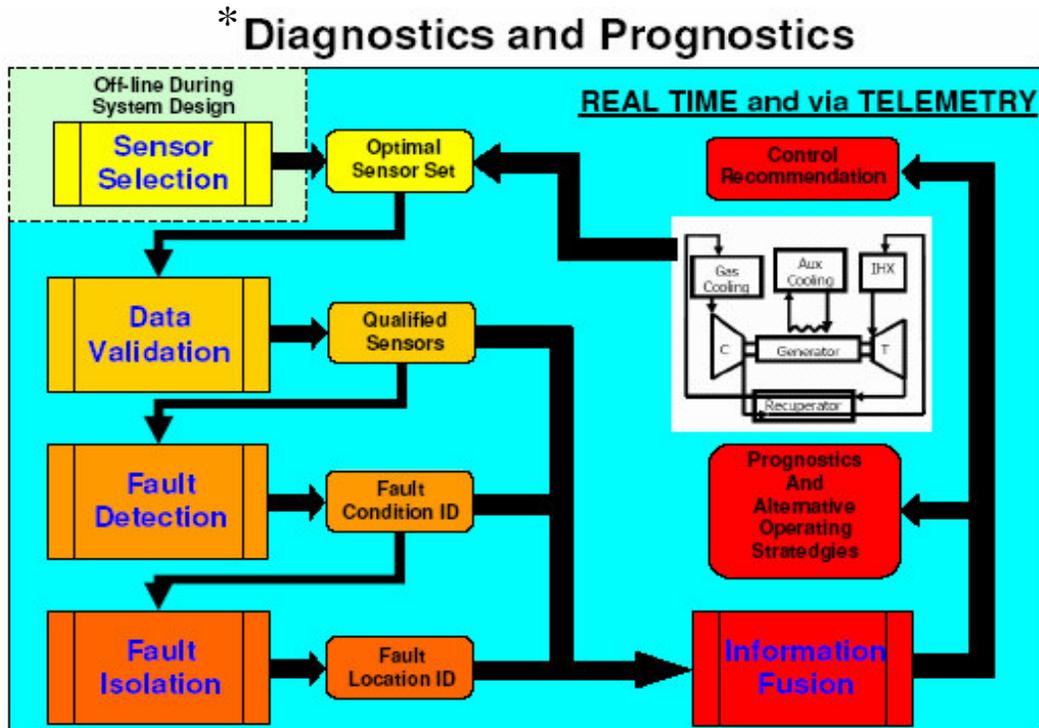


Figure 3. Component supervisor on-board diagnostics module.

## V. Needs for Autonomous Control

The needs for autonomous system operation originate in well-defined mission goals and objectives. For the purposes of this study, the propulsion system mission objective is to provide safe, continuous, maintenance-free operation for 15 years while accommodating all necessary maneuvers, evolutions, and faults (un-hypothesized as well as hypothesized). An example autonomous system architecture was presented in Section IV. This section discusses the areas that need to be addressed in order to provide this level of autonomy for the propulsion system presented in Section II. Implicit is the need for appropriate placement of physical sensors, analytic or virtual sensor capabilities, methods to minimize system status uncertainty via, for example, sensor fusion techniques, the ability to extend the useful life of the components via intelligent control, diagnostic techniques and health management, and the development tools (i.e., the infrastructure) necessary to provide rapid-prototyping capabilities for subsequent down-select. The needs for autonomous system operation may be broadly divided into the following areas that define the scope and implementation of the autonomy desired: Guidelines for High-level Autonomy, Functional Description of an Autonomous Control System, Faults and Failure Modes, Hazards Analysis, Metrics for an Autonomous Control System, and Software Quality Assurance and V&V. Each of these areas is described below.

### Guidelines for High-Level Autonomy.

- The autonomous control system will enable the propulsion system to meet the operational power requirements for all mission phases, during nominal and off-nominal conditions.
- The autonomous control system will identify, mitigate and resolve system faults.
- The autonomous control system will identify system degradations and use recovery actions, if needed, to maintain mission objectives.
- The autonomous control system will document design intent, and any changes.
- The autonomous control system will allow for on-board software upgrades.
- The autonomous control system will be verified and validated.

Functional Description of an Autonomous Control System. An autonomous control system can be viewed as doing three things: observing, processing, and managing. Each of these can be further reduced to the following:

*Observing:*

- Monitoring – observations from sensors and calculated health measures.
- Recording – data, commands, status bits, reports, log files.

*Processing:*

- Tracking – using mental map (models/rules) of expected nominal system behavior.
- Condition Assessment – detecting threshold crossings or mode changes.
- Inferencing – reasoning about likely causes for anomalous observations.

*Managing:*

- Executing — interacting with vehicle to control it.
- Planning – whether to continue on course or to re-plan under failure conditions.

