Advance Technologies for Future Spacecraft Cockpits And Space-based Control Centers

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The National Aeronautics and Space Administration (NASA) is embarking on a new era of Space Exploration, aimed at sending crewed spacecraft beyond Low Earth Orbit (LEO), in medium and long duration missions to the Lunar surface, Mars and beyond. The challenges of such missions are significant and will require new technologies and paradigms in vehicle design and mission operations. Current roles and responsibilities of spacecraft systems, crew and the flight control team, for example, may not be sustainable when real-time support is not assured due to distance-induced communication lags, radio blackouts, equipment failures, or other unexpected factors. Therefore, technologies and applications that enable greater Systems and Mission Management capabilities on-board the space-based system will be necessary to reduce the dependency on real-time critical Earth-based support. The focus of this paper is in such technologies that will be required to bring advance Systems and Mission Management capabilities to space-based environments where the crew will be required to manage both the systems performance and mission execution without dependence on the ground. We refer to this concept as "autonomy." Environments that require high levels of autonomy include the cockpits of future spacecraft such as the Mars Exploration Vehicle, and space-based control centers such as a Lunar Base Command and Control Center. Furthermore, this paper will evaluate the requirements, available technology, and roadmap to enable full operational implementation of on-board System Health Management, Mission Planning/re-planning, Autonomous Task/Command Execution, and Human Computer Interface applications. The technology topics covered by the paper include enabling technology to perform Intelligent Caution and Warning, where the systems provides directly actionable data for human understanding and response to failures, task automation applications that automate nominal and off-nominal task execution based on human input or integrated health state-derived conditions. Shifting from Systems to Mission Management functions, we discuss the role of automated planning applications (tactical planning) on-board, which receive data from the other cockpit automation systems and evaluate the mission plan against the dynamic systems and mission states and events, to provide the crew with capabilities that enable them to understand, change, and manage the timeline of their mission. Lastly, we discuss the role of advanced human interface technologies that organize and provide the system and mission information to the crew in ways that maximize their situational awareness and ability to provide oversight and control of all the automated data and functions.

1. INTRODUCTION

NASA and other space agencies, have renewed goals of expanding our domain of space travel and exploration, anchored in LEO for the last 3 decades. Propelled by a new mandate to return to the Moon in the next decade and to eventually send humans to Mars, NASA has initiated the execution of the early phases of that mandate. In the near term, a new crewed spacecraft will be developed to replace the Space Shuttle as the main US-provided transportation system to LEO, and eventually transport astronauts to lunar orbit. However subsequent space exploration missions beyond LEO will face challenges comparable to those experienced by the engineers and scientists that planned, designed, developed and executed the first space pioneering missions, such as the early Russian and American orbital flights, and ultimately the Apollo program. The new space exploration missions will combine two characteristics that make them especially challenging for human spaceflight: long distance and long duration. Furthermore, these missions will require system capabilities that have not yet been designed or applied to human spaceflight, and may lead to paradigm shifts in the way we design for or execute such human space missions. One such requirement is the migration of a much greater share of the management of the vehicle systems and mission to the space-bound or space-

based crew. This is due primarily to the intrinsic communication lags, and necessity of the crew to take control of their systems if the connection with the Mission Control Center is lost. With these challenges in mind, this paper explores the capability requirements, and technologies to be considered in the design of systems for future cockpits or space-based control centers to meet and mitigate the challenges to next-generation human space exploration.

Technology Needs vs. Technology Solutions

The discussion of new capability needs for future spacecraft systems is often approached from two different angles, depending on the source of the discussion. The research community, for example, has invested significant effort in developing and maturing new technologies that may provide innovative capabilities on-board the spacecraft if implemented (e.g. Integrated Vehicle Health Management (IVHM) or spacecraft automation). From the operations perspective, however, discussion on specific technology takes a second role to required improvements on specific functions to meet new program and missions' goals, objectives, and ultimately program requirements (e.g. maintaining crew safety despite limited communications coverage). In this paper, we attempt to outline the Systems or Mission Management requirements for long-duration, long-distance human space missions, and evaluate technologies or applications that may provide the required capabilities.

2. Systems/Mission Management Evolution: from LEO to Mars

Space systems required to support long distance / extended duration missions beyond LEO will have a complexity beyond what we have experienced in any previous human space program. Beyond the basic technical challenges derived from the distance or duration characteristics, such as communication infrastructure, propulsion systems, etc, there are other factors that further complicate mission operations. The logistics approach to support the execution of such mission will far exceed the complexity of any previous program, and most likely will have significant impact on the system design – simply put, there will be no FedEx or UPS to deliver spare parts to the far reaches of the solar system!

During the **Apollo** program, while the missions included Moon-surface operations, the duration of the longest mission was 12 days; therefore issues such as the storage of consumables, system maintenance, and logistical sparing were not a significant concern. Also, the location of the surface operations (near side of the moon) along with the duration of such, limited the amount of communication blackouts from Earth. **Skylab** was the first NASA program to experience long-duration mission characteristics; however the mission duration for the longest crewed visit was only 84 days. Due to the multiple technical issues experienced during the launch (early solar shield shroud deployment and subsequent complete damage to solar array) the flight operations team had to perform extensive analysis, automated control of the vehicle, and preparation of numerous repair tasks (via EVAs) to sustain extended manned missions. Although the three Skylab crews were successful in completing several science experiments, much of their time was dedicated to system maintenance. Today's **Space Shuttle** missions are in LEO for a typical mission duration of 1-2 weeks. Systems maintenance during a mission is usually not an issue and is limited to malfunctions that affect safety-critical functions. In most cases, critical functionality is preserved through system redundancy engineered into the vehicle design. Due to the relatively short duration of Shuttle missions, logistics is also not an issue, since the system is self-contained and no sparing is usually necessary. The **International Space Station** (ISS) is arguably the most complex space platform ever built, combining systems designed and built in several countries, hosting multiple types of visiting vehicles, and comprised of several laboratory modules. In many cases these different multi-national components will not be mated or electronically connected until their final assembly on-orbit. Even in its current incomplete assembly state of 5 habitable modules, 3 docking ports, 2 airlocks, and 3 truss components, the ISS has undergone extensive system maintenance, both internal and external (via EVAs). These maintenance periods have included repairs and replacement of electrical switch boxes, air generation systems, command and control computers and attitude control Gyroscopes. Unlike the Space Shuttle, most sensor data and control commands are available electronically and can be viewed and controlled from on-board laptops and via command uplinks and telemetry, with over a hundred thousand channels of data.

Considering this level of complexity and the limitations of on-board data storage and processing, it is reasonable to expect that most real-time and off-line systems management and mission execution management for the ISS is performed by or with extensive support from the flight control team on Earth. In all cases, the ultimate interface between system "raw" data, mission timeline / flight plan, and mission goals and objectives is the human, both on-board and on the ground. Moreover, the level of automated processing and integration of system and mission data has increased significantly across all the programs discussed. Yet, in most cases it still requires significant human processing to reach a sufficient level of understanding of vehicle systems or mission level significance.

In the case of systems management, for example, to obtain a system-level health state assessment, subsystem data often requires additional diagnosis, correlation with other system data, and evaluation of its impact to other subsystems or functional availability. Furthermore, if system-level actions

(multi-subsystem commands) are required for nominal or off-nominal events, humans are required to trigger or manually perform them based on their assessment of the system-level health, mission phase, etc. In mission management, an example is the impact of system events to the mission goals or timeline. The humans integrate the individual subsystem and system-level health state assessment, with timeline requirements, such as required systems to perform an activity, and mission goals. Based on the dynamic parameters of such, they can execute as planned, re-plan, or potentially modify mission goals and objectives, depending on remaining functional availability and resources. Obviously, such human-centered management requires extensive system and mission knowledge, along with complex training and multidisciplinary human interaction, such as crew-to-Mission Control Center (MCC), or controller-to-controller interface in the MCC. Furthermore, it requires multiple groups of people performing different functions, from system analysis to planning. Whereas the on-board crews retain the final decision authority, and are the designated "first-responders" for conditions that require time-critical actions, they remain dependant on MCC support for real-time tactical support, as well as strategic support.

Historically, this operations paradigm has held true and effective for the last 40 years of spaceflight. However, the characteristics of future Space Exploration missions may challenge this paradigm through several factors, including degradation of communications effectiveness, logistics complexity, safe-haven / emergency return-to-Earth options, and the number of manned / unmanned systems to manage and control. The complexity of the space systems to perform these missions is probably going to be equal to or higher than the most complex systems currently operated. At the same time, the availability of near-real-time support of MCC for their traditional tactical Systems and Mission management will decrease, in some cases significantly. Also, the requirements to maintain critical functionality to keep the crew alive and provide "Safe-Haven" will be substantially higher than in current systems, since the return-to-Earth options may be on the order of weeks or even months. Beyond the technical feasibility, it may not be fiscally viable to have the same level of ground support we currently have for ISS or Shuttle, on several systems that may potentially be needed at the same time (e.g. ISS, CEV, Lunar Base, Mars Exploration Vehicle, etc.).

Therefore, future spacecraft systems must accommodate system capabilities that enable the transition (as depicted in Figure 1) from human-centered real-time Systems and Mission Management, to human oversight of real-time management performed by the systems in an automated or autonomous fashion.

