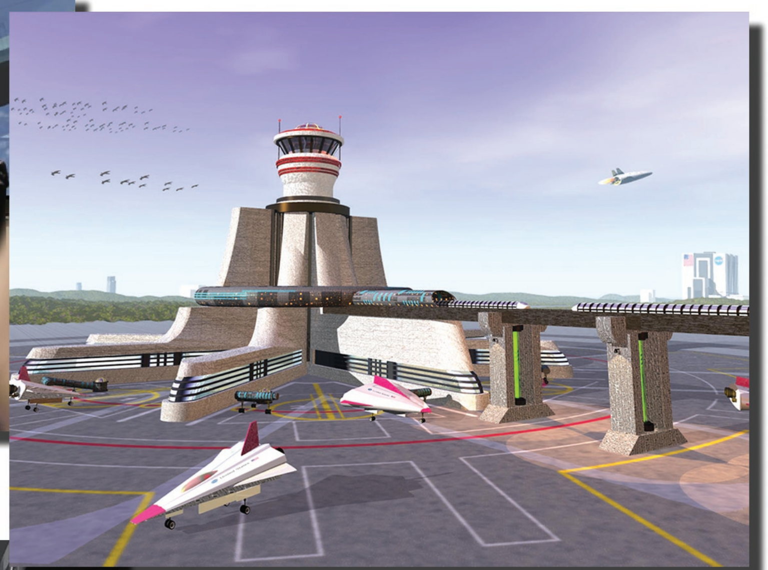
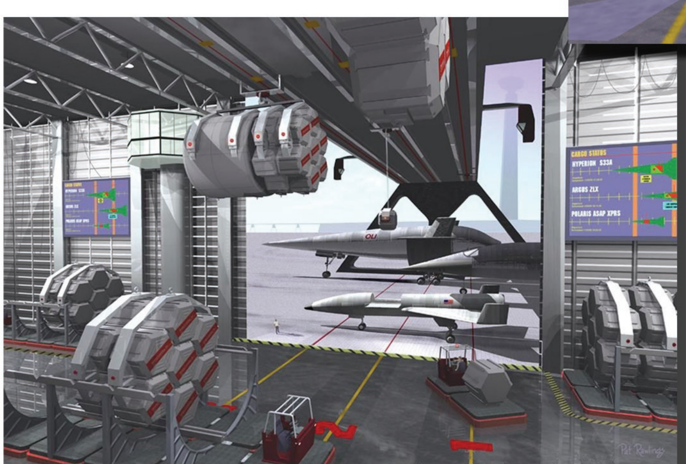
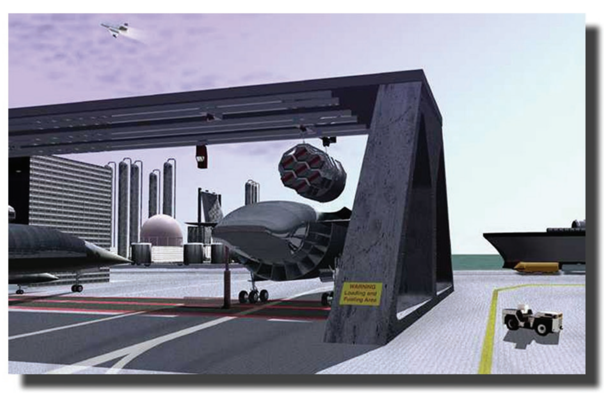
Vision Spaceport artwork by Pat Rawlings







Future ground support systems technologies

5 How do we make this vision a reality?

Infuse the ground support systems with new technologies.

The more efficient and economical spaceport operations depicted in the Plug & Play vision can be realized by infusing the ground support systems with new technologies. To achieve this vision, we must identify the underlying technologies associated with the functional capability roadmaps and the challenges and technical approaches for each Plug & Play phase. Once we identify the technologies, we can capture and document them in a technology plan. We start by answering the following questions:

- **What are the technology focus areas (TFAs) that correspond to the vision?**
- **What are the technology elements needed to realize the Plug & Play vision?**

