Progress Report

Project Title: Remote Manipulation for D&D Exhibiting Teleautonomy and Telecollaboration
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Lead Principal Investigators: Thomas F. Ewing, J. Edward Colgate
Co-Investigator : Young S. Park, Michael A. Peshkin
Graduate Students: Eric L. Faulring, Brian DeJong

1. Research Objective: The purpose of the work is to enhance remote operations of robotic systems for D&D tasks by extending teleoperation with semi-autonomous functions. The work leverages the $1.2M dual-arm work platform (DAWP) developed with broad participation for the CP5 D&D, as well as 2,000 hr DAWP D&D operational experience. We propose to develop a reactive, agent-based control architecture well suited to unstructured and unpredictable environments, and *cobot* control technology, which implements a virtual fixture that can be used to guide the application of tools with force-feedback control. Developed methodologies will be implemented using a structured light sensor and cobot hand controller on the dual-arm system.

2. Research Progress and Implications: This report summarizes work of the third year of a three year project. The third year's R&D effort focused on the integration of component technologies to demonstrate two approaches in enhanced teleoperation, namely 'teleautonomy' and 'telecollaboration'. In teleautonomy, the robot executes task motions autonomously while the human operator intervenes the process as supervisor – sort of a 'cruise controlled' operation. In telecollaboration, the operator's motion is passively constrained to a virtual fixture, but the operator feels and controls the progress of what is happening at the same time. The work was conducted as a joint research of Argonne National Laboratory and Northwestern University, and the following progresses were made.

Teleautonomy

The progress in teleautonomy part of this research has been focused in the development of perceptual basis and motor behaviors.

<u>Complete prototype development of sensor module</u>: The perceptual basis of the reactive control system is built upon structured light system and proximity sensor array. A structured light system consists of a camera and laser patterned beam projector. By projecting a known beam pattern onto an object and analyzing the position and distortion of its image in the camera's view, the s-D pose of the objective can be estimated with relatively simple computation. Also, in order to support various perceptual mechanisms and strategies, multiple sensors may be utilized, for which an external calibration method is developed. Since structured light is not effective in close range, an array of proximity sensor is implemented at the end of

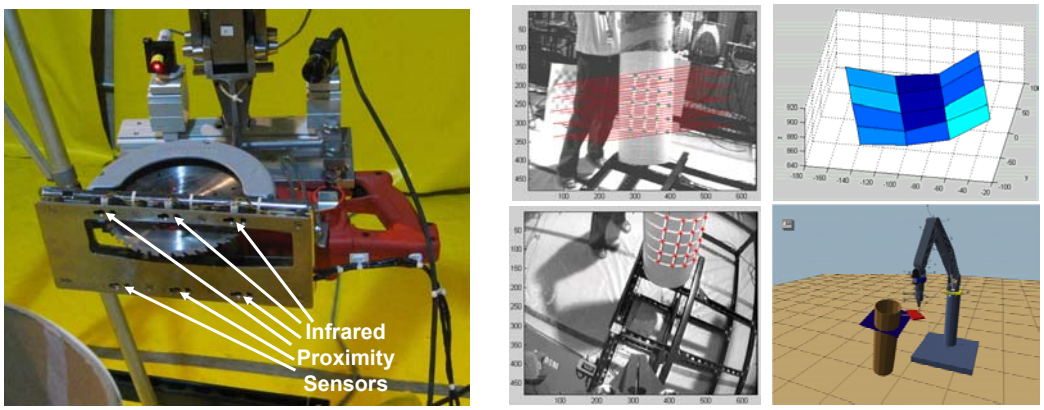
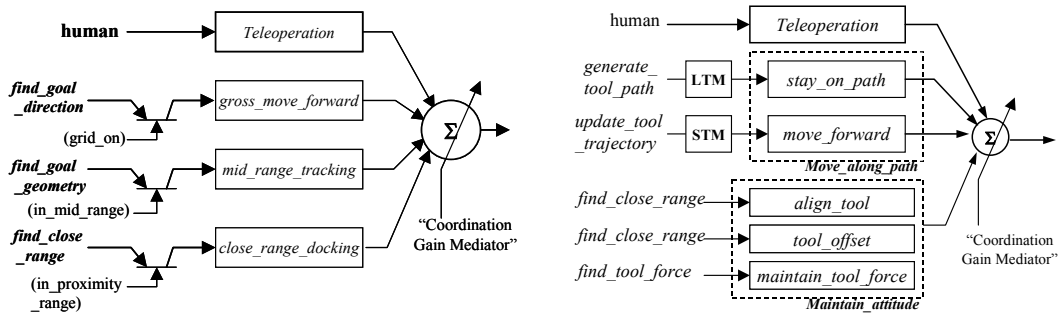


