Semi-automatic Teleoperation for D&D

Young S. Park, Hyosig Kang, Thomas F. Ewing

Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439, ypark@anl.gov

J. Edward Colgate, Michael A. Peshkin, Eric L. Faulring

Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208-3111, colgate@northwestern.edu

Abstract – *For deactivation and decommissioning (D&D) of contaminated structures in the weapons complex, remotely operated robotic systems are expected to replace human workers from hazardous radiation and difficult work environments, while improving productivity and reducing costs. Nevertheless, the major drawback of currently available remote operation technology is that teleoperation is a slow and imprecise process, mainly due to the difficulty of transferring perception and manipulation over a remote location. To this end, this work presents a semi-automatic teleoperation system that facilitates efficient and precise teleoperation. Building upon behavior based robotic architecture and a proprietary Cobotic hand controller, two types of enhanced teleoperation - tele-autonomy and tele-collaboration – are implemented.*

I. INTRODUCTION

For decontamination and dismantling (D&D) of highly contaminated and difficult-to-access facilities in DOE nuclear and weapons complex, robotic systems are expected to replace human workers from hazardous tasks. Due to the unstructured and unpredictable nature of the task environment, teleoperation is widely adopted as a practical alternative to the automated or autonomous robots. However, teleoperation, which relies heavily on perception-action capability of human operator, is an extremely slow and imprecise process, as evidenced by a previous experiences of deploying the teleoperated Dual-Arm Work Platform (DAWP) system for dismantling a research reactor, CP-5, at Argonne National Laboratory. Furthermore, the complex robotic systems require substantial set-up time and are subject to frequent breakdowns. These factors have been the major barrier to wide deployments. What is needed is the implementation of a new semi-automatic telerobotic system, whose operation combines automation and teleoperation in a simple and flexible manner.

Robotic control can be approached based on either deliberative reasoning or reactive behaviors. The conventional deliberative control system, characterized by hierarchical structure and well-defined flow of information flow from sensing to action, is capable of predicting the outcome of its action and optimizing its performance, given a precise description of world. However, it lacks the flexibility to cope with the unpredictable and unstructured world. Also, complete system hierarchy has to be engineered before testing can be performed, and the substantial complexity of the control system may become hindrance to deployment. On the other hand, reactive control is a technique in which perception and action are tightly coupled through multiple, distributed agents, typically in the context of motor behaviors, to produce timely robotic response in dynamic and unstructured worlds. It also has advantage that less than entire system is required to be built before testing is feasible.

Taking such advantages of reactive system, this paper introduces implementation of semi-automatic telerobotic system based on a behavior-based robotic architecture, and demonstrates effectiveness of its use for D&D tasks in partially structured environment. Specifically, two types of enhancements are explored: tele-autonomy and tele-collaboration. In tele-autonomy, the robot executes motion autonomously while human operator intervenes the process as supervisor – sort of a ‘cruise controlled’ operation. In tele-collaboration, 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.

II. BEHAVIOR-BASED ROBOTIC ARCHITECTURE

In this paper, robotic architecture refers to software architecture, rather than the hardware side of the system. The presented semi-automatic telerobotic system was implemented based on a behavior-based robotic architecture similar to the one introduced by Arkin [1]. Here, motor agent is the basic unit of behavior from which complex actions can be constructed, as depicted in

Fig 1. A motor agent consists of the knowledge of how to act or perceive as well as the computational process by which it is encoded. Each motor behavior is encoded as continuous function that relates stimulus input to a vector representing the strength and direction of motion. With such an encoding method, it is straightforward to translate the output, through potential field method, to classical manipulation problems such as path planning, obstacle avoidance. The resultant behavior of a complex behavior emerges from multiple individual behavioral responses through behavioral coordination. No hierarchy exists for coordination; instead behaviors are configured at run-time as vector addition of multiple behaviors, which are instantiated at any time based on perceptual events. Due to the distributed and independent nature fo the architecture, it is simple to implement new behaviors and reconfigure the behavioral control system at any time.