This transition should result in cockpit or space-based Control Center capabilities that enable the crew to obtain the necessary processed information of their system state and its relation to the mission, much like they currently get from MCC. On-board systems should provide the following Systems and Mission Management capabilities:

- **System health state determination**, which correlates individual subsystem or element health and status information with inter-system dependencies, vehicle-level fault propagation, and other relevant mission information, to provide the system-level health state.

- **Task/Procedure automation** capabilities that execute system-wide nominal or off-nominal tasks depending on pre-defined conditions, system states or failures, and human-driven commands (and monitor/confirm the successful execution of such task sequences). This includes off-nominal **Systems reconfiguration** in response to failures and other anomalies that degrade spacecraft function or interfere with the execution of planned events.

- **Timeline planning and re-planning** capabilities with the necessary built-in resource analysis tools linked to system data, to support on-board real-time automated or autonomous re-planning based on dynamic system availability, crew preference, or other mission conditions.

- **Human-Computer Interfaces** with information management applications combined with advanced displays and vision systems that allow the crew to access and understand all the necessary data generated by the on-board systems, retaining the capability to provide efficient oversight and control of manual, automated or autonomous functions, while maximizing their situational awareness and minimizing cognitive overload during critical maneuvers or off-nominal events.

Nevertheless, crews will require and continue to depend on strategic MCC support, including extended systems diagnosis, failure troubleshooting, health prognosis, maintenance, and mission planning. However, the effectiveness of such support to maintain crew safety and system availability to perform the mission is currently dependant on constant reliable communications. Moreover, other critical capabilities not discussed in this paper include on-board training, to maintain and enhance critical skills on long duration missions, and space-based maintenance support including the use of Class V Interactive Electronic Technical Manuals (IETMs) linked to the system data for real-time maintenance procedure execution.

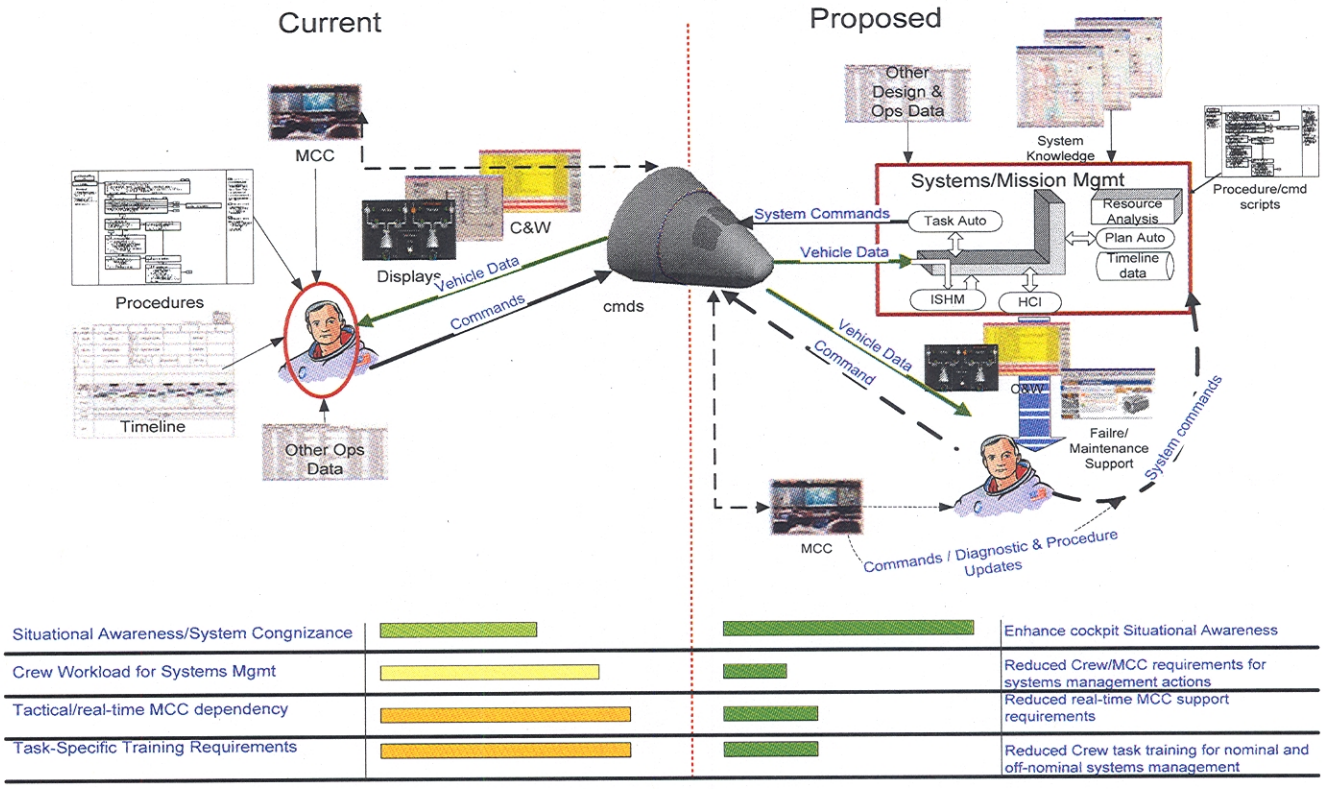

Figure 1: Evolution from human-centered direct systems and mission management, to human oversight of real-time autonomous management.

3. TRANSFERRING CONTROL ON-BOARD: THE CREW PERSPECTIVE

Throughout the history of human space exploration, crewmembers have continually pushed for greater autonomy. From the earliest days of NASA's Mercury program, the souls on board space vehicles have desired more insight as to their vehicle's state, and options of control within their means onboard. Portholes / windows for viewing were an issue from the first capsule designs, through the International Space Station (ISS). A similar issue for a crew removable hatch has likewise been prevalent throughout the program. This need was magnified by the loss of three astronauts to a cockpit fire, during a pad practice countdown for Apollo 1.

Reliance upon the crew's ability to operate on their own has also shown through. From the lessons learned during manual proximity operations during the Gemini program's initial rendezvous missions, the Apollo 11 descent and landing on the moon, the manual burns required during the Apollo 13 mission, and finally on to manual dockings and landings used throughout the shuttle program, manual crew inputs have been a mainstay of America's human spaceflight program. Much effort and technology has been expended to enhance the information available to the crewmembers for which to base their inputs on.

There is probably no better example of trying to put the right information in the hands of the crew to improve their situational awareness and autonomy than the proposed Shuttle Orbiter Cockpit Avionics Upgrade (CAU) to the Multifunction Electronic Display System (MEDS). When initially designed and implemented, the MEDS computer generated graphical displays were to mimic the original "steam gauge" mechanisms of the shuttle's instrument panel. This was carried out to the extent of incorporating all the on-orbit attitude information on the Attitude Direction Indicator (ADI) during ascent and entry phases when they would be more of a distraction than pertinent. The mimicry of the ADI extended to the point of including the physical slot (belly band), which is an artifact of the hardware mechanism to mount the original ball within the instrument.

The true benefits and capabilities of MEDS were promised as a future upgrade, which was eventually presented to the NASA astronaut office in the form of CAU. This upgrade made use of the MEDS color graphics displays, flexibility, and capabilities, and promised a major improvement to the crews' situational awareness, and hence autonomy. It was user friendly in comparison to the heritage displays, and would promise a segue to Enhanced Caution & Warning (ECW). The decision to curtail the lifespan of the Shuttle Program, along with the loss of Columbia and ensuing decrease of remaining flights (along with budget concerns),

led to the cancellation of CAU just prior to implementation. Although the new Crew Exploration Vehicle (CEV) will lack the sophistication and capabilities of the Shuttle, the astronaut office will no doubt expect CAU to be a base-level starting point for avionics and display capabilities.

NASA has spent decades in Low Earth Orbit (LEO). The administration is ready to move out of the LEO business and on to deeper space. In addition to bringing new excitement to the program, this also brings new challenges, such as communications, as explained in previous sections.

This beckons for onboard Systems and Mission Management capabilities to assist the crew in monitoring systems, and guide them through procedures in the event of failure. An effective implementation needs to be flexible. Depending on the phase of flight, systems management capabilities can: direct the crew's attention, diagnose the failure and prescribe a malfunction procedure, lead the crew through an imbedded procedure, or perform some or all of the procedure, informing the crew of its progress. Furthermore, it can be tailored to the needs / desires of each crew (just as some crews decided to train with 2 of 3 displays set to Backup Flight Software (BFS) during ascent, with the original Shuttle cockpit).

One of the most important aspects of the onboard systems will be to earn the confidence of the crew. This will require Systems and Mission Management automation capabilities developed with crew office input from day one. The system will need to be deployed early on to increase crew confidence. A bolt-on design will not exhibit the robustness necessary for the requirements of a flight to Mars. To prove worthwhile and successful, automation capabilities must be incorporated into the design of the entire system, from subsystems to multiple system elements. By having the system in place from the onset of the program, failure scenarios/signatures may be included in the knowledge base and compared with telemetry-based analysis within the MCC. This period of crosscheck and growth will inspire confidence in such capabilities and the technology that enable them, within the flight control team, the program office, and most importantly, within the astronaut corps. Last but not least, this build-up approach the implementation of technology that facilitates Systems and Mission Management automation decreases both fiscal and schedule risk; thus making it more palatable to the funding organizations for the program.

4. Key Elements of a Smart Cockpit

This section defines the specific functions and basic requirements for the Systems and Mission Management components that the authors propose for future spacecraft cockpits and space-based control centers.