Wood et al.<sup>9</sup> suggest the three basic building blocks of an autonomous control system are control algorithms, diagnostic algorithms and decision algorithms. The various inputs to and outputs from these functional blocks are commands, observations, status readings and decision feedback. In addition they also recommend a hierarchical framework for autonomous control of the reactor with interfaces to other systems. The layers in this hierarchy reflect the functional layers of the physical system. So the design of the controller will be understood and inspected more easily, which leads to a safer design. Autonomous control involves the complete path from sensing the value of a particular measurement to the execution of a particular action that enables optimal performance. In general, techniques in classification, inference, projection, and decision making can be applied to areas such as diagnosis and prognosis. How to balance the partition between diagnosis, prognosis and “designing-out” failures is still an emerging art for space applications.

Diagnosis can be performed using inductive learning such as decision trees, case-based reasoning, rule-based or model-based approaches, explanation-based learning, genetic algorithms for search and optimization, neural networks, fuzzy learning and soft computing techniques. The selection of specific diagnostic approaches has to be guided by their respective strengths and limitations, and by their suitability for the particular control architecture being considered. Choosing the right control architecture is an important step in the top-down design process from requirements to software implementation (from abstract function to specific implementation).

Faults and Failure Modes. The design space consists of what the autonomous control system is required to do (capability requirements), and the constraints within which it must operate, such as plant constraints, domain knowledge constraints, and actuator constraints. Within this space, we can identify what fault types are required to be covered. Faults can be broadly categorized as:

- When they occur: during the initial phase, during the regular operation phase or end-of-mission phase (there is usually a “bathtub curve” for probability of fault occurrence versus time)
- How long they last: whether permanent, temporary, or intermittent.
- How they manifest: whether discrete or continuous (e.g. leak), abrupt or gradual.
- How they relate to other faults: whether independent, correlated, cascading, or simultaneous faults with a common cause
- What causes them: inherent in design (structural or functional), due to uncertainties in operating envelope, or due to external conditions
- What they affect: the component, the subsystem or the system (or all three).
- How critical are they: non-critical, recoverable or mission-critical

Fault knowledge involves fault models, component failure rates, and fault/symptom associations (context-dependent knowledge). Expected failure rates are usually outlined in a Failure Modes and Effects Analysis (FMEA)<sup>10</sup>. Other domain knowledge comes from schematics, block diagrams, instrumentation list (sensor type, location, number, redundancy, sampling rates), telemetry list and the operations timeline. There may also be information from fault analyses – fault trees, event trees, and probabilistic risk assessment.

Density and coverage of faults is a useful estimate to have, early in the design phase. Sensor selection and placement can be guided by such models of fault coverage. Testability analysis tools provide good estimates of fault coverage.

Hazards Analysis. It must be noted that failures are different from hazards<sup>11</sup>. Hazards are conditions that can lead to an accident, even when no component has failed. Hazard Level is a combination of severity and likelihood of occurrence of the hazard. For deep space missions some likely hazards are:

- Contamination/corrosion – chemical disassociation of material
- Radiation – Nuclear, Electromagnetic, Ionizing, Thermal/Infrared, Ultraviolet
- Temperature extremes – high, low, or rapid changes
- Impact/collision – meteoroids

There are emerging techniques in *Design under Uncertainty* that can address the controller's sensitivity to random environmental inputs.

Metrics for an Autonomous Control System. A benchmark is a standard task, representative of problems that will occur frequently in real domains. A testbed is an environment to test standard tasks. It enables this by providing (hardware and software) tools for data collection, for external parameter control, and for scenario generation.

Since autonomous control of a nuclear reactor-based propulsion system is a relatively new field there are no benchmarks or testbeds. So, relevant metrics may initially be hard to assess. However, based on experience in other diagnostic systems, some suggested metrics are:

- Accuracy – false/missed alerts, robustness to real-world effects (noise)
- Speed – hard real-time critical versus near real-time
- Coverage – multiple/intermittent faults, subsystem-level versus system-level
- Cost — time to develop, integrate and test, additional hardware requirements
- Ease of Engineering – modular, reusable, scalable, understandable

Software Quality Assurance and V&V. The software implemented for propulsion system control will be a safety-critical, real-time system. It must satisfy explicit and very tight response time constraints. In addition, it must integrate with external software (such as diagnostic software from the flight control system) for the sharing of information. To implement such high performance software, appropriate software engineering practices must be followed immediately. This encompasses all phases of software design from requirements definition through release and maintenance and includes definition of executable specifications, reliable coding practices and code generation, performance analysis, and verification and validation of the system. To facilitate software debugging and upgrades, a modular (object oriented) architecture should be employed.

