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THE ROLE OF THE REAL-TIME SIMULATION FACILITY, SIMFAC, IN THE DESIGN, DEVELOPMENT AND PERFORMANCE VERIFICATION OF THE SHUTTLE REMOTE MANIPULATOR SYSTEM (SRMS) WITH MAN-IN-THE-LOOP

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ABSTRACT

The Real-Time Simulation Facility, SIMFAC, is a powerful and adaptable engineering tool for the conduct of studies relating to man-in-the-loop manipulator systems. SIMFAC has played a vital role in the design, development and performance verification of the Shuttle Remote Manipulator System (SRMS) to be installed in the NASA Space Shuttle Orbiter. The facility provides for realistic man-in-the-loop operation of the SRMS by an operator in the Operator Complex, a flight-like crew station patterned after the Orbiter aft flight deck with all necessary man-machine interface elements, including SRMS displays and controls and simulated out-of-the-window and CCTV scenes. The characteristics of the manipulator system, including arm and joint servo dynamics and control algorithms, are simulated by a comprehensive mathematical model within the Simulation Subsystem of the facility.

Major studies carried out using SIMFAC include SRMS parameter sensitivity evaluations; the development, evaluation, and verification of operating procedures; and malfunction simulation and analysis of malfunction performance.

Amongst the most important and comprehensive man-in-the-loop simulations carried out to date on SIMFAC are those which support SRMS performance verification and certification when the SRMS is part of the integrated Orbiter-Manipulator System.

1 INTRODUCTION

The development of a general purpose, real-time Remote Manipulator Simulation Facility, SIMFAC, was initiated in 1974. The first application for this facility was created as a consequence of an agreement, reached between the Government of Canada and the U.S.A., that the Remote Manipulator System (RMS) for the National Aeronautic and Space Administration (NASA) Space Transportation System (STS) would be developed by a Canadian industrial team under contract to the National Research Council of Canada (NRCC), with Spar Aerospace Limited as the prime contractor.

The Shuttle Remote Manipulator System (SRMS) is intended for operation in space in a zero gravity (0-g) environment and as such, cannot be operated or fully tested in a 1-g, on-earth environment. SIMFAC provides evaluations of - and operator familiarization with - the SRMS performance characteristics that would be exhibited in the on-orbit environment and inputs to the design and development of the SRMS itself.

SIMFAC came into service in support of the SRMS Program early in 1977 and has since then been playing a most important role in the design development and performance verification of the SRMS. In addition, it has provided valuable data in support of the development of SRMS operating procedures prior to actual orbital operations.

II THE SHUTTLE REMOTE MANIPULATOR SYSTEM (SRMS)

The SRMS is an anthropomorphic man/machine system with six control degrees-of-freedom for use on the Shuttle Orbiter in deploying, manipulating and retrieving a wide range of payloads (small to voluminous and massive) in space (Figure II-1).

The SRMS is operated in both automatic and manual modes from the aft port window location of the Orbiter crew compartment by an SRMS specialist using dedicated SRMS controls and with the aid of direct viewing and closed circuit television.

It is required that the manipulator be capable of safely deploying and retrieivng a 32,000 lb. cylindrical payload of diameter 15 feet and length 60 feet and, further, of deploying a 65,000 lb. payload of the same size.

Failsafe operation is a basic requirement of the SRMS design and a 10 year, 100 mission life is specified for the system.

The manipulator arm mechanical assembly comprises a series of six active joints and seven structural links, as shown in Figure II-2. These provide a gimbal order of shoulder yaw, shoulder pitch, elbow pitch, wrist pitch, wrist yaw and wrist roll. Each active joint of the manipulator arm is driven by a servo whose output, provided by a brushless DC motor, is transmitted to the arm via a high reduction gearbox.

A standard end effector is attached to the wrist for grappling and applying loads or motions to the payload or for releasing payloads into orbit. Mounted at the wrist roll joint is a wrist CCTV camera and viewing light assembly and near the elbow pitch joint there is provision for an elbow CCTV camera and pan and tilt unit assembly. These cameras, together with cameras in the Shuttle Orbiter cargo bay, provide specific and selectable views for the operator via the television monitors mounted in the RMS operating station in the crew compartment.

The arm, when fully extended, has a reach of approximately 50 feet and the arm booms are approximately 13 inches in diameter.

SRMS CONTROL

The manipulator arm is controlled from a Display and Controls (D&C) system using SRMS software resident in the Orbiter General Purpose Computer (GPC) through a Manipulator Controller Interface Unit (MCIU), all mounted within the Orbiter cabin. The MCIU supplies the data interface between the D&C system, SRMS software in the GPC and the manipulator arm.

The SRMS is a man-in-the-loop system, the operator forming an integral part of the control and monitoring system. Operator interaction and control, are effected by means of the following:

- Rotational and Translational Hand Controllers (RHC, THC) for Manual Augmented Mode Operation, which provide end effector translational and rotational velocity commands to the control algorithms within the SRMS software resident in the Orbiter GPC.

- The Display and Controls (D&C) panel (and electronics), which provides arm status data to the operator and performs secondary control functions.

- The mission keyboard, which provides operator access to the orbiter GPC.

- A GPC CRT which presents detailed SRMS status and health data to the operator.

The primary source of composite arm position and attitude data is the operator's own direct vision through the crew compartment aft bulkhead and overhead windows, augmented by CCTV views from the arm and payload bay-mounted camera. Figure II-3 shows the locations of the SRMS controls in the orbiter crew compartment.