As illustrated in Figure 2, the management and autonomy functions in current manned spacecraft systems is often distributed amongst different components performing management and autonomy functions at different levels. It is important to understand the similarities and differences between these levels, since this paper targets the needs and potential solutions on some specific levels of systems and mission management.

1. **Subsystem Component level management**. Subsystem hardware (not shown on Figure 2), including instrumentation, and firmware (FW) local to different subsystem components, which acquire sensor data and perform subsystem component-level processing, and Failure Detection, Isolation and Recovery (FDIR) locally. **E.g**. *Electrical power switch sensing current and "tripping" (open-circuit) upon sensing the current above the designated upper-limit threshold. Sensor data validation is often handled at this level.*

2. **Subsystem level management**. Subsystem software (SW), which controls subsystem-specific functions, such as health and performance algorithms specified in different modes and states, as well as subsystem-level fault detection isolation and recovery (FDIR). The subsystem-level health management may include complex state estimation algorithms, limited parameter trending and FDIR actions bounded to that subsystem. E.g. *Thermal Control System (TCS) software that detects a cooling pump malfunction (pump is off due to switch trip), and as response, sends commands to activate the backup pump and re-configures valves.*

3. **Vehicle level management**. Provides coordination and arbitration of subsystem performance, mission phase and vehicle mode and states transitions, and health management functions, such as FDIR that requires multiple subsystem inputs for detection and issues multi-subsystem commands as response. Command and Control (C&C) SW, and Enhanced C&W message generation are included in this level, as well as human-driven integration of subsystem data for vehicle-level health determination and management, or to integrate System Management data with Mission Management. E.g. *C&W messages generated for electrical switch trip, and TCS pump off condition (no power). Operators identifying switch trip as "root-cause" failure, and manually optimizing system reconfiguration considering tripped switch, primary TCS pump un-powered. Ultimately, operators (mostly) and crew evaluate impact of the failed switch and its loads (including TCS pump) to the system, and troubleshoot switch failure to determine if repairs or replacement are necessary.*

4. **Mission level Management.** The functions on this level are related at integrating the performance of the vehicle, including health state and system availability, with mission goals, objectives, mission plan, etc. This is

currently a human-centered function, mainly directed and executed from MCC. E.g. *Operators evaluate mission impacts derived from failed switch, and loss of power to its loads, and re-plan timeline to exclude activities with constrains associated with such switch or its loads.*

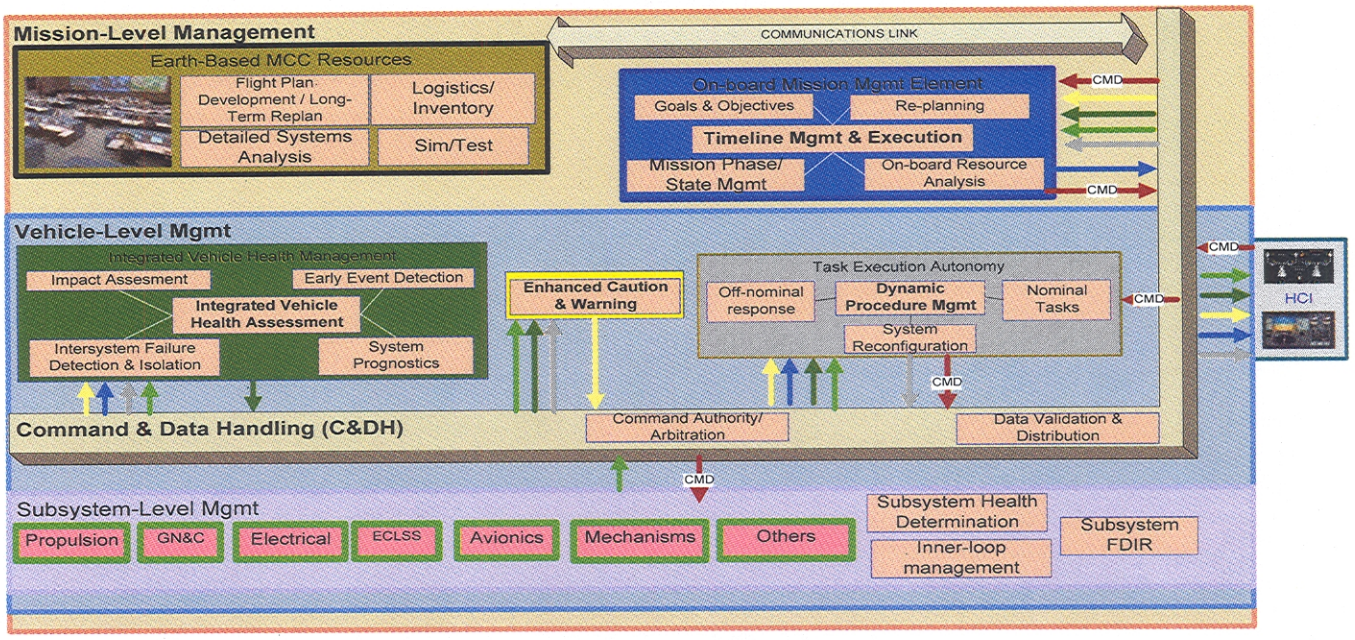

Figure 2 Distribution of Mission and Systems Management functions between subsystem components and SW, on-board autonomy capabilities, the crew and the Earth-based MCC. On this notional architecture, the on-board systems provide the crew with the necessary information and automation capabilities to manage the system and mission on-board.

5. **System level Management (not shown on Figure 2).** Similar to vehicle-level but the coordination and arbitration, as well as health management integration occurring across multiple systems, such as multiple Lunar-base modules, or systems such as a Mars transfer vehicle-Mars Lander vehicle.

Whereas technology evolution in all Systems / Mission management levels will be necessary to endeavor into the future space exploration missions, from more efficient hardware to advanced prognostic algorithms, this paper focuses on applications that provide automation capabilities at the Vehicle / System and Mission management levels, since such capabilities are in the critical path to meet the requirements of Systems and Mission Management automation.

Vehicle / System Health Management

The base, onto which critical automation capabilities for future cockpits or space-based control centers can be built upon, is the understanding of the vehicle or system health state. System Health Management starts at the instrumentation and Subsystem hardware levels, and is carried through the Vehicle and System management levels. Understanding the health of the system or vehicle is often the minimum requirement to execute other system and mission management functions, such as nominal scheduled tasks (e.g. EVAs, dockings, vehicle state transitions, etc,), or mission planning and execution. This fact drives the current manned spaceflight operations paradigms (tactical MCC support-centric), due to the lack of capabilities or confidence on the integrated vehicle/system health data provided by the on-board systems.

Since acceptable levels of automated health state determination for the component and subsystem management levels have been achieved (Built-in-Test, etc) in existing spacecraft systems, we will focus on the needs at the vehicle/system management level. Vehicle Health Management at this level requires the integration of individual vehicle subsystem health and status data, generated at the component or subsystem levels, to obtain or formulate an assessment of the vehicle-level health state. In the case of the System Health Management, the integration must take place for the different elements of the System. Therefore, the main functions and capabilities available on-board for managing the vehicle/system health are:

- Correlating all the subsystem data to determine vehicle functional availability.

- Detect and isolate vehicle failures to a "root-cause" or reduced ambiguity group amongst all the anomaly indications from the subsystems.

- Perform vehicle (system) – level impact assessment to provide post-failure functionality degradation, redundancy degradation, and "critical to" information on components that pre-failure had less criticality.

- Track subsystem performance degradation with vehicle (system)-level implications (e.g. negative energy balance, cooling deficiencies, air quality or consumable degradation).

- Perform early event detection of anomalies, to identify component, subsystem or system performance data that generates residual values from expected behavior. The real-time detection of such residual data may enable real-time or off-line multi-variant analysis that may identify the onset of potentially critical failure.

The information generated by a vehicle-level system health management function serves as the foundation of data for robust cockpit or space-based control center functions. **C&W message generation and classification** should be based on the correlated and integrated set of failure indications from multiple subsystems affected by the failure. The lack of this capability on current systems results in C&W systems that generate cryptic messages based on individual failures or anomaly data, with no indication of which are "root-cause" (e.g. power switch trip) versus just conditions that resulted from the root-cause failure (power switch loads losing power). This will reduce the number of nuisance-messages and provide the crew and operators with actionable failure information on system failures that require little extra diagnosis to respond or understand. Moreover, C&W messages should have the capability to either trigger automated response actions, or provide high-confidence recommendations for individual actions or procedures to execute in response to the failure.

In order to provide a complete picture of the failure condition and the resulting state of the systems, the information related to the nature of the failure must be combined with the impact of such failure to the system, which we refer to as "**impact assessment**." Currently, operators and crew determine the impact of system failures using precompiled documentation that describes the impact of certain significant failures to critical functions, components, or their redundancy. It is, therefore, necessary for them to perform the complete failure diagnosis manually, before they can access and interpret this "impact analysis" documentation correctly. In future cockpits or space-based control centers, the function of isolating the failure to the lowest possible and reasonable level and identifying the impact to the system should be automated or autonomous, and integrated with the C&W system. This capability will result in the availability of actionable information necessary to automate the response or enable the crew to promptly understand the actions they must take and be fully cognizant on the state of their vehicle or base.

