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SPACE STATION ROBOTICS PLANNING TOOLS

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1.0 Introduction

Planning for a complex Shuttle Remote Manipulator System (SRMS) mission can require close to 5,000 manhours. This time is used for kinematic, dynamic, and clearance analyses, procedures development, verification, validation, and construction of the Flight Data File. SRMS missions, with their one-shot, one-robot nature, have been able to accommodate 5,000-manhour planning schedules. The Space Station Freedom Program (SSFP) cannot accommodate manhour-intensive planning schedules for multiple, international robots over a 30-year lifetime of changing configuration and continuous operations.

In this paper, we will describe the concepts for the set of advanced Space Station Freedom (SSF) robotics planning tools for use in the Space Station Control Center (SSCC). We will also show how planning for SSF robotics operations is an international process, and we will indicate baseline concepts for that process. Current SRMS methods provide the backdrop for this SSF theater of multiple robots, long operating time-span, advanced tools, and international cooperation.

2.0 Present RMS Planning Tools and Flight Data File Development

SRMS planning begins several years prior to the launch of the payload, with a study of the payload to be deployed, retrieved, or manipulated. These activities examine the payload's compatibility with the Space Shuttle and ensure that the payload customer's requirements are met. Examples of payload customer requirements include thermal, pointing, or plume-impingement constraints.

Performance of these initial payload assessments includes identification of the required analyses. Initial analysis is nearly always kinematic; the primary SRMS kinematic analysis tool is the RMS Planning System (RPS). The second step is a dynamic analysis using the Payload Deployment and Retrieval System Simulator (PDRSS). The third step is detailed clearance analysis using the Clearance Analysis Tool (CAT). Other simulators will be used to verify and validate procedures. The final outcome of the analysis process is the Flight Data File (FDF), which is the set of procedures astronauts follow onboard to operate the SRMS. This entire process is highly iterative.

Each of the SRMS analysis and procedures development tools is independent. However, results of one tool often affect the initial settings for another simulator. Subsequently, data sets are exchanged.

2.1 RPS Tool

RPS analysis (including model development) for a complex flight averages 520 manhours, beginning two years prior to the launch of a payload (L-2). Analyses performed on this 3-D graphics kinematic simulator include:

- payload grapple fixture location
- trajectory definition
- reach, visibility, and approximate clearance
- initial procedures and timelining
- initial flight software parameter definition (Level C data tapes).

Until this year, RPS was hosted on an HP9000™ platform. It has now been re-hosted to a Silicon Graphics Iris™ workstation.

2.2 PDRSS Tool

PDRSS performs non-graphical dynamic analysis for SRMS. Formerly hosted on a Univac™, PDRSS has now been re-hosted to Silicon Graphics Iris™ workstations. Re-hosting the simulator to these workstations enables output of PDRSS data files to Clearance Analysis Tool (CAT) in "playback" mode to drive a graphical simulator. Thus, results of dynamic analyses can now be viewed.

Examples of PDRSS analyses include:

- capture loads
- appendage jettison
- loads
- RCS-induced loads and motion
- maneuvering loads
- other externally applied loads

PDRSS math models include:

- servo-mechanisms
- rigid and simplified flex SRMS models
- latest flight software for modelling RCS forces and moments
- orbital mechanics models.

The Shuttle program formerly performed extensive analyses to determine impacts of an SRMS runaway. However, SRMS flight operations combined with reliability analyses of runaways have shown that the probability of an SRMS runaway is extremely low. Therefore, in March, the Shuttle program eliminated requirements for runaway analyses.

Two additional dynamic simulators are used for RMS planning:

- Draper Laboratories' Draper RMS Simulator (DRS)
- Spar Aerospace's All Singing, All Dancing (ASAD).

DRS is used primarily to analyze Digital Auto Pilot (DAP) stability and DAP initial software loads (I-loads). ASAD has full payload-flex models.