In a behavior-based robotic system, perception is viewed as a partner process with action. The need for motor control provides context for perceptual processing, whereas perceptual processing is simplified through the constraints of motor action. To take this interplay into account, embedded in each motor agent is a perceptual agent that provides information to the motor agent on need-to-know basis: an individual perceptual agent provides the information immediately needed by the motor agent, which decides on an action, rather than representations of the environment. The inherent parallelism and more targeted processing of behavior-based robotics permits much more efficient sensor processing.

Based on this robotic architecture, two specific types of semi-automaitc teleoperation are explored, namely tele-autonomy and tele-collaboration, which are depicted in Fig. 2. In tele-autonomy, the robot executes motion autonomously while human operator intervenes the process as supervisor – sort of a 'cruise controlled' operation. In tele-collaboration, 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.

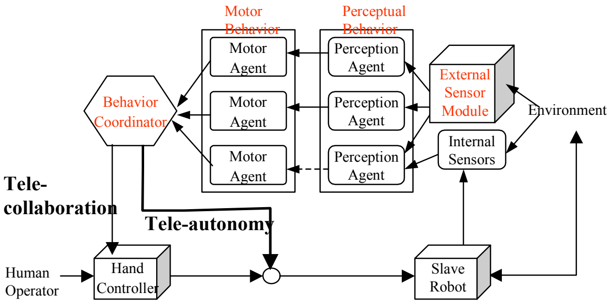


Fig. 2. Semi-automatic teleoperation sysetm

III. PERCEPTUAL BASIS

A reactive system reacts upon sensory input, which perceives environmental status the robot is acting on. To attain this information, perceptual basis is established, which consists of sensor system and perceptual agents.

III.A. Range Measurement with Structured Light Sensor

The sensor system is the hardware part of the perceptual basis, and it consists of structured light sensors and proximity sensors. A structured light sensor is composed of a camera and a laser beam projector, as shown in Fig. 3. By projecting a known beam pattern onto an object and analyzing the position and distortion of its image in the camera's view, the 3-D location and shape of the object can be estimated with relatively simple computation. Also, in order to support various perceptual mechanisms and strategies, multiple sensors may be utilized. They may be mounted at various vantage points on pan/tilt device at the platform, at the manipulator wrist, or on the tool, as illustrated in Fig. 4. Making