## **VI. Modeling Needs for Autonomous Systems**

Modeling needs for an autonomous system are heavily dependent on the ultimate use of the model. Initially, the modeling and simulation tools that are employed to support the development of a new design or application focus primarily on scaling up (or down) similar existing systems and emphasize system configuration, nominal steady state performance, and minimum spacecraft weight. While these models are usually sufficient to predict steady-state behavior, they are not adequate for analyzing the system at the level of fidelity required for diagnostic and prognostic applications and fault accommodating control. Dynamic analysis of these systems is usually delayed until the designs are set and components built. Ideally, initial dynamic model-based analyses should be part of the trade-space studies to ensure that the component operates satisfactorily under steady-state and transient conditions as part of the integrated plant. The models used for these initial studies may (depending on the technology investigated) be low-fidelity, with parameter values bounded by extremes to provide worst and best-case transient performance. As designs are finalized, high-fidelity models and simulations that can more accurately predict system transient behavior under any condition are required. These models would allow the injection of failures typically experienced by the system and track their effects as they propagate throughout the system. The data generated would be used to develop diagnostic strategies to assess the state of the system. In addition, failure models would characterize system wear and fatigue as well as enable the prediction of failures, which would support on-board as well as high fidelity prognostic capabilities. High fidelity models, however, are typically non real-time and inappropriate for use in control system implementation. Models that support prognostics and are used to predict component life based on current and historical data can provide a basis for future decisions. Such decisions can result in system reconfiguration that may be preformed several days in the future. These models may be more detailed and do not

necessarily need to be real time - if the added complexity is warranted, these models may be run back on earth in supercomputing environments if necessary.

Development and validation systems (i.e., the infrastructure discussed previously) should employ a variety of low/med/high fidelity models, configured as simulation modules, to provide a means to rapidly determine the fitness of a group of sensors or controller algorithms given appropriate performance measures. To this end, the existence, scope, and availability of existing simulation models for the major subsystems and components should be determined immediately, with these models leveraged if possible, and adapted for use in a common model development environment. These same modules should be easily transformed into models suitable for use in model-based control and diagnostic systems i.e., real-time embedded system applications.

The level of fidelity of on-board models will in part be dictated by the processing hardware chosen for the mission. Model uncertainty can be incorporated into controller design and be determined by comparing the lower fidelity models used with higher fidelity models or test data. Model fidelity and complexity are also determined by the degree of autonomy desired i.e., some component details may have a simplified representation in on-board models if a more accurate representation is not essential to the corrective action taken. In the absence of high fidelity dynamic models, assume worst-case uncertainties and interaction among the subsystems. The following guidelines provide example subsystem model capabilities that would typically support autonomous system development:

- The model should be capable of providing response characteristics for routine evolutions such as startup-shutdown, load following, etc. These characteristics may be lifetime dependent (e.g., dependent on reactor fuel burnup) for possible use in nonlinear gain-scheduled or model-predictive control schemes.
- The model should be capable of simulating key high-bandwidth transients and faults. This may require the use of stiff-system, adaptive time step numerical integration techniques. These models may require order reduction and conversion to constant time step solvers for use in real-time, on-board control and diagnostic systems.
- Systematic methods for producing high fidelity reduced order models for on-board control and diagnostics. Research currently underway in the jet propulsion industry involves deriving low-order models, suitable for use in on-board model predictive control schemes, from high-order, non-linear performance models. This expertise should be leveraged.
- Component models of devices whose malfunction may require system reconfiguration such as control drives, coolant pumps, valves, etc., should be of sufficient complexity to represent the specified fault.
- Sensor models capable of providing appropriate bandwidth characteristics (e.g., accelerometers used for structural health and component monitoring) as well as malfunctions such as drift, bias etc., are also required.
- Sensors specific to a component need to have modeling features that support any unique diagnostic information that the sensor may provide. For example, models of reactor SiC ex-core neutron sensors should accommodate neutron noise and power distribution irregularities.
- The ability to locate sensors at random, physically acceptable locations in the system is essential for optimal sensor placement studies.

## VII. Sensor Needs for Autonomous Control

Some of the more pressing challenges for sensor development are in the areas of long-life, radiation-hardened sensors and electronics. Sensors for terrestrial nuclear and aerospace applications<sup>12</sup>, which have historically consisted of accelerometers for vibration, thermocouples and resistance detectors for temperature, venturis or orifice plates combined with differential pressure transmitters for flow, and ion chambers for reactor power measurements are presently not capable of meeting the requirements imposed by long-duration space missions e.g., 15 year maintenance-free continuous operation. Reactor power monitors using gas-filled ion chambers require periodic maintenance, and will likely be replaced by solid-state detectors, such as the SiC-based detectors currently under investigation by the terrestrial nuclear industry<sup>13-15</sup>. Other instruments operating in and in close proximity to the reactor must possess long-term tolerance to high temperatures as well as a mixed neutron-gamma field. The radiation fields experienced by the remainder of the spacecraft would have neutron dose rates significantly diminished due to primary (i.e., reactor) system shielding, with the dose rates predominantly due to background gamma<sup>3</sup>. Electronics utilizing SiC-based components are well suited for high temperature operation, which may result in reduced cooling requirements. In addition to harsh environment constraints, size and weight limitations as well as minimizing the number of penetrations in piping and the primary shield also impact the instruments (sensors and electronics) selected for a particular mission.

