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Intelligent flight support system (IFSS): a real-time intelligent decision support system for future manned spaceflight operations at Mission Control Center

Madjid Tavana*,[1]

Management Department, La Salle University, Philadelphia, PA 19141-1199, USA

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Abstract

The Mission Control Center Systems (MCCS) is a functionally robust set of distributed systems primarily supporting the Space Shuttle Program (SSP) and the International Space Station (ISS) mission operations. Forged around the uniquely complex and demanding requirements of human spaceflight, the MCCS has evolved within the limits of the technological capabilities of the time. The dynamic environment in which MCCS functions has demanded that the systems architecture continue to evolve as well.

The MCCS provides the primary means of controlling crewed spacecraft operated by NASA. Flight controllers (FCs) monitor the spacecraft systems through telemetry sent from the spacecraft to the ground and from the ground to the vehicle. FCs utilize several application software to present telemetry data in a variety of output presentations. While most displays simply provide a densely packed screen of telemetry data, only a few provide graphical representations of the vehicle systems' status. New technological advances in user interface design have not penetrated into MCC especially since the SSP and ISS systems were developed when these technologies were not available. The Intelligent Flight Support System (IFSS) described in this paper promotes situational awareness at MCC with an interactive virtual model of the ISS and Space Shuttle combined with data and decision support displays. IFSS also incorporates an intelligent component to model various characteristics of space vehicle systems when predictable results of unknown scenarios are required. IFSS supports FCs in the planning, communications, command, and control operations of the ISS and Space Shuttle by providing knowledge and skills that are unavailable from internal representation.

Keywords: NASA; Decision support system; Graphical user interface; Virtual reality; Systems design

1. Introduction

Throughout the history of human spaceflight, the Mission Control Center Systems (MCCS) at the Johnson Space Center (JSC) has been a model for mission planning, communications, command, and control architectures. The Mission Operations Directorate (MOD), overseeing the Mission Control Center (MCC) and MCCS, must ensure that the overall system performance meets current and planned needs while looking for innovative ways to curtail operational costs and continually address evolving operational scenarios. The Directorate must also enforce the highest return on investment on the funding it receives annually. This vision provides a basis for the long-term, as well as day-to-day, decision-making that ultimately impacts requirements, design change, and budget plans. The MCCS Architecture Team, a multidisciplinary group of MOD experts and scientists is chartered to redefine the next generation of MCCS by developing integrated systems design architecture.

The original MCCS was designed as nonintegrated pieces of a whole independently supporting the larger goal of human spaceflight operations. While more advanced computing capabilities have allowed the MCCS to morph from completely independent functioning systems into a distributed design architecture, the technological advances of the last several years have allowed for the potential implementation of a true integrated systems design architecture. The MCCS, which has always served as the nerve center of US human spaceflight operations,

* Tel.: +1-215-951-1129; fax: +1-775-213-9343.
E-mail address: tavana@lasalle.edu (M. Tavana).
[1] URL: http://lasalle.edu/~tavana.

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has evolved from a centralized mainframe computer architecture in which all aspects of mission planning, communications, command, and control were performed predominantly from multiple buildings located at JSC to a distributed architecture with multiple remote facilities located around the world.

The current MCCS is a functionally robust set of distributed systems primarily supporting the Space Shuttle Program (SSP) and the International Space Station (ISS) mission operations. The MCCS also performs the following functions: real-time data (telemetry and trajectory) monitoring and analysis; real-time command; near real-time data storage, retrieval and analysis; space-to-ground and ground-to-ground voice, video, data, and mail distribution; as well as real-time and near real-time planning and simulations.

Forged around the uniquely complex and demanding requirements of human spaceflight, the MCCS has developed and evolved within the limits of the technological capabilities of the time. The dynamic and continually evolving environment in which MCCS functions has demanded that the over-arching structure of the systems—the systems architecture—continues to evolve as well.

As a result of dwindling funding for the foreseeable future, the MCC must focus on ways to reduce costs while still maintaining and even expanding its capability to support the SSP and an increasingly larger and more complex ISS. As part of a previous MCC Mission Computing Strategy study, the MCC adopted the following set of goals that the MCCS Architecture Team uses as major evaluation factors in its early proof-of-concept work toward the vision:

- *Design for change*. Commercial standards compliant, standard interfaces, and simplified configuration management processes for migration.
- *Design for flexibility*. Accommodate future manned spaceflight program requirements and operations concepts without significant impacts to existing architecture design.
- *Design for connectivity*. Information transfer between International Partners, MCC users (Flight Control), payload community, joint space operations with Government, industry, and academia collaborations using the Internet where practical.
- *Design for access*. Security commonality/simplification-robust but simple security for user concurrent access to multiple security levels that does not constrain system functionality.
- *Design for cost reduction*. Commodification (a move toward an infrastructure that can be supplied by many different vendors), consolidation, operational concept modifications, and re-engineering.
- *Design for ease of use and effectiveness*. Intuitive graphical user interface layouts that supports data visualization, and intelligent systems; minimal steps for task completion, effective decision making and job productivity.
- *Design from a systems perspective*. Develop and test new systems and process improvements that address all issues and concerns relative to the overall systems as a whole entity.

The MCCS provides the primary means of controlling crewed spacecraft operated by NASA. Flight controllers (FCs) monitor the spacecraft systems through telemetry sent from the spacecraft to the ground and from the ground to the vehicle. They also communicate among themselves, with the crew, and with other support staff located at external sites. Several application software systems are utilized to present telemetry data in a variety of output presentations. While most displays provide a densely packed screen of telemetry data, only a few provide graphical representation of vehicle systems status. New technological advances in user interface design has not penetrated in MCC especially since the SSP and ISS systems were developed when these technologies were not available.

