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MAGIK Robotics Simulation: **A Window on Space Station Freedom**

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MAGIK (Manipulator Analysis-Graphic, Interactive, Kinematic)

The MAGIK program is the primary kinematic analysis tool used by the Robotic Systems group at MDSSC. It allows users to conduct man-in-the-loop analyses to evaluate space robotic operations, including reach, clearance, and accessibility. MAGIK can be used to model, specify, simulate, analyze, and modify n-jointed type manipulators and their respective control algorithms. The MAGIK simulation currently implements kinematic models of all robotic devices currently baselined on Space Station Freedom (SSF).

Brief History

The need for planning and analysis software to support the Shuttle Remote Manipulator System (SRMS) was recognized early in the National Space Transportation System (NSTS) program. To support these activities, the Remote Manipulator System (RMS) Planning Software (RPS) was developed. With RPS engineers were able to analyze payload deployment and retrieval techniques and operations and to generate flight computer data loads for specific payloads and flights. RPS was designed specifically for the SRMS and cannot support other robotic systems. As plans for the SSF developed, engineers at MDSSC and Johnson Space Center (JSC) realized that generic robot manipulator software would be needed to model the SSF manipulators and to perform similar analysis for SSF assembly and operations planning. Thus, in 1985, MDSSC began the development of MAGIK as a derivative of RPS, but with the goal of modeling generic manipulators in an interactive graphics simulation to support SSF robotic analysis activities. MAGIK was developed in parallel with other software tools, with which it now interacts.

Current MAGIK Environment

The MAGIK environment currently consists of three software tools: a Solid Surface Modeler (SSM), a Tree Display Manager (TDM), and MAGIK. SSM is a graphics model building tool to create 3-D solid surface models. TDM is a graphics display package that provides for multi-window control, model rendering, tree manipulation, collision detection, and graphical user interface. MAGIK simulates the kinematics of the RMS, provides object animation calculations, and a graphical user interface. They all come together to form the MAGIK simulation environment. These graphics tools share a common rendering library developed in the Integrated Graphics and Operations Analysis Laboratory (IGOAL) at JSC by Barrios Technologies and NASA civil servants.

The notable features of the MAGIK simulation environment include:

- Generic software to allow modeling of n-jointed robotic systems.
- High resolution color graphics, using Silicon Graphics Iris workstations.
- Data-driven modeling that allows new robotic devices to be configured and simulated without rewriting software.
- Specification and control of manipulator operator control modes and the operational reference coordinate system.
- Operator control of manipulators through keyboard, hand-controller devices, or mouse-driven interface.
- Real-time collision detection among payloads, manipulators, and workspace elements.
- Payload data base management of payload-specific mass properties and control constraints.
- Auto sequence editor to specify and modify manipulator trajectories.
- Scripting capability to specify or record manipulator operations and views for subsequent retrieval or playback.
- Manipulator design utility for creating accurate graphic models of manipulators for use in MAGIK.
- User-friendly interface with on-line help.

Solid Surface Modeler (SSM)

SSM is a graphics software application for wire-frame and solid surface 3-D geometric modeling developed in the IGOAL. The program uses features of Constructive Solid Geometry (CSG) functions (union, difference, and

intersection) to develop complex graphic models from primitive geometric building blocks. SSM provides features for controlling color, shading, transparency, reflectivity, and surface texture properties of the resulting models.

Tree Display Manager (TDM)

TDM, which was developed through a cooperative effort between the LinCom Corporation and McDonnell Douglas, is designed to run as a graphics server. Using TDM, visual scenes are represented in a tree structure, with the branches of the tree specifying the geometric relationship among objects in the scene. The models displayed by TDM are developed using SSM. TDM allows client simulations to be developed independently of the graphics system. For example, TDM is used by the MAGIK program to display its visual scenes. TDM can also be used with non-real-time dynamic simulations to aid in interpreting results.

TDM serves other applications or operates in a stand-alone mode. For example, TDM was used with Shuttle down-link data to animate RMS operations in real-time (updated every 2 seconds) for the Hubble Space Telescope deployment. The significance of this capability is that these simulations may evolve into control center applications to be used for teleoperation of space robots, while a simulated scene of the space environment is viewed in real time. This would allow the operator virtually any view of an operation, without adding costly onboard hardware (such as cameras and sensors).

Current Space Station Applications

MAGIK can be used to analyze the kinematics of any space station robotic operational scenario. It serves as a proof-of-concept tool for planned robotic operations. Starting from engineering drawings, models can be built to the desired level of fidelity, manipulators can be accurately modeled kinematically, and man-in-the-loop simulations can be running within hours. The ability of engineers using MAGIK to answer the "what if" or "is it possible to" questions - quickly and accurately - continues to amaze even those who are familiar with its capabilities.