Sensor redundancy would, to some degree, address issues associated with periodic maintenance – rather than removing and replacing a malfunctioning sensor (obviously not an option with the hypothetical mission presented), simply switch the redundant sensor into service in the same (approximate) location. However, since the redundant sensors would be located in close proximity to the original on-line sensor, they too would need to satisfy the same lifetime requirements with respect to the operating environment. Only issues associated with sensor operation e.g., deterioration due to application of an electric field or unanticipated malfunctions, would be accommodated by redundancy. For deep-space missions where spacecraft size and weight are of concern (i.e., limited “real-estate”), MEMS-based sensors would seem to provide a means for simultaneously satisfying the redundancy requirement and space limitations<sup>16, 17</sup>.

To minimize the non-environmental dose received by the computing equipment on board the spacecraft, as much of the instrumentation as possible would be located at points distant from the reactor. Use of radiation-tolerant electronics would have the added benefit of reducing primary shield weight, thereby reducing the total spacecraft weight at launch. To minimize the number of instrument cables (and shielding penetrations) required, radiation-hardened multiplexers would be required<sup>9</sup>. The state of the art in radiation-hardened electronics relies on components constructed primarily of SiC<sup>15</sup>. Further development in this area is needed to provide devices that provide the lifetimes required. Piping penetrations could be minimized by advancement of carbide-compound, MEMS-based remote sensing (where sensors are implanted into the walls of the pipes<sup>19</sup>) and passive acoustic tomography technologies<sup>20</sup>. Development of minimally-intrusive thin-film multifunction sensors to provide, for example, simultaneous measurements of strain, heat flux, and flow in a single package is an example of existing research that could be leveraged in this area<sup>16</sup>. All of the sensors in the trade-space must also provide the bandwidth characteristics necessary for monitoring system transients and fault detection (e.g., accelerometers used for structural health and component monitoring). With the sensors required by each system determined and well-characterized, sensor placement studies may commence.

In the power and process industries, sensors are often placed in the most convenient locations dictated by the system designers. These locations may not be optimal in terms of the *quality* of information the sensors could provide with regards to monitoring the overall health of the system. In the initial stages of system design there is usually some latitude with regards to sensor location. Some sensor locations may be considered optimal over others from the standpoint of detecting faults, and adding extra sensors in key locations may allow estimation of component efficiencies and provide the information necessary for *analytical redundancy* of some sensors. Analytical redundancy refers to the model-based estimation of an otherwise sensed parameter, such as temperature or pressure, for the purposes of verifying the information coming from the actual sensor. The estimation is typically based on measurements from sensors other than the one being verified. Many times, information on parameters that can not be directly measured (e.g., flow rates, temperatures, efficiencies) can be provided by a model-based *analytical sensor*, providing an estimate of the parameter of interest<sup>21</sup>.

Systematic sensor selection (SSS) is an enabling technology for sensor placement currently applied to rocket engines<sup>22</sup>. Figure 4 provides an overview of the SSS process. The process requires three categories of information. The first category consists of identifying targeted fault and sensing requirements. Risk reduction factors are associated with each fault to enable ranking of the faults in terms of the risk reduced by timely identification. The second category contains candidate sensor information which includes sensor type and location (a “sensor suite”) and estimated variance for normal operation. The third category defines fault scenarios that correspond to the targeted faults in terms of hardware-specific indications. Combined, the three categories effectively condense available engineering experience and process physics required for sensor selection. As shown in figure 4, a nonlinear (or linear) inverse process model provides a mapping from the trial sensor suite to the corresponding system states. The states calculated by the inverse model are compared to a set of “true” states (which may be based on test data or a high-fidelity model), with the difference used as an input to a quality measure (merit function). The corresponding merit values are used by a genetic algorithm that iteratively improves the quality measure by adjusting the contents of the sensor suite (sensor type or location). Speed and fidelity of fault detection, support for risk reduction, and fault source discrimination are examples of additional input quantities to the quality measure. Finally, a statistical evaluation algorithm is used to determine the probability that the fault identification produced by the optimal (or near-optimal) sensor suite might be confounded by control system-induced sensor variation or noise. A final assessment that assimilates all of the recommended sensor locations will determine the best overall sensor suite. Final sensor suite selection must be complete prior to the design and implementation of any control, diagnostic, or health management system.