We live in the information age [1]. MCC, however, is in the data age with a real information age just around the corner. MCCS generates terabytes of telemetry data everyday. Rapid technological advances have almost resolved data generation and collection problems at MCC. In this millennium, MCC is faced with the challenge of extracting hidden predictive information from large volumes of data. The next generation MCCS need to develop new tools and technologies to process telemetry data into useful information and knowledge intelligently and automatically.

With the increased need to reduce the time required to solve engineering problems of ever-increasing complexity, having the right information at the right time is crucial for making the right decision. Intelligent information representation can facilitate problem-solving and decision-making by providing an efficient and effective mechanism for expressing the data. In the past, visualizing meant constructing a visual image in the mind. Today, computer-supported visualization enables humans to perceive, use, and communicate abstract data and amplify cognition [2]. Extant data visualization taxonomies can be characterized as either structural or functional. Structural categories focus on the form of the graphic material rather than its content [3,4]. In contrast, functional taxonomies focus on the intended use and purpose of the graphic material. For example, consider the following situation described by Tufte [5]. On January 1986 the decision was made to launch the Space Shuttle Challenger. Two rubber O-rings leaked and the shuttle exploded. The posterior investigation showed that the available data about the launch history would have been enough to properly assess the risk of O-ring failure. Tufte's [6] redesign of data presented by the Challenger engineers as they made a case for launch delay shows how important it is to present information in a clear, logical manner that enforces conclusions such as causality.

Decision support and knowledge-based systems have evolved at a rapid pace over the past two decades.

An Intelligent Decision Support System (IDSS) has been defined as ‘a computer-based information system that provides knowledge using analytical decision models, and providing access to data and knowledge bases to support effective decision making in complex problem domains’ [7, p. 12]. The basic concept of an IDSS is the integration of classical decision support capabilities including access to information and analytical decision models with those of knowledge-based systems including reasoning and inferencing. Knowledge-based systems embody the knowledge of experts and manipulate this expertise to solve problems at an expert level of performance [8].

Real-time intelligent decision support systems are knowledge-based systems deployed in larger host systems with real-time response requirements. Many real-time intelligent decision support systems are built in safety-critical large-scale systems such as aviation and aerospace [9,10], nuclear power [11], transportation [12,13], and financial systems [14] to guide users’ actions in complex systems. Animation and virtual 3D technology are seldom integrated with decision support and knowledge-based systems. Gonzalez and Kasper [15] discussed the role of animation in decision support user interfaces and systematically examined the effect of animation on decision quality. They found that decision quality is affected by animation and that parallel navigation translates to superior decision quality. The Intelligent Flight Support System (IFSS) described in this paper, promotes situational awareness at MCC with an interactive virtual model of the ISS and Space Shuttle combined with data and decision support displays, and an intelligent component to model various characteristics of space vehicle systems when predictable results of unknown scenarios are required.

IFSS is a real-time intelligent decision support system that assists FCs in planning, communications, command, and control operations of the ISS and Space Shuttle. Because IFSS provides information that can be directly perceived and used, little effort is needed to process and interpret it. The IFSS can provide real-time operations supporting capabilities such as monitoring:

- the reaction control and orbital maneuvering systems;
- the vehicle guidance and navigation control systems;
- the avionics, cabin cooling and cabin pressure control systems;
- the electrical generation and distribution systems;
- the propulsion and interim control module activities;
- the thermal control system;
- the life support system;
- the power availability to payloads and core systems; and
- the operations of the robotic arm and mobile servicing system.

While the system was designed for all FCs at MCC, we illustrate the system with examples from the electrical power system and its FC Phalcon. The ISS requires an electrical power system for various functions, such as command and control, communications, lighting and life support. Power generation onboard the ISS includes the conversion of solar energy to electrical energy as well as the regulation of that electrical energy. The power generation function is accomplished by a set of solar array wings onboard the ISS. Solar array wings are a collection of photovoltaic cells wired in series providing the large light-collecting surface required for meeting the ISS power needs. In order to maximize the collection of usable solar energy in an orbiting vehicle, the solar array wings must be oriented to face the Sun. The scenario demonstrated in this paper involves the docking of the Space Shuttle with the ISS.

How do you park a $2 billion spaceship the size of a DC-9 at a seven-story space station while both are circling the planet at over 25 times the speed of sound? Bringing two such massive craft together at a 10th of a foot per second about 220 miles above Earth is not exactly like pulling the family minivan into a parking space at the neighborhood grocery store [20].

2. Architecture

The current flight control system is mainly data driven. The ISS Array Tracking presented in Fig. 1 as an example is

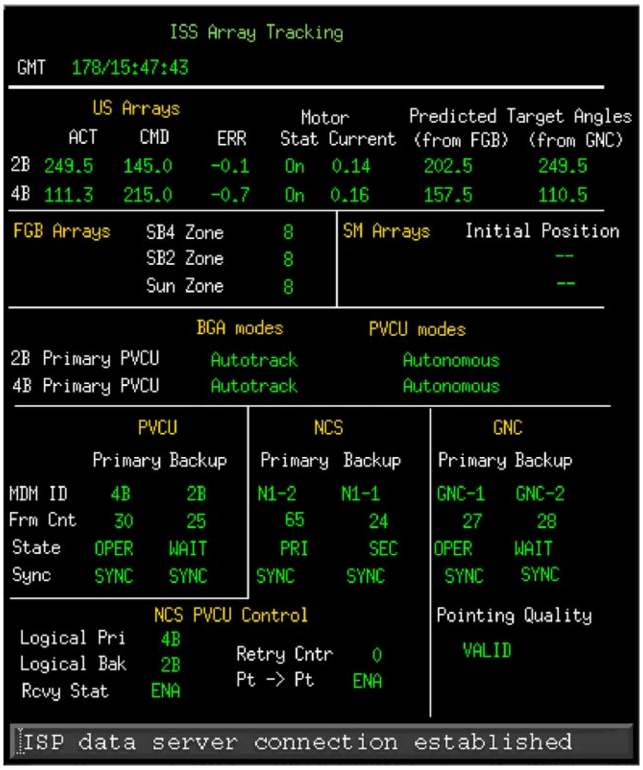

Fig. 1. A sample graphical user interface screen shot of the current flight control system.

