The Flight Telerobotic Servicer Project: A Technical Overview

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Abstract

The Flight Telerobotic Servicer (FTS) Project is developing an advanced telerobotic system to assist in and reduce crew extravehicular activity (EVA) for Space Station Freedom. The FTS will provide a telerobotics capability to the Freedom Station in the early assembly phases of the program and will be employed for assembly, maintenance, servicing, and inspection throughout the lifetime of Freedom Station. The FTS will also be capable of operation on the Orbital Maneuvering Vehicle (OMV) for remote servicing activities. A planned evolution of the FTS capabilities will take place over time with technology transfer between U.S. industry, universities, and other Government agencies as an integral part of the program.

The FTS technical challenge is the development and integration of a spaceflight quality system with both teleoperation and autonomous capabilities. The system must be safe and operate reliably in the space environment. The technical output of the FTS development process will not primarily come from the development of new sensors, manipulator actuator mechanisms or other robotic components. The state of the art in these components is already highly sophisticated. The major contribution of the FTS to the advancement of the state of the art will come from the integration of these components into an operational system which meets the broad spectrum of Space Station Freedom requirements. This paper will provide background and rationale leading to the desired FTS telerobotic capabilities and then describe some of the specific technical requirements to which the FTS must be designed in order to meet these goals as well as operate effectively in the space environment.

1.0 Introduction

Robotic technology must make major advances beyond the current state of the art to even approach human capabilities in areas such as vision processing and task planning. In acknowledgment of these limitations, the FTS must be designed with sophisticated teleoperation capabilities to keep the human in the control loop whenever there is a requirement for tasks to be accomplished in an unstructured environment. However, it is also required that the initial FTS system have the capability to perform autonomously when the task environment can be sufficiently structured. The evolution of the FTS will allow autonomous operation in less and less structured environments.

2.0 Teleoperated Systems

Manipulator systems which employ teleoperation techniques have been developed by the nuclear industry for the repair and maintenance of nuclear reactors and by the undersea industry for offshore gas and oil rig assembly, repair and maintenance, as well as for undersea salvage operations. Teleoperation allows the operator to accomplish work at a relatively unknown or unstructured worksite in a hostile environment such as the sea floor or inside a nuclear reactor while he or she remains in a safe, shirt sleeve environment.

2.1 Hand Controllers

The primary feature of a teleoperated system is that a human operator is directly responsible for all motion of the manipulator or manipulators at the worksite. He or she is situated remote from the actual manipulator task operations at a workstation. The operator directs the motions of the "slave" manipulator(s) via some form of hand controller device. These devices have several configurations depending on the system.

Systems such as the Space Shuttle Remote Manipulator System (RMS) employ joystick type devices. This type of hand control device provides rate control of the manipulator in a cartesian coordinate frame. The RMS uses two of these devices to control its six degrees of freedom; one for X,Y, and Z and the other for roll pitch and yaw. More recently, rate control devices have been developed that allow the operator to control six degrees of freedom with one hand.

For smaller, more dextrous manipulator systems, hand control devices that provide position control instead of rate control are often preferred. A position control system provides positional correspondence between the hand controller and the slave manipulator. That is, the slave manipulator tracks the positional motions of the hand controller. This method of control is preferred for dextrous manipulation because it more closely simulates the natural hand-eye coordinated arm motions of the human operator.

There are two basic types of position hand controllers; the replica master and the so-called mini-master. The replica master is built to be a kinematic replica of the slave manipulator. There is, therefore, a joint for joint correspondence between the motions of the master and the slave. A major advantage of such a system is that no mathematical transformations are required between the master and the slave to determine motions. The primary disadvantage of this configuration is that the master hand controller must be equal in size to the slave manipulator. This may require a prohibitively large working volume at the workstation. The mini-master reverses this situation. It is not a kinematic replica of the slave and can be built considerably smaller than the slave. However, kinematic transformations between the master and the slave are required which adds a major computational load to the control of the system.

2.2 Manipulator Attributes

Manipulator systems designed explicitly for teleoperation are generally designed to minimize weight and inertia. They provide ample compliance at the manipulator end-point through backdrivability. These features are necessary to prevent damage if the operator inadvertently bumps objects in the workspace or requires compliance during assembly and disassembly operations. Such requirements usually result in a mechanically flexible manipulator design. This tends to preclude a feature generally required for autonomous robot systems. This feature, repeatability, is the capability to return to a prerecorded manipulator pose autonomously. In fact, the capability to record poses does not even exist in most teleoperation systems. Lack of repeatability is not a problem in a teleoperated system because the operator is always visually in the loop.

2.3 Operator Feedback

Visual information from the worksite is clearly the most important feedback to the operator when performing a teleoperation task. In some cases the operator can see the worksite directly but usually he or she works from monitors in the workstation connected to video cameras at the worksite.