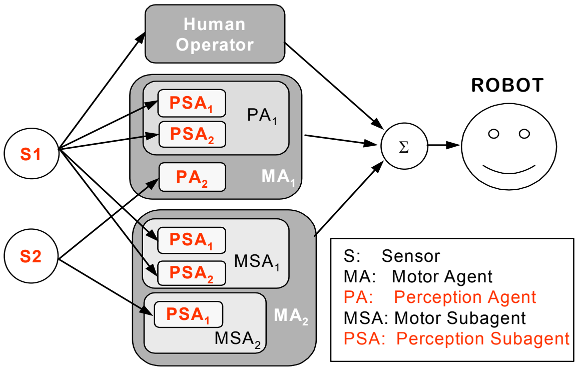


Fig. 1. Reactive robotic atchitecture

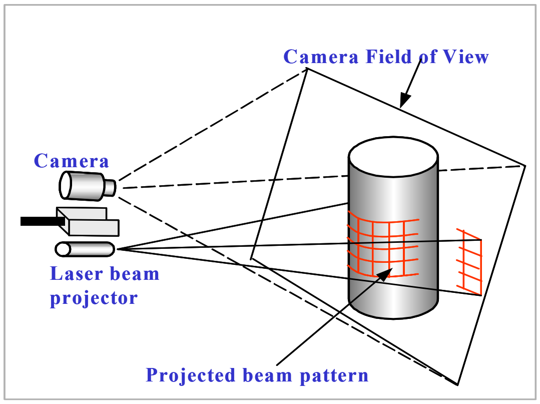


Fig. 3. Structured light sensor

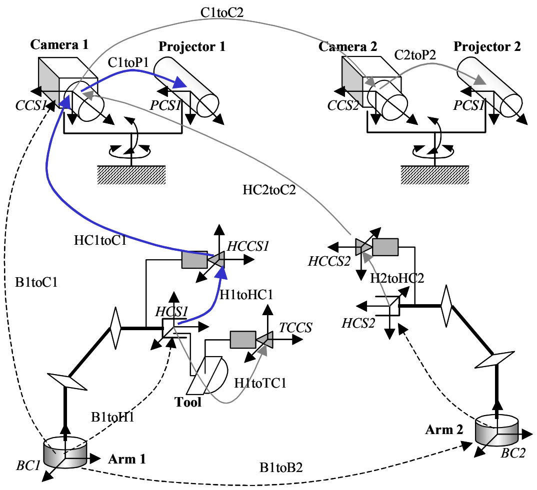


Fig. 4. Multiple sensor coordinate frames

measurement with multiple sensors prerequisites that geometric relationships, represented in the figure as various kinematic transformations, between the multiple sensors and parts of the robots are established. These processes are incorporated in various calibration and measurement processes as illustrated in Fig. 5. Referring to the figure, camera calibration refers to finding camera's intrinsic parameters, such as focal length, principal point, skew and distortion. Camera-projector calibration refers to determining the geometric relationship between the camera image and the projector geometry, which forms the basis for 3-D range measurement. A novel algorithm is developed for this purpose. When a camera is mounted on the robot hand or on a tool, hand-eye calibration is required, which determines the location of camera frame with respect to robot hand frame. For this purpose, a novel vision-based procedure is developed extending the baseline algorithm of Shiu [3].

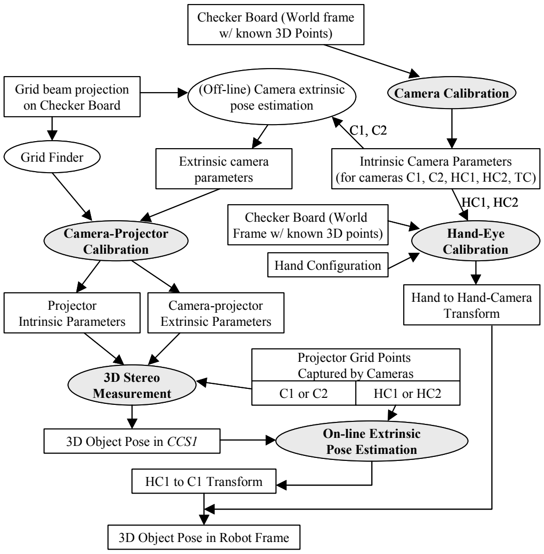


Fig. 5. Multiple sensor calibration procedure

When calibrated, the primary purpose of the sensor system is to determine the pose of an object. The term 'pose' refers to the combination of position and orientation parameters, of which there are six. Using the multiple structured light systems, pose measurement involves of the following operations:

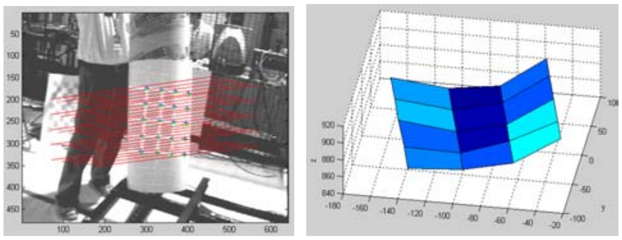
- 3-dimensional position measurement using structured light sensor,
- on-line estimation of extrinsic parameters relating the measurement to robot frame, and
- geometric model based estimation of object pose.

The 3-dimensional position measurement is accomplished based on stereo measurement. The intrinsic and extrinsic parameters obtained by the camera-projector calibration are sufficient to establish the epipolar geometry between the camera and the projector. Then, based on epipolar geometry between the camera and the projector, stereo matching is established between the grid points in the camera image and the projector's grid points, as illustrated in Fig. 6(a). The 3-D distance from the camera to the grid points is determined from the disparity between the matching image points. Fig. 6(b) illustrates a 3-D range map generated for a cylindrical object. For details about stereovision, refer to O. Faugeras [3].

