The Development Test Flight of the Flight Telerobotic Servicer: Design Description and Lessons Learned

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Abstract—The Development Test Flight (DTF-1) system design is described and the technical, operational and safety considerations that affected the design are discussed. Also discussed are the “lessons” that were learned during the design and early development stages in an effort to capture some of the knowledge from the program.

I. INTRODUCTION

For several years, NASA was developing a telerobotic system called the flight telerobotic servicer (FTS) at Goddard Space Flight Center. A development test flight of a robotic manipulator, labeled DTF-1, was planned for a Shuttle mission in 1993. The purpose was to evaluate the design of the manipulator and workstation and correlate system performance in space with ground tests.

Although the funding for DTF-1 was eliminated in September 1991, the design of the DTF-1 system was completed and the flight hardware was in different stages of development. Some items, such as the end-effector, were already built, qualified and delivered.

With its manipulator, end-effector, cameras, force/torque transducer, computer and operator control station, the DTF-1 system design incorporated the fundamental building blocks of the original FTS, the end product of which was to have been a lightweight, dexterous telerobotic device that would evolve into an autonomous robot. The approach was to adapt current teleoperation and robotic technologies into a system that could operate in space. This was a new undertaking for NASA, something that had never been done before, and something that was full of challenges.

II. TECHNICAL CONSIDERATIONS

The primary objective of the FTS Project was to bring robotics out of the laboratory and apply it for use in the harsh environment of space. Everyone working in robotics has a laboratory where they stage demonstrations under controlled conditions. Such demonstrations are essential to the development of new technologies, but these demonstrations only indicate a feasibility of a particular implementation. They do not guarantee that such a system can work in space after being subjected to launch and when constrained by Shuttle and manned system interfaces.

Designing space-qualified hardware for the DTF-1 system was far different from building laboratory demonstration models. The DTF-1 engineers had to consider requirements in the areas of environment, interfaces to the Shuttle, space station, the crew, evolution and safety. In addition, the DTF-1 manipulator differed from a laboratory manipulator. It combined the qualities of a force-reflecting teleoperated system with the capabilities required for a fully autonomous robot. Also, the hardware and software had to meet the stringent Shuttle and manned systems integration standards and qualify for operation in space.

Flying a force-reflecting system in space was a new idea. One consideration in developing the DTF-1 force reflection system was the amount of force feedback the astronaut would require as he/she became accustomed to the weightlessness of space. For example, the planned maximum force of 22 N may have been excessive on-orbit. Therefore, the system was adjustable with selectable gains that could be tuned to the astronauts' needs.

Another goal of the FTS Project was to have the DTF-1 system evolve toward autonomy so that it could relieve the astronauts from performing mundane tasks. The path to autonomy starts from the factory-like tasks requiring tight resolution and repeatability, and extends on up through higher levels of intelligence implemented in the computer and software architecture. The manipulator was designed to handle this full range of tasks. This led to a resolution requirement of 0.0254 mm and 0.01 degrees, and a repeatability requirement of 0.0508 mm and 0.05 degrees. These numbers would not be required for a strictly teleoperated system. In fact, they could be relaxed by two orders of magnitude.

Safety was another significant design driver. The Shuttle payload safety requirements dictated that the DTF-1 system be two-fault tolerant in controlling catastrophic hazards. Two-fault tolerant means that three independent control paths for controlling each hazard must be in place. The only approach to meeting this requirement with a highly complex system like DTF-1 was to use computers to control the hazards. In using computers in this way, the Project set a precedent in the arena of Shuttle payload safety.

The next few paragraphs will not only elaborate on the design, but also examine the impact of the requirements on the DTF-1 design.
A. Configuration Design

The DTF-1 system configuration consisted of a payload bay (PLB) element and an aft flight deck (AFD) element.

Payload Bay Element: The PLB element (see Fig. 1) included the telerobot body, a 7-degree-of-freedom (DoF) manipulator, a force/torque transducer, a vision subsystem, an electrical and power subsystem, a task panel and most of the data management and processing subsystem (DMPS). The PLB element’s primary support structure was a multipurpose experiment support structure (MPESS), which would mechanically attach the DTF-1 hardware to the Shuttle. The telerobot body was large and contained all the electronic components that were not in the manipulator. It was not necessary to minimize the size, weight and power of the telerobot body components for this test flight. The mission was well within the Shuttle’s quarter bay allocation for DTF-1.