The following sections give examples of space station analyses that have been accomplished using MAGIK in the areas of robotic assembly and maintenance, simulated viewing, astronaut training facility test setup, dexterous manipulator tasks, control algorithm development and testing, collision detection, evolution concept evaluation, servicing facility functionality, and in-space assembly of large space vehicles.

Robotic Assembly and Maintenance

The current space station assembly sequence is being developed using MAGIK for shuttle manifest assessment; grapple fixture placement; and manipulator reach, clearance, and access analysis. Each element of the station is represented by a solid surface model in the graphics simulation. The analyst simulates the assembly operations for each flight with the current on-orbit stage and the shuttle cargo bay configured according to the proposed flight manifest. MAGIK is used to simulate the respective manipulator performing each assembly operation from beginning to end (Figure 1). When reach, clearance, or manipulator kinematic restrictions are found during an operation, alternative assembly methods and/or hardware changes are identified.

This ability to quickly model and simulate operations made MAGIK an indispensable part of the recent restructuring of the SSF. The design teams would discuss the technical issues, develop potential design solutions, and then see those solutions implemented in MAGIK within hours.

The most difficult thing for the hardware designers to visualize is how their individual system's requirements will integrate with other systems and their associated requirements. By kinematically simulating the robotic assembly of the station and integrating the system elements, designers are able to see the space station as an interactive system. An example of this is grapple fixture placement on payloads to facilitate robotic manipulation from the orbiter cargo bay to its on-orbit position. The MAGIK simulation allows analysts to work with the hardware designers to define workable locations for those grapple fixtures to enable the final assembly. This is an iterative process because a grapple fixture location must be found which will satisfy the orbiter launch constraints, the payload bay operations, the on-orbit space station operations, and the design constraints of the hardware.

When the assembly operations and grapple fixture locations for each element are satisfactorily developed, the auto sequence is recorded on a VCR tape to illustrate the proposed assembly operation. The video representation of the

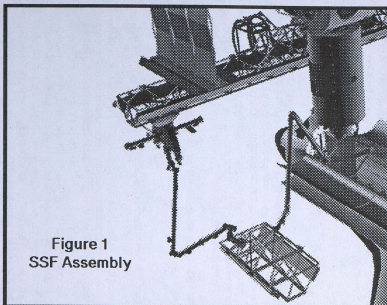


Figure 1
SSF Assembly

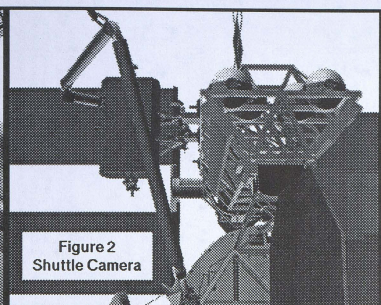


Figure 2
Shuttle Camera

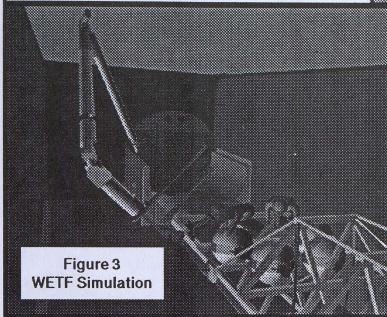


Figure 3
WETF Simulation

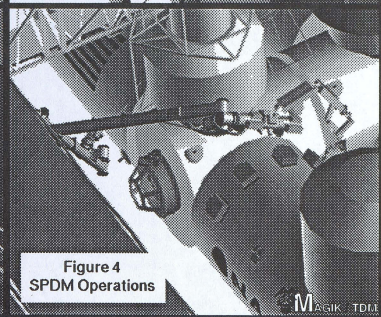


Figure 4
SPDM Operations

flight gives the Mission Operations Directorate (MOD) a baseline robotic assembly sequence to work with and it gives the hardware developers the grapple fixture locations they need.

Simulated Viewing

Space station assembly will involve numerous robotic operations. Many systems need to be integrated on-orbit by a robotic operator inside the station. Intervening structure often obscures the astronaut's direct view of the assembly task. The astronaut must mate the systems, usually within a three inch tolerance. These robotic operations will be performed using video cameras mounted at several locations on each manipulator and on the space station structure.