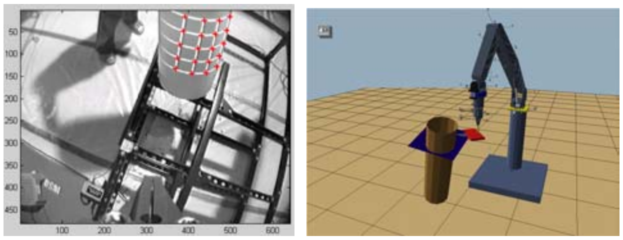
Structured light systems mounted on pan/tilt devices can be driven to point to objects at various locations. Once the object pose is determined with respect to camera frame, for instance *CCS1* in Fig. 4, it is necessary to relate it to robot base coordinate frame, for instance *BC1*. Referring to Fig. 4, this reduces to problem of determining the kinematic transformation **B1toC1**, which can be determined by

$$\mathbf{B1toC1} = \mathbf{B1toH1} * \mathbf{H1toHC1} * \mathbf{HC1toC1}.$$

Since **B1toH1** is available from the robot control system, and **H1toHC1** is available as a result of hand-eye calibration, it is necessary to determine **HC1toC1**, which is the geometric relationship between the hand camera and the structured light sensor. Ordinarily, this is equivalent to the off-line baseline calibration problem in a stereovision system. In our cases, however, the sensors and robots are in frequent motion, and it is necessary to re-establish the extrinsic baseline parameters at every moment. Therefore, an on-line extrinsic parameter estimation technique is developed. When structured light system takes a measurement, the grid image is captured at the same time by the hand camera, as illustrated in Fig. 6(c). From the array of 3-D object point locations and the matching point positions in the hand camera image, nonlinear optimization is carried out to determine the relative locations between the two camera frames.



(a) stereo matching (b) 3D range map



(c) grid image at hand-camera (d) cylindrical object pose

Fig. 6. Pose measurement with multiple sensors

Given a priori information about general shape of the object geometry, the range data may be used to estimate the size and orientation of a cylinder, as illustrated in Fig. 6(d). This is implemented as a perceptual agent in the next section.

III.B. Perceptual Agents

Perceptual agents provide perceptual information to the motor agents on need-to-know basis. To provide efficient perception targeted for motor agent, compound sensing strategies, such as sensor fission, fusion and fashion, are adopted. Furthermore, since perception is a process deeply intertwined with the motor action, some active perception incorporates motor agent as an integral part. These processes are implemented in the following perceptual agents, and also as summarized in Table I.

grid_on: Flags if grid beam projection is on.

in_mid_range: From the size of the grid image, make a coarse measurement of distance to the grid projection. Flags when the distance is within a preset value.

find_goal_direction: From the center position of the projected landmark pattern in the camera field of view, it determines the direction to the grid location.

find_precise_range: Make precise range measurement of the grid points using the structured light sensor as described in the previous section.

find_shape: Identify shape of an object from a range map.

find_goal_geometry: Estimate geometric parameters of an object of known geometry from a range map.

generate_tool_path: It generates desired tool trajectory from object geometric model and grid projection. The result is stored in long-term memory.

in_proximity_range: Flags if the proximity sensor readings reach within certain proximity of the goal.

find_close_range: Measure close range distance and orientation of an object surface from multiple proximity sensor readings.

update_tool_trajectory: Obtain the multiple proximity sensor readings, and updates the motion template, which is a short-term memory. The motion template updates the tool motion trajectory along the tool path.

TABLE I. Summary of Perceptual Agents

Perceptual Agents	Sensor	Output	Time
grid_on	camera	binary	fast
in_mid_range	S.L.*	binary	0.1sec
find_goal_direction	S.L.	continuous	0.1sec
find_range_map	S.L.	5x5 array of vector	~2 sec
find_shape	S.L.	discrete	~2 sec
find_goal_geometry	S.L.	vector	~2 sec
generate_tool_path	S.L.	LTM**	~2 sec
in_proximity_range	infrared	binary flag	fast
find_close_range	infrared	6-vector	0.1sec
update_tool_trajectory	infrared	STM***	0.1sec

* S.L.: structured light sensor
** LTM: long-term memory
*** STM: short-term memory

IV. TELE-AUTONOMY

In tele-autonomy, the robot executes precise motion autonomously, while human operator intervenes the process by providing rough motion.

