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MANIPULATORS IN TELEOPERATION

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Background

Teleoperators are machines which effectively project man's innate mental and physical capabilities across distance and physical barriers.[1] Various remotely operated systems used in nuclear applications are correctly viewed as teleoperators. Remote maintenance systems, which usually have rather sophisticated handling capabilities, are the most complex remotely operated systems in use today. Figure 1 depicts the basic elements or subsystems generally included in remote maintenance systems. The subsystems shown serve the following basic functions necessary to accomplish the overall operation: (1) operator interfacing, (2) signal and power transmission into the remote environment, (3) mobilization, (4) manipulation, and (5) remote sensing and viewing. The individual characteristics of these subsystems and their integration determine the effectiveness of the overall teleoperated maintenance system.

Development History

The manipulation function involves the greatest technical complexity and serves the role of transferring into the remote environment the human operator's ability to handle objects (e.g., tools, components, materials). The fidelity of this transfer process is a dominant factor in the overall efficiency of the teleoperated system and is directly related to the dexterity and controllability of the manipulator subsystem. This paper discusses the issues, traditions, and experiences, associated with the development of teleoperated manipulators for remote systems.

The history of manipulator developments is summarized in Figure 2. Two basic types of manipulators have been developed. Unilateral manipulators are single-sided in the sense that the force interaction in the remote environment (which the slave manipulator experiences) is not transferred to the operator's environment. Bilateral manipulators are two-sided in that active manipulators (master and slave) are interconnected so that the operator receives force-interaction feedback from the remote environment. Mechanical master/slave manipulators and electronic servomanipulators provide force reflection, while unilateral electromechanical manipulators do not. Typical industrial robot manipulators are essentially unilateral designs.

The bulk of manipulator research and development has been funded through government-sponsored nuclear work. The foundation of manipulator technology was laid by the Remote Systems Division research staff at Argonne National Laboratory from around 1940 through the early 1960s. In the past five years, many new development programs have begun as today's microelectronics and materials technologies are applied to manipulators. The Central Research Laboratories' Model M2 manipulator[2] (shown in Figure 3) marks the first extensive use of distributed digital control in bilateral master/slave manipulators. The Hitachi SM and the BILARM 83A and Prototype-I hybrid manipulators by Meidensha Electric Company (see Figures 4, 5, and 6) reveal the Japanese approaches. The most famous teleoperated manipulator is the NASA Space Shuttle Remote Manipulator System (RMS). The RMS (shown in Figures 7 and 8) was developed by the SPAR Corp. of Canada to provide large reach in a zero-gravity environment. The RM-10 system (Figure 9) recently introduced by Remote Technology Corporation is a master/slave-operated unilateral manipulator with slave manipulator modularization and a somewhat operating speed. The advanced servomanipulator[3] being developed in the DOE Consolidated Fuel Reprocessing Program at ORNL is the first attempt at the development of a remotely maintainable bilateral servomanipulator. Figures 10 through n show other manipulator systems that are represented on Figure 2. Each of these systems has played an important role in the stepwise development of the technology.

Issues and Predictions

The examples shown in the previous section are an indication of the many different types of teleoperated manipulators which have been developed. The differences between these manipulators reflect differing basic philosophies and the results of design tradeoffs. There is a direct relationship between a manipulator's design characteristics and the tasks it can perform. Generally, the range of admissible tasks for a manipulator increases with its inherent dexterity and sophistication. Also, overall teleoperator work efficiency, tooling, and application (work environment) design constraints correspond to dexterity. In other words, the better a manipulator reproduces human dexterity, the more likely that the operator will be able to use the manipulator to do the full range of tasks he can do directly with his hands. The manipulator development environment is regulated, however, by the competition between complexity, cost, and reliability. Manipulator complexity and cost are roughly proportional to dexterity. Reliability is a function of not only complexity but also technology. The author believes that the wide range of current manipulator concepts are a reflection of the weighting factors given these tradeoff issues by different organizations in the context of their specific problems and goals. These matters of basic remote control philosophy may very likely converge as the cost and risk of dexterity decreases through new technology.

The ingredients for high-dexterity teleoperation are at the doorstep. Experimental results[4] have shown that bilateral servomanipulators and CCTV viewing can function with efficiency and task range of mechanical master/slave manipulators (MSMs). Preliminary work[5,6] shows that the digital controllers of modern servomanipulators can be used to implement new forms of robotic slave manipulator operation that will further increase remote work efficiency. Failure mode characteristics and fault tolerance of these complex microprocessor-based systems remain as key issues.

For the future, we expect that extensive research and advances in basic systems and slave manipulator design issues will influence cost and performance. The ergonomics of human teleoperation are complex, to say the least. Human factors engineering will continue to influence operator station design dramatically through computer graphics display and voice input/output technologies along the lines of the ORNL system[7] shown in Figure N+1. Human-machine interface design issues will interact with manipulator design, particularly as nonkinematic replica master controllers (which are physically less obtrusive) are developed. Automation and manual control will merge to form the concept of a telerobot. The telerobot will provide selectable robotic operation that will permit the operator to further optimize overall system productivity while retaining the opportunity for effective human-based control for unexpected and difficult tasks. Faster and larger digital computer architecture will facilitate control algorithm improvements and more complex sensory feedback. Force/torque transducers will be used to augment or replace standard bilateral servomechanism force-reflection techniques.

Advancements in slave manipulator systems for harsh remote environments will be the focus of wider applications and improvements. Manipulator performance and modularization to permit manipulators to be used for remote repair of other manipulators will be developed along the lines of the ORNL ASM.[8] Mobile system applications, both in the nuclear industry and in the military, require weight minimization; this will motivate improvement in manipulator load capacity/weight ratios. The lowest ratio achieved to date in a bilateral system has been the TeleOperator Systems SM-229 (1:4). Since the bulk of a manipulator's weight is made up of its motors, gears, and bearings, advancements in electric actuator power density and drive train concepts will be needed. The simplistic six-degree-of-freedom kinematic configurations of (most of) today's manipulator will be replaced with more flexible redundant joint designs (Figure N+2) that will be able to work more human-like in complex and cluttered environments (e.g., reach around piping obstructions). Such concepts are the subject of current research around the world and pose very difficult control system and sensor augmentation problems.

Currently, advanced manipulators for teleoperation are produced essentially on a single-unit basis with labor-intensive practices. Future developments should concentrate on design concepts that will reduce fabrication and assembly costs through increased use of computer-numerically-controlled (CNC) machining and other labor-reducing ideas. Projected replications costs must be reduced before wider applications can be expected.

Summary

Teleoperated manipulators represent a mature technology which has evolved over nearly 40 years of applications experience. The wide range of manipulator concepts developed thus far reflect differing applications, priorities, and philosophies. The technology of teleoperated manipulators is in a rapid state of change (just as are industrial robotics) fueled by microelectronics and materials advances. Large strides in performance and dexterity are now practical and advantageous. Even though improved controls and sensory feedback will increase functionality, overall costs should be reduced as manipulator fabrication and assembly labor costs are reduced through improved manufacturing technology. As these advances begin to materialize, broader applications in nonnuclear areas should occur.