Manipulator: The DTF-1 manipulator (see Fig. 2) was approximately 1.68 m long from the shoulder to the tool plate. The manipulator could produce 89 N of force and 27 N-m of torque at the tool plate anywhere in the work envelope. The shoulder roll, yaw and pitch actuators were of a similar design, each capable of producing 160 N-m of torque; the elbow pitch actuator could produce 83 N-m of torque; and the wrist yaw, pitch and roll actuators could each produce 33 N-m of torque and were of similar design.

The manipulator was originally designed to work with a 28 V dc power supply that was compatible with the Shuttle’s system, but not Space Station Freedom’s system, which would supply 120 V dc. The challenge was to design a manipulator that would be compatible with both the Shuttle and the space station.

The manipulator was modified to the 120 volt system, which was more efficient for the FTS joint actuator motors. A dc/dc converter was designed to convert from the Shuttle’s 28 volt system to Freedom’s 120-V system.

The joint actuators consisted of a primary brushless dc motor, harmonic drive transmission with 100:1 ratio, redundant output joint torque sensors, redundant inductive encoder output position sensors and fail-safe brakes with manual release. The actuators also incorporated a secondary motor winding with a redundant set of hall effect sensors, which permitted independent control and safing of the manipulator through...
a hardwired control system that bypassed the computers and allowed the operator to drive a single joint at a time.

Flat conductor cables, that were to be used to transmit power, data and video signals through the actuator, consisted of as many as 33 layers. This innovative design met the requirement for a wiring harness configuration that would not impair joint motion, would not snag and would not fail from flex fatigue. This low-torque method of routing the cable internal to the actuator and shielding the layers to prevent interference were new developments.

Safety dictated that the manipulator be removable by an astronaut during extravehicular activity (EVA) in the event that one or more of the joints became frozen during operation and the manipulator could not be safely stowed for landing. This requirement led to brakes that could be manually or robotically engaged or disengaged, backdriveable joints, an EVA disconnect at the shoulder and inserts for EVA handles at selected places along the arm.

Within the links of the manipulator were housed three joint controllers: the shoulder controller for controlling the shoulder roll and shoulder yaw actuators; the upper arm controller for controlling the shoulder pitch and elbow pitch actuators; and the lower arm controller for controlling all three wrist joints as well as the end-effector. Each joint controller was similar in design. Each consisted of a CPU board with an INTEL 80386 processor and 512 Kbytes of random access memory (RAM), an input/output board, a power supply board, a dc motor drive board, a dual position acquisition board and an analog acquisition board.

A redundant force/torque transducer (FTT) was mounted on the end of the manipulator. Two independent strain gauge elements and associated electronics in the FTT measured the forces and torques produced at the tool plate. The FTT generated two sets of six differential, analog signals that roughly corresponded to the six independent components of the force and torque vectors. Two independent controllers digitized and calibrated the analog signals resulting in a digital representation of the force and torque vectors at the FTT.

The Shuttle’s electromagnetic compatibility requirements were of concern in developing the FTT. During testing, each of the strain gauge leads acted as a small antenna. To solve the problem, special shielding that would not interfere with flexing of the FTT was developed.

The end-effector was a parallel jaw gripper (see Fig. 3) with a special cruciform gripping interface that ensured positive grasping of the task elements. The gripper contained a brushless dc motor, pancake harmonic drive transmission, finger
position and output torque sensors, redundant fail-safe brakes and associated gear reduction, sensor amplifiers, wiring and connectors. The gripper provided a peak gripping force of 222 N over a 10 cm gripping range and was two-fault tolerant against inadvertent release of hardware.

Four caging mechanisms, two on the lower arm link and two on the wrist, secured the manipulator during launch and landing. The system could withstand worst-case landing loads with the failure of any of the manipulator caging mechanisms.

Vision Subsystem: The vision subsystem included three, charge-coupled device, color cameras: a wrist-mounted camera and two head-mounted cameras. The wrist camera gave the operator a view of the end-effector, permitting intricate tasks to be performed and allowing close-up inspections of completed work. The fixed head cameras with their zoom, focus, and manual iris control capabilities provided views of the worksite.

The vision subsystem was planned for use with the Shuttle’s Closed Circuit Television (CCTV) System. The camera video output would interface to the Shuttle’s video switch and could be displayed on existing Shuttle monitors. The output could also be recorded on the Shuttle video recorders.