IV.A. Motor Behaviors

A robot performing D&D operation, call it *D&D_robot*, may be expressed using process algebra as following,

D&D_robot = (*Start* ; (done?, *D&D_operation*) : *Start*)

D&D_operation = (*teleoperation*, *home*, *move_to_goal*, *apply_tool*, *inspection*)

Translating, the D&D_robot consists of a robot that, beginning from an initial Start state, sequentially transitions to D&D_operation state and which then remains to the D&D_operation state until the task is done. D&D operation is composed of many concurrent states. D&D_robot can also be expressed using a state transition diagram as shown Fig. 7, in which each state represents a large grain motor behavior. Each of the states, assembled from motor agents based on the reactive robotic architecture described in section II.

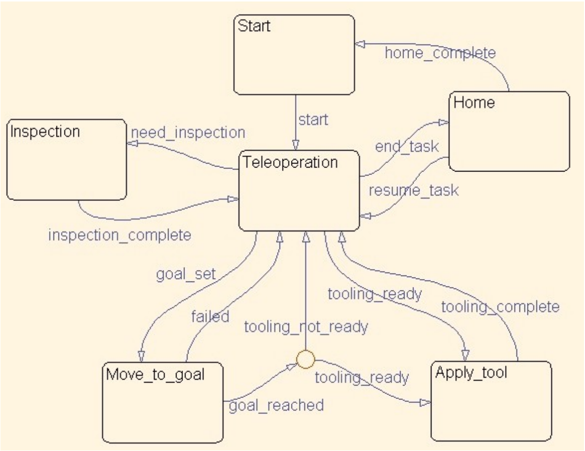


Fig. 7. State-transition diagram for D&D operation

Move_to_goal behavior moves the end-effector, or equivalently the tool, to a goal location with proper alignment at the end. As shown in Fig. 7, this behavior provides preliminary motions before commencing tooling operations. As depicted in the stimulus-response (SR) diagram of Fig. 8, it is constituted by sequencing the actions of the following three motor agents:

gross_move_forward: Whenever the presence of a certain landmark pattern is recognized, the robot will move the end-effector move toward the landmark.

mid_range_tracking: This behavior is triggered whenever the presence of a certain landmark pattern is recognized and the distance to the landmark is within a certain range. The robot will move the end-effector toward the landmark, while aligning the end-effector orientation in accordance with the geometric shape of the target work piece.

close_range_docking: When the robot is too close to the target work piece, the camera system is no longer useful. When this condition is recognized by the proximity sensor, the robot moves its end-effector slowly in the surface normal direction of the work piece until the end-effector touches the work piece.

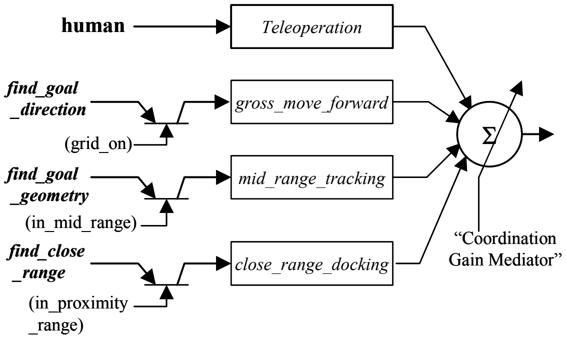


Fig. 8. *Move_to_goal* behavior

Apply_tool motor behavior commences the action of actually applying tools on work pieces. As can be seen in Fig. 8, the tooling behavior requires moving the tool along a specified tool path (*move_along_path*), while maintaining tool angle and depth (*maintain_attitude*). *Move_along_path* is asserted by the following motor agents,

stay_on_path: It provides primary reference points for the tool motion, by making reference to the global tool path, stored in a long-term memory.

move_forward: It makes on-line path modification by referencing the state of motion template in a short-term memory, and generates trajectory for next incremental motion along the modified tool path.

Mainitain_attitude It provides reactive behaviors that maintain tool orientation (*align_tool*), depth of cutting (*tool_offset*), and other tool dependent parameters during the tooling operation. Since the controlled parameters are dependent on the requirement of individual tooling operation, this behavior is designed separately for each tool. For a circular saw operation, the behaviors respond to close range sensor readings, as shown in Fig. 9.