2.3 CAT

The CAT platform is a Silicon Graphics Iris™. The software used is Deneb IGRIP™, which is a 3-D graphics commercial software. Data files of properly sequenced joint angles for an SRMS trajectory are delivered to CAT. These data files are then used to drive the CAT graphical simulator to determine detailed clearances and visibility.

For a complex SRMS payload, CAT/PDRSS analyses begin about 18 months prior to the launch. The analyses (and model development) require full-time effort for that period, for a total of 2880 manhours.

2.4 Shuttle Engineering Simulator (SES)

Much of the analysis and basic procedure outlines required for a mission are completed one year before the flight. At that point, mature procedure development and verification begin, using the Shuttle Engineering Simulator (SES). Timelining of tasks and approximate clearance assessments will also be performed in the SES. SES time per payload averages 112 hours.

2.5 Shuttle Mission Simulator (SMS)

The primary use of the SMS is for training flight crew and flight controllers. However, SRMS planners also use SMS to validate procedures. These sessions represent about 50 additional manhours per year per payload, if the validation sessions can "piggyback" on the training sessions. Additional sessions are very possible.

Procedures are validated in the Shuttle Mission Simulator (SMS) at a cost of about eight percent of the total procedures development time or about 50 manhours per year. *This is RMS Section time*; it does not include training personnel time, crew time, SMS personnel support time, etc.

2.6 Flight Data File Development

Flight Data File (FDF) preliminary development begins 10 months prior to a mission. Basic procedures are published 3.5 months prior to a mission, and final procedures are published one month prior to a mission. Because the FDF development is based upon earlier analysis and may occur during the analysis period, an exact assessment of required time is difficult. However, approximately half a man-year, or 1040 man-hours, is estimated for this aspect of planning.

To estimate the actual manhours required for planning RMS missions, we can sum the estimates for the various types of analysis and planning. This exercise is shown in Table 1-RMS Planning Manhour Requirements.

Table 1-RMS Planning Manhour Requirements

Type of Activity	Manhours Required
RPS	520
Dynamic/Clearance Analysis	2880
Procedures Development/Validation	180
FDF	1040
TOTAL	4620

3.0 SSCC Robotics Planning Tools

As Table 1 indicates, the burden of analysis/planning activities for Shuttle arm mission designers and analysts is very heavy. As Section 1.0 stated, SSF cannot accommodate this burden. Subseqently, requirements have been written for a set of SSF robotics planning tools which will reduce the burden. Those requirements define a set of integrated tools for use in the SSCC which perform kinematic, clearance, and dynamic analysis, and which also develop preliminary procedures. These planning activities will be performed by an integrated team of US/Canadian mission controllers for US/Canadian onboard robots. Although Japan will have the Japanese Experimental Module Remote Manipulator System (JEMRMS), Japanese personnel will be solely responsible for analysis and procedures development for their system.

The entire environment for planning/analysis/procedures development is called the Robotics Task Analysis Environment (RTAE). RTAE also incorporates the Robotics Task Library (RTL), and it will utilize the Graphical And Mass Properties (GRAMPS) Library. Plans are to host these tools upon a platform compatible with the Silicon Graphics™ platforms used by Shuttle arm planners to insure continuity/cooperation with them. All tools will be highly graphical, interactive, and integrated.

3.1 Robotics Task Analysis Environment

The primary SSF analysis tool will be the Robotics Task Analysis Environment (RTAE). This tool will include kinematic and dynamic models of all SSF robots and associated hardware:

- Mobile Transporter (MT)
- Mobile Servicing System (MSS)
  - ◊Space Station Remote Manipulator System (SSRMS)
  - ◊Special Purpose Dexterous Manipulator (SPDM)
  - ◊Mobile Remote Servicer Base System (MBS)
  - ◊MSS Maintenance Depot (MMD)
- Japanese Experimental Module Remote Manipulator System (JEMRMS) comprised of:
  - ◊JEM Main Arm (JEMMA)
  - ◊JEM Small Fine Arm (JEMSFA)
- SRMS