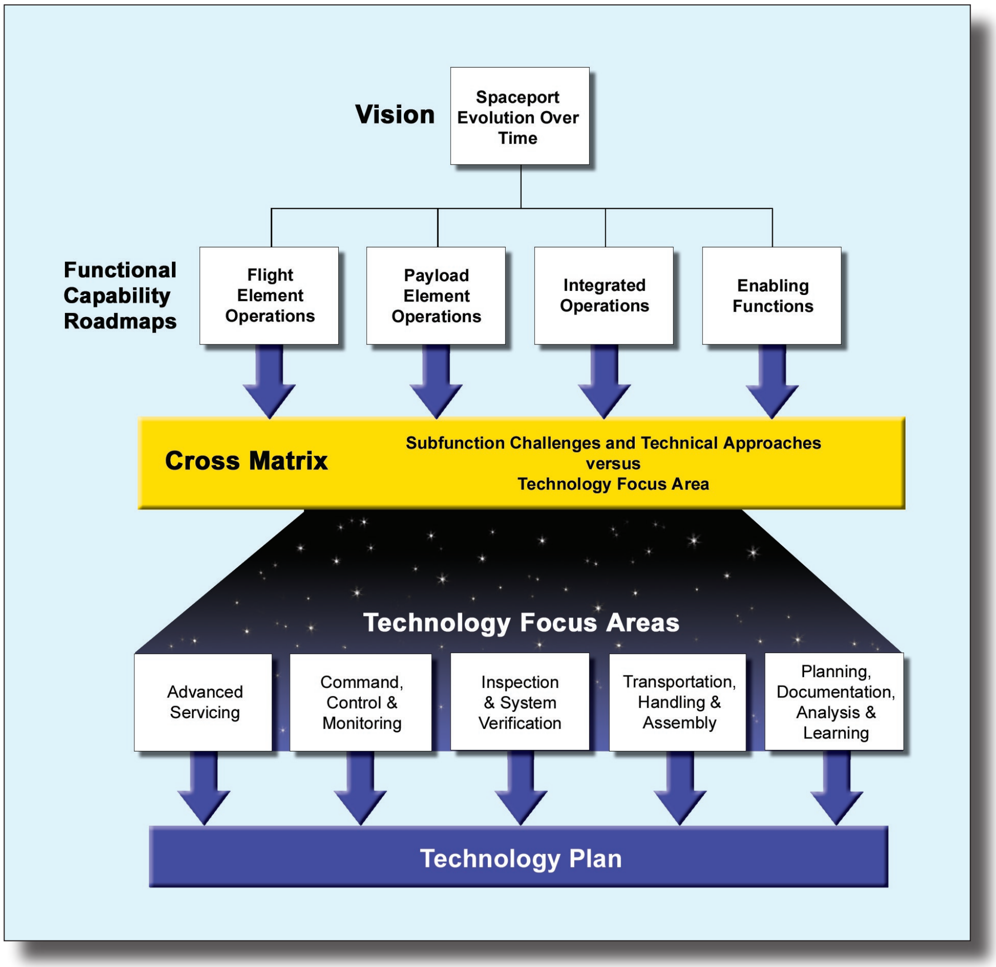


Figure 34. Linkage between capability roadmaps, cross matrix, and technology plan

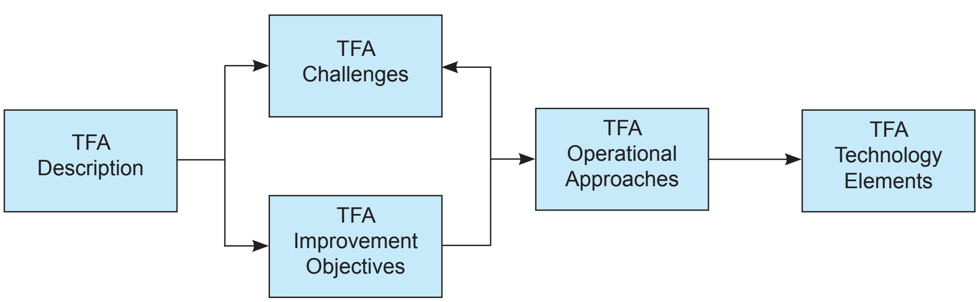


Figure 35. TFA presentation structure

5.1 What are the technology focus areas that correspond to the vision?

- *Advanced Servicing*
- *Command, Control, and Monitoring*
- *Inspection and System Verification*
- *Transportation, Handling, and Assembly*
- *Planning/Documentation/Analysis/Learning*

These technologies were commonly occurring themes in the capability roadmaps. Figure 34 provides a cross matrix between these TFAs and the functional capability roadmaps.