CONTROL ALGORITHMS

The primary function of the SRMS control algorithms is to convert the various input drive commands into a resolved output rate demand for each joint of the arm so that the end effector or payload follow the commanded trajectory. The algorithms output these rate demands within limits defined according to arm and individual joint loading conditions present at the time of computation. The rate demands are passed to the joint servos via GPC-to-MCIU and MCIU-to-Arm Based Electronics (ABE) data busses.

The control algorithms supply the joint rate demands necessary to control either end effector translational and rotational rates or end effector position (rate or position control). The control algorithms obtain feedback on joint angles from high precision position encoders within the joint drive trains.

SERVO CONTROL

Classical servo loop compensation techniques are employed to ensure good stability over a wide dynamic operating range, as well as good steady state system performance. Feedback is obtained from digital and analogue tachometer data combined in a complementary fashion, and from high precision encoders providing joint position data, as shown in Figure II-4.

SRMS CONTROL MODES

The SRMS may be controlled in the following modes:

- Manual Augmented Control Mode
- Automatic Mode
- Single Joint Control Mode
- Direct Drive Control Mode
- Backup Drive

The Manual Augmented mode of control enables the Operator to direct the end-point of the manipulator arm (or point of resolution in the payload) using the two three-degrees-of-freedom hand controllers to provide end effector (or payload) translation and rotation rate demands. The control algorithms process the hand controller signals into a rate demand to each joint of the system.

The automatic mode of control enables the operator to move the end point of the manipulator arm using a mission-keyboard entered trajectory (operator commanded auto-trajectory) or a pre-programmed trajectory. Any four pre-programmed automatic trajectories out of a total of twenty loaded in software may be active on the D&C panel. Storage is provided for up to two hundred positions and orientations in these automatic sequences.

The Single Joint Drive Mode enables the operator to move the arm on a joint-by-joint basis with full GPC support. The operator supplies a fixed drive signal to the control algorithms via a toggle switch on the D&C panel. In response, the algorithms supply joint rate demands to drive the selected joint while maintaining joint position on the remaining, unselected joints.

Direct Drive is a contingency drive mode, by-passing the MCIU, GPC and data busses and servo control loop by enabling the operator to provide a direct drive command to the MDA via hardwires. During operation in Direct Drive, brakes are automatically applied to all uncommanded joits. SRMS status information may be available to the operator via the D&C subsystem in this mode.

The Backup Drive Mode is a contingency drive mode used when no prime channel drive modes are available, enabling joint-by-joint performance. Backup drive is designed to fulfill the failsafe requirement of the SRMS by using only the electro-mechanical drive train of the selected joints, by-passing the rest of the system. No status information is available to the Operator through the D&C subsystem in this mode.

OPERATOR COORDINATE SYSTEMS

There are four Manual Augmented control operating modes available to the operator and selectable via a mode switch on the D&C panel, each of which refers point of resolution control to one (or more) of four different operator coordinate systems. The operating modes and associated operator coordinate systems are identified below.

Operating Mode (Manual Augmented Control)	Point of Resolution (POR)	Control Action Referred To
Orbiter Unloaded	Tip of End Effector	Orbiter Body Axis System for POR translations. rbiter Rotation Axis System for POR rotations.
End Effector	Tip of End Effector	End Effector Operating System.

Operating Mode (Manual Augmented Control)	Point of Resolution (POR)	Control Action Referred To
Orbiter Loaded	Pre-determined point within payload	Orbiter Body Axis System for POR translations. Orbiter Rotation Axis System for POR rotations.
Payload	Pre-determined point within payload	Payload Operating System.

Details of the coordinate systems are given in Figure II-5.

The operating modes and associated coordinate systems are chosen on the basis of providing for the Operator the most natural response to his controls during various critical task phases, so as to reduce his workload in making mental transformations as the SRMS takes on different configurations.

III THE SIMFAC FACILITY

Figure III-1 is a block diagram of SIMFAC showing the modular approach adopted in the design of the facility. The major subsystems are:

- the Simulation Subsystem
- the Scene Generation Subsystem
- the Operator Complex
- the Master Control Complex

THE SIMULATION SUBSYSTEM

The Simulation Subsystem is a self-contained computer complex for the manipulator mathematical model, control algorithms, servo software modules and data update to the Scene Generation Subsystem.

The Simulation Subsystem computer complex is shown in Figure III-2. Two TI-980B minicomputers, each with an associated floating point processor, are used in a master-slave configuration. The computers are augmented by an array processor in which the matrix calculations are performed.

Software is divided into three categories: the operating system, applications and service software.

The operating system software capabilities include:

- a real-time executive to perform synchronous and asynchronous task scheduling,
- interrupt processing and data transfer,
- foreground/background operation
- comprehensive disc file management,
- interactive operator communications,
- diagnostics

The Applications Software includes the models of the SRMS, payload and the orbiter.

The orbiter model includes mass properties and rotational dynamics (pitch, yaw and roll degrees-of-freedom). Orbiter stabilization can be established in either the inertial attitude mode, or earth pointing mode.

A number of payload model options have been configured, including the maximum envelope payload (a 15 ft. diameter, 60 ft. long cylinder) with weights 32,000 lb. (design case) and 65,000 lb. (design maximum). Each payload is fitted with a simulated grapple fixture and a sighting target to aid the operator in the tracking and "capturing" of payloads using the television camera on the SRMS wrist.

The SRMS model is subdivided into:

- configuration and mass properties,
- arm dynamics,
- joint servo, gearbox and drive models,
- arm control laws

The configuration and mass properties of the SRMS established during design and development testing provide the basic software data base used in the arm dynamics software.