Large and complex space systems that are to be managed primarily by small space-based crews should provide automated and autonomous FDIR capabilities at all management levels, to ensure crew and system safety and the preservation of critical functionality. However, **automated FDIR** actions should only be initiated when there is a high level of confidence that the triggering conditions are truly met, to prevent further failure propagation or functionality degradation. Currently, automated FDIR is common for subsystem components and the subsystem itself, where the conditions can be bounded to a limited number of parameters and rules. However, vehicle-level FDIR is normally performed manually, since the combinatorial aspects of different subsystem failures and conditions to respond to are significantly more complex than when isolated to a single subsystem. For **vehicle-level FDIR** it is necessary to correlate subsystem data with vehicle domain knowledge, such as system hierarchy, intersystem dependencies and fault propagation trees, to gain the entire failure condition and health picture that may lead to triggering multi-system reconfiguration actions. Hence, this information must be captured and made available on-board for health management applications to use for real-time data integration/correlation that leads to the formulation of vehicle (system) –level health state assessment. The health management applications must, therefore, provide highly deterministic and reliable vehicle-level health information that can be relied upon as triggers of automated failure responses and multi-system reconfiguration sequences in response of failures, or dynamic system and mission events.

Beyond providing data for safety critical functions, health management data can be used to enhance the efficiency and quality of information provided to the crew via the Crew Interface System, thus improving their situational awareness and reducing their systems management workload. **Continuous systems monitoring**, currently an MCC function, must migrate on-board, and be executed autonomously by the spacecraft or space-based systems, reporting integrated and "raw" information to the crew and MCC (when available) for oversight.

The data generated to perform the functions already discussed, must also be used to execute other Systems and Mission Management functions on-board, as stated before. Thus, vehicle health and status data must be available in the appropriate buses and formatted according to interface requirements from mission planning systems, Task/procedure automation systems, human computer interfaces, and space-based maintenance support applications.

Task and Procedure Automation

Whereas today's operations and system design rely on the human to provide the link between the system or vehicle data / commands and operational products, such as procedures, advances in cockpit automation technology offer the potential to break that dependence. Enhanced on-board automation capabilities at the vehicle and mission-level management may lead to the transition from human-centered task / procedure execution to automated or autonomous execution with human oversight, retaining inhibit and override capabilities.

There are three main elements which participate in the process of selecting and executing a task or procedure in space flight. These are the health state of the systems necessary for the execution of the procedure, the mission timeline (which can drive the execution of procedures associated with scheduled activities), and finally, the procedure itself. To achieve full autonomy of the execution sequence, the executive functions onboard must be able to perform a process similar to the one performed by humans when executing this activity. This requires determining when the procedure has to be executed (timeline driven or event/condition driven), verify that the system/mission conditions support the execution, execute it, and verify successful execution.

Applications to automate the actual execution of a set of actions in a task/procedure, and even to verify the individual effect of each command (end-item response), have been implemented successfully in robotic space flight. Automated command sequence execution is feasible when conditions to initiate execution and to verify successful execution are simple and straightforward. This is often the case for many nominal and off-nominal subsystem level tasks, and for a limited amount of vehicle-level tasks. However, when the conditions for execution or system readiness verification are complex, such as it requires vehicle-level health state assessment data, human-input is required to initiate and carry out the execution. The human, then, must be available to execute and remain fully knowledgeable on the conditions and actions. If the only humans available are the on-board crew, the burden upon them for real-time vehicle / system management is significant. Thus, the automated execution capabilities of single or sequences of commands (already existing), must be coupled with automated systems health management capabilities previously described, and also have electronic access to the current mission timeline.

Ultimately, future spacecraft-systems and space-based control centers should have the capability to automate the execution of:

1. Nominal vehicle/system-level tasks. These are sequences of actions/commands that have a nominal planned execution, and must be executed upon pre-determined system, mission events or other conditions. **E.g.** execution of tasks to power up dormant systems (multiple subsystems), perform systems checks, and upon verification of successful completion, perform system powerdown to dormant state.

Under nominal vehicle/system-level task we include the sequences necessary to perform system activation/de-activation, mission phase/state transitions, system-level self test, and routine maintenance sequences (e.g. power system battery maintenance charge/discharge cycles). Nominal tasks may be initiated upon scheduled events, automated systems requests, such as requests from the health management system or the automated planner, and human requests.

2. Off-nominal vehicle / system level tasks or the vehicle-level Fault Recovery of vehicle-level FDIR. **E.g.** execution of critical system reconfiguration upon the detection of a major thermal cooling loop malfunction, which may cause further functional degradation if no action is taken.

The off-nominal sequences, while in most cases pre-defined, are executed in response to unexpected system conditions caused by system failures that require system-level actions, mission events, environment conditions, or human-related events. Likewise to the nominal sequences, these are triggered by other automated systems, and human requests.

The current operations paradigm divides any automated actions from the Operational Data File (ODF) that contain the procedures for both nominal and off-nominal conditions, relying on the human as the interface. However, the enhancement of autonomy capabilities and automated functions integration (i.e. health state determination, planning / re-planning, and task execution), should drive a direct relationship between automated tasks or command sequences execution, and readable operational procedures that enable the human to perform manual execution of such command sequence, if so desired or required. Whereas this paradigm shift may not occur in one upgrade of systems design (e.g. Space Shuttle to CEV) it should set the aim for technology research, application development and system design for future cockpit or space-based control center implementation. Therefore, such paradigm shift may evolve from current *modus operandi* to enhanced automation of system-level task execution and integration of vehicle-level autonomy capabilities, while maintaining the traditional ODF products, to merging such procedures with the command scripts or other artifacts that are part of the automated sequences..

Mission Planning and Re-Planning

Mission planning is currently one of the "long-poles" towards automating tactical mission management functions on-board. It is particularly complex, due to the amount of complex resource and flight dynamics analysis required to validate potential plan options, as well as the need to integrate such with detailed knowledge on the health state of the vehicle. Furthermore, the integration also has to be extended to automated task execution components, to introduce automation capabilities to the execution of the selected mission timeline. Currently, for ISS operations it takes a team of 50 mission planners to develop the timeline for one crew member. For ISS real-time operations support, NASA has been able to reduce the core Flight Control Team (FCT) contingent from six to two flight controllers during night and weekend hours, where the execution activity is low or the crew is in their sleep period. However, the planning support, which also represents one of the largest in the FCT, is still required. This discipline is also one in which the crew has less capability on-board, and thus dependent almost entirely on earth-based capabilities for mission plan analysis and real-time re-planning. Whereas for strategic and long term planning, including significant mission re-planning and mission goal re-prioritization, this may continue to be acceptable, the dependency for short term and real-time re-planning are likely to not be sustainable on future exploration missions. Therefore, the main requirements discussed in this section revolve around automation capabilities necessary to shift the tactical planning function from MCC to the cockpit or space-based control center.

Mission Planning can be generally divided into the extensive analysis required to develop the plan and developing the flight plan timelines. The analysis includes mission goals and objectives definition, flight dynamics, resources (consumables and otherwise), and crew time. The flight plan design includes the integration of system resources, with required activities, procedures, and crew work cycles.

The analysis component often requires significant computing resources and integration of different types of information and expertise. It can also be performed or updated in a non-real time basis, and therefore may not be required to migrate on-board. However, a subset of such analysis capabilities is required for the tactical element of re-planning timelines to accommodate for human, mission or system changes. Such is flight dynamics and system resources, like power, thermal and propellants.

The cockpit or space-based control center capability goals for the planning/re-planning function are therefore, centered in the crew's ability to manage and change the mission plan to adapt to the dynamic characteristics of a manned mission. Specifically, the combination of on-board automated planning applications and the crew should be able to perform the following functions with no assistance from MCC required in real-time.

1. Perform significant or minor mission plan updates, and required analysis, to exercise and early return to earth.

This capability primarily supports abort modes and is based in Flight Dynamics analysis or pre-determined template selections to execute. This capability is directly related to the execution of such mission abort by the spacecraft C&C components and other subsystems, such as GN&C.

2. Enable the crew to develop a short-term flight or mission plan, based on their assessment of mission goals and objectives and state of the systems and mission. This includes the ability to develop "what-if scenarios" to optimize their plan development.

To achieve such capability, the planning applications will require analysis capabilities and built-in knowledge on activity Ground Rules & Constraints, and procedure information, to ensure no conflicts between the developed plan and vehicle system or crew resources. This capability is also tied to other on-board system data, such as current state of resources, and the availability of vehicle/systems functions and automated sequences/procedures for specific activities.

3. Automated execution, when determined by humans, of the mission or flight plan activities.

This capability is divided between different Systems and Mission Management components, such as:

-The planning component that controls the timeline and the activities, with all the, rules, constraints and procedures associated with such activities. This component controls manages the specific tasks that need to be performed, and the timing of the execution.

-The Task / command autonomy applications that will receive the activities to execute and perform the execution of associated command sequences, etc.

-The System Health Management application that provides key information on system availability and functionality of the subsystem, which is necessary to validate the activity rules and constraints.

-Crew interface system, which provides the information to the crew and allows them to manage the timeline execution, including the ability to override, inhibit or initiate such execution. This element is particularly important since disengaging or negating the control of this function from the crew would result in a net loss of management capabilities for them, instead of enhanced capabilities for mission management.

All of these components must interface with each other in a framework that enables functional autonomy, sharing and

providing information and actions to each other and the crew.

These capabilities must result in the crew's ability to understand the plan to execute, modify it if necessary, and provide oversight on the automated execution of such (if desired) with no or minimal MCC assistance.