used to show the US array angles (ACT) are tracking the Sun target angles from the ISS Guidance Navigation and Control (GNC) system. These angles should match within a couple of degrees when the arrays are in autotrack. If GNC target angles are unavailable, the Functional Cargo Block (FGB) Sun sensors are used to approximate the position of the Sun. The FGB Sun zones are converted into equivalent angles and displayed as Predicted Target Angles (from FGB and GNC). The remaining data in this display relates to the status of the controlling Multiplexer/Demultiplexers (MDMs), which are essentially computers. This information provides the health of the MDMs and whether pointing data is valid or invalid.

It is very difficult for the FCs to use these individual pieces of information to build good situational awareness. In contrast, the IFSS is designed to visually communicate the overall flight dynamics of the ISS and Space Shuttle. It consists of a virtual 3D environment and a graphical user interface developed with Microsoft Visual C++ and Microsoft DirectX. The virtual environment includes all the ISS and Space Shuttle geometric models and assembly configurations combined with real-time telemetry data and analysis and planning tools. The numerical data provided by the ISS GNC system is used to represent the attitude of the station, the location of the station over the Earth (state vector), the direction to the Sun, etc. This provides the FCs with advanced visualization and the ability to perform real-time interactive data analyses.

The integration of the analysis tools with the advanced visualization capabilities in IFSS provides a unique method for investigating dynamic spatial problems. The IFSS uses a simple joystick driven navigation paradigm to navigate throughout the environment by simply flying through the space. In this manner, the FC has the ability to move around and into the ISS while maintaining a fixed gaze towards the ISS. This allows the FC to view the ISS and Space Shuttle from different perspectives and perform several different analyses that provide input to the IFSS visualization software (see Figs. 2 and 3).

The user interface is comprised of two distinct data and intelligent components. The data component provides FCs with all currently used displays at MCC while the intelligent component is used to provide the FCs with what-if, goal-seeking and graphing capabilities. In addition, an expert system is embedded in the intelligent component allowing FCs to perform more sophisticated analysis, such as dual angle operations, feathering for docking, shadow analysis, auto tracking. Fig. 4 shows a sample screen of the 3D visualization and the menu components used in IFSS.

What-if analysis. What-if analysis is a trial-and-error method that determines the impact of changes in decision variables and assumptions. FCs use this option to adjust one or more variables and analyze the overall effect on the data and the virtual model of the ISS and Space Shuttle. For example, the IFSS can calculate the secondary power

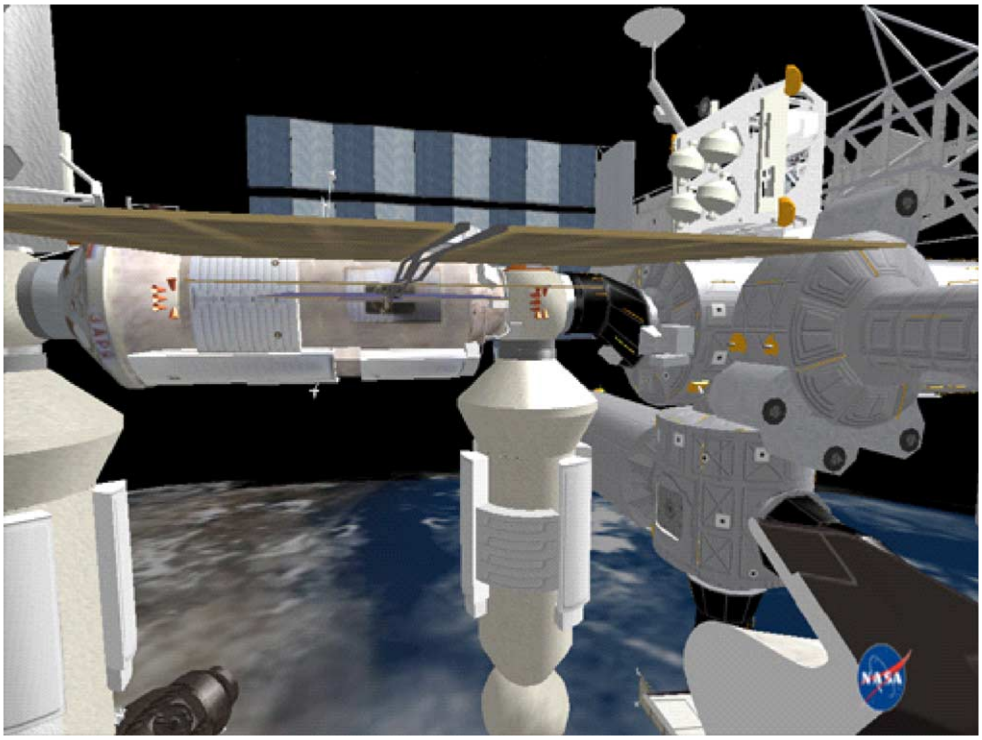

Fig. 2. A sample screen shot of the exterior of the ISS.

Fig. 3. A sample screen shot of the interior of the ISS.