The dynamics of the manipulator system are represented by a complex set of non-linear equations whose characteristic modes of motion exhibit wide variations by virtue of the large range of mass properties of the payloads handled and the various geometric configurations of the manipulator arm attainable within the reach envelope. As an example, the period of the fundamental structural bending mode for the straight arm configuration varies from approximately 2 seconds for the unloaded arm to about 50 seconds when a 65,000 lb. payload is attached. Similarly, the characteristic frequencies change by about 100% when the elbow moves through its range with a massive payload attached. In view of these wide dynamic ranges and of the fact that fine tuning of the integration step size to each condition (to maintain accuracy and avoid numerical instabilities) is not possible with a real-time simulation facility, a compromise between accuracy and speed of solution is necessary. In the case of SIMFAC, the compromise is affected by modelling the manipulator arm as a 23 degree-of-freedom system which includes the first six structural flexibility modes of motion (Table III-1) and by partitioning the equations into various loops which have solution update intervals of 2, 10 or 50 milliseconds.

The servo-mechanisms for the six SRMS joints are similar in configuration and, therefore, since they are not coupled (except through arm/payload dynamics), are simulated using the same basic software modules. Each module is made up of the models which represent the main servo hardware and electronic units, such as the motor, tachometer (analogue/digital) brakes, gearbox and position encoder.

The control algorithms provide the operator with control of the End Effector trajectory. They also respond to the attainment of limits of travel (reach limits) of any joint and to the occurance of predetermined computational singularities, where a controlled degree-of-freedom is lost through the particular relative alignments of certain joints. These SRMS control algorithms are reproduced in the SIMFAC Applications Software, as are all of the SRMS control modes available to the Operator in the real system .

The service software processes all displays and control inputs and outputs. It also communicates with the Application Software via a data base comprising action flags, inter-module communications, invariant parameters and initialization parameters.

THE SCENE GENERATION SUBSYSTEM

The Scene Generation Subsystem is a three-computer complex augmented by an array processor which receives updated data from the simulation subsystem and, through a series of transformations, produces the four visual images that are used by the operator. Figure III-3 is a block diagram of the Scene Generation Subsystem showing the interconnections between the major units.

Two identical IDIIOM graphics generators are used, each generating two of the images. Graphics #1 produces direct (window view) images and #2 produces CCTV images. The graphics systems are of the vector type in which the images are formed by line drawings. Up to 2000 vectors per graphics system can be generated, of which 1300 are dynamic.

THE OPERATOR COMPLEX

The Operator Complex is an enclosed flight-like crew station patterned after the Orbiter aft flight deck, with all necessary man-machine interface elements including·

- Displays and Controls Panel,
- Hand controllers,
- Systems monitors and keyboard for engineering data and parameter changes,
- CCTV camera controls, and
- Four monitors, providing the window and CCTV views

The Displays and Controls Panel enables the operator to select the control modes. Displays on the panel provide for warnings and for the status of selected parameters.

The two direct view images look aft (into cargo bay) and upwards, the monitor CRT faces being placed against the windows. The direct view perspective is adjusted to a specified viewpoint in the Operator Complex and a lens system is incorporated which effectively places the image at infinity, thereby creating the illusion of depth to the Operator.

THE MASTER CONTROL COMPLEX

The Master Control Complex includes work stations for the Test Conductor and Systems Engineer and provides for full interactive control and monitoring of tests and communication with the Operator Complex.

The Test Conductor Panel, contains timers, CCTV controls, recorder controls and communications, and the the Systems Engineers anel contains a duplicate set of operation controls, arm parameter displays and system monitors, A portable interactive terminal and a CRT monitor and keyboard are included in the complex.

Tasks may be frozen and restarted, or, if desired, re-initialized.

The Test Conductor can monitor engineering data on a CRT display system, by calling specified CRT "pages". Hard copy of a displayed page is available.

Simulated malfunctions may be inserted by the Test Conductor and/or cleared by keying-in an appropriate "malfunction number". Recording devices, selectable from the Master Control station, include 24 channels of pen recorders, audio (voice communication) recorder, video recorder, 9-track magnetic tape and a line printer.

IV VALIDATION OF SIMFAC

Validation of the SIMFAC simulation model is achieved via an extensive set of performance comparisons with the comprehensive non-real-time SRMS simulation model, ASAD, developed by Spar for in-depth technical evaluations. ASAD is the most detailed and versatile model of the Orbiter-SRMS-Payload system currently available and, as such, is used as the Master Simulation model against which all other SRMS models are validated.

The ASAD program is modular in design, the principal modules being the SRMS Control Algorithms, Joint Servo and Gearbox, Manipulator Arm Dynamics and Orbiter Attitude Control System (ACS) modules. The program can accept an unlimited number of SRMS and Orbiter crew commands and can be used to analyze the effects on SRMS performance of up to seventy-six degrees-of-freedom.

Parameter changes in ASAD prior to a particular run may be implemented by the user to satisfy specific requirements. In particular, the integration step size, number of flexible modes retained when integrating the system differential equations, the updating period of system variables and "grid vector" used to suppress undesired degrees of freedom may be preselected as necessary to maximize simulation acuracy, minimize run time/cost, or achieve an acceptable compromise.

ASAD runs on a Control Data Computer system - a CDC 6600 - and operates typically at 30 times real time.