Human-Computer Interface

An effective and efficient Human-Computer Interface (HCI) is essential to the crew's capabilities to understand the mission plan, to execute and modify it if necessary, and provide oversight on the automated execution of such (if desired) with no or minimal MCC assistance. Developing a common and effective HCI and applying it to the CEV, the Lunar / Mars Surface Access Modules, as well as ground-based mission control sites and lunar habitats is cost-effective in terms of both equipment and training. A common and effective HCI is also critical for shared situation awareness and collaboration across a network of humans in space and ground-based controllers.

Recent advances in display and computing technology have made feasible the development of a common HCI utilizing large format, high resolution virtual displays which allow for a more efficient and intuitive presentation of information graphically, while maintaining the same "look and feel" from one implementation platform to another. Given the highly autonomous nature of future long duration human space missions, this common HCI should strike an optimum balance between keeping the human engaged and "in the loop" and total automation control. A common HCI would also provide for increased situation awareness, as well enhanced safety and mission effectiveness, while reducing the training and maintenance costs typically associated with complex HCIs interfacing with complex system of systems.

While we have discussed the requirements for automation capabilities to meet future Exploration mission requirements, the commercial and military aviation industry has shown that increasing automation in the cockpit always has unanticipated consequences. Every time a problem is solved by technology, a new one will be created. A particularly relevant example is what has been termed "automation surprises", or the failure of the human operator to track, monitor, or anticipate the actions of an automated system leading to unintended system behavior[1]. A better understanding of the factors that contribute to these automation surprises will allow industry to detect and counteract the risks that may arise from implementation of new automated systems. Design-induced human error and automation problems cause nearly 80% of aviation accidents, which attributed to poor interfaces of the automation capabilities to the crew.. Additionally, a crew interface architecture that is not human-centered is often unable to accommodate change and growth. Lessons learned in the commercial and military cockpit has shown that the best approach to human / automation interface is to define the optimal role for the crew first, and make the system conform to that role, resulting in increased safety, reduced training, greater efficiency, and higher mission success probability. One aspect of automated systems interfacing to humans is that they often present more information than the human can process in the time available, resulting in an information overload condition. Increasing crew responsibilities, more data to manage, and more automation leads to increased training requirements, increased workload, and a higher error potential. In the absence of a good cockpit information management, integration and layout design, the human crew often does not recognize potentially important information.

Traditionally, human space programs from Mercury through Shuttle have expected the crews to generate their situation awareness from raw data gathered from electromechanical gauges and other tactile instruments, such as knobs and switches. Even with the advent of feasible CRT and subsequently flat-panel LCD technology for space, the interface was still designed to mimic a largely heritage electromechanical presentation of data augmented by rudimentary textual capabilities. Such an interface design presents a major challenge to human operators because the input bares no resemblance to the cognitive structures it is trying to create. One study found that nearly 25 percent of commercial aviation pilots who accessed a flight-management computer information screen containing erroneous data failed to detect the error due to the poor layout of the information. Such was the case with the original display layout in the Shuttle. The information presented on the original Orbiter CRTs was mostly text oriented and required astronauts to scroll through pages of monochrome textual data to view the information. With the implementation of the Multifunction Electronic Display System (MEDS) cockpit upgrades, full color graphics, cues and warnings indicate the priority of each specific problem now presented to the astronauts on the new flat panel LCD displays. Unfortunately, despite the modern graphical capabilities of MEDS, it was decided to replicate the original orbiter elecromechanical layout in the HCI in order to keep the panel "familiar" and avoid retraining costs, yet neutering the potential for an enhanced and more cognitive approach to the presentation of data and information.

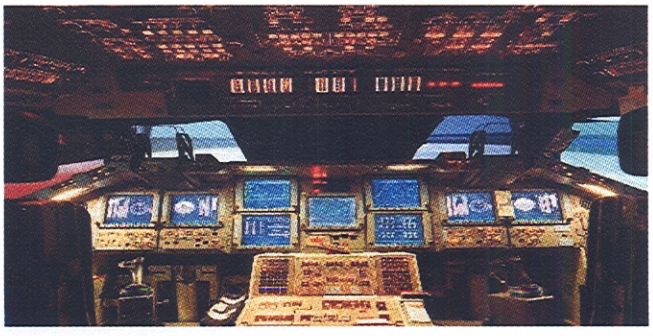

Figure 3 Shuttle MEDS, *while using modern LCD flat panel technology still mimics the cognitively challenging presentation of elecromechanical gauges and indicators.*

An historical assessment of the Apollo crew interface indicates that for missions, the astronauts had to rely on significant intuition, mental calculations and estimates to identify and navigate landing areas and footprints. Additionally, the Apollo astronauts were encumbered with the need to memorize a vast number of vehicle specific procedures, operational information, switch settings and positions that necessitated a lengthy and expensive vehicle specific training regimen. Given that the next generation human-space exploration mission objectives well exceed that of heritage Apollo, a significantly more capable and common HCI that can be extended across exploration platforms will be required.

Advances in cognitive psychology, as well as computer and display technology since Apollo have made feasible the development of a common HCI utilizing large format, high-resolution displays which allow presentation of information more graphically and more intuitively to the operator while maintaining the same "look and feel" from one spacecraft to another. Such an HCI would provide many benefits over traditional human space crew displays. Large format displays together with sensor fusion and computer generated information make it possible to create intuitive "better than out-the-window" functionality. Reconfigurable and upgradeable software components could be used to support operator decision making and situational awareness, while allowing for increased extensibility and a more cost-effective system. On demand information and procedures could be presented to the operator readily in any desired location within a display or displays, providing for better information access, better data integration and increased situational awareness. Perhaps most importantly, the HCI should be multi-purpose; it can be used by an operator onboard the CEV, onboard a Mars spacecraft, from a remote lunar habitat or from an earth-based mission control center without a huge cognitive adjustment. Specifically, crew and mission controllers should be presented with information allowing them to remain acutely aware of vehicle endurance parameters and windows of opportunity for critical mission milestones, such as trajectory adjustment burns, landing, ascent and rendezvous. HCI capabilities must be present to reduce crew / controller cognitive workload while enhancing situation awareness.

Central to the HCI would be visualization tools and presentations (e.g., on-screen smart checklists, advanced vision systems and predictive visualizations) with capabilities for various selectable orientations such as a "God's eye" view, "wing man" view or "out the window" view for enhanced situation awareness and mission planning. The capability must exist to provide on-demand information access and "sharing" of data among spacecraft crews and mission controllers on the ground (be it Earth or Moon). Finally, the HCI should be easily reconfigurable and tailorable to support multiple system configurations such as crew positions while retaining its fundamental common "look and feel".

Developing effective HCI for space is obviously not without its challenges and complexities. Several lessons have been learned by industry over the past several years to reduce design complexity inherent in the development of human-centered designs (HCD) for space, commercial and military applications. First, effective development teams for HCD must be comprised of different disciplines. Essential to an effective and well-balanced design team is an adequate representation of human factors expertise with enough authority to ensure human factors principles are considered and implemented in the design. When product specifications are written, the product teams take the results of the previous human factors studies and analyses and construct the necessary specifications. Also, human factors personnel should be extensively involved in the testing process along with the customer, users, certification authorities, and product groups. Flight testing should ensure that the human factors requirements are accomplished. These lessons learned may be encapsulated within an effective HCD process.

5. Enabling Technology Development For the Smart Cockpit

Understanding the capability requirements for future cockpit or space-based control centers is necessary to evaluate technology or applications that may enable such capabilities. This paper provided an overview of such capability requirements for specific Systems and Mission Management functions. This section offers an overview of some technologies that show potential or currently offer solutions to meet such capability requirements. Whereas we do not cover the entire spectrum for spacecraft functions, or technologies available for one specific function, the examples areas selected offer an overview of the technology characteristics that ought to be considered, and development to transition them into on-board applications.

Integrated System Health Management (ISHM)

The term Integrated Vehicle Health Management (IVHM), ISHM, or even Integrated Health Management (IHM) has been used to describe multiple, distinctly different technology or applications in the industrial, aerospace and military sectors. The same acronym has been used to describe smart sensors that perform local processing of the health data acquired on a single system, to inference engines that correlate massive amounts of data from multiple distributed systems to provide an integrated system health view. Furthermore, different technology approaches to achieve a similar solution are also labeled with similar acronyms. In this paper we are focusing on technology and

applications that provide solutions to the problem domain described in previous sections; the integration of subsystem or system element individual health state information to provide a vehicle or system-level health state.

To perform such function, it is necessary to go beyond traditional rule-based methodologies, since the complexity of system relationships and vehicle-level fault propagation exceeds the ability of such methodologies to capture enough of the domain space to enable true health state integration. We look beyond the traditional algorithms, towards applications that are able to capture inter-system dependencies, system hierarchy, system-level fault propagation, and have the ability to utilize this information for real-time correlation of individual health and status inputs to achieve the vehicle or system level diagnosis and health state assessment. Yet, the determination of vehicle-level health state leads to system and mission critical decisions, such C&W and FDIR, thus the methodology to obtain such must be fully deterministic and reliably accurate. Therefore, the candidate technologies for this function must combine the advance reasoning capabilities, with reliability and determinism.