Figure 1. Sensory Module

tool plate. To provide efficient perception targeted for motor agents, various perception behaviors are implemented.

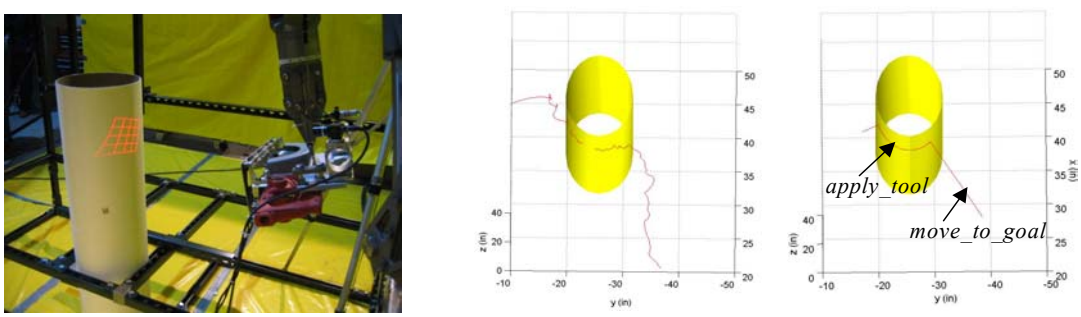
Demonstration of motor behaviors: A robot performing D&D operation may be represented by a few large grain motor behaviors, such as *teleoperation*, *move_to_goal*, *apply_tool*, and *inspection*. *Move_to_goal* behavior moves the tool to a goal location with proper alignment at the end. As depicted in Figure 2(a), it is constituted by sequencing the actions of the three motor agents: *gross_move_forward*, *mid_range_tracking*, and *close_range_docking*. *Apply_tool* behavior commences the actions of actually applying tools on the workpiece. As can be seen in Figure 2(b), the tooling behavior consists of moving the tool along a specified tool path (move_along_path), while maintaining tool angle and depth (maintain_attitude).



(a) move_to_goal (b) apply_tool

Figure 2. Motor behaviors of teleautonomy

The motor behaviors are demonstrated using a telerobotic system consisting of a Schilling Titan 7F hydraulic manipulator. Figure 3 shows the manipulation of a circular saw that cuts around a circular pipe – a structure commonly encountered during D&D. Compared to manual teleoperation, much more efficient and precise cutting operation was made possible with teleautonomy.



(a) Manual teleoperation (b) Teleautonomous operation

Figure 3. Demonstration of teleautonomy

Telecollaboration

Our progress on the telecollaboration part of this research has been focused in four areas:

- Implementation of the Hand Controller Cobot
- Study of spatial transformations with implications for graphical display set-up
- Visually augmented teleoperator interface
- Creation of a testbed for teleoperation and demonstration of teleoperation (including telecollaboration) between Northwestern University and Argonne National Labs.