RTAE will be an integrated analysis tool which can perform kinematic, clearance, and dynamics work. Using RTAE, an analyst will be able to export all the relevant parts of one type of analysis into another, e.g., joint angles, trajectories, initial flight load software, and initial simulation settings. RTAE can perform kinematic and dynamic analyses for manipulators with N degrees of freedom. As a result of these analyses, RTAE can generate software parameters needed by onboard SSF robotic systems. At each step in these analysis process interfaces, RTAE will provide reporting and quality assurance checking of results. RTAE will also evaluate flight and simulation data.

RTAE will utilize powerful graphical simulation technology to enable visual displays of an analysis. If an operation (e.g., extremely complicated dynamics analysis) is not especially interactive and/or requires extensive Central Processing Unit (CPU) time (and thus would be extremely slow to watch), RTAE will allow an operator to conduct an interactive operation in the foreground while batch processing activities proceed in the background.

RTAE will also be used to develop initial procedures. In this capability, RTAE will be used to develop timelines and to analyze crew workloads, intra-vehicular activity (IVA) workstation usage, worksite lighting, visual cues, and video requirements. Once procedures are verified, RTAE can output robot task commands and trajectories for automated sequences in an uplinkable, executable format for use by on-board systems.

3.2 Robotics Task Library

A second tool for the SSF robotics analyst is the Robotics Task Library (RTL). This is a library or database of task data which includes:

1. Task name
2. Task description
3. Robots and tools used
4. Stage of task development
5. Resources required or estimated
6. Constraints
7. Station configuration/increment(s) with which the task is associated or approved
8. Trajectory and procedural data or auto sequence command files used in executing the task.

The tasks included in RTL may have been previously executed, previously planned, or in the process of planning.

RTL is totally compatible with RTAE. No manual translation will be required to transfer RTL data into RTAE. RTAE planners can scan through the RTL task listings by the eight or more categories. If the search by category indicates a possible match or similarity to a task being planned, RTAE users can import the task data file. Once the data is within RTAE, it can be used to drive RTAE's graphical simulators, thus providing the analyst with a visualization of the task. If the task can be re-used, RTAE analysts can "cut and paste" all or part of the RTL data file into RTAE. Any modifications can then be performed within RTAE. Because many SSF robotics maintenance tasks may be very repetitive, such a utility is necessary to streamline the planning process.

3.3 GRAMPS Library

The third tool necessary to planning, visualization, and interactive and graphical analysis is the SSF Graphical And Mass Properties (GRAMPS) Library. This library is a database of all objects at the ORU or structural element level on SSF, stored in a format that can drive graphical simulations. Each of these "base objects" can be accessed by any combination of the following categories:

1. object name or key word
2. location [e.g., all objects within a given volume of space around a given point (x,y,z)]
3. station subassembly name
4. desired increment
5. logistics control number
6. pictorial representation from a catalogue of objects
7. any combination of the above.

GRAMPS object models must be accurate to within one-half inch and one degree for detailed clearance analysis and collision avoidance. The types of data that will be maintained in GRAMPS for each base object include:

1. object identifier
2. physical dimensions
3. surface properties
    a. material
    b. texture
    c. color
    d. albedo
    e. locations of guides and markings
4. mass properties
    a. mass
    b. center of mass
    c. moments of inertia
5. interface definitions
    a. location (relative to the origin)
    b. size and shape
    c. type (e.g., electrical, fluid, structural, grapple)
    d. gender (male, female)
    e. flow direction (e.g., input, output, bi-directional, n/a).