Model-based system health diagnosis has been utilized widely in different industries to capture system information described above, and utilize such for real-time correlation and reasoning. Within model-based approaches there are several options, based on what type of model is utilized. These options include:

Model-based state estimation, such as the Ames Research Center-developed Livingstone software, which uses a model of the system to predict its behavior. If actual behavior diverges from the model's predictions, a diagnosis is made to isolate the cause of the discrepancy to a specific failure. Therefore, ultimately it is a comparison of expected behavior vs. actual behavior that triggers the diagnosis. Livingstone has been used as the reasoning engine for multiple prototypes of vehicle-level health state diagnostic engines, including flight test on Deep Space 1 and EO-1, where it was used as part of a flight experiment.

An alternate solution is model-based methodologies based on ***multi-signal dependency modeling and evidence-physics-based run-time reasoning.*** On this approach, the model represents the sub-system or system element dependencies, capturing components, functions, propagation paths, sensors, tests, probabilities and other information. Diagnosis is accomplished by following dependencies from the tests or sensors, which are the indications of failure symptoms, back along known propagation pathways, to the originating cause of the failure, such as a component or a particular failure mode of a component. The multi-signal dependency models capture the vehicle's topology, functions, intersystem dependencies and fault propagation paths across multiple subsystems (e.g. power system failure resulting in the loss of power to multiple components). In the system view, these are inter-element dependencies (e.g. Orbiting element to Planetary Base element).

This approach is typically comprised of two application components; the tools used to create the models and perform analysis on the system design as represented in the models, and the run-time reasoners that perform the diagnostic analysis in real-time. The off-line models are transformed into Dependency Matrices, or other executable code that can be reasoned upon efficiently. The off-line models can be built in the form of graphical representation of the dependencies, data-bases, etc. Whereas this approach has not utilized for system health management applications in manned space systems, it has widely been used in the commercial and military aerospace industry for different off-line and real-time integrated diagnostic applications, as well as in other sectors such as the automotive and petrochemical industries. Qualtech Systems Inc. (QSI) TEAMS tool set combines the off-line diagnostic modeling and run-time reasoning application for an integrated solution. In QSI's solution, the domain knowledge capture is enabled by Team-Designer, which provides graphical modeling, and testability analysis, as illustrated in figure 4.

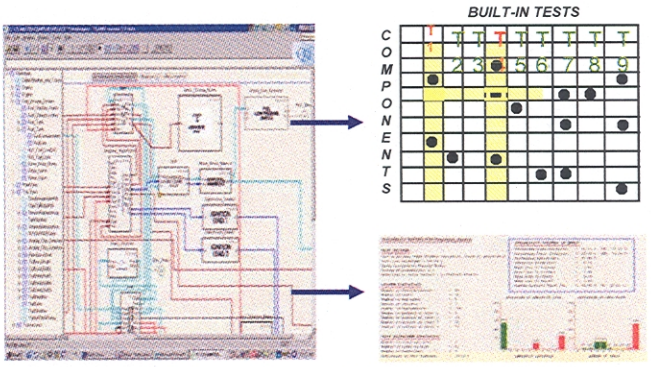

Figure 4 TEAMS models provide system design diagnostic analysis and executable domain data for diagnostics

This off-line Windows-based tool provides capabilities to capture vehicle and system dependency and topology information, as well as many other parameters from component reliability to Mean-Time-Between-Failures (MTBF) data, if desired. This information is then exported as a Dependency Matrix for use by the TEAMS-RT diagnostic reasoner, which correlates the individual results of the test points, which can be populated by sensor inputs, algorithms, etc, to provide the integrated view of the health state, or fault propagation path. DSI International, Inc. provides the eXpress tool, which also targets the domain capture and diagnostic analysis capabilities, to ensure that the vehicle design supports the required levels of fault coverage, health visibility into all aspects of the system, and ultimately, the optimum instrumentation coverage and placement. Figure 5 provides an example of and eXpress diagnostic model.

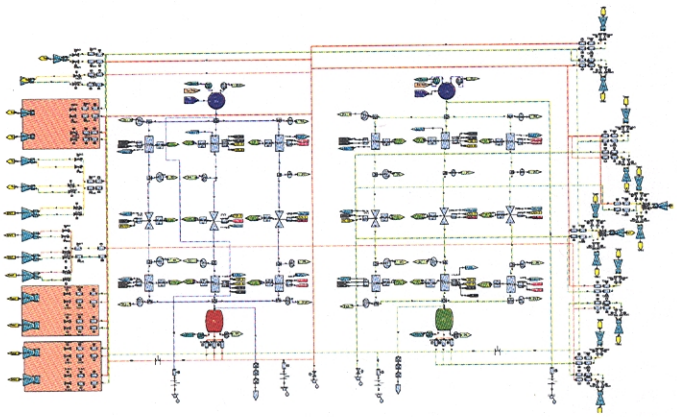

Figure 5 eXpress diagnostic models of a manned spacecraft Reaction Control System design

Whereas the eXpress models are used for analysis off-line, these models can be exported to other run-time model-based diagnostic reasoners, such as the Impact Technologies' ReasonPro, or custom develop reasoners that can read the standard model-export format. Through the early use of tools like eXpress, the platform design is optimized for Fault Detection and Isolation capabilities and well as sensor selection and placement to support the automated health management application design. Prognostics / physics of failure candidates are also selected during the front end diagnostics design using eXpress. Effective Run-Time health management is based on the run-time application's interface with the front end design process, which in turn provides the domain information necessary for effective correlation and integrated reasoning. The developers of eXpress, for example, have teamed with Impact Technologies, developer of ReasonPro, to provide an integrated solution, dubbed eXpress-RT, of off-line and run-time solution, similar to the QSI's TEAMS toolset.

Ultimately, these COTS applications do not provide, standalone, the entire solution to meet specific ISHM capabilities required for future cockpits or space-based control centers. The specific requirements for vehicle and mission critical functions, including systems and mission management automation, will lead to custom designed applications for the operation systems. However, the current proven capabilities both in diagnostic and testability analysis and run-time applications, demonstrate that the technology foundation necessary for the custom applications has been developed. Furthermore, the successful heritage and maturity of such technology, with demonstrated deterministic behavior, is a significant risk reduction over the implementation non-deterministic or lower Technology Readiness Level (TRL) rated technology approaches to achieve similar automated reasoning capabilities. This risk reduction is especially significant since any such cockpit-based application must endure the stringent Validation and Verification (V&V) process, as well as flight certification required for human-rated systems.

The combination of such technology (multi-signal dependency models with evidence/physics-based reasoners), with traditional approaches (i.e. rule-based), and system-specific interfaces and applications, will lead to the development of applications that provide the required on-board ISHM capabilities. Moreover, the customization of models, reasoners, or the combination of capabilities with other non-deterministic approaches providing supporting information, may lead to end-to-end health management capabilities that cover the real-time critical requirements, and also maintenance and long-term system prognostics needs on-board.

Command Scripting and Class V IETMs

Whereas, integrated health management is necessary to enable any automation of other system or mission management functions, the automated execution of tasks or command sequences is the "execution arm" of the automation systems. To achieve significant on-board independence from MCC to perform systems and mission management, it is necessary to not only provide the crew with accurate and timely information on the integrated health state of the system, but also to provide them with automation capabilities for nominal tasks and off-nominal event response. Autonomy capabilities for task automation can be embedded in different components of the system. Health management applications have the insight into vehicle health state and provide direct information related to conditions that may required automated vehicle-level responses, thus it could perform the vehicle-level FDIR functions. The planning systems manage the mission timeline, and therefore could have an execution branch to automate the execution of tasks in the timeline.

Nonetheless, comprehensive task automation must cover all the task execution options within the cockpit or the control center, including vehicle-level FDIR, nominal tasks in the timeline, and crew or operator directed initiation of automated execution. Furthermore, it must not be exclusive to one specific functions, such as health management, but aide the crew in any nominal or off-nominal system management task. Hence, we focus on technologies that may provide such comprehensive automation capabilities for task execution.

The most basic mode of automating the execution of commands is to provide command scripting capabilities on-board, such as pre-determined command sequences can be executed upon pre-determined triggers. The triggers can range from human input to system health management inputs, planning system inputs, etc. The level of autonomy is then decided by the capabilities that trigger the sequence execution initiation, which can be highly complex algorithms, or simple rules, such as parameter limit violations, or modes/states changes.

There are currently command scripting applications that have been human-rated and are currently in use in a variety of aerospace and industrial applications. The Draper Laboratories Timeliner application is used in ISS payload operations to automate different aspects of ISS Rack and payload systems initiation, operations and safing. Timeliner is also resident in the C&C flight software, however it has not yet been extensively used for core-system task automation.

ICS' Spacecraft Command Language (SCL) also provide command scripting capabilities, similar to those of Timeliner, which can be integrated as a stand-alone command scripting application, or part of the C&C system for vehicle management.

As command automation technology implementation takes a foothold on future spacecraft design and operations, the ideal progression of capabilities point beyond the execution of pre-defined static command sequences. The static sequence execution upon dynamic conditions should shift towards the dynamic command sequences, not entirely pre-defined, upon dynamic conditions. Moreover, these capabilities should merge the traditional crew and operator procedures for nominal, malfunction, activation and checkout, etc, resident in the ODF, into an electronic repository of tasks that can be executed manually, with mixed initiative (autonomous) or fully automated.

Class V Electronic Technical Manuals (IETMs) reflect such capabilities, where the procedure action are determined by the dynamic system or mission conditions, instead of having a static sequences pre-determined prior to flight. There are several approaches to Class V IETM development. One of those is offered by QSI, utilizing the same diagnostic models developed for forth the testability analysis, and the run-time integrated diagnostics and health assessment. This commercial product, called TEAMATE, dynamically produces operator actions to further diagnose health anomaly ambiguities to achieve a root-cause diagnosis, as illustrated in Figure 6.