We use our detailed station configurations to perform viewing studies. The simulation allows analysts to "view" the station operations, just as an astronaut would, through current and proposed camera locations on the station, orbiter, and manipulators and through various windows (Figure 2). The simulation allows the user to assess the available views and determine their adequacy. This process helps to identify operator viewing design requirements for the assembly and maintenance of SSF. A number of changes to proposed camera locations have been identified using the MAGIK simulation.

Astronaut Training Facility Test Setup

MAGIK is used as a test planning tool in support of the astronaut training and evaluation facilities at JSC. In facilities such as the Systems Engineering Simulator (SES), the Manipulator Development Facility (MDF), and the Weightless Environment Test Facility (WETF), test setup can be very expensive in both time and money. MAGIK can be used in the test planning phase for hardware design studies and procedures development. Test coordinators get the maximum results from their simulations.

To date MAGIK has been used primarily as an SRMS precursory tool for the crew evaluations and training. The crew will perform simulated manipulator operations with payloads and assess the viewing cues for payload alignment during the operations. We have recently begun to use MAGIK to analyze the WETF testing setup to determine the best use of the limited volume in the tank. The JSC engineers would like to evaluate EVA operations of ORU change out, while the astronaut is attached to the Space Station RMS (SSRMS), but all the hardware can't be accommodated in the WETF. MAGIK modeling and analysis allows test facilitators to make the most of the available hardware and limited underwater volume (Figure 3).

Dexterous Manipulator Analysis

MAGIK can model generic manipulators, including dexterous robots. We use MAGIK to assess the ability of the Special Purpose Dexterous Manipulator (SPDM) to accomplish servicing tasks before the hardware is built. This pre-assessment allows design improvements to be made before large investments in building and testing hardware. It also allows for the development of control laws to govern the operation of the dexterous robots to be performed in parallel, while analysts perform simulated operations.

We recently analyzed the placement of the externally mounted Orbit Replaceable Units (ORUs) on the international elements (the European Module and the Japanese Experiment Module) of the SSF (Figure 4). These ORUs are designed to be robotically compatible. By using MAGIK to simulate the SPDM to service these ORUs, we found that several of the options being considered for the placement of the ORUs were not viable for robotic change out. MAGIK enabled the expedient analysis with the dexterous robot, which will help the international partner's design teams to place their ORUs in a location accessible by the SPDM.

Manipulator Control Algorithm Development and Testing

MAGIK enables control system engineers to test control laws for redundant degrees of freedom and algorithms for coordinated motion. This testing allows early assessment of control performance on operational tasks and shortens the design and testing phase of development.

Unlike the 6-jointed SRMS, for which a unique arm configuration exists for each end effector position and attitude, the 7-jointed SSRMS will have several possible configurations which can be illustrated by analogy with the human arm. For example, if the palm of the hand is placed firmly on a table, with the shoulder position held constant, the elbow is still free to move. This type of manipulator (which possesses a redundant degree of freedom) provides a

great deal of operational dexterity. With that added dexterity comes a formidable problem for control: For each desired end effector position, what is the best arm configuration? When moving the end effector, how should the arm configuration change?

MAGIK has proved to be an excellent tool for studying such problems. By implementing proposed algorithms and studying their behavior on operational tasks, much insight has been obtained into these control problems. To date, algorithms have been implemented that keep each joint near its mid-range, which selectively locks out degrees of freedom, and which avoid joint reach limits. Also, an entirely new algorithm has been implemented and tested in MAGIK that defines a unique configuration for each end effector position, which reduces arm interference with the end effector, payload, and manipulator base structure. Further studies will help determine the relative merits of each of these proposed control schemes.

Collision Detection Analysis

Another feature in our MAGIK environment is collision detection. The engineer can check the designs of each of the elements as they come together to form the complete system. Does it all fit together? By simulating the assembly, incompatibilities between interfacing elements can be found quickly and efficiently through the use of a collision detection algorithm within the TDM software. When two models in the simulated scene touch, which in the physical world would constitute a collision, it is annunciated by the software. This feedback allows the analyst to either find an alternate path for the assembly or correct a flaw in the system design that would prohibit the elements from fitting together.

Without a collision detection algorithm, analysts or operators are forced to continually evaluate the proximity of various payloads by frequently changing cameras, making the operations very time consuming. A proximity detection scheme is implemented by enclosing an object with an artificial envelope, so that when a detection is annunciated, the operator knows that the required clearance between object and structure has been violated. Two feet is currently considered to be a maintainable minimum safe separation distance.

