Coordinated Control of a Dual-Arm Dexterous Robot Using Full Immersion Telepresence and Virtual Reality

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ABSTRACT

Telepresence is an approach to teleoperation that provides egocentric, intuitive interactions between an operator and a remote environment. This approach takes advantage of the natural cognitive and sensory-motor skills of an on-board crew and effectively transfers them to a slave robot. A dual-arm dexterous robot operating under telepresence control has been developed and initial evaluations of the system performing candidate EVA, IVA and planetary geological tasks were conducted. The results of our evaluation showed that telepresence control is very effective in transferring the operator's skills to the slave robot. However, the results also showed that, due to the kinematic and dynamicsinconsistencies between the operator and the robot, a limited amount of intelligent automation is also required to carry out some of the tasks. Therefore, several enhancements have been made to the original system to increase the automated capabilities of the control system without losing the benefits of telepresence.

KEYWORDS AND PHRASES

Anthropomorphic, dexterous robotics, human-factors, telepresence, virtual reality.

INTRODUCTION

The current baseline approaches to robot teleoperation in the Space Shuttle as well as on the International Space Station Alpha (ISSA) are based on "joystick" type hand controllers. The visual feedback is provided by multiple cameras, most of which are mounted on the robot arms and at the worksite. For demanding tasks that require a high degree of coordination, the "joystick" approach is inadequate, and may overload the visual and manual capacities of the operator. As a result, the operator's skill is not effectively transferred to the slave robot. A different approach to robot teleoperation is *telepresence*. In telepresence, the master control and feedback devices are designed to maximize the use of the operator's innate cognitive and sensory-motor skills [1][3].

This paper describes an evolving telerobotics testbed at the NASA Johnson Space Center (JSC) that utilizes virtual reality (VR) and telepresence as its baseline mode of operation.

The testbed consists of a master and a slave system. The slave system is a dual-arm dexterous robot called the Dexterous Anthropomorphic Robotic Testbed (DART). DART is controlled by the Full Immersion Telepresence Testbed (FITT), which is the master system of the overall testbed. FITT consists of several VR related input and output devices including a speech recognition system[3][4].

Besides describing the overall system, this paper will also discuss the results of our preliminary evaluations and the enhancements made to improve the capability of the original system.

OBJECTIVES

The main objective of the DART/FITT testbed is to develop and demonstrate technologies leading to a highly versatile and productive space telerobot. Specific objectives include: (1) develop a control scheme that permits the

human operator to easily coordinate complex robot motions in demanding space tasks; (2) improve versatility and productivity; (3) maintain compatibility with existing and future crew interfaces (e.g., handles, tools); and (4) build in the capability for the testbed system to evolve.

DESIGN APPROACHES

Due to the inability of today's autonomous robots to perform complex unplanned tasks in a non-stationary, unstructured environment, we chose teleoperation as the baseline mode of operation. In teleoperation, the human operator can provide the cognitive and sensory-motor skills necessary to carry out these tasks.

With teleoperation chosen as the baseline mode of operation, the challenge now becomes how teleoperation can be made more effective. To meet this challenge, we applied the telepresence and VR technologies.

To complement an ergonomic telepresence/VR interface, we designed the slave robot to take on a human-like configuration and dexterity, so that the master-to-slave mapping is more direct.

Finally, we developed an open control architecture for shared control and "plug-and-play" capability. Shared control can increase the robot's productivity through the use of automation without sacrificing the versatility offered by the human operator. The "plug-and-play" modularity of the architecture will

permit the robot to evolve by incorporating new automation capabilities as they emerge.

Following the above approaches, we developed the DART/FITT testbed system for laboratory evaluation (Figure 1). The following section describes the DART/FITT system in greater detail.

FITT

The FITT testbed, shown in Figure 2, is centered around a motorized chair and includes equipment for controlling DART's head camera unit, robotic arms and hands. The FITT also includes foot pedals that command direct drive motors on both the FITT base and the DART base, as well as initiate and terminate voice commands.

A VR helmet displays the remote stereo camera images with a 60 degree field of view and includes stereo head phones for audio feedback and a microphone for voice commands. The depth perception provided with stereo imaging is one of the testbed's most important immersion features. A magnetic tracker sensor located on the top of the helmet commands the orientation of the remote robot's camera head unit. The same sensors attached to each of the operators wrists provide x,y,z and roll, pitch, yaw controls for manipulator tool points. Glove controllers worn by the operator read the finger joint angles and use the information to control the robotic hands.