Electrical and Power Subsystem: This subsystem interfaced electrically with the Shuttle’s power system, conditioning this power to meet the needs of the telerobot, and distributing the power to the DTF-1 subsystem loads. The electrical and power subsystem also permitted a safe power-up and power-down sequence and performed the power switching required by subsystem loads. It performed line filtering and electromagnetic interference power quality filtering and provided power health and status reports to the computers. The electrical and power subsystem was capable of generating $+/-15$ V dc and $+5$ V dc from the Shuttle’s 28 V dc for the DMPS and thermal control subsystems, and regulated 30 V dc for the cameras and lights. It also could generate 120 V dc for the manipulator actuators and brakes.

Task Panel: The DTF-1 task panel was mounted on the MPESS in front of the manipulator and held the task elements for testing the FTS capabilities. The tasks consisted of a peg-
in-hole pattern, a contour board, a space station truss node, a space station fluid connector, an 11-kg removable mass, and a series of precision machined holes for n-point pose estimation using wrist camera video data.

Data Management and Processing Subsystem: The data management and processing subsystem (DMPS) (see Fig. 4) was a distributed system of computers, controllers, and data and video recorders for supporting the DTF-I software and system architectures. The computers were connected through two MIL-STD-1553B data buses.

The DMPS consisted of one telerobot control computer (TRCC) and eight controllers. The TRCC contained three 20 MHz 80386 CPU's with 4 Mbytes memory each. It was the primary control processor. In the forward loop, it took commands from the handcontroller, computed the inverse kinematics and produced the required motion at the manipulator. In the return loop, the TRCC received inputs from the FTT, computed impedance commands for the manipulator, and performed boundary management and touch control (BMTC) and housekeeping safety checks.

The eight controllers included the telerobot redundant computer (TRRC), display assembly controller, power module controller, three joint controllers, payload bay controller and the handcontroller electronics. The TRRC performed backup BMTC checks and housekeeping checks. The display assembly controller provided the operator interface through the control and display panel (C&DP) and the Shuttle-provided Payload and General Support Computer (PGSC). The power module controller provided uplink and downlink through the Shuttle. It also controlled the head cameras and caging mechanisms.

With eleven 80386 processors and over 16 Mbytes of RAM, the DMPS met the requirements for evolution toward a fully autonomous system. The plan was to have the architecture and extra computer capacity in place and qualified as part of the DTF-I mission.

The PGSC, which was actually a commercial lap-top computer, was used, with several floppy disks, to initialize the software. Initialization would occur through an RS-422 bus from the PGSC to the display assembly controller. Software load files were to be prerecorded before launch. The detailed software design was written in the Ada program design language, which was the adopted machine-compatible, high level language for Space Station Freedom. One of the contributions made by the Project was the implementation of an Ada real-time system for robotic applications.

Control System: The control system offered many options to the operator. Although the primary control mode was a position-based, impedance control with force reflection, the system could also operate without force reflection or in a rate control mode. The ability for the crew to change various system options and gains was included, such as, selection of any combination of command degrees-of-freedom, impedance
stiffness, impedance damping and handcontroller force/torque reflection gains.

Additionally, DTF-1 operated in an autonomous mode during certain of the on-orbit tasks, which required pre-programmed trajectories to be followed. Autonomy to perform structured and somewhat unstructured tasks was an evolutionary goal of the FTS, but was not developed for DTF-1.

In the primary control mode, the handcontroller generated Cartesian commands that were converted through inverse kinematics into joint commands at the servo level. The impedance loop and the Cartesian position loop operated at 50 Hz (see Fig. 5). The joint controllers implemented a digital proportional-derivative (PD) controller at 200 Hz nested around an analog torque loop.

Using a planar arm with flight-like hardware and control algorithm software, the free space performance of the DTF-1 manipulator was verified while performing both teleoperated and autonomous maneuvers. For the speed of response, step inputs were used to verify a rise time of less than 0.6 s to reach 98% of the step input. The maximum overshoot or undershoot of the response was less than 2%. Frequency responses were generated to verify gain and phase margins greater than 6 db and 30 degrees, respectively, for each joint.

An additional study was conducted in the area of contact stability [1]. Analysis results, backed up by tests on the planar arm, showed that the system was stable when contacting relatively soft and relatively stiff environments. For environmental stiffnesses between these two extremes, the system went unstable. The joint servo control law was modified with an augmented damping feedback loop operating at 200 Hz. This change produced a stable system over the entire range of environmental stiffnesses and was verified on the planar arm.