Hand Controller Cobot: The design, construction and implementation of the Hand Controller Cobot, a six-degree-of-freedom haptic master, into the teleoperation test-bed at Argonne National Laboratory is

complete. A graphical user interface was developed on the Windows architecture, whereby a modestly proficient user could setup constraint surfaces for the slave tooling to follow. These surfaces can be derived from sensor data, or developed manually. The resulting virtual constraint surfaces are utilized at the slave and felt at the master. The crispness of the constraints at the master is much improved over other existing haptic displays. Constraints feel very hard, while motion is not impeded at all along the constraint surfaces.

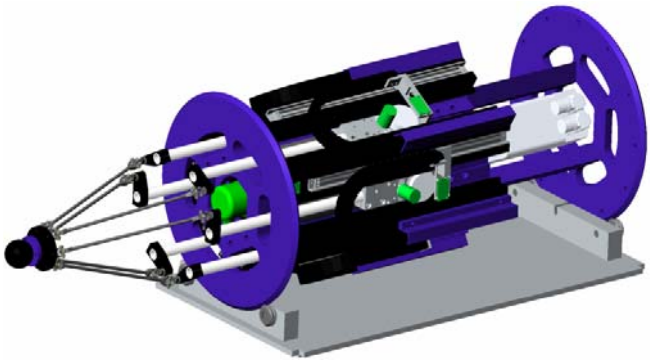


Fig.5. 6 degree-of-freedom cobot developed for teleoperation research

Spatial Transformations: When performing teleoperation, an operator must establish coordination between his or her hand motions (applied to the hand controller) and the resulting motions of the slave as viewed on one or more monitors. This type of coordination can be difficult with even a single display, but exceedingly demanding when using multiple displays, especially if there is a different transformation from hand motion to observed slave motion for each display (see figure below). These types of spatial transformations were studied in detail, and a means of arranging displays in order to minimize "mental gymnastics" was conceived. As set of experiments confirmed that this type of interface design led to greatly improved teleoperation performance.

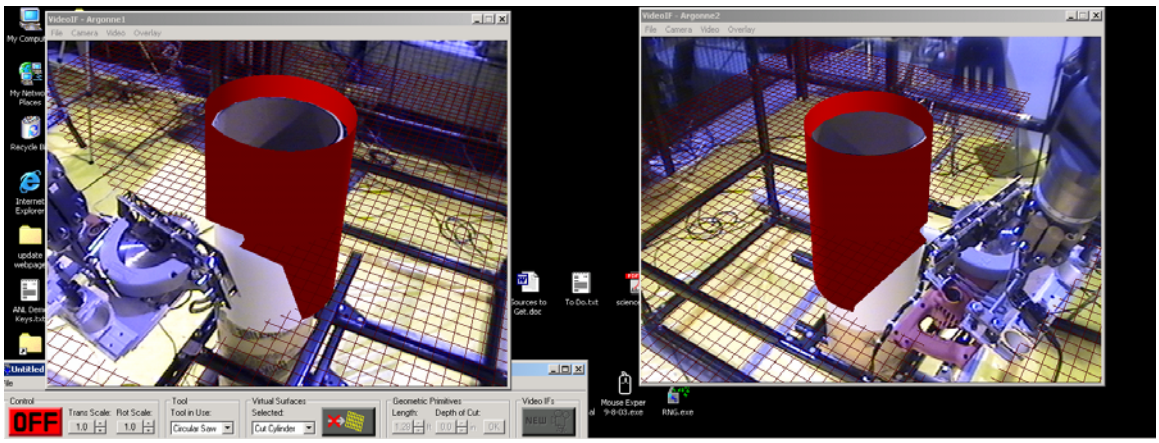
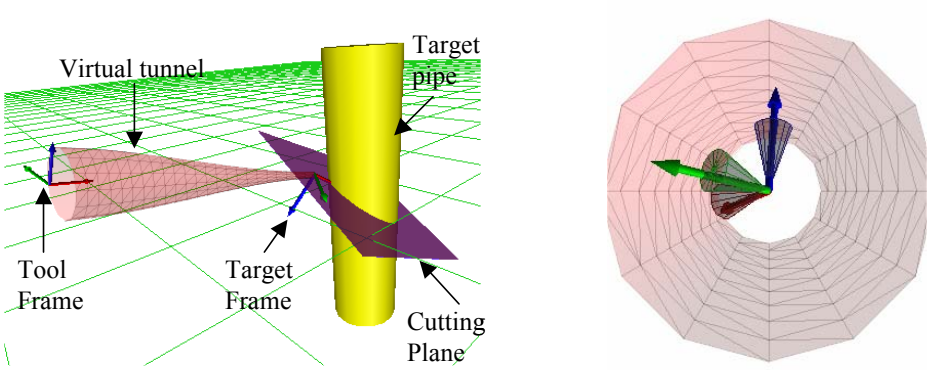