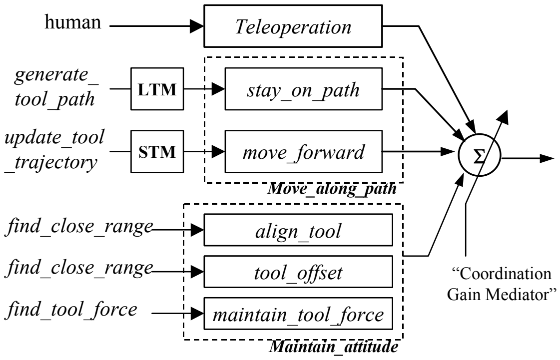


Fig. 9. *Apply_tool* behavior

IV.B. Behavioral Coordination

Both *move_to_goal* and *apply_tool* behaviors are assembled from multiple simpler behaviors. The resultant behavior emerges from these multiple behavioral responses through behavioral coordination, which is accomplished as weighted vector addition. The responses of motor agents are individually adjusted by respective gains and aggregated, which is basically a potential field method. How we assign the gains to individual behavioral response may define another high-level behavior of the robot system. In this regard, the following high-level behaviors further characterize D&D_robot as following,

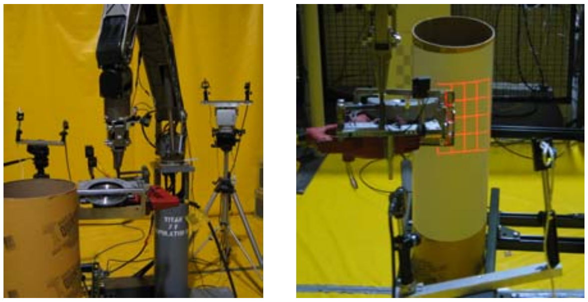
D&D_robot(*robust_robot*, *efficient_robot*, *cautious_robot*)

Robust_robot puts more weight to teleoperation so that it is robust to adapt to unstructured environment. *Efficient_robot* places more weight to autonomous behaviors so that it is suitable for tasks in structured environment with higher degree of automation. For applications where safety is critical, *cautious_robot* limits the speed and acceleration and makes conservative choices in executing motions when safety is in doubt. This behavior works as a mediator of multiple behaviors, as depicted in Fig. 8 and Fig. 9.

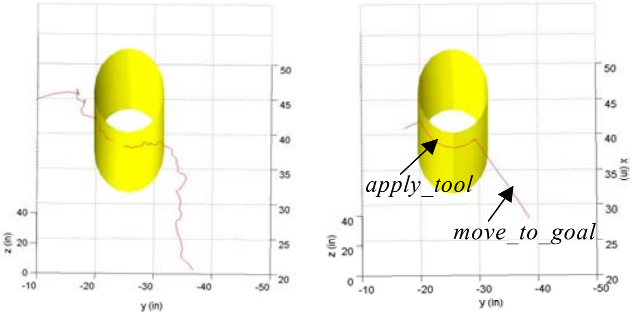
IV.C. Experimental Demonstration

The motor behaviors are demonstrated using a telerobotic system consisting of Schilling Titan 7F six degree-of-freedom hydraulic manipulator, telerobotic control system, sensory system and graphical display system. The telerobotic control system consists of a slave robot servo controller, master input device, and a control computer. The sensory system consists of multiple infrared proximity sensors and structured light sensors, for which a dedicated computer is assigned. Two other computers are assigned for real-time graphic display. The multiple remote computer systems are interfaced through network, which allows accessing remote distributed objects via Java Remote Method Invocation (RMI).

Circular saw is a popular D&D tool commonly used for sectioning nuclear reactor walls and pipes. Its operation requires maintaining precise alignment and reinsertion of tool blade, as well as commencing steady forward motion in the cutting direction. During a previous previous D&D demonstration at a research reactor, CP-5, manipulation of this device was proven inefficient with manual teleoperation of DAWP. To demonstrate the usefulness of tele-autonomy, experimental operations were performed, in which the manipulator holds a circular saw with its gripper and cuts around the circumference of a circular pipe - a structure commonly encountered during D&D. Fig. 10 shows the tool paths during both manual teleoperation and semi-automatic teleoperation. As can be seen in Fig. 10(c), manual operation resulted in poor trajectory control. It was difficult to align the tool to the work piece and maintain tool motion along a desirable tool path with proper orientation, and moreover, the process was extremely time consuming. On the other hand, in tele-autonomy, much better trajectory control was accomplished with help of motor behaviors, as can be seen in Fig. 10(d). Fig. 11 shows the rotational path in terms of roll, pitch, and yaw angles during the execution of *approach_goal* and *apply_tool* behavior. It can be seen that the motor behaviors effectively maintained the tool orientation through uniform motion during the approach and cutting process. As a result, the operation under tele-autonomy enabled precise cutting to be performed in much shorter time. Such an operation was easily conducted performed by non-trained personnel.