Fig. 4. IFSS menu system graphical user interface screen shot.

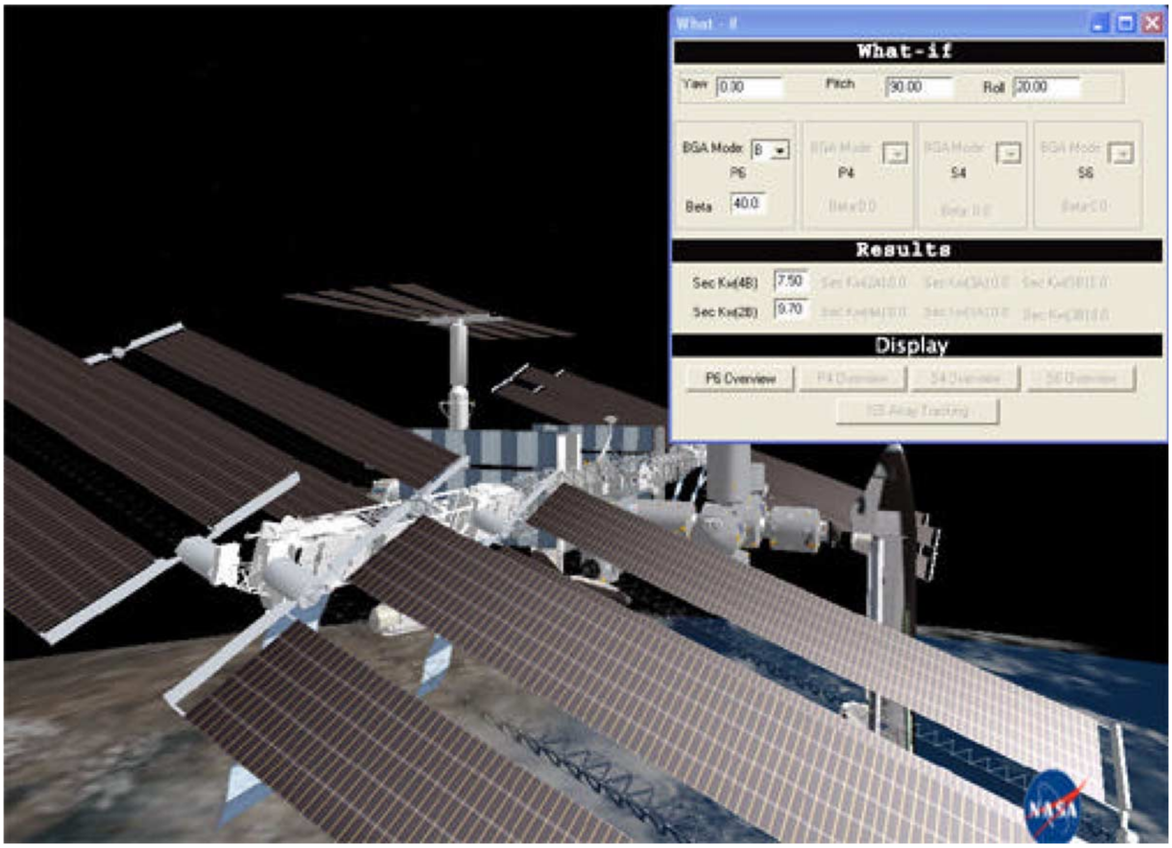

Fig. 5. ‘What-if’ analysis graphical user interface screen shot.

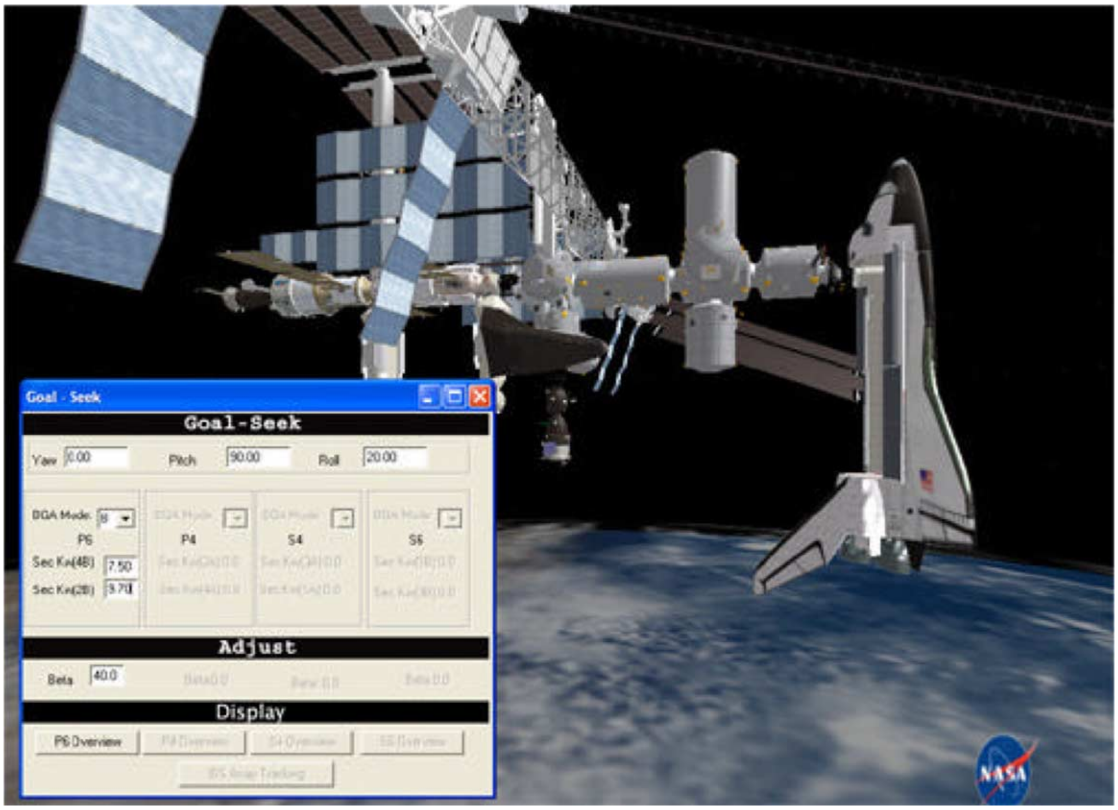

Fig. 6. ‘Goal-seeking’ graphical user interface screen shot.