Each TFA subgroup, consisting of subject matter experts from across the country, worked on an ad hoc and voluntary basis to identify the desired capabilities over time; performance goals for each functional area; and objectives, technical challenges, and approaches for each subfunction. Through the same process, each subgroup identified examples of applicable current technologies and remaining technical challenges. They presented each TFA in terms of five components: description, challenges, improvement objectives, operational approaches, and technology elements. See Figure 35.

The ASTWG team recognizes that the following products can and should be further refined to address inadvertent omissions and developments in current and new technologies being pursued in various government, commercial, academic, and international environments. We therefore intend to continue to evolve and refine these products and produce future updates of the capability and technology roadmaps presented in this baseline report.

5.2 Advanced Servicing

Fueling, purging, and loading/ replenishing the consumables of the vehicle systems, payload systems, and ground support systems.

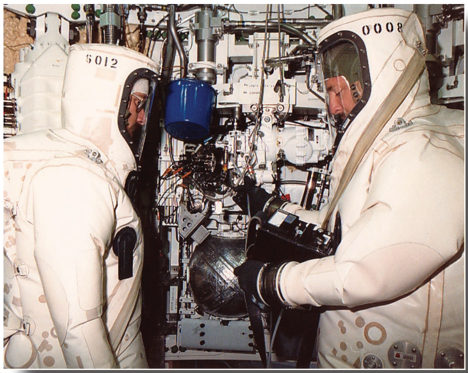
Description

Advanced Servicing addresses the safe and efficient acquisition, management, addition, replenishment, storage, drain, and disposition of fluid/gaseous/power commodities for both flight vehicles and ground systems. Servicing commodities include but are not limited to the following:

- Propellants (liquid hydrogen, liquid oxygen, RP-1, nitrogen tetroxide)
- Pressurants (gaseous nitrogen, gaseous helium)
- Lubricants (oil, grease)
- Coolants (glycol, ammonia, Freon)
- Working fluids (hydraulic, pneumatic)
- Life support (oxygen, water)
- Electricity (ground power, battery charging)
- Cleaning agents (solvents, detergents)

The primary focus of Advanced Servicing is to enable safe, rapid, efficient, and economical servicing operations. The functions of servicing can include production or acquisition; storage; purification or refinement; transportation and distribution; and disposition. To carry out these functions, servicing operations employ numerous technology elements. Each servicing system is tailored to the unique requirements of its commodities. Examples of hardware elements included in typical servicing systems can include:

- Interface and umbilical hardware
- Storage vessels
- Transfer lines
- Flow control valves
- Pumps or vaporizers
- Temperature, pressure, and flow rate sensors
- Filters and particle screens
- Insulation and coolant systems
- Weather protection systems
- Ventilation and spill containment systems and scrubbers



Challenges

It is likely that vehicles and payloads of the future will continue to employ hazardous propellants because of the performance they enable. There are numerous challenges for ground processing in safely dealing with such commodities. Handling multiple hazardous fluids leads to a significant number of challenges. Autonomous operations are of paramount importance to improve safety by isolating workforce from hazardous operations. For example, leakage of cryogenic propellants poses a serious risk from potential exposure of the workforce to low temperatures and from potential explosion. Many of the specific challenges associated with servicing of hazardous materials are provided in Table 15.

Table 15. Current hazardous-commodity servicing challenges

- Dangerous
- Requires extensive leak detection
- Often nonroutine
- Labor-intensive
- Generates waste streams
- Requires certifying equipment
- Requires contamination control
- Requires the workforce to wear cumbersome protective equipment
- Includes multiple grades of fuels and commodities
- Induces thermal stresses on equipment
- Inadequate situational awareness and reaction capability
- Requires multiple experts for complex cryogenic system operations

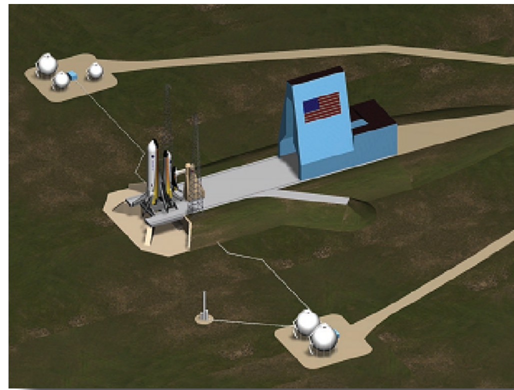
Improvement Objectives

To meet the performance requirements defined within the Plug & Play model, Advanced Servicing needs to accomplish a set of objectives. These objectives focus on decreasing the amount of servicing that is completed in the critical path at the spaceport and on improving the process by which any servicing is completed. Decreasing the amount of servicing focuses on eliminating the wide range of servicing that is completed by using standardized commodity services. Specific objectives for Advanced Servicing are provided in Table 16.