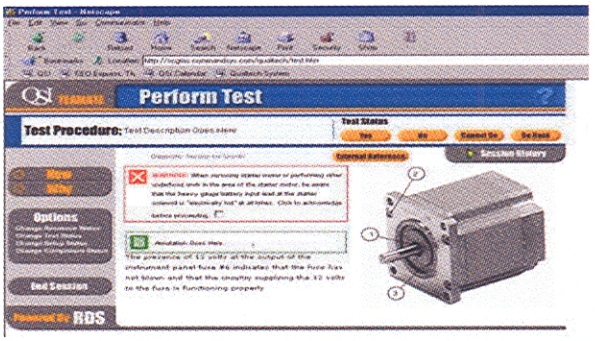

Figure 6 TEAMATE user interface for dynamic procedure execution, based on enhanced diagnostic models

The applications and capabilities discussed above provide the foundation for future applications, perhaps combining different technologies and approaches for decision autonomy and execution, that will provide critical automation capabilities for command and activity execution.

Constraint-Based Planning and Scheduling

As previously discussed, current short-term timeline development is a highly manual task, as well of the real-time re-planning and modification of such. Large contingents of people from different system disciplines (e.g. planners, resource analysts, systems operators, etc) are necessary to maintain the plan current and re-plan in real-time. While there is automated planning technology that can address both mission plan development pre-flight, and real-time re-planning, we are focusing on the latter due to its tactical nature, which has more significance on the capability requirements for mission management automation on-board.

Even when the mission plan has been developed, and different timeline options for short-term execution are available, certain amount of real-time analysis is required to validate the current timeline, or develop additional options. Moreover, when the system state or mission conditions change (e.g. crew member ill) the new asset availability, both crew and systems, changes the validity of the current plan, and therefore must be re-planned. Therefore, the automation capabilities must cover limited systems, flight dynamics and resource analysis, as well as constrain analysis, de-conflicting techniques, and plan options evaluation and rating capabilities, as illustrated in Figure 7. Automating such planning functions would provide the crew with the necessary information to select plan options and execution approaches.

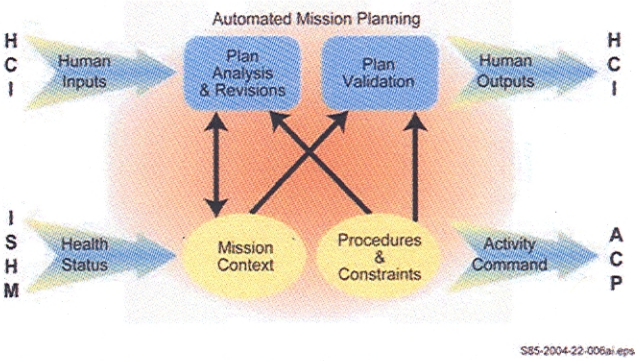

Figure 7 Automation in planning requires analysis and plan validation capabilities, as well as close integration with the crew and other systems management components

We, again, revert to technologies with proven capabilities in relevant fields, and with similar or superior parameter and condition complexity. For this section we focus on methodologies that offer model-based mission activity and resource representation, incorporating mission ground rules, constraints and procedures that is compatible with proven automated planning tools. Constraint-based planning

provides decision technology that can solve and optimize the world's most complex scheduling and resource allocation problems.

The main purpose of automated planning capabilities is to enable the crew to control their mission timeline and have the capability to change it if required. Constraint-based planning enables strong mixed-initiative automation, integrating the human input, or override into the process. Constraint-based planning technology also relies on domain and scheduling models, which contain the relevant activity, constrain, and ground rules information to be applied to the re-plan activity. Such models can be developed in a variety of ways, from more automated to manually, as in current processes. Hence, automation in the development of such models could further increase the efficiency of the process. However, automation of domain model development and pre-flight mission plan development are not necessary to migrate tactical mission re-planning on-board, since even complex missions to Mars will support some level of communication with Earth, thus retaining the ability of acquiring additional or modified models, as well as long-term mission plan files.

The heritage of such algorithms, enabling the automation of complex scheduling problems in the aerospace (and petrochemical) industries also ensures the ability of such approaches to be implemented on systems with strict V&V requirements.

Information Management and Displays

Since NASA's first rendezvous attempts during Gemini, culminating with the Lunar landing and rejoin of the Apollo Lunar and Service Modules, one of the key issues for a safe completion of human spaceflight mission objectives has been the ability of the crew to have adequate visual references. This capability has been essential to both manually controlling the spacecraft during rendezvous/docking & approach/landing, and to visually verify that automated GN&C involved with these operations is working properly. This capability has always been in direct conflict with the structural engineering desire to eliminate or at least to minimize the spacecraft windows providing the outside view. Even more critical to ground mission controllers and planners is the ability obtain and maintain a high degree of situation awareness involving the vehicle and its mission at a distance without the benefit of natural views through windows of any kind.

Advances in avionics computing, graphics processing and display and sensor technology, since Apollo, makes it possible now to present a "better than natural" view outside the spacecraft. Using Advanced Vision Systems, next generation human space exploration vehicles could be equipped with an exterior array of image plane sensors and a high-resolution landing zone terrain database that would be used to render a synthetic image of a virtual outside world. The computer generated scenery would be appropriately overlaid with real images fused from a combination of other sensors including visible, infrared (IR), millimeter wave (MMW) and LIDAR to name but a few. Such a system (display shown in Figure 9) may actually be superior to natural human vision in that it could allow crews, operators and controllers to "see" in darkness, bright sunlight conditions or through Martian dust storms. Moreover, the scene potentially could be zoomed and manipulated electronically; this would provide operators and crew with supra-normal artificial visual acuity, thereby affording earlier landing site evaluation, obstacle identification and touchdown point redesignation. Fusing real world "enhanced" vision imagery avoids the obvious limitations of purely model based, exclusively "synthetic" vision systems. In addition to enhancements provided by sensors and synthetically generated terrain, flight data symbology, data graphics and other vehicle parameters would be overlaid in what is called Advanced Symbology to provide crew and operators with a single point of reference and thereby increase situation awareness while reducing cognitive workload.

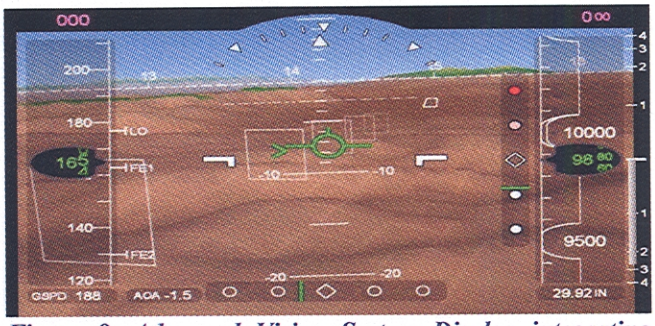

Figure 9. Advanced Vision System Display integrating Enhanced Vision, Synthetic Vision and Advanced Symbology.

An historical assessment of Apollo crew interface indicates that for lunar landing missions, the Apollo astronauts had to rely on memory, significant intuition, mental calculations and estimates to identify and navigate possible landing areas and landing footprint areas (NASA, 1975). Due to the limitations of window size and geometry on the LM, it was difficult for the astronauts to sense relative size of obstacles, descent rate and radial velocity; only a limited number of landing site re-designations were available due to these constraints (McCandless, McCann, & Hilty, 2003). Operators and crew should not have to make command decisions through such error prone methods (Lintern, Waite, & Talleur, 1999). Instead of relying on memory which under significant pressure can be flawed at best (Wickens & Hollands, 2000), humans engaged in supervisory control should be provided with direct perception-action visual representations in as natural a depiction as possible. Such a direct depiction allows operators and crew the ability to establish and maintain a high degree of situation awareness facilitating the ability to make correct and timely decisions,

and reduce errors in the process (Rasmussen, 1998; Shneiderman, 1998). Given the future human space exploration parameters of light / dark, polar or equatorial landing site requirements of lunar and Martian missions that go beyond Apollo, some sort of AVS capability seems to be essential for safety and mission success.

Decades of experience in the military and civilian aviation domains has demonstrated that the largest fraction of vehicle control problems (e.g., near misses, loss of control, controlled flight into terrain) have been due to the inability to recognize (due to night and/or marginal visibility) normal objects that the operators normally utilized in maintaining situation awareness (SA) and control. This increased the pilots' workload further exaggerating the negative effects.

Advance Vision Systems (AVS) technology has been demonstrated to significantly increase safety and operational flexibility for spacecraft, aircraft and land vehicles operating in low or no-visibility conditions. The all-condition visibility provided by AVS facilitates maneuvering allowing normal operations under conditions that normally would dramatically slow or even halt activity. AVS affords an opportunity for future windowless cockpits for next generation space vehicles.

The Advanced Vision System consists of three primary components:

- Synthetic Vision – derived from a terrain database;
- Enhanced Vision – from onboard sensors: video, IR, millimeter wave (MMW) radar, or LIDAR

Advanced Symbology – a visual vocabulary and format engineered to make the fused information immediately intelligible to the user and indicative of the precise relationship of the aircraft / vehicle to the environment.