A second, less important but critical, source of feedback information to the operator is force and torque. That is, the operator needs to know what forces and torques are being applied at the worksite. The most sophisticated method of supplying the operator with this information is a system called bilateral force reflection. This system allows the operator to feel the slave manipulator forces and torques in the hand controller. This capability greatly enhances the operator's ability to perform delicate and/or dextrous operations. Implementation of bilateral force reflection adds considerable complexity to the teleoperation system. The hand controller must have actuators with which to impart forces and torques to the operator. This means that the hand controller is actually a robot itself and must therefore have its own robot control system. The actual implementation of bilateral force reflection then becomes the cross coupling of the master and slave robot control systems into a single integrated control loop. Several such systems are in operation today in nuclear and undersea applications.

3.0 Robotic Systems

The manufacturing industry typically operates its manipulator systems autonomously. This is generally referred to as robotic operation. These systems must operate very rapidly and accurately in order for them to compete economically with the human labor force. This is accomplished by creating a highly structured worksite for the robotic system. This can be done fairly easily on a factory floor where equipment and work pieces can be accurately positioned and where conditions and access can be tightly controlled.

3.1 Manipulator Attributes

Manipulator systems designed for factory floor applications require good repeatability because all operations are pretaught and are performed repetitiously with no human intervention. However, human intervention is required when problems arise because the typical manufacturing robotic system has little or no sensing capability to detect anomolous conditions or to modify actions to adapt to changes in the work environment. Manufacturing robots are very massive and stiff in order to provide the needed repeatability. These manipulators also must move rapidly, and therefore, have large actuators which consume considerable amounts of power. The excessive weight and power of these manipulator systems does not generally pose a problem in the factory setting because the robots are fix mounted to the floor and are rarely transported. There is also ample power and cooling capability available on the factory floor. This is in contrast to the typical field operations of a teleoperated system where weight and power must be conserved.

3.2 Advanced Autonomous Control

There is extensive research currently underway investigating advanced autonomous control techniques for robotic systems. These techniques, as they are developed, will allow a robot to operate in environments with increasingly less imposed structure. The following capabilities are necessary for a robot to operate truly autonomously: (1) The robot must have a strategic plan. This is a high level plan of objectives, sequences of operations and recoveries in case of contingency. Such autonomous planning capabilities are of great interest to the artificial intelligence community. (2) At a lower planning level, the robot must have the ability to navigate in the workspace including manipulator path planning and collision avoidance. This will require extensive on-board geometric reference models, machine vision and image analysis capabilities with the capability to recognize objects in ambiguous lighting. (3) The robot must have the ability to relate observations to models to confirm that a scene is consistent with expectations. (4) Each action that the robot takes will require a success confirmation criteria and alternate sequences in case of failure.

4.0 Telerobotic Systems

A telerobotic system is a hybrid of a teleoperated and robotic system. The human operator is currently required to perform the advanced autonomous control activities discussed above such as image interpretation and planning. Current robotic systems are capable of performing tasks of lesser scope autonomously when such tasks can be well defined and reasonably well structured. A telerobotic system must be designed so that the operator can do what he does best and the robot can do what it does best. As the autonomous capabilities of the system increase,the human can retract into more supervisory roles. This is the approach that is being followed in the development of the FTS.

As discussed, existing teleoperated and autonomous systems were designed to quite different sets of requirements for quite different applications. The FTS system design must encompass the capabilities of these currently existing teleoperated and robotic systems. In addition, the FTS system design must bridge a substantial gap between these two types of systems. In order for the FTS system to be telerobotic and be capable of evolution toward more autonomous operations it must have the following attributes: (1) it must support sophisticated teleoperation including features such as bilateral force reflection, (2) it must have the mechanical and computational capabilities for autonomous control, (3) it must allow easy blending of teleoperated and autonomous modes, and (4) it must have designed-in capabilities for evolution. Of particular importance here is that the system have a well structured control architecture which encompasses future needs. To fulfill this last requirement the FTS has adopted the NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM) [1].

5.0 FTS Design Requirements

The following paragraphs highlight some of the specific design requirements that have been imposed on the development of the FTS to ensure that it has the telerobotic capabilities discussed above. [2]

5.1 Two, 7 Degree-of-Freedom Manipulator Arms

The FTS will have two, 7 degree-of-freedom, manipulator arms. Only six degrees of freedom are required to establish the position of the end effector in space. The seventh degree of freedom allows placement of the elbow as well as the end effector providing the capability to reach around obstacles in the workspace. The seventh degree of freedom also provides additional capability for smoother control through the avoidance of manipulator singularities. Each FTS manipulator arm will have a repeatability of 0.005 inch in position and +/-0.05 degree in orientation. The required repeatability will enable the FTS to be programmed to perform simple repetitive actions autonomously.