A hardwired control system permitted stowage of the payload in the event of failures in the normal computer control path. Switches on the C&DP bypassed the computers and directly controlled individual manipulator joints, manipulator and mass caging mechanisms, the end-effector and the cameras and lights.

Control System Architecture: The early FTS studies identified the requirement for a telerobot architecture that would define a set of standard modules and interfaces that would facilitate the incorporation of new capabilities. It was a requirement that individual components in the architecture be easily modifiable and capable of executing new algorithms and communicating with new system elements. The control system architecture selected as a result of Phase B trade studies [2] was modeled after the NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM) [3].

NASREM was selected because it defined a logical computing architecture for telerobotics that meets the requirements for evolution while capturing architectural features from a number of concepts that had been developed in earlier research programs or were being developed as part of on-going research programs within NASA, the military and several universities. It is an all-encompassing model wherein the software and computer architecture implementations support, and are driven by, the functional architecture hierarchy.

The NASREM telerobot control system architecture is both hierarchically and horizontally structured, as shown conceptually in Figure 6. High level commands, or goals, are decomposed both spatially and temporally through a hierarchy of

![Joint controller block diagram.](image-url)
control levels into strings and patterns of subcommands. The sharing of data is horizontal between modules at the same level. The DTF-I design implemented the three lowest levels: the Elementary or "E-move" level, the primitive level and the Servo level.

**Aft Flight Deck Element:** The aft flight deck element consisted of the workstation, which was situated in the port side corner of the Shuttle's aft flight deck close to the shuttle remote manipulator system (RMS) controls (see Fig. 7). A single operator could control the telerobot and conduct DTF-I operations from the workstation using the two, Shuttle-provided TV monitors located in that corner. Direct viewing of the telerobot was not required; however, the operator could see it through the aft flight deck windows.

Located in the workstation was a handcontroller with electronics, the Shuttle-provided PGSC, a C&DP, a display assem-
The DTF-I handcontroller was a 6 DoF, force reflecting controller, a power control and distribution unit (PCDU), and a crew restraint system to support the operator during force-reflecting operations in zero gravity.

The DTF-I handcontroller was a 6 DoF, force reflecting handcontroller (see Fig. 8). The handcontroller electronics consisted of a computer, analog to digital converter, input/output device, and pulse-width modulated power drivers. The handcontroller supported rate and position control, with and without force reflection. It could provide 22 N of force and 1.1 N-m of torque into the operator's hand.

The detachable handgrip was similar to bottom-mounted, flight joysticks. It had an activation switch that activated the handcontroller and permitted re-indexing of the handcontroller-to-manipulator transformation; an end-effector enable switch, which enabled the end-effector to open or close; and the end-effector rocker switch, which commanded the end-effector fingers to open or close. This approach met safety requirements by preventing inadvertent release by the end-effector of an object into space.

The PGSC displayed system status and function and was used to initialize the software, as mentioned above. The workstation operator used the function keys and the numeric and cursor keypad functions of the PGSC keyboard for menu and data entry operation. The C&DPU had a section of switches, indicators, and annunciators for manual control, emergency shutdown (ESD), and mode control.

III. ON-ORBIT TASKS

DTF-I on-orbit tasks consisted of both teleoperated and autonomous operations.

Teleoperated tasks included peg-in-hole insertion, contour following, grasping and handling of a space station truss node and a space station fluid connector, and grasping and handling of an 11-kg removable mass. These tasks were to be performed using both rate and position control (with and without force reflection) to assess the relative performance of each mode with a crew member in a zero gravity environment. Data gathered was to include: video and audio recordings of the manipulator and the crew operating the system; answers to questionnaires; and all position and rate commands from the crew, forces and torques sensed by the manipulator, forces and torques reflected to the crew, all system gains, and other data, as required by the specific test objectives.

Automated tasks included accuracy, repeatability and resolution tests to measure the performance of the manipulator subsystem. Due to the cost and complexity of developing a completely independent sensor to measure these parameters, innovative techniques were proposed to gather the necessary data. [4]. Accuracy and repeatability measurements were to be derived from video recordings from the wrist camera of 36 points placed on a precision machined plate and using an n-point pose algorithm. Resolution was to be measured using the high resolution joint position sensors.

Other tasks included characterization of the control system and data gathering for stability analysis. These tasks were performed in the teleoperated modes and in the autonomous mode. These tests would have been performed with and without the removable mass.

IV. SAFETY CONSIDERATIONS

The design of the DTF-I system was driven heavily by safety considerations [5]. Specific requirements and design criteria included material compatibility and flammability, deployment and separation, contingency return, rapid safing and mission procedures. The focus was to maintain the integrity of the Shuttle and protect the crew.