In view of the importance of ASAD as a detailed SRMS design, development and performance verification tool and as a basis for the validation of SIMFAC (and other SRMS simulation models), it has been necessary to apply considerable and detailed effort to the task of validating - and reconfirming the validity of - ASAD throughout the SRMS Program. This on-going work has involved:

- validation by analysis;
- validation by comparisons with SRMS unit and subsystem test performance (breadboard, engineering model, qualification and flight hardware);
- validation by comparisons with other analysis and simulation programs - including SRMS applications of finite element programs, such as

"NASTRAN", "STARDYNE", together with other independent SRMS simulation models.

The primary aim of the SIMFAC validation against ASAD is to ensure that SIMFAC behaviour is consistent with that of ASAD within specified bounds. Emphasis is placed on validating the control algorithms and the arm dynamics model to establish the adequacy of SIMFAC to perform its primary function -- to provide an accurate visual representation of arm performance and behaviour to an operator such that the operator reactions to these displays will, in turn, be realistic.

Although the ASAD results have reflected the presence of the higher frequency flexible modes modelled, excellent correlation has been demonstrated at the lower frequencies which are controllable by the operator. The SIMFAC mathematical model is thus validated for the SRMS application.

V PRINCIPAL SIMFAC STUDIES PERFORMED

Some of the major tasks carried out using SIMFAC are:

- SRMS Parameter Sensitivity Evaluations,

  The Evaluation, Development and Verification of SRMS Operating Procedures,

- Malfunction Simulations and Analysis of Malfunction Performance, and

- Formal Simulations in Support of SRMS Performance Verification.

SRMS PARAMETER SENSITIVITY EVALUATIONS

A considerable number of parameter sensitivity studies have been performed throughout the SRMS Program. Based on the results of these studies, a "short list" of SRMS parameters which, under worst case tolerance conditions, might significantly influence the ability of the SRMS to meet performance requirements has been generated.

The SIMFAC parameter sensitivity study has addressed each of these parameters in turn, selected runs having been performed with the parameter value varied over a suitable range. A final set of sensitive SRMS parameters has thus been selected from which worst case combinations have been derived as a basis for system verification/certification simulations.

The sensitive parameters and the worst case combinations established from the SIMFAC parameter sensitivity study are identified in Table V-1.

It is significant to note that even through greater than expected sensitive parameter tolerances were used in these worst case combinations and quantitative differences between nominal and off-nominal performance were noted on ASAD, the operators were unable to detect any significant different in performance.

EVALUATION, DEVELOPMENT AND VERIFICATION OF OPERATING PROCEDURES

The development, evaluation and verification of SRMS operating guidelines, procedures and constraints has been achieved through a large number and range of studies which have addressed all aspects of the SRMS design (mechanical, electrical, thermal, software and interfaces) and have examined the integrated Orbiter/SRMS mission requirements. From the results of the studies, operational requirements and limitations compatible with the SRMS design capability and anticipated on-orbit tasks have been identified and subsequently interpreted in terms of the appropriate SRMS operating procedures and constraints.

The purpose of the operating procedures and constraints is to provide the Operator with clear, detailed operating instructions for on-orbit preparation, checkout, operation, system management and shutdown of the SRMS, including SRMS software activation and initialization. Major SIMFAC studies have been conducted in which on-orbit tasks have been defined and carried out by NASA operators. Acceptability (and, ultimately, verification) of the procedures and appropriate constraints developed has been judged on the basis of:

- task (or subtask) success,
- operator workload,
- time to completion
- the operator's assessment of (and responses to) the characteristics encountered

The on-orbit tasks defined for the studies have all been carried out by the test operators under the control of a test conductor and have comprised:

- full end-to-end payload deployments and retrievals.
- automatic mode operation (addressing operator procedures for auto mode entry, monitoring, interrupt and exit).

- Special subtasks for specific evaluations, involving, for example, maneuvering of the arm in the neighbourhood of singularities and reach limits, maneuvering of the arm in SINGLE JOINT, DIRECT DRIVE and BACKUP DRIVE modes.

These SIMFAC studies have confirmed that the SRMS operating procedures and constraints developed are realistic under flight-like conditions and that they provide for acceptable on-orbit task times and operator workload.

MALFUNCTION SIMULATIONS AND ANALYSIS OF MALFUNCTION PERFORMANCE

Extensive malfunction simulations and evaluations of malfunction performance have been carried out on SIMFAC. In one major study over five hundred data runs with malfunction insertion, were performed with the participation of nine test operators. Payload deployment and retrieval tasks were performed with payloads ranging from 1000 lb. to 65,000 lb. Malfunctions modelled in SIMFAC and evaluated in this study included the following:

- Single axis and all-axis failure of the translational hand controller resulting in a sustained "hardover" maximum command,

- Single and multi-joint worst-case runaway failures,

- Seized, sluggish and joint free failures,

- Joint position encoder failure,

All malfunctions were activated by the Test Conductor to coincide with high operator workload conditions and, where possible, difficult fault detection conditions during the SRMS task. Operators were not able to predict when in a run the malfunction would occur.

All of the malfunction studies carried out on SIMFAC have involved the accumulation and evaluation of comprehensive qualitative and quantitative data on the malfunction effects, in terms of SRMS uncommanded motions induced (and resulting hazard created), operator observations and responses and (where applicable) stopping distance following brake application.

Any loaded arm runs involving indicated contacts between the payload and the cargo bay have been analyzed using an off-line contact detection program which provides confirmation that a contact occurred and quantitative data on the contact velocity and kinetic energy.