5.2 Teleoperation

The FTS will be capable of operating with and without bilateral force reflection. The FTS will also provide the capability for resolved rate control of the manipulators and the control of individual joints.

5.3 Shared Control

The FTS will be capable of shared control in which the operator control motion in one or more coordinate axes, and the telerobot autonomously controls the motion in the other axes. This will include active compliant control. (Active compliant control means that the compliance of the robot, when it contacts the environment, is controlled by sensing forces and torques and reacting to them in an active control loop. This removes the need for the robot to be mechanically compliant in its design as required by current teleoperated systems.)

5.4 Dual-arm Coordinated Control

The FTS will be capable of dual-arm coordinated control of a grasped object using a single hand controller. This is a "semi-autonomous" capability which controls both manipulator arms in a coordinated fashion so that the operator need only concern himself with the motion of the grasped object.

5.5 Supervised Autonomous Control

The FTS will be capable of supervised autonomous execution of selected operations, such as those that are required frequently. Any autonomous task activity will be functionally assumable in real-time by teleoperation. The FTS will provide the capability for smooth and coordinated transfer between teleoperated and autonomous modes as a routine operation.

5.6 Camera and Lighting System

The FTS will have a vision subsystem that will include at least four video cameras, one on or near the wrist of each manipulator and two positionable cameras for task specific worksite viewing. The vision subsystem will also include lighting of controllable intensity adequate for task viewing. The vision subsystem will provide the capability for the remote control of positioning, orientation, zoom, focus and aperture of each camera. The capabilities of the vision subsystem are intended to support teleoperation. However, the same system is intended to support machine vision as these capabilities are added to the FTS.

5.7 Workstation and Hand Controllers

The FTS workstation will provide the capability for one person to control and monitor the telerobot in all of its teleoperated and autonomous control modes. The workstation will contain video monitors connected to the vision subsystem which allow the operator to control the telerobot without direct viewing. The workstation will contain two independent hand controllers for simultaneous control of the two telerobot manipulator arms. The workstation will provide control methods for the vision subsystem such that the operator can control the cameras and lighting while his or her hands are both engaged in manipulator teleoperation.

The FTS handcontrollers will be configured to provide the operator with easy access to the full envelope of the manipulators' range of motion. They will accommodate position control of the manipulators with and without bilateral force reflection including operation of the end effectors. The hand controllers will also be configurable to accommodate rate control of the manipulators and operation of the end effectors.

5.8 Control Architecture, Computers and Software

There are three architectures associated with the control of the FTS system; the functional architecture, the software architecture and the computer architecture.

The functional architecture, NASREM, (see reference [1]) defines the functional elements and basic structure of the system. It defines interfaces for system modularization and provides structure for interleaving of teleoperation and autonomous control. The NASREM architecture provides common reference terminology for sub-elements of the FTS control system and will provide interface definition between these sub-elements. Therefore, integration of sub-elements from different organizations and vendors is possible. This will be particularly important to the future evolution of the FTS.

The software architecture supports the functional architecture. It defines input, processing and output of each functional module. The software architecture specifies execution timing and control interdependencies. It also specifies data structures and data flow.

The computer architecture supports the functional and software architectures. The processors and inter-processor communication capabilities must be configured to provide adequate computational speed and memory capacity. After all control requirements have been satisfied for the initial implementation of the FTS it is additionally required that there be 50% CPU capacity and 35% RAM margin for future software growth and evolution.

5.9 Safety Requirements

In the space environment safety is of utmost importance. All possible precautions must be taken to prevent the FTS from injuring an EVA astronaut or from damaging a mission critical element of the shuttle or the space station. Because of this, special requirements have been placed on the safing of the FTS in case of failure.

The FTS will have the capability to detect failures within its subsystems and operations and to automatically assume a safe state upon such detection. This capability will be two-fault tolerant which means that the detection and safing hardware and software itself must be capable of sustaining two internal failures and still performing the necessary actions.

6.0 Conclusions

The technology base for FTS development will come, primarily, from manipulator systems developed for nuclear and undersea applications and from robotic technology developed for the manufacturing environment.

A system which effectively combines both teleoperation and autonomous capabilities has never been built. Additionally, the FTS must have the designed-in capability to accommodate more advanced technology elements as they become available. To accomplish these goals, the FTS design must incorporate sophisticated sensor-driven control techniques into a well structured control architecture which supports good teleoperability as well as the necessary attributes which allow the system to be programmed for autonomous operations. No new basic technology elements need to be developed to enable the development of the FTS initial capabilities. However, the design, integration and operation of a telerobotic system of this complexity will represent an important advance in the state of the art in the field of robotics.

7.0 References

[1] J. Albus, H. McCain, and R. Lumia, "NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM)," SS-GSFC-0027, December 1986.

[2] "Flight Telerobotic Requirements Document for Phase C/D", SS-GSFC-0043, Attachment B.