For objects which are comprised of base objects, each layer of a model above the base level contains the following data:

1. list of objects which are components of the layer
2. position and orientation of each object in the layer relative to the origin for that layer (mating of interface points)
3. dynamic envelope of each object in the layer relative to the origin for that layer
4. physical dimensions of the layer if viewed as a single object

5. mass properties of the layer if viewed as a single object
    a. mass
    b. center of mass (relative to the origin for the given layer)
    c. moments of inertia
6. interface definitions
    a. location (relative to the origin)
    b. size and shape
    c. type (e.g., electrical, fluid, structural, grapple fixture)
    d. gender (male, female)
    e. flow direction (e.g., input, output, bi-directional, n/a).

Besides SSF, robotics analysts require models of other objects. These include the Space Shuttle, payloads, any free flyers which will interface with robotics devices, and EVA crewmen.

RTAE will utilize the graphical models within GRAMPS for detailed clearance analysis. Without GRAMPS, robotics analysts will be unable to see the tasks they are planning or to assess clearances.

4.0 Canadian Analysis/Procedures Development Tools

Because SSRMS, SPDM, MBS, and MMD, unlike the SRMS, will be owned by Canada, Canadian Space Agency (CSA) has invested considerable capital and effort into ensuring the existence of analysis, procedures development, and training facilities. Those Canadian Ground Segment facilities include the Procedures Management System (PMS) and the Manipulator Development Simulator Facility (MDSF).

The current Mission Operations Directorate baseline concept is that normal operations procedures development will be performed in the SSCC. CSA/Spar will provide all procedures which are system-specific or which involve envelope expansions of the Canadian robots.

The first step in the development of the Operations Date File (ODF) is the analysis process. Once analysis has been completed, RTAE, through its links with the SSCC procedure development tool, will generate a set of integrated, increment-specific task procedures. These procedures will incorporate system-specific procedures for both Canadian arms developed by CSA/Spar Aerospace.

System-specific procedures include generic and increment-specific operating procedures, system malfunction procedures, and task primitives (lift, rotate joint X degrees, etc.). Generic procedures include power-up, power-down, checkout, etc.

Increment-specific procedures must be closely coordinated with corresponding SRMS Flight Data File procedures for situations such as hand-offs. They must also be coordinated with other SSF mission planners, e.g., Guidance, Navigation, and Control; Operations Planning; Maintenance, Inventory, Logistics Planning (MILP); Extra-Vehicular Activity Systems (EVAS); Communications and Tracking (C&T), etc.

The integrated US-Canadian SSCC robotics planning team will utilize the RTAE to perform analysis and build preliminary integrated procedures Other simulators which will be used to further develop, validate, verify, and train personnel in robotics integrated procedures include:

- Mobile Remote Manipulator Development Facility (MRMDF) - JSC
- SES -JSC
- Shuttle Mission Training Facility (SMTF) -JSC
- Space Station Training Facility (SSTF) -JSC
- MDSF -CSA
- PMS - CSA

Ideally, RTAE will be able to electronically exchange data files with the Canadian PMS. At worst, the two systems should be capable of importing and translating data from each other into a usable format. Once the two planning systems have established a basic set of task procedures through iterative activities, MRMDF, SES, and MDSF will be used to further test, develop and validate them. SMTF, SSTF, and MDSF will be used for final procedure verification and crew/mission controller training on the final procedures. Once the procedures are finalized, they will be generated as an official segment of the Operations Data File using SSCC procedures tools and the RTAE. Figure 1, Robotics Procedures Development Process, indicates this process flow.

5.0 Summary and Conclusion

Today, planning for a complex SRMS mission requires nearly 5,000 manhours. Part of the reason for this heavy burden is the disconnected nature of the tools. SSF cannot sustain continued labor-consuming analysis methods.

Therefore, requirements for a suite of tools designed to streamline the planning process in the SSCC have been written. These tools are the Robotics Task Analysis Environment, Robotics Task Library, and Graphical And Mass Properties Library. These tools will enable robotics task planners to input data from one type of analysis into another, thus reducing re-entry of data and streamlining the planning process. The Robotics Task Analysis Environment will be the primary planning tool; it will be graphical, interactive, and integrated. It will operate with the Graphical And Mass Properties Library to graphically display the results of task analysis and show detailed clearances. The Robotics Task Library will enable re-use of entire tasks or portions of them to build new tasks.