The data from these SIMFAC malfunction studies have provided valuable insight into the effects of failures on man-in-the-loop performance and have provided major inputs for the development of formal SRMS malfunction procedures. In addition, the studies have identified clearly instances when, for a particular malfunction, occuring under worst case conditions, human operator responses (however fast) to the fault annunciations, alarm and/or visual cues were ineffective in preventing a payload/orbiter contact. Under such circumstances a design change (hardware and/or software) has been necessary to maintain failsafe SRMS performance. Confirmation that the design change has achieved this objective has been established from the results of repeat malfunction runs on SIMFAC with the design change incorporated.

A further major role played by SIMFAC has been in the evaluation of SRMS operational capabilities in the irect Drive and Backup Drive modes after a malfunction has occurred. Studies have confirmed that the manipulator arm (with or without payload attached) can be safely and accurately maneuvered in these modes, demonstrating compliance with the SRMS failsafe requirement.

SRMS PERFORMANCE VERIFICATION

Amongst the most important and comprehensive man-in-the-loop simulations carried out to date on SIMFAC are those which support integrated SRMS performance verification and certification.

These indepth simulations take account of the effects of tolerances on "sensitive" system parameters by using chosen combinations which give worst case effects relative to specific performance characteristics (Reference Table V-1).

The objective of the simulations on SIMFAC is to verify SRMS compliance with specific performance requirements detailed in the SRMS Contact End Item (CEI) Specification. Each CEI specification requirement so addressed may be catagorized as either quantitative or qualitative.

Quantitative requirements specify numerical upper limits for either the magnitude of a variable of interest, or the magnitude of departure of a variable of interest from a specified command, or datum.

The verification criterion applicable to a quantitative CEI specification requirement is, therfore as follows:

Compliance is considered to be demonstrated - and verification with respect to the requirement achieved - when, under simulated worst-case conditions, the magnitude of the variable of interest, or its departure from the referenced command/datum, does not exceed the specified numerical upper limit.

Qualitative requirements are those which call up specific SRMS functional - or operational - capabilities, or design features not expressable in numerical terms.

The verification criterion applicable to a qualitative CEI specification requirement is dependent on the specific quality (SRMS functional/operational capabiity, or design feature) called up.

In general, it is necessary to establish, on the basis of worst-case simulation data, that the SRMS capability - or design feature - identified exists and adequately fulfills the objective(s) specified in the requirement. Adequacy in fulfilling the specified objective(s) is judged on the basis of factors which include speed and accuracy of task performance, safety and operator workload.

SRMS performance verification using SIMFAC involves the following steps:

- Validate SIMFAC against the non-real-time simulation model ASAD
- Prepare operating procedures and operating checklists for the verification runs
- Perform complete checkout of all verification runs under data run conditions, including off-nominal parameter and malfunction runs
- Conduct verification simulation readiness review
- Carry out operator briefing and familiarization runs
- Conduct verification data runs
- Analyze results and generate verification report

A great many "flying" hours have been conducted on SIMFAC in support of SRMS performance verification and each CEI performance requirement has been rigorously addressed, the runs carried out having been selected to cover the impact of both off-nominal SRMS parameters and worst case configuration and maneuvering conditions.

By this means it has been possible to demonstrate convincingly that the SRMS design fulfill the performance objectives specified, which include:

- full end-to-end payload deployment and retrieval capability,
- fail-safe capability,

- operation in all control modes,

- rate and positioning accuracies for joints, end effector, payload point of resolution, and

- management of singularities and reach limits.

In performing this verification support role, SIMFAC has made (and is continuing to make) a major contribution in the process of formally establishing that the SRMS meets all design, performance and safety requirements.

VI CONCLUSIONS

The many major simulation studies performed on SIMFAC since the facility came into service in 1977 have demonstated repeatedly the importance of its role as a design, development and verification tool for the SRMS. SIMFAC has provided for the development of man-machine interfaces operator's primary hand controllers and displays and controls panel) and manipulator control software, the development of flightlike operating procedures, operating constraints and malfunctions procedures, an the verification of the SRMS performance with man-in-the-loop.

SIMFAC has shown clearly that the SRMS is capable of safely carrying out all of the on-orbit tasks for which it was designed and, as a result, has provided early confidence that the SRMS will perform successfully during the forthcoming orbital flight tests.

SIMFAC is not, however, limited to studies within the SRMS program; the facility is, by design, extremely versatile and is capable of supporting the design and development of manipulator systems for non-space environments which are of high technical complexity.