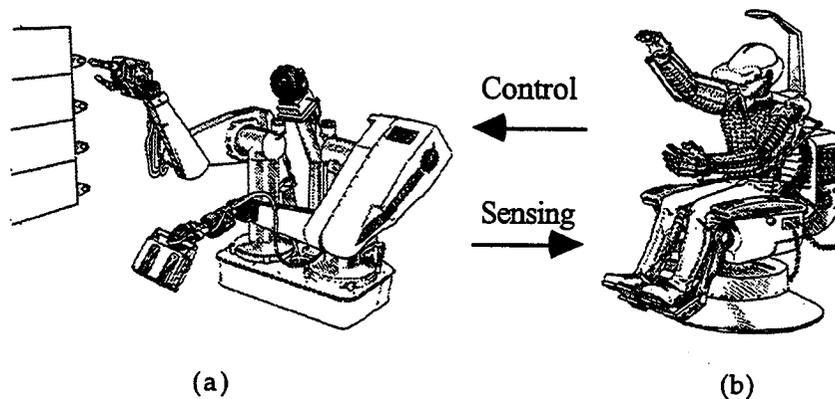(a)   (b)

Figure 1. Telepresence control of a dual-arm dexterous robot. (a) The Dexterous Anthropomorphic Robotic Testbed. (b) The Full Immersion Telepresence Testbed (concept drawing).

Since the operator's hands and eyes are virtually immersed in the robot's environment, and are not available for initiating keyboard commands, the voice recognition system provides a convenient means of blending automated commands with the baseline telepresence control. The operator simply presses a foot pedal, gives a verbal command, and then releases the pedal. This technique prevents the voice recognition system from picking up extraneous inputs. The command is also processed and played back to the operator over a voice synthesizer for confirmation. These voice commands vary in complexity from a simple repositioning of a robot arm relative to a human arm (to take advantage of the greater travel of the robot arm) to a more complex maneuver such as grappling onto a dial and turning it a preprogrammed number of times.

The software that communicates and controls the FITT systems is hosted on a UNIX/VME workstation and a 486 PC equipped with a voice recognition board. Data from the magnetic tracker sensors, the glove controllers, and foot pedals, is sampled at approximately 100 Hz and then sent out over Ethernet using the TeleRobotics Interconnect Protocol (TelRIP)[7].
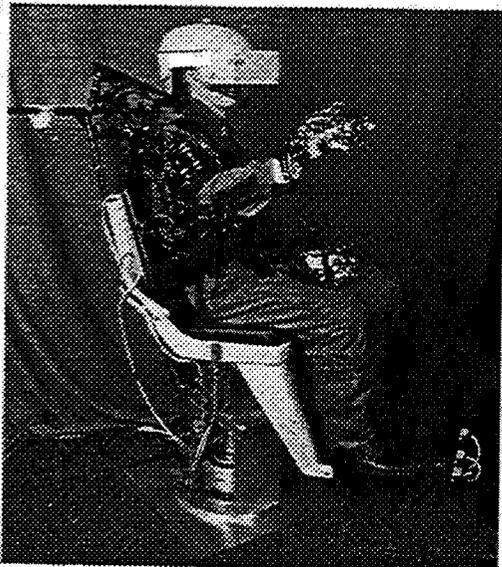

Figure 2. Full Immersion Telepresence Testbed.

TelRIP is a high-level, object-oriented communication package that makes the low level socket interfaces transparent to the programmer. For example, the voice recognition system samples data at a natural speaking speed and sends out TelRIP objects

that initiate a prescribed semi-automated or automated action. A remote robot such as DART can set up its client communications program to receive any or all of the commands from FITT by registering "interest" in the appropriate TelRIP objects.

The force-reflective Exoskeleton Arm Master (EAM), worn by the operator in Figure 2, is not currently integrated with the FITT system. Nevertheless, we expect that the operator will be able to perform more complex tasks with an increased level of performance once the EAM is integrated with the FITT system.