However, robotics planning will not be isolated within the SSCC, as will other types of mission planning. Because SSRMS and SPDM are Canadian systems, analysis and procedures development will involve both the SSCC and relevant facilities of the Canadian Ground Segment, especially the Procedure Management System and the MDSF. Specific details of the procedure development process have yet to be worked out; this paper has indicated the Mission Operation Directorate's baseline concept for international, integrated SSF robotics analysis, planning, and procedure development.

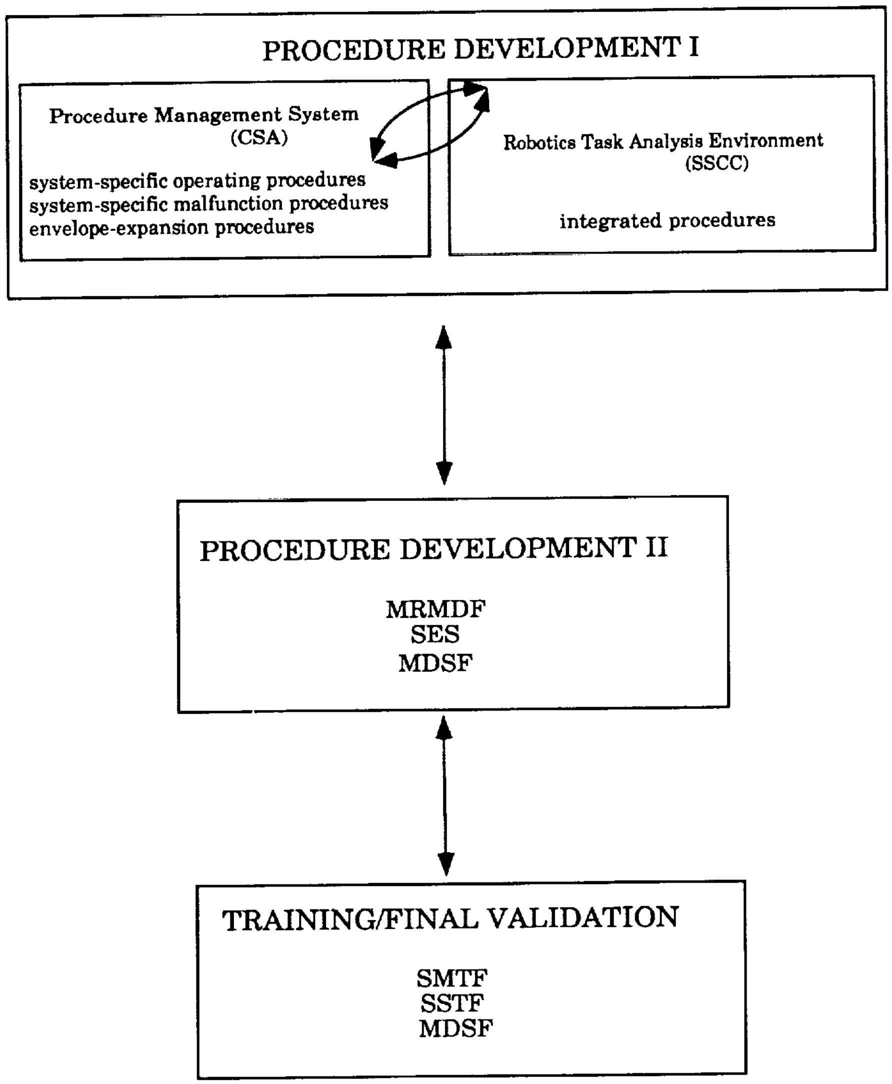

Figure 1 - Robotics Procedures Development Process

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