The DTF-I hazard control system addressed the following hazards unique to robotic applications: (1) unplanned contact/impact of the end-effector with another object or element within its reach; (2) unplanned contact or impact of the individual joints of the manipulator (joints contacting hard stops) during operations; and (3) excessive forces and torques generated at the end-effector during planned contact.

The DTF-I hazard control system used an integrated computer control, sensor and feedback system. This system proactively processed the commands to the manipulator and reactively monitored hazardous conditions through dual paths. In addition, separate electronics monitored certain safety critical parameters and the TRRC acted as a safety watchdog-monitoring computer. If safety limits were exceeded, electrical power was removed from the actuator motors and the failsafe brakes engaged. This process was called an Emergency Shut-down (ESD). It could be either manually initiated by the operator or automatically initiated by the telerobot in the event of a self-diagnosed failure or other unsafe condition.

Force and torque commands were limited at the Cartesian level and at the joint level. Cartesian-level control limited the Cartesian position, velocity, force and torque at the manipulator and end-effector. Joint-level control prevented the motor and gear actuator assemblies from exceeding rated design torques. Joint-level control also provided a rapid response to joint "run away."

A boundary management and touch control (BMTC) system controlled collision and impact hazards. This system set imaginary boundaries in and around the workspace. Limits on manipulator travel restricted the manipulator position to within...
the predefined workspace. Limits on velocity controlled the force with which the manipulator impacts its surroundings. Cartesian-level controls limited the manipulator movement in the workspace and joint-level controls limited individual joint movement in joint space.

The Shuttle requirements [6] did not adequately address safety for a system like DTF-1. For example, Shuttle safety required that at least one of the catastrophic hazard control methods be independent of computers. However, the mathematical complexity of the DTF-1 controls and the speed with which response to hazardous conditions must be made demand computer control. Also, Shuttle safety required that the system have independent computers, each executing uniquely developed instruction sequences to control hazards. However, the computer architecture design of the DTF-1 system dictated the interdependencies among the various processors. The TRRC was included in the design as a safety watchdog-monitoring computer independent of the TRCC. But even this computer could not be completely independent of all the other computers because it depended on the joint controllers for position data that are collected, processed and checked at the joint level before being sent to the TRCC and TRRC. The Project broke new ground in solving this dilemma by designing a two-fault-tolerant equivalent hazard control system.

V. LESSONS LEARNED

As mentioned earlier, the FTS Project brought robotics out of the laboratory and applied it for use in the harsh environment of space. Building space-qualified hardware for the DTF-1 system proved to be far different from building laboratory demonstration models. In designing such a system to operate safely in space, engineers learned much about manipulator control, hazard control, safety system operation and data system architecture. The following paragraphs contain recommendations for developing and implementing a tele-robotic system based on the experience and lessons learned from DTF-1.

A. Manipulator Design

One of the major lessons learned during the DTF-1 design phase was that the kinematic configuration selected, although commonly used, presented difficulties when performing the more dexterous tasks. The design of the wrist joints proved to be the major impediment to the system’s kinematic dexterity.

A total systems view must be taken when designing a space telerobot. Although this was largely the case during the DTF-1 design phase, there were some exceptions that are now clear in hindsight. The primary issue revolved around the failure to view the manipulator as more than just the collection of actuators and links between the shoulder plate and the tool plate. If the manipulator had been viewed as extending to the fingers of the tool, then issues such as system dexterity would have been detected earlier and corrected. This also applies to system safety, which will be discussed below.

The distributed nature of the DMPS proved to be a major hindrance to the performance of DTF-1. The joint controllers and telerobot control computers were distributed throughout the robot and connected, as stated earlier, by a MIL-STD-1553B bus. This bus architecture placed significant timing limitations on the system and resulted in low control frequencies of only 50 Hz. Although this was believed to be acceptable, higher speeds were desired to improve operator feel and stability. During the DTF-1 design phase, this weakness was identified and studies undertaken to correct the DTF-1 shortcomings [7]. Figure 9 shows a proposed architecture that would have increased loop rates to 200 Hz.

Design of the manipulator control system was heavily involved with the computer architecture, the communications, the software implementation, and the mechanical design of the hardware. One important lesson learned was that the control system is a big part of the total systems engineering of the manipulator. The control system engineers must get involved early in specifying such system parameters as the performance parameters for the actuators, the distribution of the computations among the processors, the speed of communication between processors, the stiffness of the structure and the placement of sensors such as the force/torque sensor.