DART

DART, shown in Figure 3, includes several robotic devices, controllers, and supporting workstations. The robotic arms are PUMA 562's each with an 8.8 pound payload capability. Each arm also has a force-torque sensor. On the right arm is a Stanford/JPL hand. Each finger has a urethane fingertip to provide a high static friction surface and can be hyper-extended to provide a large manipulation envelope. On the left arm is a parallel jaw gripper. The head camera unit that provides video feedback to the teleoperator supports 3 axes of rotations and contains two color CCD cameras. The driver level software is executed on two Tadpole™ multiprocessor systems. Each multiprocessor system has four M88000 processors and runs a multiprocessor version of the UNIX operating system. The vision system is implemented on a DataCube™ pipeline image processor board.
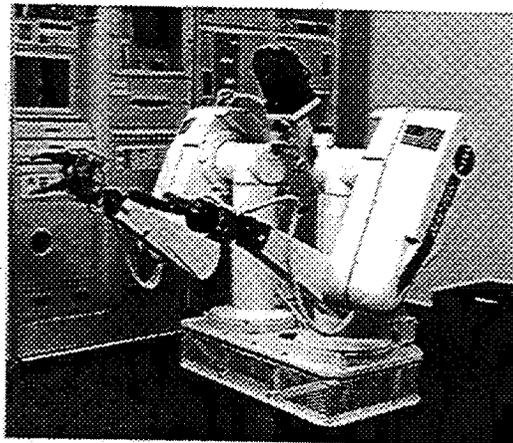

Figure 3. The Dexterous Anthropomorphic Robotic Testbed (DART).

CONTROL ARCHITECTURE

DART and FITT each has a distributed control architecture. Each subsystem spans one or more processes. The subsystem processes are distributed across several different computers, networked on an Ethernet backbone. Figure 4 shows how the DART and FITT systems are networked. Computers to the left of the SPARC-10 are part of the DART testbed; computers to the right of the SPARC-10 are part of the FITT testbed. The SPARC-10 itself serves as a message router and hosts the speech synthesis software.

The software architecture is shown in Figure 5. The subsystem processes communicate and are synchronized by TelRIP. This architecture provides a flexible environment for development, maintenance, and future enhancements. FITT controls DART by linking to this Ethernet backbone and commanding the subsystems through TelRIP. The router process, denoted by R, is responsible for transmitting data to the appropriate subsystem processes.

PRELIMINARY EVALUATIONS

Preliminary evaluations of the DART/FITT system were conducted using operators of varying skill levels, ranging from several years of robotic experience to absolutely no engineering experience. This allows the intuitiveness of operation to be qualitatively evaluated. The tasks ranged from inspection to object handling to dexterous manipulation.

Inspection tasks were comprised mainly of bringing an object towards the head camera and viewing it from different angles. These tasks provide information about the required display resolution, stereo perception, as well as the effect of working with *egocentric* views of the workspace. The object handling tasks include picking up objects of various sizes and shapes (*e.g.*, balls, pipes, tools) and placing them at a different location, and handing objects back and forth between the dexterous hand and the gripper. Some of the dual-hand dexterous tasks performed were tying a knot with a rope, folding and unfolding a thermal blanket, and manipulating an electronic task panel which contains toggle and rocker switches, push buttons, sliders, and a dial. These tasks reflect some of the basic dexterity and skills required for on-orbit extra- and intra-vehicular activities (EVA/IVA).

To further evaluate the DART/FITT system as a "planetary geologist", we put the system through a battary of tasks including holding up a light source while the operator examined a rock sample, picking up a rock sample and placing it into a bag or container, chipping a boulder with a hammer, picking up rock samples with an extended tong, and placing a gnomen next to a rock sample as a scale and color reference.
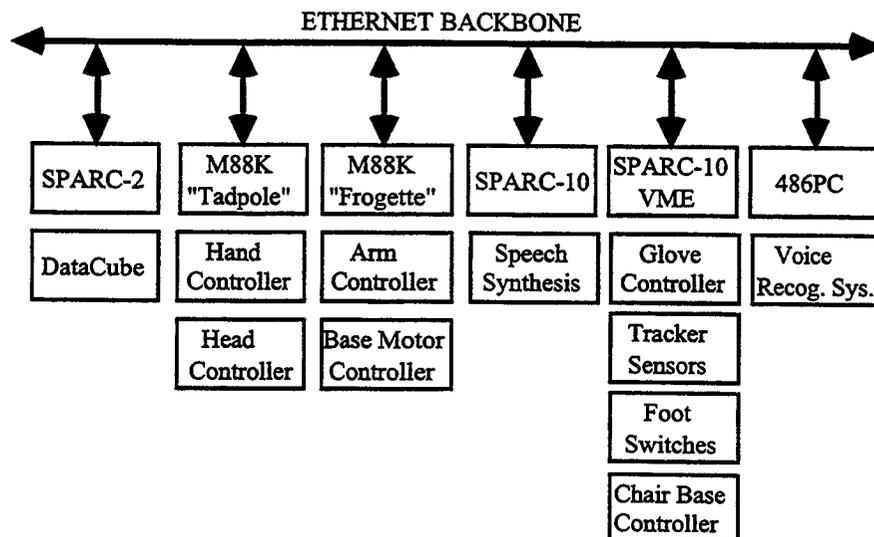