Evolution Concept Evaluation

Since we have graphical models of the station, we can easily evaluate evolutionary concepts of the station growth beyond the Permanently Manned Capability (PMC). This tool allows engineers to see what the station build would look like at various stages of development beyond the year 2000. With an understanding of the station's possible growth patterns and their associated assembly advantages and disadvantages, we can ensure selection of viable options that are consistent with the currently planned station (Figure 5).

For example, three module pattern growth configurations were recently studied. Each of the proposed growth patterns explored alternative methods of progressing beyond PMC, resulting in the same final number of station elements. Each pattern was found to be kinematically feasible to assemble, however, in each pattern, several growth elements needed modifications or additional grapple fixtures need to be added to the baseline configuration elements.

From the results obtained in the MAGIK analysis, a much better understanding of potential module pattern growth was realized and a new set of issues for further investigation was raised. This information will help decision makers to determine a feasible direction for growth and allow designers to work toward a common goal. This type of early information will save money for the program in the future.

Servicing Facility Functionality

MAGIK has also been used to evaluate the capabilities of an advanced space station based servicing facility. This facility would serve as a depot and maintenance garage for a vehicle that would provide transportation between Low Earth Orbit (LEO) and lunar orbit. Such a servicing facility would likely include a RMS of some sort; several manipulator concepts have been evaluated in a recent trade study.

During this study we concluded that the currently baselined SSRMS would not have the reach necessary to perform all of the operations required during the refurbishment of a conceptual Lunar Transfer Vehicle (LTV). We developed requirements for new manipulator designs ("growth" versions of the SSRMS) that would offer the necessary reach. These analyses have provided preliminary requirements for the servicing facility capabilities. This process continues today through MAGIK analyses aiding NASA programs in all stages of development.

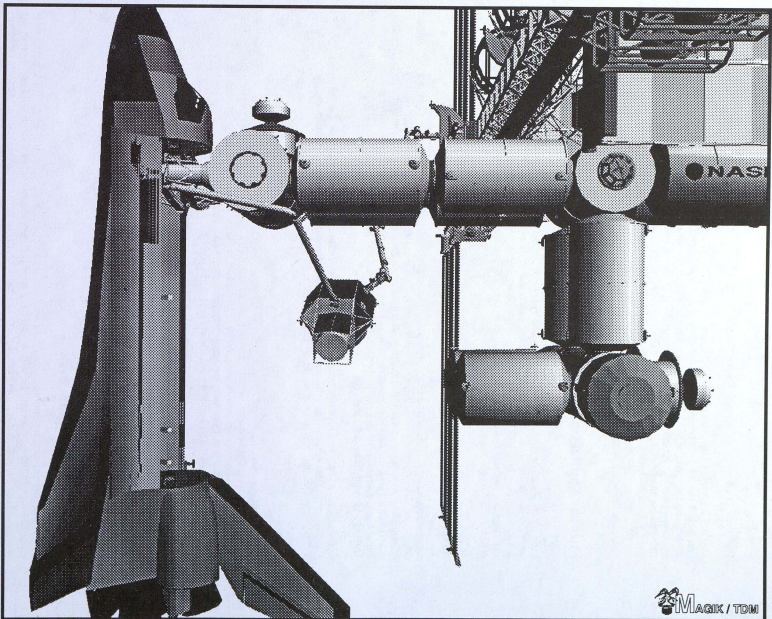


Figure 5 - Evolution Space Station Operations

In-Space Assembly of Large Space Vehicles

MAGIK was used to simulate the on-orbit assembly of the Mars Piloted Vehicle (MPV). This analysis provided a first look at the concerns related to assembly of large space vehicles in LEO using robotic manipulators. As a result of the analysis, some of the operations necessary to assemble such a large vehicle may present significant reach problems, possible dexterity limitations while working in closed quarters, insufficient mass handling capabilities, and need for an operator feedback system to detect the rates of payloads for the currently baselined SSRMS. Future space vehicle designs must take these limitations into consideration if they plan to use off-the-shelf hardware from the SSF program. This also may be an indication to manipulator designers that they must consider "growth" options in the future to accommodate assembly of large vehicles, such as the MPV.

Future Applications

Although this section is called future applications, many of these applications are either being done now on a limited basis or are under development as an application. Many of these applications are planned, while others are just envisioned. There is no clear reason to distinguish between them because they all remain within the realm of possibilities that MAGIK has enabled us to think about and act on. The following discussion will focus on advanced manipulator design, automated path planning, SSF operator familiarization training, desktop integrated systems simulations, and educational utilization.