Table 16. Advanced Servicing improvement objectives

Decrease amount of servicing required at spaceport in the critical path	• Reduce number of servicing requirements • Minimize drain, purge, inert, and propellant hazard requirements • Standardize commodity services • Increase reliability of systems (flight and ground)
Improve the servicing process	• Minimize breaking the system • Eliminate use of pyrotechnic systems • Decrease need to condition lines • Standardize interfaces • Increase design life of vehicle systems (orders of magnitude) • Increase use of preventive maintenance

Operational Approaches



To accomplish these Advanced Servicing objectives, specific operational approaches can be taken. Operational approaches focus on substantially reducing the need for servicing and using a standard service approach. Since payloads are serviced within payload carriers, standardizing those carriers will promote a standardized overall servicing approach. But other operational approaches are also possible, such as the "service station" approach, which would employ standard interfaces from the ground propellant supply systems to the vehicle and resemble the functionality of the current-day gas station for automobiles. Regardless of the shape of the vehicle or fuel type, the gas station can service the vehicle. Table 17 summarizes the some of the possible servicing operational approaches.

Table 17. Advanced Servicing operational approaches

- Onsite commodity production and distribution
- In-place, modular servicing
- "Service station" approach
- Move to later in the process – Gas & Go
- Self-contained flight/payload elements
- Clamshell operations

Technology Elements

Vehicles and payloads of the future will most likely employ cryogenic propellants because of the performance they enable; however, there are challenges for ground processing in using such propellants. Leakage of cryogenic propellants poses a serious risk because of their potential for explosion and hazards to the workforce. Therefore, advances in quick-disconnect **sealing technology** are critical not only to ensure the safety of the workforce but also to reduce the hours expended performing leak checks prior to each operation.

Durable and efficient **low-maintenance insulation systems** are needed to maintain the thermal characteristics required for servicing as well as to reduce any unnecessary boiloff of cryogenic fluids. The goals are to allow for long-distance, energy-efficient transfer of cryogenic propellants as well as for the combination of hot-side and cold-side thermal protection systems for cryogenic tanks. Potential materials to investigate for these efficient and robust insulation systems include aerogels, polyamides, glass bubbles, multilayer insulation (MLI), and composites.

Safety systems are paramount in any propellant servicing system. **Inexpensive, nonintrusive hazardous gas and leak detection systems** are crucial to ensure a safe environment for both the vehicle/payload and personnel during servicing operations. Advanced systems that provide real-time gas concentration data can allow operations personnel to differentiate between propellant system leaks during vehicle servicing, detect predetonable mixtures in enclosed systems or areas, and alert personnel to potentially dangerous situations. These advanced instrumentation and monitoring systems must be rugged and require only minimal calibration, while providing highly accurate information.

Advances in **vehicle interface systems,** such as umbilicals, can also significantly reduce operational turnaround times. Technology development in the areas of **alignment, mate, and release mechanisms** can offer reliable single- and multiple-connector mates by implementing sophisticated connectors that reduce high-misalignment mates and advanced vision systems that enable reliable, automated mating, disconnection, and reconnection. Investments in **latching technologies** such as shape memory alloys and pneumatic collets should also be explored for high-speed disconnect operations. An autonomous verification system is needed to ensure umbilical mate integrity.

Spaceflight vehicles use high-energy, volatile fuels. Technology development to allow for fast, **autonomous fueling** will require advances in sensors and system components to improve reliability, accurately detect and report health status, and provide self-healing capabilities to minimize or eliminate "red crew" access for real-time repairs. In addition to improvements in system hardware, advances in software are required for health management and to develop and implement reason-based decision making to maintain continuous safe fueling operations and to respond to system faults. Finally, improvements in software verification and validation techniques will be required to certify these advanced software systems for critical hazardous operations.

Enhancements in **production, recovery, and disposal management systems** should also be investigated to identify novel approaches to perform waste disposal, neutralization, incineration, scrubbing, ventilation, and spill containment.

Table 18 summarizes the Advanced Servicing technology elements.