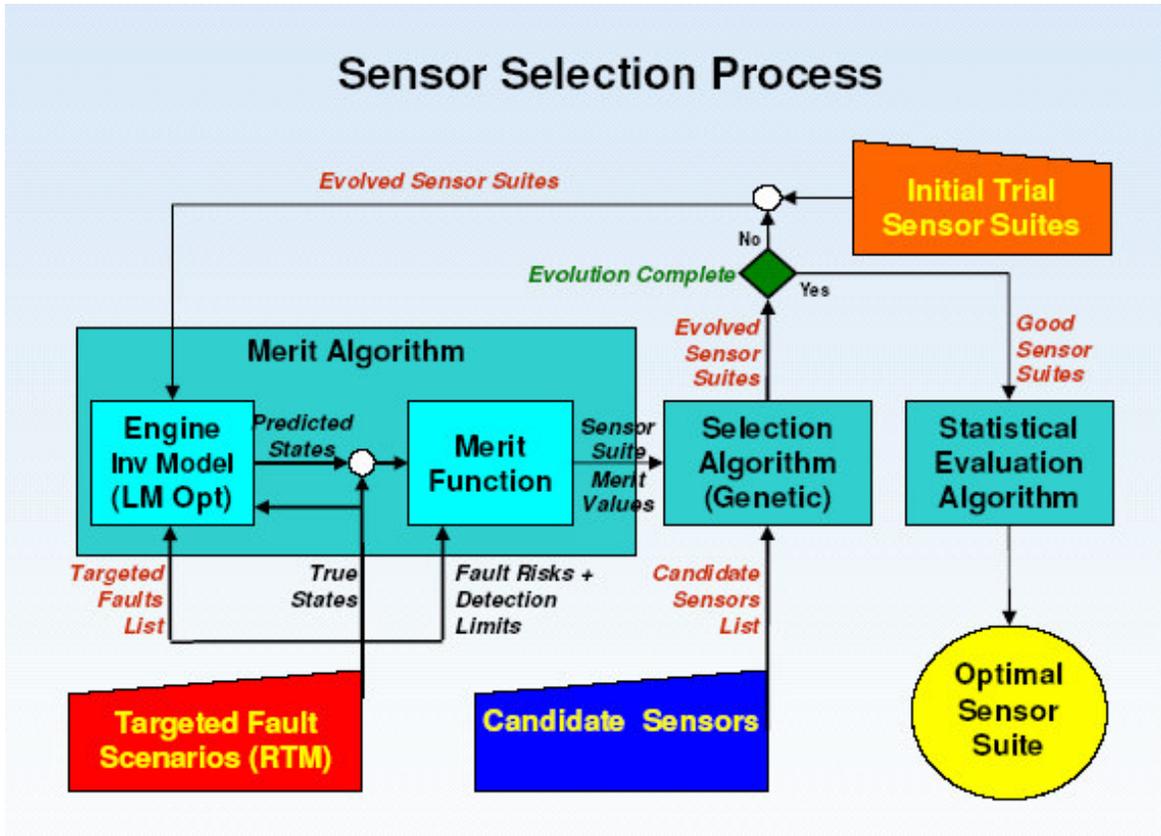


Figure 4. Overview of the systematic sensor selection process.

### VIII. The Role of Health Management in Autonomous Control

Health management (HM) technologies are utilized and applied to systems where a “supervisor” understands and assimilates system information so that mission goals are protected and robust operation is ensured. The structures of these HM systems are composed of software algorithms that can be as diverse as the systems onto which they might be applied<sup>23-25</sup>. For instance, the data available from the power system might have very different rates and resolutions than the data available from the propulsion system; this might require different types of signal processing algorithms for each HM system. There are, however, fundamental “building-blocks” in a basic architecture that any HM system can utilize, and this is illustrated in figure 5.

The foundation of any well-designed HM system is a well-defined system and concept of operations. Since the failure, modes, and effects analysis (FMEA) and system requirements naturally follow from these two elements and form the basis for the HM system, without these two essential elements the HM system can not be adequately designed. In addition, high risk failure modes will need to be identified that the HM system must be able to detect and isolate. Optimal selection of sensors and their locations within the system will enable the greatest potential for successful health diagnosis and prognosis while at the same time maximizing risk reduction for the system as a whole. The diagnostics and prognostics capabilities of the HM system are comprised of software algorithms that can perform data validation, fault detection, fault isolation, and information fusion; this ultimately provides information for any recommended control actions, maintenance plans, and refinement of system operations. In the end, the HM system needs to protect the system it was designed to manage in an efficient, robust, and timely manner.

The need for HM in autonomous nuclear space propulsion is illustrated via a subsystem common to virtually all nuclear systems currently in the trade space, the power management and distribution system. Advanced PMAD technologies will enable the future success of long duration space-flight missions, new launch vehicles, operation of ground- or space-based stations, and deployment of satellites<sup>26, 27</sup>. Illustrated in figure 6 are some PMAD components and their relationship to others within the power subsystem.