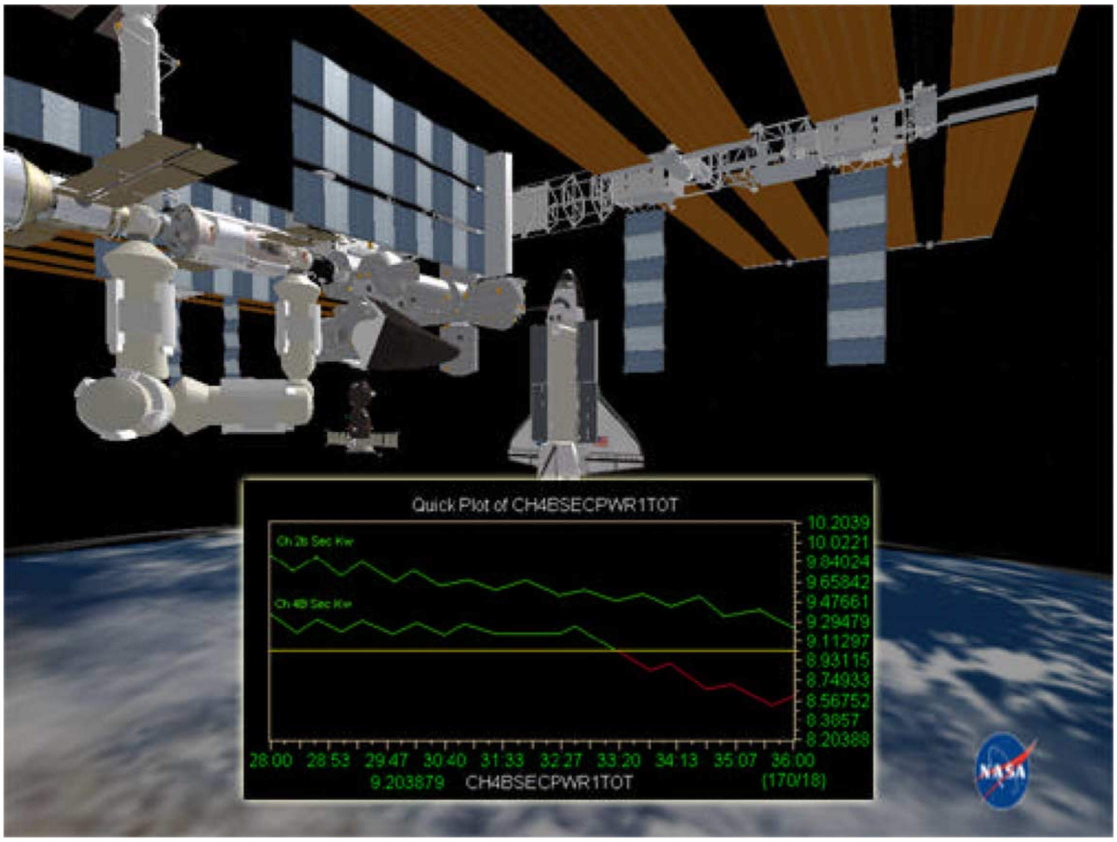

Fig. 7. Sample graph graphical user interface screen shot.