Table 18. Advanced Servicing technology elements

- Self-safing and inerting vehicle systems
- Standardized servicing approaches
- Advanced fluid handling approaches
- Leak-free quick disconnects
- Automatic deicing and contamination removal quick disconnects
- Multiparameter leak detection
- Advanced materials
- Robotic servicing
- Multispectral imaging systems – hydrogen/helium gas visualization concepts for remote imaging
- Nonintrusive instrumentation for fluid system (gas and liquid) operation for flow rate, temperature, pressure, and density
- Nonintrusive to fluid path, purity flow stream analyzers, and instrumentation
- Accurate level gauging
- Zero-loss or heat recovery storage tank technologies
- Smart components (e.g., pumps and valves with built-in health verification, self-diagnostics, and no dynamic seals)
- Nonpyro hydrogen burn system for disposal
- Self-aligning, self-checking, and wireless data and power systems
- Repairable, self-healing seals
- Hydrogen, helium, and oxygen gas recovery, purification, and reliquefaction systems
- Vision, laser, ultrasonic autonomous controls

Advanced Servicing Technologies Roadmap

Figure 36 displays the major technology areas, with time-phased recommendations regarding particular technologies to pursue in improving the ability of spaceports to perform the Advanced Servicing function.

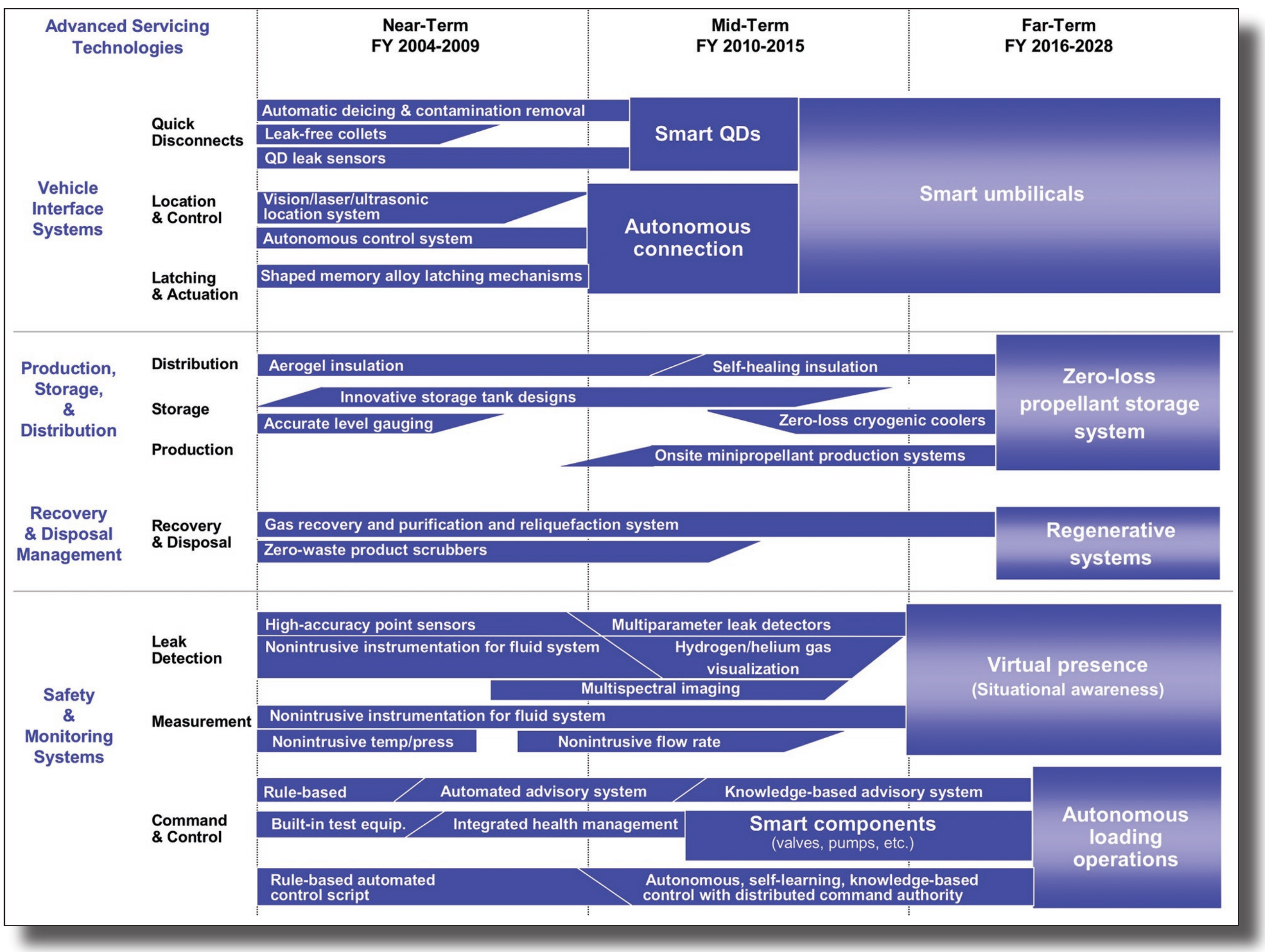


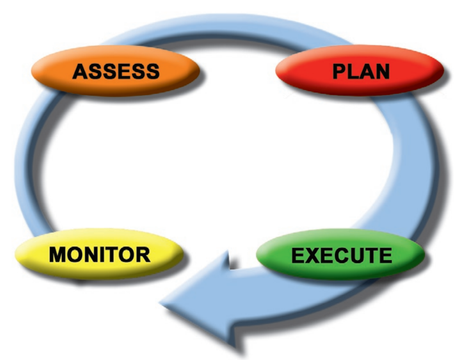
Figure 36. Advanced Servicing technoloies roadmap

5.3 Command, Control, and Monitoring

Information infrastructure needed to support automated testing, informed maintenance, advanced situational awareness, and improved safety and security across all aspects of the spaceport.

Description

Command, Control, and Monitoring (CCM) provides the infrastructure to control the vehicle and spaceport support systems. This control follows the data from the sensing element to the decision maker and then follows the resulting commands all the way to the affected component. The goal for CCM is to reduce the cost of this infrastructure while increasing safety. CCM can be decomposed into the following processes: **Monitor**, **Assess**, **Plan**, and **Execute.** We will identify the technical challenges within each of these areas that prevent today's systems from operating as an ideal spaceport.



Monitor

Monitoring deals with sensing the environment that is being controlled, converting the resulting data into a usable format, and routing it. The user can either be a human or a software component that assesses that data. Some of the key elements of this process are:

- Sensors
- Data acquisition systems
- Wires, cables, and connectors
- Telemetry and communications infrastructure (including networks)
- Visualization of the data
- Standardization of hardware and software architectures

Assess

Assessment deals with processing the raw data into meaningful information that allows a higher-level understanding of the situation. Elements within this process include:

- Data analysis/correlation/understanding
- Automated diagnostics
- Simulation and modeling
- Decision support
- Standard interfaces between analysis components and offline data

Assessment is traditionally the domain of the human decision makers. While humans will remain in the loop for at least the foreseeable future of human spaceflight, advanced software tools and capabilities will provide support for humans to make better decisions.

Plan

Planning deals with determining what to do about the assessment that was made of the monitored data. Elements within this process include:

- Real-time task planning
- Integration of real-time data with offline workflow processes

Real-time task planning involves the capability to automatically schedule test sequences in response to the assessed situation. These test sequences can represent a generic response that is tailored to the situation by the real-time planning agent. To achieve this capability, greater success is required using autonomous goal-seeking agents in hazardous, safety-critical applications.

Execute

Execution deals with commanding hardware assets. This commanding can take the form of automated test sequences initiated manually or in response to another automated system. Distributed software with command authority over a specific range of problems can be developed to extend the autonomy to the lowest level that makes sense. Where specific command authority has not been given, the distributed agent may request command authority from a centralized system or, based on specific rules, may go directly to a human with command authority using a variety of modes (to a terminal, two-way pager, cell phone, or wireless PDA). Here the human could grant command authority or redirect specific actions into the centralized system, which would then inform the distributed agent, who would initiate the command, if authorized. Automated software interaction and requests to human operators should always provide a concise summary of relevant data so determination can be made without extensive additional probing.