ACKNOWLEDGEMENTS

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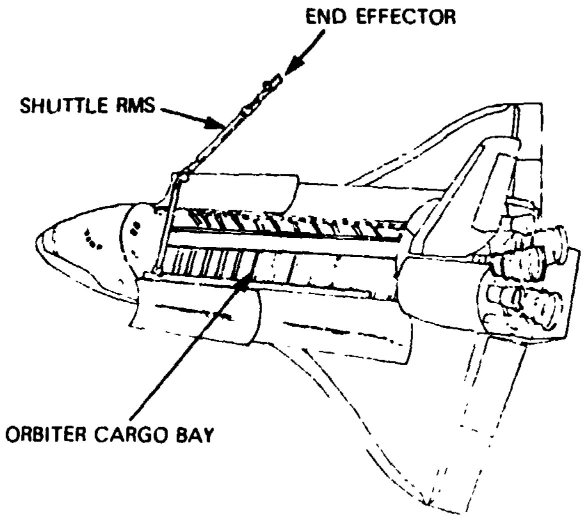
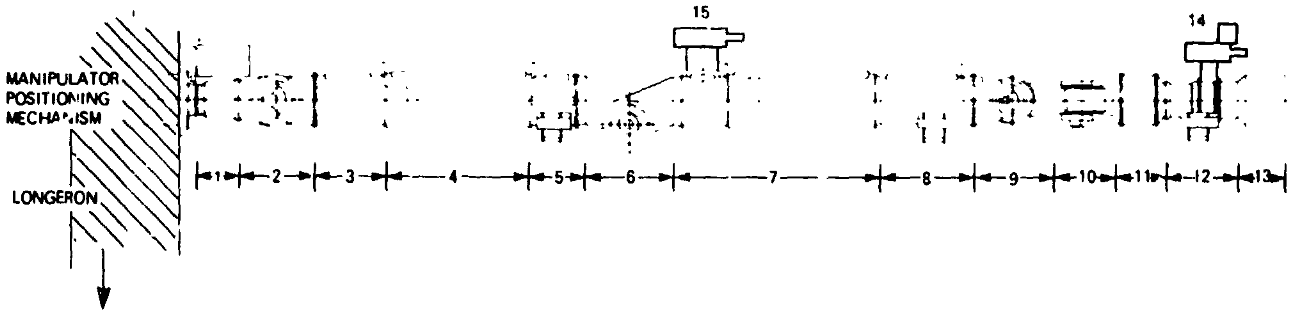


FIG. II - 1 SHUTTLE RMS ON THE ORBITER



COMPONENTS

1 SHOULDER YAW JOINT
2 SHOULDER PITCH
3 SHOULDER ELECT. COMP.
4 UPPER ARM BOOM
5 ELBOW ELECT. COMP.
6 ELBOW JOINT
7 LOWER ARM BOOM
8 WRIST FWD. ELECT. COMP.
9 WRIST PITCH JOINT
10 WRIST YAW JOINT
11 WRIST AFT ELECT. COMP.
12 WRIST ROLL
13 STANDARD END EFFECTOR
14 CCTV CAMERA & VIEWING LIGHT - WRIST LOCATION
15 CCTV CAMERA WITH PAN/TILT UNIT – ELBOW LOCATION

(SHOULDER PITCH JOINT ROTATED THROUGH 90° FROM STOWED POSITION)