Fig. 5. Different views of the pipe-cutting task. The operator must maintain hand-eye coordination when switching from one view to the next. Our research provides guidelines for setting up displays such that operators naturally maintain coordination.

Visually augmented teleoperator interface:

Virtual fixtures displayed either haptically or visually may enhance teleoperation performance. An effort is directed toward implementation of visual display of virtual fixture. To guide tool motion, a virtual funnel is devised to assist the operator with translational guidance to the target position. As approaching the target, the virtual funnel shrinks so that the operator can easily guide the position of the tool as shown in figure 6. In addition, virtual alignment cones are devised to assist the orientational alignment. Such visaul guidance

may effectively be overlaid on video display, such as stereo visual display as shown in the figure. The experimental operation reveals that even though the operator waggled, he was able to approach the target position effectively. Also shown in the figure is a operation assisted with haptically displayed virtual fixture implemented with handcontroller cobot. Synergistic effect is expected by combining both visual and haptical display of virtual fixtures.



(a) Virtual Funnel (b) Orientational alignment cone

Figure 6. Visual display of virtual fixture

Teleoperation Testbed : A teleoperation testbed has been created including an ANL robot, an ANL structured light sensing system, a NU cobotic hand controller, and a NU user interface with graphical overlays. This testbed has been implemented over the internet such that the robot and sensors are at ANL and the hand controller and interface are located some 40 miles away at NU. This testbed has been used to demonstrate the set up and implementation of virtual surfaces for telecollaboration. The virtual surfaces are presented haptically via the cobotic hand controller and visually via the augmented reality on live video. The addition of haptic and visual virtual surfaces greatly improves operator performance, resulting in faster completion time and essentially no position error.

3. Planned Activities:

- Development of meta behaviors combining virtual fixture and motot behaviors (August, 2004)
- Prepare final Report (September, 2004)

4. Information Access:

http://www.td.anl.gov/Programs/ti/robots/index.html
http://www.mech.northwestern.edu/dept/research/lims.html

Publications

Brian P. DeJong, J. Edward Colgate, and Michael A. Peshkin. "Improving Teleoperation: Reducing Mental Rotations and Translations," *American Nuclear Society 10th International Conference on Robotics and Remote Systems for Hazardous Environments*, Gainesville, Florida, March 2004

Brian P. DeJong, J. Edward Colgate, and Michael A. Peshkin. "Improving Teleoperation: Reducing Mental Rotations and Translations," *Proc. of IEEE International Conference on Robotics and Automation*, New Orleans, April 2004.

Faulring, E.F., Colgate, J.E., Peshkin, M.A. "A High Performance 6-DOF Haptic Cobot." In Proceedings of IEEE International Conference on Robotics and Automation, 2004. *Best Student Paper Award*

Park, Y., Kang, H., Faulring, E.F. Colgate, J.E., Peshkin, M.A. "Enhanced Teleoperation for D&D." In Proceedings of IEEE International Conference on Robotics and Automation, 2004.

Park, Y., Kang, H., Ewing, T.F., Faulring, E.F. Colgate, J.E., Peshkin, M.A. "Semi-automatic Teleoperation for D&D." In Proceedings of American Nuclear Society Conference, 2004.