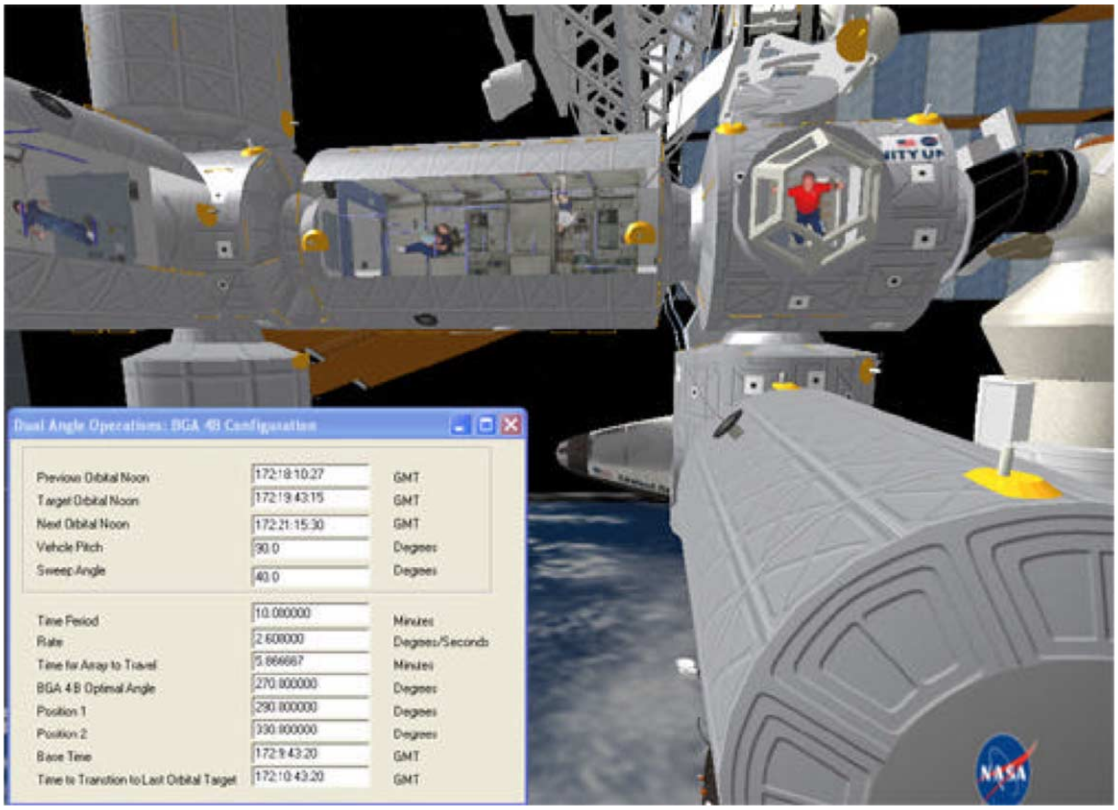

Fig. 8. Expert system graphical user interface screen shot.

output (Sec Kw) for any solar channel onboard ISS for a given attitude (yaw, pitch, and roll) and rotate angle. The actual algorithm used to calculate the secondary power output is quite complex. However, we present a simplified formula that can be used to approximate the secondary power output (SKW) as a function of BGA Mode, beta rotate angle (β), the Sun vector during periods of sunlight (V) and a given yaw (Y), pitch (P), and roll (R). The linear interpolating angle (Z) between two adjacent records, T_1 (Time 1) and A_1 (Angle 1), and T_2 (Time 2) and A_2 (Angle 2), for T_n (arbitrary time) can be calculated as: $Z = A_1 + [(A_2 - A_1)(T_n - T_1)/(T_2 - T_1)]$ where $T_1 < T_n < T_2$ and $\mathrm{SWK} = Z/\beta V\sqrt{Y^2 + P^2 + R^2}$. Once the secondary power output is calculated, the changes alter appropriate downlinked parameters from the ISS and update various displays as well as the virtual model of the ISS as depicted in Fig. 5.

Goal-seeking. Goal-seeking allows the FCs to determine the required value of a parameter to achieve some predetermined target, for example the solar channel angle for a given attitude (yaw, pitch, and roll) needed to provide a desired secondary output (Sec Kx) for a solar channel. In response, the new solar channel angle calculation changes the appropriate downlinked parameters from the ISS. Various displays are populated accordingly and a virtual representation of the angle for the selected solar array is provided as in Fig. 6.

Graphing. Graphing provides the FCs with capability to create a graph of selected variables from the displays. For example, in response to the selection of solar panel secondary outputs (Sec Kx) and a line graph format, the system presents FCs with the dynamic graph presented in Fig. 7.

Expert system. The expert system embedded in the intelligent component of IFSS is a rule-based system designed and developed to provide FCs with advice concerning various tasks such as dual angle operations, feathering for docking, shadow analysis and auto track. Fig. 8 presents a scenario for dual angle operations and solar array configuration. As it is shown, the expert system provides the FC with optimal angle setting of the solar array in response to input variables such the orbital noons, vehicle pitch and sweep angle.

3. Evaluation

The evaluation process began by investigating the importance weight of the factors adopted by MCC as part of the previous MOD Mission Computing Strategy Study. These factors were selected to serve as major evaluation criteria when the MCCS Architecture Team performs early proof-of-concept work. Analytic Hierarchy Process (AHP) was used to develop these importance weights. A mathematical summary of AHP is presented in Appendix C. Using the questionnaire presented in Appendix A, the MCCS Architecture Team was asked to provide their subjective assessment of each pairwise comparison. The responses were processed with Expert Choice [16], and those with inconsistency ratios greater than 0.10 were asked to reconsider their judgments as it is suggested by Saaty [17–19]. The mean importance weights were calculated for the MCCS Architecture Team after necessary adjustments were made to the inconsistent responses. Each MCCS Architecture Team member was presented with his/her individual score along with the group mean weights. The MCCS Architecture Team members were given the opportunity to rethink their judgments and make revisions to their pairwise comparison scores based on this feedback. Some MCCS Architecture Team members took advantage of this opportunity and revised their judgments in the second round. The mean importance weights for the first and second round are presented in Table 1. As it is shown, the second round results differ slightly from the first round results.

Table 1
The first and second round importance weights of the Technology Assessment Evaluation Factors Questionnaire

Evaluation factor	Round 1	Round 2
Ease of use and effectiveness	0.296	0.293
Systems perspective	0.184	0.191
Flexibility	0.140	0.132
Access	0.086	0.083
Connectivity	0.091	0.091
Change	0.088	0.084
Cost reduction	0.116	0.126
Inconsistency ratio	0.081	0.068

The IFSS was tested and evaluated by 24 FCs at JSC. A second pairwise comparison questionnaire, presented in Appendix B, was used to compare the IFSS with the system currently used by the FCs. FCs were asked to compare the two systems using the seven evaluation factors adopted by MCC. The median scores, presented in Fig. 9, show that IFSS was rated higher on all of the assessment dimensions adopted by MCC. We also performed a Wilcoxon signed ranks test on the median scores. As shown in Table 2, all the medians were statistically different from zero for $\alpha = 0.05$. The Wilcoxon test reinforces the conclusion that IFSS was preferred to the current system for all criteria identified by the MCCS Architecture Team.