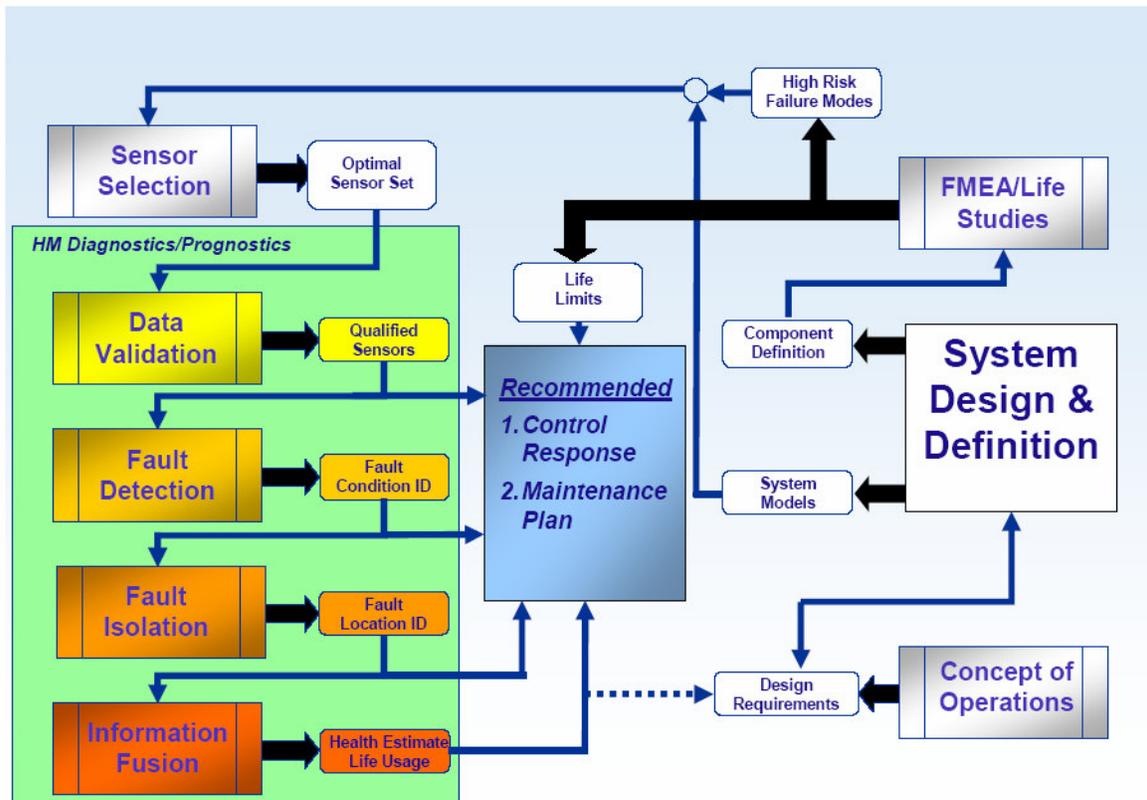


Figure 5. Systematic health management development.

The function of the PMAD subsystem has a direct influence on the operation of the other subsystems. For example, with an unhealthy PMAD, there could be an interruption in power to the rest of the system, which might disable the communications system or the electronics for the control systems. Therefore, the detection and isolation of a fault in this subsystem is important to the overall function of the entire system. In other words, the “health” of the PMAD subsystem is inherently important to the overall “health” of the entire system.

Fault modes in the PMAD subsystem manifest themselves in many ways. A problem due to an electrical degradation might be exposed as a failure or declining performance in a component. Likewise, arc, leakage, and corona are “hidden” system electrical faults that are hard to detect. A health management system for the PMAD subsystem will need to detect and isolate faults like the ones listed above and recommend mitigating actions so that they do not become critical.

Current research on modular electrical power systems indicate improvements in reliability and safety, while at the same time lowering development and operational costs, by using unique distribution topologies and “modularizing” the power system to provide higher degrees of flexibility in the PMAD. However, this increases complexity and indicates the need for a health management system that can analyze the power system data, assess system health, and optimally reconfigure the power system autonomously. In addition this will also reduce the amount of ground support personnel and support systems needed over the life of a mission. The integration of PMAD health management technology will greatly enhance the system reliability and safety of power systems that will be required in any Office of Exploration Systems program.