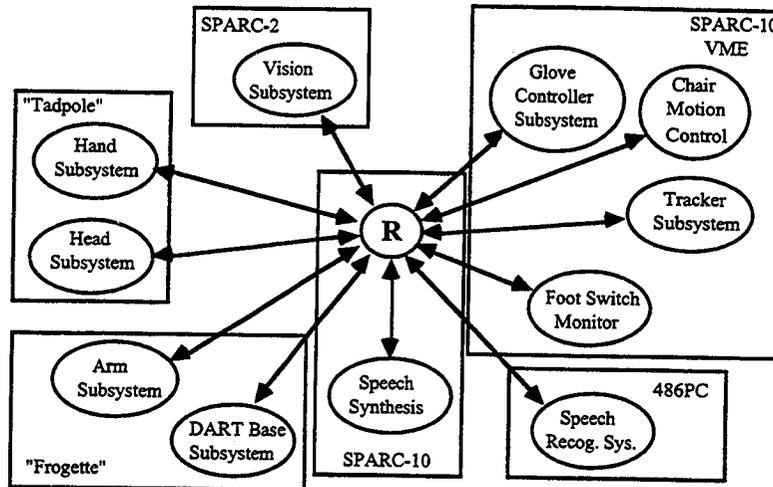Figure 4. The DART/FITT computer configuration.

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Figure 5. The distributed control architecture of DART/FITT.

OBSERVATIONS

One of the most significant observations from the preliminary evaluations is the short time it takes a new operator to become proficient with the system. For example, operators with no previous experience were able to transfer objects between the two hands and manipulate the controls on the panel within a 30 minute session. Operators with considerable experience in "cock-pit" type control have also found the training time greatly reduced due to the intuitiveness of the motion controls and the immersiveness of the visual feedback.

We have also identified several areas needing improvements. The weight of the exoskeleton glove controller caused muscle fatigue when it was necessary to maintain a specific position for a long period of time. This observation suggests the need for a mechanism that will allow the operator to re-adjust his or her arm positions (e.g., indexing), and to use light-weight glove controllers.

While teleoperation of the dexterous hand offers much flexibility for grasping, it was found inadequate for manipulation. The difficulty lies in the kinematics dissimilarity between the robot's and the operator's hands.

The operator can also experience mild motion sickness when using the system due to a slight delay between the motions of the operator's head and the DART camera system. This only occurs when the operator makes large, quick head movements. Motion sickness usually occurs whenever there is a significant mismatch between the robot's and the operator's rate of motion. Motion sickness can also be caused by unintended body and head movements. However, since the operator rarely has to make large head movements once focused on a task, this problem is not a major prohibiting factor.

Although the current system provides the necessary visual cues to perform many tasks, a few limitations of the visual feedback have been observed. The visual feedback the operator receives is coarse (495 X 240 pixels) and the distance between the head cameras is a little too narrow, so the depth perception of the operator is not optimal. These visual limitations can have serious impacts on the operator's performance. For example, since FITT currently does not offer force-reflection, the operator assesses the force imparted onto the environment by watching for the amount of physical compliance. The active compliance of the DART's fingers is very useful in this regard.

Another problematic area encountered is the transformation of human hand motions to DART's hand motions. Several transformation methods were explored[6]. These methods included joint-to-joint mapping, forward and inverse kinematics transformations, and a combination of joint and Cartesian control. The two major difficulties encountered when applying these techniques are the dissimilar

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kinematics of the human's and DART's hands, and the slight changes in the sensor positions when the gloves are taken off and put back on. Joint-to-joint mapping was chosen as the method of control due to the computational simplicity and the intuitiveness of the control.

The telepresence evaluations also revealed some interesting operator behaviors. For example, an initial exercise is desirable before each session to familiarize the operator with the system's behavior. The exercise typically involves having the operator command the robot's arms, hands and head in various different ways to explore the dexterity of the robot. Without the exercise, less experienced operators often have the tendency to move like a robot, not fully utilizing his or her natural coordination skill. After a few training sessions, the operator generally will learn to compensate for any kinematics dissimiliarities between the operator and the robot.