FIG. II - 2 MANIPULATOR ARM MECHANICAL ASSEMBLY

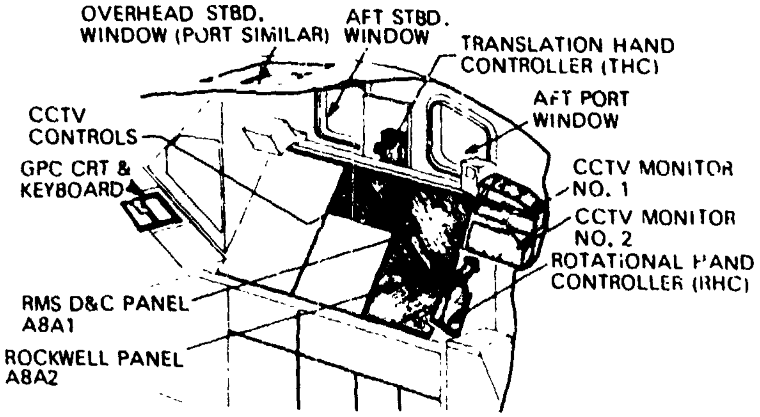


FIG. II - 3 RMS OPERATING STATION

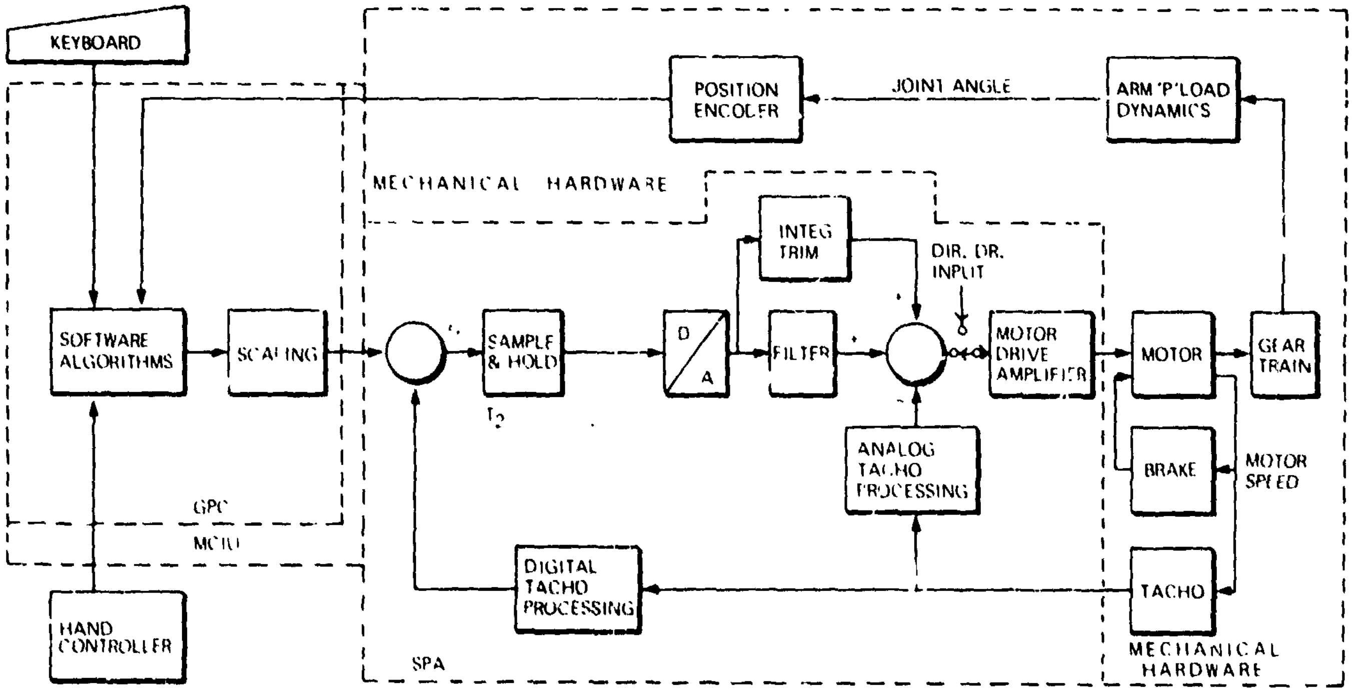
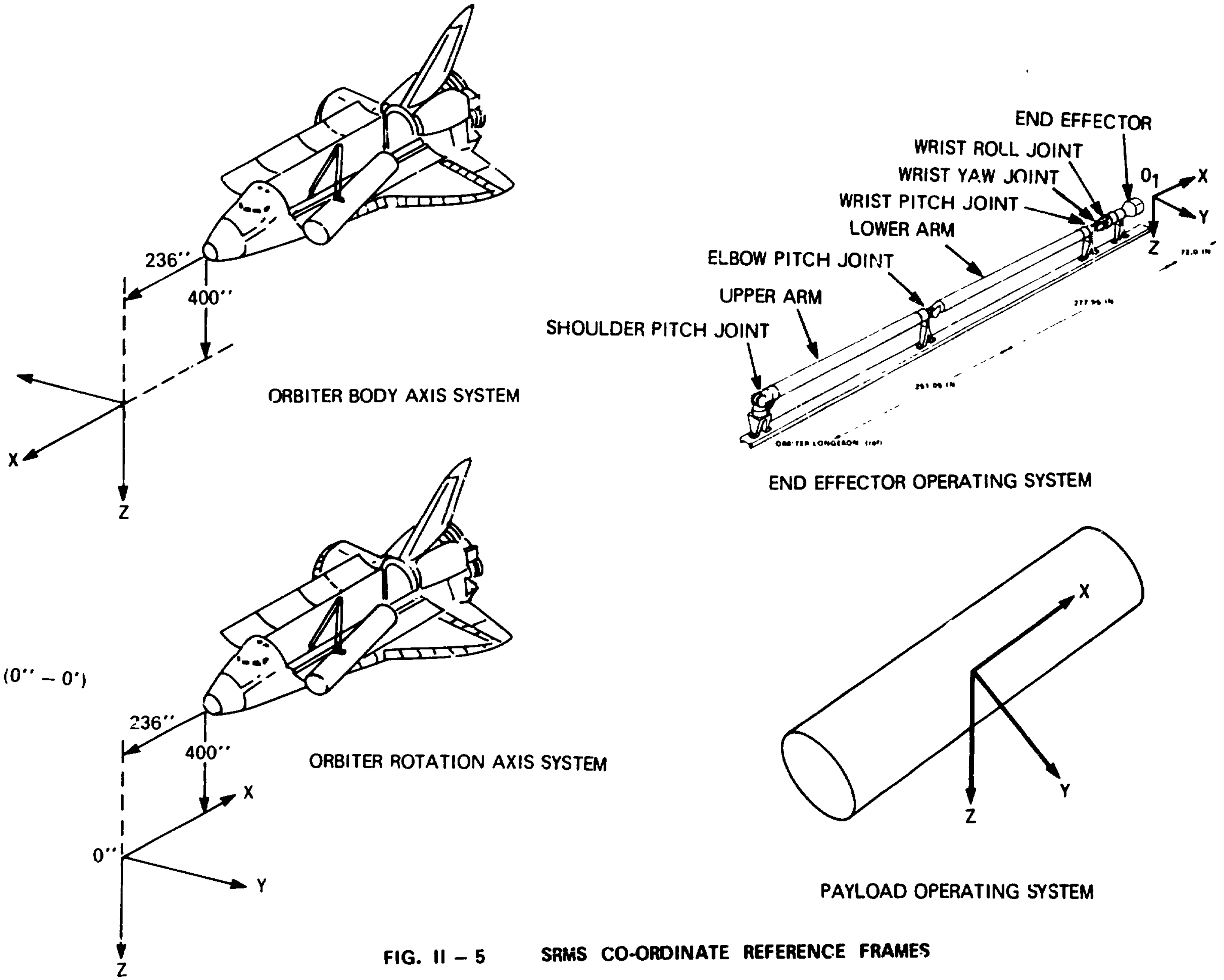