A valuable tool in the development of the control system was the planar arm version of the flight manipulator mentioned earlier in which a flight-like manipulator was supported on an air bearing table. For the DTF-1 kinematics, this allowed the shoulder pitch, elbow pitch, wrist pitch and wrist roll actuators to operate much like they would in the weightless environment of space. Here such issues as contact stability, inertia decoupling and loop timing were investigated and resolved.

Establishing requirements for handcontrollers and all crew interfaces, should be performed early in the design cycle and with early crew involvement. DTF-1 employed a 6 DoF force reflecting handcontroller design, which is considered the optimal means of controlling a dexterous telerobot. However, crew opposition to changing from the familiar rate controller used in controlling the RMS forced the FTS Project to abandon its design for future missions. Clear demonstrations of force-reflecting handcontroller advantages and disadvantages, along with early and extensive crew involvement, would have significantly improved the chances for arriving at the best design.

B. Safety System

The importance of rigorous safety analysis and development of a comprehensive safety system cannot be overstated. The experience of implementing system safety engineering on DTF-1 indicates that designing safety into the system early maximizes the safety of the design and minimizes impacts to design complexity, development cost and scheduling. In addition, close coordination among systems engineers, subsystem and component designers, system safety engineers and the Shuttle Safety Panel to clarify and interpret the safety requirements, as they may apply to complex computer-controlled systems, ensures that a balance is achieved between a safe design and one that can achieve the mission objectives.

In the area of safety controls, it is recommended that functions be allocated among separate processors. The controls
against catastrophic hazards must be two-fault tolerant and should be independent. On DTF-1, data from the three joint position sensors in each actuator were sent to the same controller. Although fault tree analyses showed that this safety implementation met the intent of the safety requirements, it would have been better if at least one of the sensors had been routed to another controller.

Diagnostic tools for ascertaining the status of the safety system during the mission should be built into the design. The purpose would be to understand failure conditions and implement recovery steps. This visibility should be broader than standard hardware bi-level and analog telemetry. Status indicators, flags, counters, messages, etc., that convey the state of the software should be used. "Instrumenting" the software in this way also simplifies its testing.

Time for the safety system to respond must be considered in the design. This time includes: 1) time to sample, filter, digitize, and acquire sensor data; 2) time for system settling, software polls or interrupts, execution of software paths, transmissions, transmission errors, retransmissions, bus control and conversion of software commands into hardware signals, and propagation of the signals; and 3) time to enable or disable power and to engage or disengage mechanisms.

Several design alternatives related to safety issues associated with the manipulator merit consideration. An alternate data system architecture has been developed as a planned follow-on [7]. This new design increases the computer power, changes the network topology, provides better data acquisition and cross straps joint controllers for redundancy. The new architecture addresses several safety issues, including speeding up the calculations, eliminating single point failures and permitting fully redundant safety systems. A laser ranger or proximity sensor could be used for collision avoidance in place of the computational intensive algorithmic approach used on DTF-1. The manipulator actuators could be designed to withstand hitting their hard stops so that joint motion is not artificially restricted by software.

VI. CONCLUSION

Through the DTF-1 design and early development phases, the DTF-1 team laid the groundwork for the fundamental building block of any space robotics—the manipulator. Requirements were identified. Technical, operational and safety issues were addressed and solutions were found. Essentially, all the drawings were complete and hardware was being built and delivered. For the first time in the history of NASA, the
combined disciplines of space technology and robotics were married to find new and unique solutions to the demanding requirements of flying a sophisticated robotic manipulator in the environment of space.

Prototyping is essential when designing a complex robotic system. Not all problems can be anticipated. The system has to be integrated and tested. This was the intent behind DTF-1. It was an engineering testbed. Unfortunately, the lessons learned were never incorporated in the next version, the flight telerobotic servicer, as planned. At least the major lessons learned have been captured here and can be of some value to the design and construction of NASA's next space telerobot.

VII. EPILOGUE

Since cancellation of the DTF-1 Project, the primary elements of the DTF-1 have been completed and delivered to NASA's Johnson Space Center (JSC). Although, there are no plans to fly the DTF-1 at this time, the authors hope that funding for a flight opportunity will become available. Additionally, a hydraulic manipulator system, which was to be used as the DTF-1 Trainer, has been completed and is operating at NASA's Langley Research Center (LaRC).

REFERENCES


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