Challenges

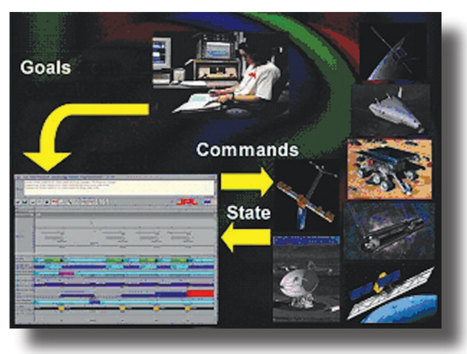
CCM faces challenges in meeting the approach defined in the Plug & Play model. These challenges are grouped by the CCM functions. The monitoring challenges focus on the sensors and systems used to collect the data. The assessment challenges focus on making sense of the data in a quick and efficient manner. The planning challenges focus on quickly developing high-quality plans to respond to the assessed situation. The execution challenges focus on improving the software used to command the hardware. Table 19 summarizes the CCM challenges.

Table19. CCM challenges

TFA Function	Challenges
Monitor (Get the data to the users.)	• Sensors and sensing systems are less reliable than the hardware they monitor. • Wires and connectors are prone to damage during routine maintenance. • Networking, telemetry formats, and data acquisition systems are limited and rigid. • Data is not delivered as information that provides users with needed situational awareness. • Locked-in-a-control-room mentality is applied to information infrastructure. • Systems are disjointed and do not integrate well.
Assess (Make sense of the data.)	• Data analysis is manual and requires a human expert. • Analysis requires human decision makers who must hunt down required information. • Analysis systems are not integrated with history, offline databases, and real-time visualization tools. • Loosely related data are not correlated. • Human must piece together information from telemetry data and video/audio sources to build a coherent picture of the situation.
Plan (Determine what to do about the data.)	• Scheduling requires a human initiator and is not tied into data events. • Training systems are typically of low fidelity. • Many manual steps are involved from problem detection to remedial action. • Offline systems do not integrate with real-time systems and information. • Software is a tool and not a member of the team.
Execute (Perform an action based on the data.)	• Test software is custom-built and generally operates at the hardware level (apply voltage to pin C) – hardware-dependent. • Spaceflight vehicle is treated like an item under test and controlled from the ground. • Software is centralized and coded for specific failures. • Ground system control is intertwined with spaceflight vehicle control (noninteroperable). • Ground software and flight software are incompatible. • Software testing continues to be a challenge to improve fault coverage. (This will be a bigger problem with more intelligent software.)

Improvement Objectives

To meet the performance requirements defined within the Plug & Play model, CCM needs to accomplish two sets of objectives. The first set aims to increase the decision-making ability. The second set aims to increase the operational efficiency of CCM. Existing spaceport CCM technology involves extensive infrastructure that is not integrated. This infrastructure typically consists of control systems, test and checkout equipment, mission planning systems, and flight safety planning and operations. The distributed expertise and legacy technology associated with this wide-ranging infrastructure lead to excessive costs, large turnaround efforts, and difficulty in managing flight safety. New technological approaches to CCM would modernize and streamline this essential infrastructure, allowing improvements in space transportation management that:



- Lower costs
- Reduce turnaround
- Improve flight safety decision making

Specific improvement objectives for CCM are provided in Table 20.

Table 20. CCM improvement objectives

- Provide worldwide CCM communications that are seamless, tailorable, multifunctional, secure, survivable, and easily accessed.
- Provide CCM systems and information that are compatible and interoperable.
- Increase decision-making ability.
  - Improve flight safety decision making.
  - Increase level of situational awareness.
- Enhance CCM operational efficiency.
  - Decrease number of unique pieces of monitoring equipment.
  - Reduce costs associated with CCM.
  - Increase capability for predictive and condition-based maintenance.

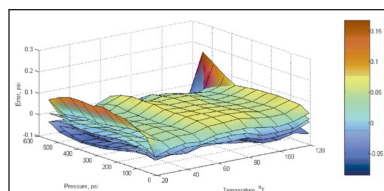
Operational Approaches

To accomplish these CCM objectives, specific operational approaches can be taken. Operational approaches focus on providing CCM functions integrated with the rest of the spaceport. Specific operational approaches for CCM are provided in Table 21.

Table 21. CCM operational and technical approaches

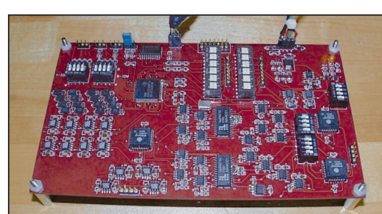
- Integrate payload and offline elements health information when the hardware is installed.
- Make specific and global history data available for prognostic health determination.
- Evolve control authority from the spaceport to the appropriate hardware – spaceflight vehicle and ground support equipment.
- Automate software verification and validation and improve testing coverage.
- Achieve human-computer team interactions. (Software evolves from tool to team member.)