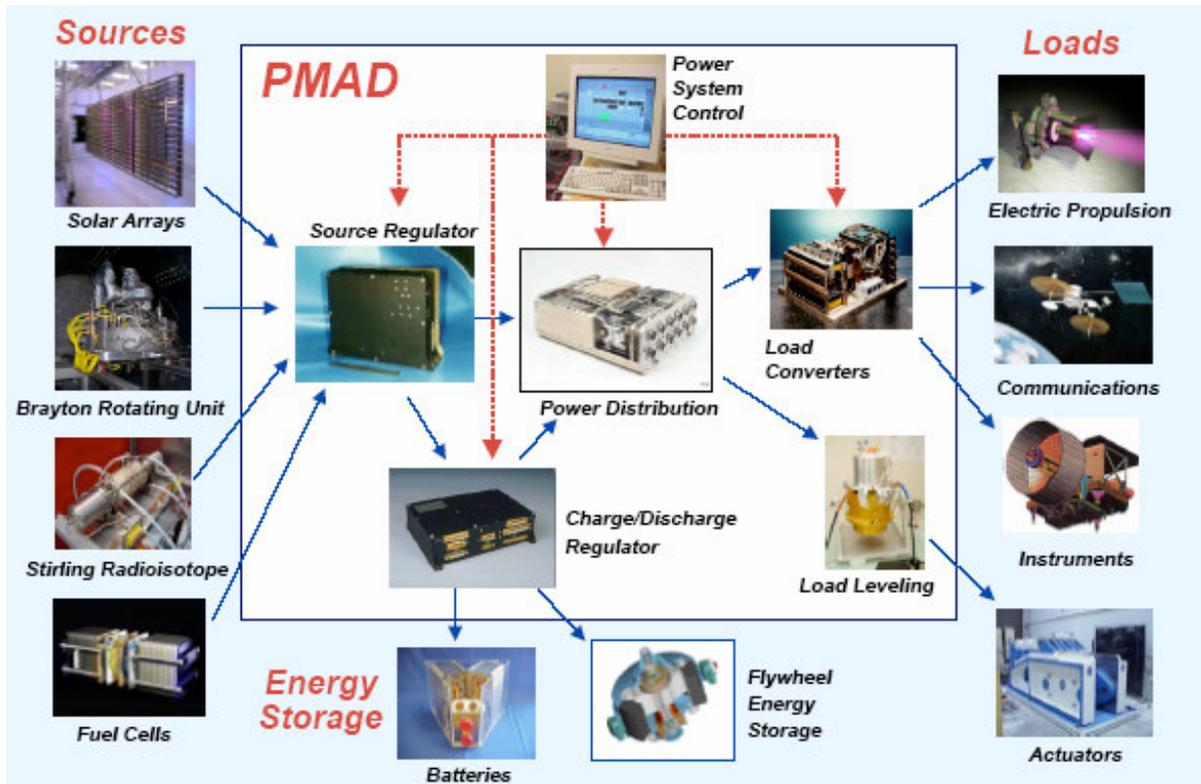


Figure 6. PMAD and power system components

## IX. Leveraging Past Experience in Autonomous System Development

Redevelopment of technology is costly and time consuming. Tight schedules and limited financial resources warrant adaptation of existing techniques whenever possible. Significant progress has been made in intelligent and autonomous system control within the aerospace and power industries<sup>8,24,28,29</sup>. Many of these control system designs can draw upon techniques developed for jet and rocket engines. For example, high and low-frequency instabilities have been observed while operating Hall-type ion thrusters<sup>30</sup>. Combustion control research is currently underway at NASA to investigate attenuation of combustor thermo-acoustic instabilities via superposition of stability control signals onto the nominal engine fuel flow demand signals<sup>31</sup>. While this research addresses a fundamentally different phenomenon, the knowledge gained and solutions developed may provide insight into control of ion thruster instabilities.

Current research into engine life extending control techniques<sup>32</sup> (such as determination of optimal acceleration schedules to minimize component deterioration) may be an example of an existing technology that can be directly leveraged for components such as the Brayton power conversion system, which are similar in dynamic system characteristics to gas turbine-based turbofan engines. The following provides some specific examples of state-of-the-art technologies that can be applied to the hypothetical space nuclear system described in Section II.

Robust MIMO control system design strategies. Robust MIMO (Multiple Input Multiple Output) control system design strategies (e.g.,  $H_\infty$  optimal control) have been used extensively in the process and active vibration control areas for over a decade<sup>33, 34</sup>. More recently, this technique has been successfully applied to research reactors<sup>35,36</sup>. Opportunities exist to apply supervisory systems (e.g., based on neural network or fuzzy logic architectures) to coordinate the efforts of MIMO robust reactor and energy conversion plant subsystem controllers. MIMO robust control techniques require quantification of plant uncertainties, which are then incorporated into the controller

design to accommodate unknown or un-modeled plant dynamics. Plant uncertainty is incorporated via transfer functions, determined experimentally or via appropriate low order linear models of higher order non-linear models. As system designs (and simulation models) mature, Model Predictive Control techniques, which employ a faster-than-real-time model to determine optimal actuator commands given a set of constraints, could also be implemented. These on-board models could be periodically updated and loaded into the control system processor using operating data acquired during the mission.

Sensor fusion techniques. Sensor fusion is a method used to reduce the uncertainty associated with the monitoring of specific operating parameters and identification of component malfunctions<sup>37</sup>. Fusing information from different sources is currently used to enhance the reliability of aircraft engines<sup>21, 38</sup> and could be applied to reactor / energy conversion systems using, for example, neutron noise, temperature, pressure, and vibration sensor signals. In the absence of measured parameters, model-based estimation techniques (e.g., Kalman filtering<sup>37</sup>) could be employed to provide best-estimate *analytical sensors* for key reactor core / power conversion system parameters, such as dynamic power distributions and compressor (turbine) efficiencies, in real-time.