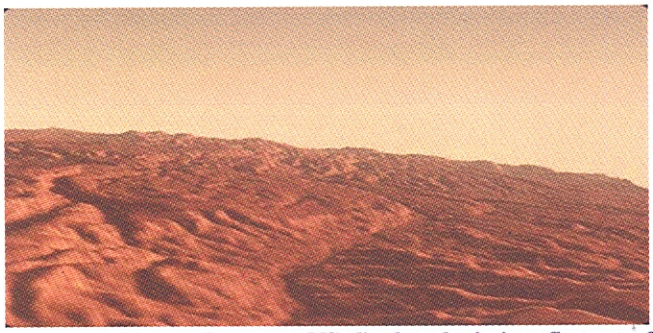

Figure 8. Large Format AVS display depicting flyover of Martian terrain.

Synthetic vision employs computer-generated terrain imagery from on-board databases, and precise position and navigational information to create a presentation of the outside world (Figure 2). The presentation to the operator is available in 3D perspective, planview, or vertical profile format dependent upon operator task. Synthetic vision eliminates poor visibility (be it because of darkness, or small or no windows) as a safety factor and enhances the operational capabilities of the vehicle. Synthetic vision may be presented to the user in either 2D or 3D and even 4D, where time may be manipulated for training and proficiency purposes, an important consideration for long-duration missions.

Enhanced vision already demonstrated and certified by the FAA for commercial aviation use in marginal visibility conditions, (e.g., night "black hole" approaches) using infrared augmentation, offers excellent night visibility, improving maneuvering accuracy and situation awareness. The future addition of millimeter wave radar capability promises even higher image quality and obscuration penetration. Honeywell has approached the difficult problem of fusion by utilizing efficient feature extraction techniques from the sensor data that significantly enhances the registration of the sensor image with the synthetic one. In the case of the use of a head-up display (HUD) to present the AVS in the aircraft world, it also enhances the registration of the sensor image with the real out-the-window view.

Advanced Symbology employs a visual vocabulary and display format that integrates information from all available sources, to present what the operator needs in ways that require less work to understand and process, improve pilot tracking performance and increase situation awareness for crews and controllers alike. This display methodology would simplify vehicle control by replicating cues basic to visual operation—including representation of outside relationships—and integrating these cues with navigation and directional information like a path vector.

By exploiting immediately understood relationships (affordances) and cues, Advanced Symbology establishes temporal and spatial relationships for the crew without the need for conscious decision. For instance, advanced symbology replicates the texture, perspective and color cues used to judge movement and distance visually—terrain shading, texturing and perspective lines, and the expanded field-of-view critical for a sense of directional movement.

A demonstrated ability to seamlessly integrate the multiple sources of information from onboard sensors and databases (e.g., navigational, geopolitical, obstacle and charts) is critical to the ability to provide the best user interface for current and future crew and operational needs.

Of course, display technology is essential to the realization of the application of AVS to space. Large-format and high aspect ratio Active matrix Liquid Crystal Display (AM LCD) have recently been used to provide the necessary space to merge the rendered terrain and advanced symbology in a way that enhances the operator's performance in path and energy management and greatly

improved situation awareness. A large, landscaped display can provide several operational advantages to the workstation as compared to a square porthole into which the same information must be squeezed to fit. In our human factors evaluations of the large landscaped displays, we have observed the potential to reduce task completion time, reduce input errors, increase situation awareness and produce an overall reduction in crew workload.

Active matrix Organic Light Emitting Diode (AM OLED) is an emerging display technology with a significant potential to challenge the well-entrenched LCD technology in many of its current applications and has attractive qualities for space applications. Compared to LCD, the advantages of AM OLED include lower power, lighter weight, being thinner and all solid state / more rugged, superior image quality with wide viewing angle and fast response time, and lower cost. AM OLED does not require a backlight or color filters like a backlit AM LCD. Currently, glass substrate based AM OLED is being developed rapidly with initial products such as displays for mobile phones and digital cameras already on the market.

Flexible AM OLED displays fabricated using plastic substrates have a potential for being very thin, light weight, and highly rugged, with greatly minimized propensity for breakage, and lower cost. The current high level of interest in flexible displays is facilitating the development of the required enabling technologies, which include development of plastic substrates, low temperature active matrix backplane fabrication technologies, and display packaging. Development of flexible AM-OLED display technology may be viewed as a natural evolution of the rigid glass substrate based AM-OLED development. In actuality, flexible AM OLED development represents a paradigm shift. Flexible AM OLED displays can provide many unique display applications including suit-based and surface EVA due to its unique form factors of conformability and roll-ability during use, transportation and storage. For example, crews exploring the lunar or Martian surface could remove a rolled AM OLED display from storage in their packs and unroll the display into a large format AVS representation of navigational and other mission data and then when finished return the display to their equipment packs in its space-saving rolled tubular form.

Commercial industry has been actively involved in the development of flexible AM OLED displays since 2000. Under a recent DARPA funded program, the world's first AM OLED developed on a flexible plastic substrate was demonstrated. This demonstration constituted development of low temperature (150°C) a-Si TFT process for fabricating the required active matrix circuitry on flexible polyethylene naphthalate (PEN) plastic substrates, design of the active matrix OLED pixel circuits and display drive electronics, and fabrication of a 64x64 pixel test displays with an 80 dpi (dots per inch) monochrome resolution. Recent demonstrations included 160x160(x3) pixel test displays (~ 2x2-inch size) with 80 cgpi (color groups per inch) equivalent resolution (Sarma et al, 2003).

The most critical area for efficient use of control station space is directly in front of the operator and about 15 degrees down from horizontal, where resting vision tends to fall. Within this forward panel area, using larger landscaped displays can minimize the amount of space consumed by bezels with respect to the amount of space provided for the usable, visible display area. Further, large, landscape displays tend to conform to the rectangular shape of most forward panels in aircraft and the wide format of the human visual field

In a full screen format, map and terrain graphics on a large landscape display can provide unsurpassed situation awareness capabilities (Figure 10). For example, in the aviation domain, air traffic controller workstations have always been designed with the recognition that large formats are required for traffic and weather situational awareness; the future collaborative decision-making environments will make it desirable to provide that same level of awareness to the crewmembers and other operators via large formats.

Honeywell has recently completed a series of human factors focused flight test programs testing the aviation version of AVS. The results indicate a very strong user acceptance and usability of the AVS concept. Study participants reported that the synthetic terrain was very visible and useable in all lighting conditions and the advanced symbology was a very useful aid to pilot performance and workload.

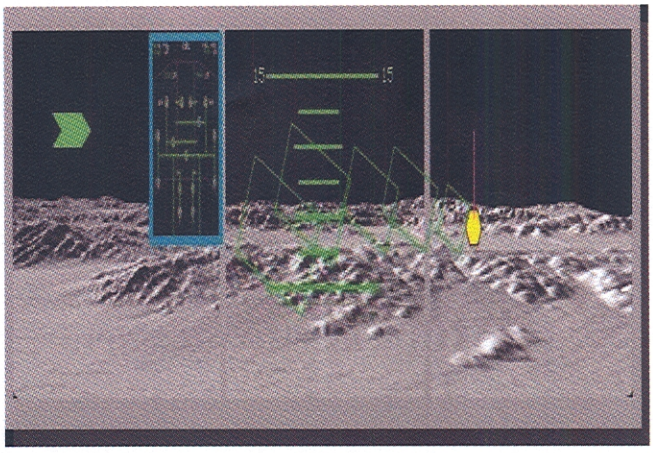

Figure 4 . AVS concept integrating information into a perspective tiled display.

A potential solution for vision in daylight conditions is to put bubble canopies or large windows on the spacecraft. However, cost, weight, and structural issues will usually eliminate most any solution that places a large picture window in any space vehicle. Regardless, missions

requiring operations in darkness or in obscuration phenomena would still make unaided vision unacceptable. Finally, every sensor has a limitation. Therefore a good fusion of synthetic and sensor data not only provides a wide range of data to select from, but it also allows for the optimal set of components to each accommodate a much larger variety of conditions and system states (e.g., a sensor failure).

6. CONCLUSION

Future cockpit and space-based control centers must employ automation capabilities in key areas of Systems and Mission Management functions, to successfully meet Space Exploration goals and objectives. These capabilities must provide the crew with Integrated Vehicle and System health information, assuming the function of constant system monitoring and integrated performance assessment. In case of anomalies, the system must detect and integrate all individual system failure indications, and provide the crew with C&W information that points to the root-cause and provides system impact information such as functional and redundancy degradation caused by the failure.

Automation capabilities should also be implemented to nominal and off-nominal task execution functions, to relieve the crew from routine systems management tasks, and complex diagnosis and execution of time-critical failure response actions, while preserving their ability to inhibit, override or otherwise control all automated or autonomous functions. In the Mission Management category, the real-time planning functions must be shifted on-board for efficient and timely mission execution, providing the crew with sufficient information to alter, or re-plan their short-term timeline in response to vehicle, system, mission or personal events.

The level and efficiency of the integration of the crew with these capabilities will determine the feasibility of the implementation of advance automation capabilities. Therefore, the design of an optimal HCI that fulfills the cognitive needs, and enables the crew to remain in control of all Systems and Mission Management functions is tantamount to success.

As discussed in this paper, there are currently technology and applications that can serve as the technology foundation for the development and implementation of such automation capabilities on-board future systems, while maintaining reasonable development cost and preserving or enhancing system and crew safety. However, active adaptation, development and maturation is required to ensure that the readiness levels are ideal when the capabilities are required.

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