Technology Elements

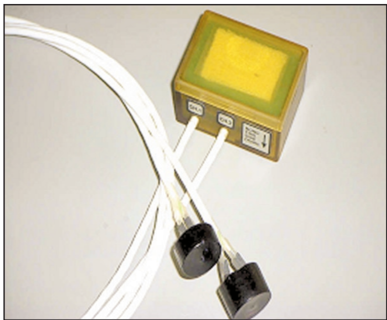


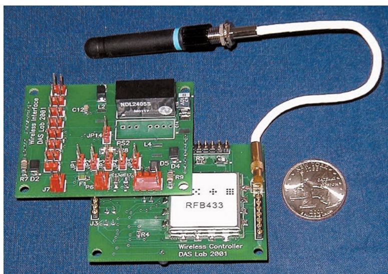
Sensors make up the front line of the monitoring capability of any CCM system. Several drawbacks exist in today's sensor systems. First, they are generally intrusive; second, they are less reliable than the hardware that is being monitored; third, most need manual calibration; fourth, they often are unable to detect when the output is degraded or has failed; and finally, they cannot detect off-nominal readings caused by the effects of failures in other parts of the system. Technologies with the following characteristics will help overcome some of these weaknesses:

- MRI-like remote sensing
- Integration of the sensing element into the environment or material to be monitored
- Autocalibration of sensors
- Sensors that detect output trends over time and communicate with other sensors, increasing the accuracy and reliability of information without depending on large volumes of data



Data acquisition systems may involve signal conditioning and conversion from analog to a digital signal, sampled at a specific frequency with a specific precision to the data. A typical problem in today's systems is designing an analog-to-digital converter with a least significant bit of 0.004 when the nominal value toggles between +1.0 and –1.0. Transmitting raw data through such a system guarantees that the measurement will change for every sample without any meaningful information being transferred.





Wires, cables, and connectors are high-maintenance items. Each demate and remate of a connector increases the possibility of intermittent contact or loss of contact. Wires are prone to damage and other age-related problems. The monitoring systems of the future should look to wireless systems that can operate in a critical fashion at the needed throughput. If wired connections are used, real-time integrity verification systems should be used to discover emerging anomalous conditions.

Current spaceflight vehicles use pulse code-modulated data streams of fixed bandwidth. If the required transmissions cannot fit within the bandwidth, multiple formats are created and a subset of the measurements is transferred. This current system is horribly inefficient from the standpoint of useful information sent through the pipe. Measurements are transmitted *N* times per second even when they have not changed. Perpetually updating unchanged data is costlier and less valuable than transmitting higher-level information that reports a change of condition (exception monitoring). The incorporation of **health monitoring and the transmission of high-level informatio**n as opposed to data will help; however, additional telemetry schemes that maximize the bandwidth need to be developed and deployed.

Once the data reaches a user, it must be integrated with additional data as well as video and audio output to give the user a complete and current picture. Visual system technology that can combine multiple heterogeneous data sources to form a single coherent view will provide the user with ideal situational awareness. A distributed architecture that allows software agents to monitor specific areas and work with the human users as members of a team will enhance the interoperability that is desired for the spaceport CCM system.

Advanced sensing capabilities, such as electronic noses, composite material-integrated structural monitoring, and image processing, will require improvements in data classification and understanding over what is available in the laboratories today. Improvements in data correlation, perhaps using distributed agent-based software, will be needed to support the correlation of data from multiple sources to determine the root cause of an anomaly from the set of effects. To reduce the dependency on the critical skills of the human system expert, we need data analysis that can determine anomalous conditions in the hardware that can only be inferred through close examination of indirectly related data.

Automated diagnostic capabilities that can support prognostic health management and condition-based maintenance are needed to take advantage of functional redundancy and maintenance isolation of faults to a line replaceable unit. An example of the difference between a functional determination and a maintenance function is the failure of a remote power controller box (RPC) resulting in the loss of main power bus-A. A diagnostic system must be able to identify the loss of the function "provide power on main bus-A," and reconfigure the system to switch to main bus-B. This is a time-critical decision. From a maintenance point of view, the support crew will need to know that RPC-2 requires replacing. This need not be a real-time decision.