Fault Detection / Isolation (FDI). Fault Detection / Isolation (FDI) algorithm development requires defining fault scenarios and corresponding plant parameter feature sets used to identify anticipated faults<sup>39, 40</sup>. For components in the final stages of design and testing, Failure Mode and Effects Criticality Analyses (FMECA)<sup>10</sup> may be used to define fault features. Data-based techniques, relying on the neural network and fuzzy logic architectures for fault classification<sup>28</sup>, as well as model-based techniques, such as the Kalman Filter estimator<sup>41</sup>, are frequently used in FDI systems. The output of the FDI system can in-turn be used by a fault accommodating reconfigurable control scheme; this of course would require the FDI system to operate in real time.

Reliability Enhancing / Life Extending Control. One of the more mature energy conversion technologies in the trade-space i.e., that based on the closed Brayton cycle (CBC), may have issues associated with its reliability when used as part of a nuclear electric propulsion system (NEP), primarily due to the need for moving parts, bearings, etc. The higher efficiencies of the CBC translate into lower material temperatures throughout the system with correspondingly longer component lifetimes. One focus area may be developing control and diagnostic systems that enhance the operational reliability of CBC-based energy conversion systems. As mentioned previously, life extending control utilizes optimally-calculated system trajectories to minimize cycling, temperature excursions, etc., to extend component lifetimes, with system uncertainty accommodated using robust control methods documented in the literature<sup>32, 42</sup>.

Propellant Management and Utilization. Some proposed aircraft engine control system designs have minimum specific fuel consumption as an optimization goal<sup>43</sup>. These same techniques could easily be used to extend reactor lifetime and conserve ion engine propellant. While reactor lifetime in the context of fuel burn-up may not be the limiting factor in attaining the proposed mission duration (possibly 15 years), optimal fuel-burn scenarios could be achieved via intelligent control, thus helping to extend the life of the mission. Limited ion engine propellant inventory (Xe, in the case of Prometheus 1) however warrants efficient use of this resource, which may be obtained via model predictive optimal control.

Health Management Diagnostic Inference Engines. Model-based diagnosis allows the development of diagnostic systems that are based on physical models rather than sets of rules alone. Model-based diagnosis is more flexible and, in general, employs models similar to the simulation models used for controller development. Livingstone is an example of a model-based software tool that can be used for fault detection, isolation, and recovery and is responsible for inferring the health of the system on which it has been applied. It does this by utilizing a qualitative model and discretized sensor and event information. As event data are received, Livingstone continually updates its understanding of the state of the various components in the system. The model is used to determine the expected observations given the component state. When there is a discrepancy between the expected observations and the actual observations, Livingstone searches for the most likely set of component states/failures that could produce the observation. In addition, it can also generate recommended recovery actions. Some applications where Livingstone has been utilized as a diagnostic engine<sup>44</sup> are: DS-1 Remote Agent Experiment, Space Shuttle Main Engine, Command and Data Handling System of the International Space Station, PITEC X-34 main propulsion system demonstration, and NASA's Earth Observing One satellite.

Infrastructure development. Many of the techniques mentioned above may, to some degree, be taken “off-the-shelf” and applied to space nuclear propulsion systems with relative ease (albeit used in other, seemingly unrelated industries and applications). However, the *development infrastructure* needs to be in place up front to efficiently and prudently do so. For example, component models, rapid prototyping environments, hardware-in-loop test beds, etc., which provide a means for rapidly assessing and validating the capabilities of candidate algorithms need to be established as early as possible. Commercial off-the-shelf (COTS) software products such as MATLAB and SIMULINK<sup>45</sup> (for dynamic model and controller development), Impact Technologies PHM Design (diagnostic system development)<sup>46</sup> and dSPACE<sup>47</sup> (for HIL testing), that can be seamlessly integrated together for controller development and testing need to be used whenever possible. Additionally, software already developed for government research projects can also be utilized if they are mature enough to be integrated. As mentioned previously, NASA Glenn has developed software to perform sensor selection and test data validation for rocket engines<sup>22</sup>. Oak Ridge National Laboratory has developed a system for prototyping terrestrial nuclear system controller algorithms<sup>48</sup>. These development platforms could conceivably be adapted for the design of control and diagnostic systems of an integrated space nuclear system as well. Both of these example platforms, however, are only effective when used with accurate dynamic models that provide the essential system characteristics as described in Section VI.

## X. Conclusions

This paper has presented an overview of the enabling control technologies necessary for the development of a reliable, autonomous space nuclear propulsion system. Optimal sensor placement and a hierarchical, supervisory control architecture would allow different levels of autonomy at various system levels. High fidelity system, subsystem and component models would allow for diagnostic and prognostic applications as well as fault accommodating control. For the harsh environment of deep space, long-life, radiation-hardened sensors and electronics would be required. Health management technologies, if employed, would ensure that mission goals are successfully achieved. Each technology presents a significant research effort in its own right and therefore needs to be addressed prior to model development, in parallel with the system design in order to have a positive impact on the integrated system. Such an approach would enable the identification of control related as well as integrated system related problem areas early in the development; avoiding potentially expensive “work-arounds” by making necessary changes in the design prior to development.

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