Finally, in an attempt to measure the effect of the importance weights of the criteria, the individual FC performance scores and the MCCS Architecture Team importance weights were combined into a set of overall weighted scores. The Wilcoxon signed ranks test was performed on the overall weighted medians. As reported in

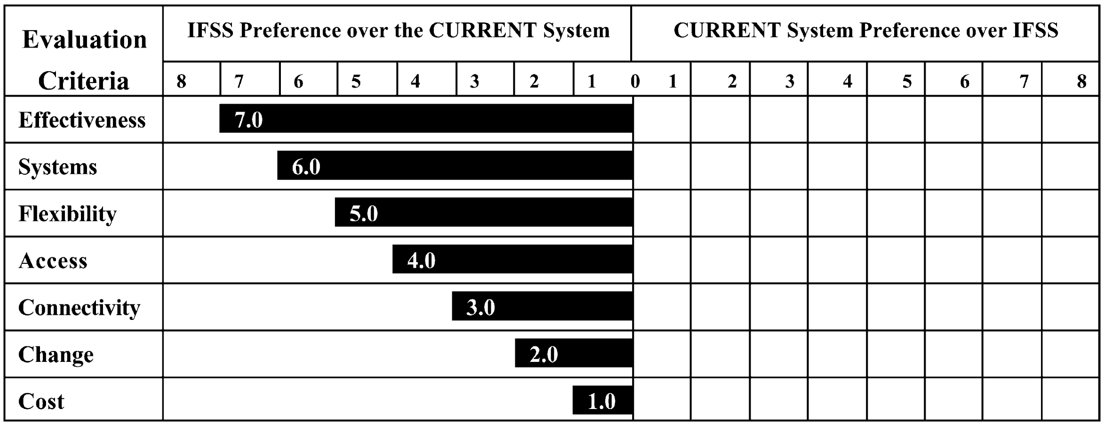

Fig. 9. The median scores for the IFSS Evaluation Questionnaire.

Table 3, all the weighted medians were statistically different from zero for $\alpha = 0.05$. Again, the Wilcoxon test of the weighted medians reinforced the conclusion that IFSS is preferred to the current system for all criteria identified by the MCCS Architecture Team.

Table 2
Wilcoxon signed ranks test of the evaluation factors' medians

Evaluation factor	Median	Significant ($\alpha = 0.05$)
Ease of use and effectiveness	7	Yes
Systems perspective	6	Yes
Flexibility	5	Yes
Access	4	Yes
Connectivity	3	Yes
Change	2	Yes
Cost reduction	1	Yes

Table 3
Wilcoxon signed ranks test of the weighted medians of the evaluation factors

Evaluation Factor	Median	Weights	Weighted median	Significant ($\alpha = 0.05$)
Ease of use and effectiveness	7	0.293	2.049	Yes
Systems perspective	6	0.191	1.147	Yes
Flexibility	5	0.132	0.660	Yes
Access	4	0.083	0.331	Yes
Connectivity	3	0.091	0.274	Yes
Change	2	0.084	0.168	Yes
Cost reduction	1	0.126	0.126	Yes

4. Conclusion

The IFSS has enabled the FCs to visualize, analyze, and communicate both information and knowledge associated with the various aspects of space operations and telemetry data. The overall goal of IFSS is to maximize *accuracy* and minimize *effort*. The fusion of telemetry data and decision support models into one visualization environment enables FCs to understand the cross dependencies of multidisciplinary data and to make invisible and transient information visible and sustainable. Also, the IFSS provides a platform that allows the FC's to process information in parallel, automatically and unconsciously, by bypassing the bottleneck of human working memory. In addition, the real-time visualization provides FCs with quick assessment of operational problems and enables them to allocate proper resources to investigate a particular scenario in more detail.

Acknowledgements

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Intelligent Flight Support System (IFSS) Evaluation Questionnaire

INSTRUCTIONS: The following goals, adopted by Mission Control Center (MCC) as part of the previous Mission Computing Strategy Study, serve as major evaluation factors when the Mission Control Center Systems (MCCS) Architecture Team performs early proof-of-concept work. Please respond by placing an 'X' on the appropriate location to indicate your preference for the Intelligent Flight Support System (IFSS) or the CURRENT system at MCC based on the critical factors identified by the MCCS Architecture Team.

Placing an 'X' at equal indicates NO PREFERENCE between IFSS and the CURRENT system

Placing an 'X' to the left of equal indicates that IFSS is MORE PREFERRED than the CURRENT system

Placing an 'X' to the right of equal indicates that the CURRENT system is MORE PREFERRED than IFSS

	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme
	<<<< IFSS Preferred >>>>										<<<< CURRENT System Preferred >>>>						
Design for Change: Commercial standards compliant, standard interfaces, and simplified configuration management processes for migration.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Design for Flexibility: Accommodate future manned spaceflight program requirements and operations concepts without significant impacts to existing architecture design.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Design for Connectivity: Information transfer between International Partners, MCC users (Flight Control), payload community, joint space operations with Government, industry, and academia collaborations using the Internet where practical.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Design for Access: Security commonality/simplification - robust but simple security for user concurrent access to multiple security levels that does not constrain system functionality.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Design for Cost Reduction: Commodification (a move toward an infrastructure that can be supplied by many different vendors), consolidation, operational concept modifications, and re-engineer.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Design for Ease of Use and Effectiveness: Intuitive graphical user interface layouts that supports data visualization, & intelligent systems; minimal steps for task completion, effective decision making & job productivity.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Design from a Systems Perspective: Develop and test new systems and process improvements that address all issues and concerns relative to the overall systems as a whole entity.	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Technology Assessment Evaluation Factors Questionnaire - Continued

INSTRUCTIONS: Please respond by placing an 'X' on the appropriate location to indicate your perception of the relative importance of the technology assessment factors for each of the following pairwise comparisons.