Perhaps the most interesting observation was that the operator's dependency on the visual feedback decreases as a function of the amount of training time. This is most evident when the operator flipped on/off an electrical switch without actually seeing the fingertip making contact with the switch. This observation can probably be explained by the circular learning theory introduced by Piaget[5], and Held and Hein[2].

Even with the observed limitations, the original DART/FITT system was able to complete all of the assigned tasks in a reasonable amount of time.

SYSTEM MODIFICATIONS

After our initial evaluations of the DART/FITT system, we began to focus on how to overcome the limitations of telepresence without losing its benefits. As DART/FITT evolves, several features have been added to maximize the system's usefulness. These features are discussed below.

To expand the robot's capabilities beyond those of the operator's arms and hands, several features have been added. First, different voice-invoked hand grasp primitives (e.g. pinch, cylindrical, hook, etc.) were made available to the operator to compensate for the kinematic dissimilarities between the human

hand and the robot hand. We have also replaced the exoskeleton glove controllers with the light weight CyberGloves™ to reduce fatigue.

Similarly, a "freeze" voice command was added to the system to enable and disable the tracking between robot and operator, allowing the operator to rest her arms. A "re-index" voice command was also added to allow the operator to control the robot in a more comfortable position. The "re-index" command also allows the operator to fully utilize the joint and reach capabilities of the robotic arms.

In a shared control scheme where the operator and the automated control primitives both have access to the robot, a method must be provided to coordinate their interactions. In the case of FITT, a speech recognition system was selected as a "hands-free" method for the operator to communicate to the robot. The operator issues commands through a microphone located on the FITT helmet. For example, the operator would say "spherical grasp" to change the configuration of the hand, or "freeze left arm" to disable tracking between the operator's left arm and the robot's left arm.

To expand viewing capabilities, a wrist camera was added to DART's right arm. The operator can switch from the "head view" to the "wrist view" for aligning the hands when grasping visually obstructed objects. Also an advanced pipeline-based vision system is being created to perform shape recognition, target location, and closed-loop visual servoing of robotic arms for grasping.

The mild motion sickness experienced by the operator when DART was rotating has been relieved by having the operator platform (a motorized chair) rotate along with the DART base. The acceleration and deceleration cues provide the operator with sufficient kinesthetic feedback to prevent disorientation.

FUTURE WORK

The early evaluations have demonstrated the versatility of the DART/FITT system and confirmed the feasibility of our approach. However, to further improve the system's productivity, the intelligent automation aspects of the system must be expanded. For example, the hand will be able to manipulate

latches and handles on space hardware, as well as flexible objects such as plastic sample bags through automated sequences. Automated arm modes will be incorporated for tasks such as using a hammer to chip a rock for planetary exploration.

Several arm upgrades are planned. A control system with coordinated motion between the two arms and hands will be added to the system for use with dual arm grasps. An additional capability, scaling, where the ratio of the amount the robot moves to the amount the operator moves can be changed, will be added to the system in order to make fine motion control of the arms easier.

The advanced vision system will be enhanced to provide basic perception of the environment needed for automated manipulation and grasping. Such capability will be especially important for planetary applications since the communication delay between the operator and robot may be large.

A second generation head camera unit will be fabricated to provide tighter head tracking and to correct the narrow interpupilary distance. A high-resolution (640 X 480 pixels) head-mounted displays will be sought to improve the operator's visual acuity.

The force-reflective dexterous arm master, (Figure 2) will be integrated with FITT to evaluate the effects of force-reflection. Additional evaluations will be conducted to quantify the performance of the DART/FITT system. New test subjects will be recruited to study the correlation between training-time versus performance, and the performance of "cock-pit" type control versus telepresence.

Virtual reality simulation of the robot will be developed and over-laid into the VR helmet as a predictive display. Virtual instrument displays such as bar graphs and meters will be used to assist the operator in various tasks.

CONCLUSIONS

Telepresence is *not* a new idea. It is, however, an idea that is becoming a reality due to the recent advances in head-mounted displays, dexterous glove controllers, motion trackers, force-reflective masters, and other human compatible interactive devices. The DART and FITT combination represents an integration of these telepresence and VR technologies for space robotics applications. While further evaluations will be necessary to completely characterize the system, we believe all of our stated objectives have been met. Many lessons were learned in our preliminary evaluations and several areas for improvement were identified. Our future work will address these areas. However, the benefit of telepresence and VR in space robotics is clearly evident by the variety of complex tasks DART/FITT can perform under the control of an operator.

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