Advanced Manipulator Design and Development

As new applications for robotic technology surface, simulations will continue to prove their worth as a front-end design and development tool. Engineers will be able to shorten the time between conceptualization of a robotic system and a working model of the system. With a working model, the design can be evaluated on its performance of an intended task and improvements can be incorporated before hardware is built. Engineers are moving from two-dimensional drafting table designs to three-dimensional simulated models with coordinated control algorithms to develop and test their robotics concepts.

Communicating ideas also becomes much easier when you have a graphic representation of a scene rather than text and engineering drawings. When the concept is developed and tested, a VCR tape of an animated operation being performed by the robot can be made to clearly illustrate the task.

Automated Path Planning

MDSSC has a research partnership with Oxford University Robotics Research to develop an automated path planning scheme to define an initial trajectory to be input to MAGIK. The idea is to give the software the ability to determine a path for a robot arm to accomplish a given task, while remaining within the constraints of a given environment. This will eliminate the analysis hours required to determine initial and optimal trajectories. Automated path planning will allow more efficient analysis of problems such as:

What is the optimal collision-free path to perform the operation?

How many paths are available using different arm configurations?

What is the total distance travelled by the end effector?

What is the optimal sequence for single-joint mode operations?

(single-joint mode is a contingency operational mode that drives the RMS only one joint at a time)

Automated path planning is a first step toward completely autonomous auto sequence development and eventually may lead to autonomous manipulator operations.

SSF Operator Familiarization Training

The ability to represent manipulator operations with simulated operator viewing of a scene while performing interactive man-in-the-loop operations, makes MAGIK a good part-task trainer for the SSF crew. Training runs can be set up to run the manipulators using actual joint rates based on the mass of the payload being handled. Operators will be informed if joint reach limits are violated or singularity (loss of a degree of freedom) regions are infringed

upon. There is a similar trainer for the SRMS, but none for the SSRMS or the SPDM. Although MAGIK is not designed specifically for training, it lends itself well to this application because of its adaptability, capability, and user interface. In fact, the Mission Operations Directorate at JSC has made recent inquiries from about adapting MAGIK for a training environment.

Desktop Integrated Systems Simulations

As NASA's computer simulation capabilities continue to evolve, real-time dynamics will be implemented. Later, the ability to simulate real-time flexible bodies will be added. By integrating the MAGIK simulation with other simulation environments (for example, complete guidance, navigation, and flight control; orbital dynamics) entire space systems could be simulated. Analysis runs of all types could be simulated in unison, with effects of each element sensed by the others, constituting a complete environment. To enhance the operation of such simulations, a network of Iris workstations will be utilized. By distributing the various math models across the network and interfacing them with the executive (or control simulation), a complete simulation environment will be achieved. This capability is now in its early stages of development.

Educational Utilization

This space technology will provide educational benefits and inspiration for our youth. It is easily portable to interested schools to allow their students to have a hands-on approach to learning. These simulation tools could be installed in computer labs to provide an interactive learning experience. The MAGIK environment coupled with computer assisted instruction would ensure that students could easily learn to apply the simulation tools to develop their own ideas. Students would have an outlet for their creativity and a place to let their imaginations run wild. This simulation environment could compel kids to seek out careers in robotics, computer software, control systems, engineering, and science.

As the price of computing power continues to drop, many schools will be able to afford computers and software of this caliber, which will allow teachers the opportunity to inspire their kids. Computer simulation of robotics and space activities is a technology area in which the future is unlimited. The related technology markets will continue to be competitive in the world of tomorrow; a world in which technology will play an important role, even more so than it does today.

Summary

The MAGIK robotic simulation software has been introduced through a brief discussion of the history of its development. The current SSF applications of MAGIK, such as robotic assembly and maintenance, simulated viewing, astronaut training facility test setup, dexterous manipulator tasks, manipulator control system development and testing, collision detection and avoidance analysis, evolution concept evaluation, servicing facility functionality, and in-space assembly of large space vehicles were all discussed. Some of the many benefits of the analyses that used MAGIK were shown. Finally, possible future applications of the tool were discussed, consisting of advanced manipulator design and development, automated path planning, SSF operator familiarization training, desktop systems simulations, and educational utilization.

MAGIK continues to undergo an evolutionary growth, continuing to add new capabilities. It is, however, a mature simulation tool with many useful applications and a growing user community. Many space programs are gaining the benefits of MAGIK analysis today, but it remains to be seen if the graphic simulation capabilities will be taken full advantage of in the future.

Note: MAGIK software development and much of the analysis performed at MDSSC is funded and monitored by the Automation and Robotics Division at the NASA/JSC.