Placing an 'X' at equal indicates that factors A and B are equally important

Placing an 'X' to the left of equal indicates that factor A is more important than factor B

Placing an 'X' to the right of equal indicates that factor B is more important than factor A

TECHNOLOGY ASSESSMENT FACTOR A	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	TECHNOLOGY ASSESSMENT FACTOR B
	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	
Change	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Flexibility
Change	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Connectivity
Change	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Access
Change	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Cost Reduction
Change	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Ease of Use and Effectiveness
Change	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Systems Perspective
Flexibility	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Connectivity
Flexibility	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Access
Flexibility	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Cost Reduction
Flexibility	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Ease of Use and Effectiveness
Flexibility	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Systems Perspective
Connectivity	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Access
Connectivity	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Cost Reduction
Connectivity	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Ease of Use and Effectiveness
Connectivity	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Systems Perspective
Access	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Cost Reduction
Access	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Ease of Use and Effectiveness
Access	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Systems Perspective
Cost Reduction	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Ease of Use and Effectiveness
Cost Reduction	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Systems Perspective
Ease of Use and Effectiveness	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	Systems Perspective

Appendix B. Technology Assessment Evaluation Factors Questionnaire

The following goals, adopted by MCC as part of the previous MOD Mission Computing Strategy Study, serve as major evaluation factors when the MCCS Architecture Team performs early proof-of-concept work. This questionnaire is designed to capture the relative importance of each of the following factors:

- *Design for change*. Commercial standards compliant, standard interfaces, and simplified configuration management processes for migration.
- *Design for flexibility*. Accommodate future manned spaceflight program requirements and operations concepts without significant impacts to existing architecture design.
- *Design for connectivity*. Information transfer between International Partners, MCC users (Flight Control), payload community, joint space operations with Government, industry, and academia collaborations using the Internet where practical.
- *Design for access*. Security commonality/simplification-robust but simple security for user concurrent access to multiple security levels that does not constrain system functionality.
- *Design for cost reduction*. Commodification (a move toward an infrastructure that can be supplied by many different vendors), consolidation, operational concept modifications, and re-engineer.
- *Design for ease of use and effectiveness*. Intuitive graphical user interface layouts that supports data visualization, and intelligent systems; minimal steps for task completion, effective decision making and job productivity.
- *Design from a systems perspective*. Develop and test new systems and process improvements that address all issues and concerns relative to the overall systems as a whole entity.

The following pairwise comparisons are developed to help us understand the importance of each factor. Your feedback is important to us in developing a benchmarking scale that can be used by the MCCS Architecture Team for evaluating technology projects.

Appendix C. A mathematical summary of the analytic hierarchy process

Assume that in an MCCS Architecture Team member's mind, $c_1, c_2, \ldots, c_n$ are the n factors that contribute to a technology initiative's success. The team member's goal is to assess the relative importance of these factors. Saaty's Analytic Hierarchy Process (AHP) [17–19, 21–23] is a method of deriving a set of weights to be associated with each of the n factors, and it works as below:

The team member is asked to compare each possible pair c_i, c_j of factors, and provide quantified judgments on which one of the factors is more important and by how much. These judgments are represented by an $n \times n$ matrix:

$$A = (a_{ij}) \qquad (i, j = 1, 2, 3 \ldots, n)$$

If c_i is judged to be of equal importance as c_j, then $a_{ij} = 1$
If c_i is judged to be more important than c_j, then $a_{ij} > 1$
If c_i is judged to be less important than c_j, then $a_{ij} < 1$

$$a_{ij} = 1/a_{ji} \qquad a_{ij} \neq 0$$

Thus, the matrix A is a reciprocal matrix (i.e. the entry a_{ij} is the inverse of the entry a_{ji}). a_{ij} reflects the relative importance of c_i compared with factor c_j. For example, $a_{12} = 1.25$ indicates that c_1 is 1.25 times as important as c_2.

Then, the vector w representing the relative weights of each of the n factors can be found by computing the normalized eigenvector corresponding to the maximum eigenvalue of matrix A. An eigenvalue of A is defined as λ which satisfies the following matrix equation:

$$Aw = \lambda w$$

where λ is a constant, called the eigenvalue, associated with the given eigenvector w. Saaty [17–19] has shown that the best estimate of w is the one associated with the maximum eigenvalue ($\lambda_{\max}$) of the matrix A. Since the sum of the weights should be equal to 1.00, the normalized eigenvector is used. Saaty's algorithm for obtaining this w is incorporated in the software Expert Choice [16].

One of the advantages of AHP is that it ensures that team members are consistent in their pairwise comparisons. Saaty [17–19] suggests a measure of consistency for the pairwise comparisons. When the judgments are perfectly consistent, the maximum eigenvalue, $\lambda_{\max}$, should equal n, the number of factors that are compared. In general, the responses are not perfectly consistent, and $\lambda_{\max}$ is greater than n. The larger the $\lambda_{\max}$, the greater is the degree of inconsistency. Saaty [17–19] defines the consistency index (CI) as $(\lambda_{\max} - n)/(n - 1)$, and provides the following random index (RI) table for matrices of order 3–10. This RI is based on a simulation of a large number of randomly generated weights. Saaty [17–19] recommends the calculation of a consistency ratio (CR), which is the ratio of CI to the RI for the same order matrix. A CR of 0.10 or less is considered acceptable. When the CR is unacceptable, the team member is made aware that his or her pairwise comparisons are logically inconsistent, and he or she is encouraged to revise the same

n	3	4	5	6	7	8	9	10
RI	0.58	0.90	1.12	1.32	1.41	1.45	1.49	1.51

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