FIG. II - 4 JOINT SERVO CONTROL BLOCK DIAGRAM



ORBITER BODY AXIS SYSTEM

ORBITER ROTATION AXIS SYSTEM

END EFFECTOR OPERATING SYSTEM

PAYLOAD OPERATING SYSTEM

FIG. II – 5 **SRMS CO-ORDINATE REFERENCE FRAMES**

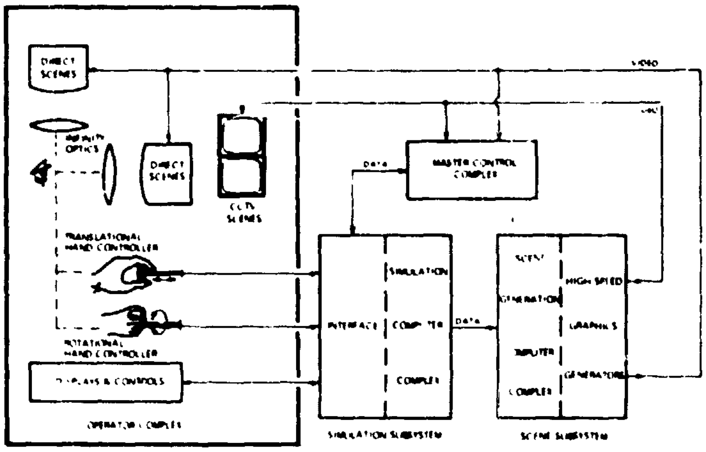


FIG. III - 1 SIMFAC BLOCK DIAGRAM

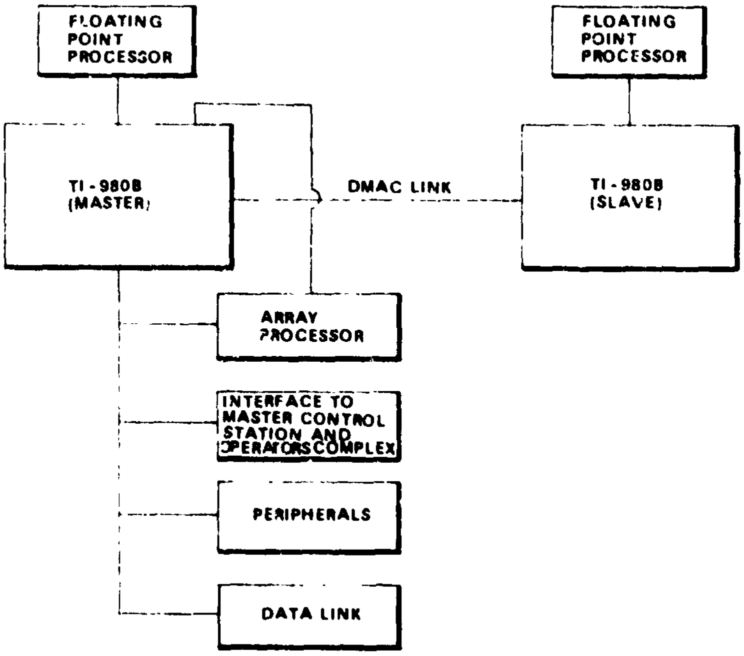


FIG. III - 2 SIMULATION SUBSYSTEM BLOCK DIAGRAM

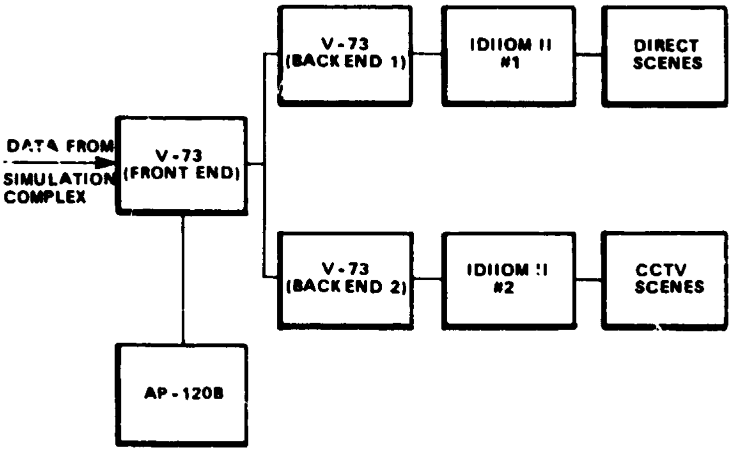


FIG. III - 3 SCENE GENERATION SUBSYSTEM BLOCK DIAGRAM

DOF	NUMBER	TYPE
ORBITER ATTITUDE	3	ROLL, PITCH, YAW
CONTROLLED	6	ROLL, PITCH YAW JOINTS
FREEPLAY	6	SHOULDER PITCH ELBOW PITCH WRIST ROLL
BENDING	8	SHOULDER PITCH, ELBOW PITCH
TOTAL	2.	

TABLE III - 1 ARM DEGREES OF FREEDOM (DOF) IN SIMFAC

TABLE V - 1 WORST CASE COMBINATIONS OF SENSITIVE PARAMETERS

PARAMETER	COMBINATION					
	1a	1b	2a	2b	3a	3b
GEARBOX EFFICIENCY	lo	hi	hi	lo	hi	lo
JOINT SERVO OUTER LOOP GAIN	lo	hi	lo	hi		
INTEGRAL TRIM LIMIT	lo	hi	lo	hi		
MOTOR CURRENT (TORQUE) LIMITS	lo	hi	lo	hi		
JOINT FRICTION	hi	lo	lo	hi	lo	hi
MOTOR FRICTION	hi	lo	lo	hi	lo	hi
BRAKE SLIP TORQUE					lo	hi
GEARBOX FULL RANGE STIFFNESS	lo	lo	lo	lo	lo	lo

SYSTEM CHARACTERISTICS

COMBINATION 1a GIVES – low drive torque/speed, sluggish response

1b GIVES – high drive torque/speed, rapid response

2a GIVES – low backdrive resistance

2b GIVES – high backdrive resistance

3a GIVES – low braking torque

3b GIVES – high braking torque.