(a) robot with multiple sensors (b) teleautonomous operation



(c) manual teleoperation (d) teleautonomous operation

Fig. 10. Tool trajectories during teleoperation

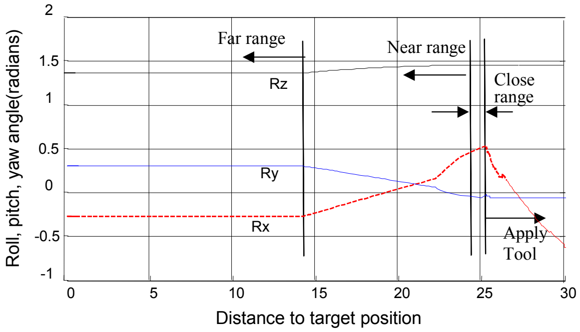


Fig. 11. Tool orientation during teleoperation

V. TELE-COLLABORATION

Tele-collaboration is another enhanced form of teleoperation addressed in this work. In tele-collaboration, the same motor behaviors as for tele-autonomy might be available; however, instead of being functions of time, the behaviors become functions of spatial parameters, thus forming *virtual fixtures*.

V.A. Virtual Fixture

Virtual Fixtures are defined, according to [8], as "abstract percepts overlaid on top of the reflected sensory feedback from a remote environment such that a natural and predictable relation exists between an operator's kinesthetic activities (deference) and the subsequent changes in the sensations presented (inference)". A familiar conceptual model with which to understand the concept of a virtual fixture is a straightedge. Consider using a pencil to draw a straight line on a piece of paper. The straightedge is a physical fixture that may be overlaid to simplify the task. Virtual fixtures may, like the straightedge, provide force feedback, or they may take other forms, such as visual or auditory display.

V.B. Cobotic Hand Controller

To effectively display the virtual fixture kinesthetically, a new hand controller is developed, based on Cabot technology. Cobot is a proprietary technology capable of providing safe and smooth yet extremely strong constraints through the use of non-holonomic constraints[9-11]. A steered wheel, un-powered about its rolling axis, creates a relationship between the two components of its linear velocity. Higher dimension cobots utilize varying geometries of rolling contacts. Cobots can either be operated in "free-mode," where the intent of the operator in the full dimension of the task space is followed completely, or in "virtual-surface" mode, where a lower dimensional surface than the task space guides the operator's intent tangent to that surface, and the non-homonymic constraints of the rolling wheels, not the torque of any actuators, prevent motion normal to the virtual surface.

The design of this 6-DOF Cobotic Hand Controller utilizes the kinematics of a parallel platform introduced by Merlet[11] (Fig. 12). The proximal links are coupled by three degree-of-freedom universal joints to the distal links, and these in turn are coupled via two degree-of-freedom universal joints to an end-effector platform. A force sensor on the end-effector is used to determine the user's intent. Our addition to Merlet's kinematics has been to couple the six linear actuators to a central "power cylinder" through non-holonomic constraints. Linear actuation of the proximal links is achieved via a rotational to linear continuously variable transmission (CVT), namely a steered wheel. The angle of each wheel relates the linear velocity v_i of each proximal link to the rotational velocity of the power cylinder ω. When the wheels are steered such that their rolling axis is parallel to the power cylinder ($\phi_i = 0$), a ratio $v_i / \omega = - r \tan(\phi_i) = 0$ is set. If the wheels are steered either direction from $\phi_i = 0$, ratios between ± infinity can be achieved. In practice, wheel slip limits this range. It is also evident, that turning all six wheels to $\phi_i = 0$ locks the six actuators, and turning them to $\phi_i = \pi/2$ completely decouples the actuators from the cylinder's velocity, although the cylinder would then be unable to turn.

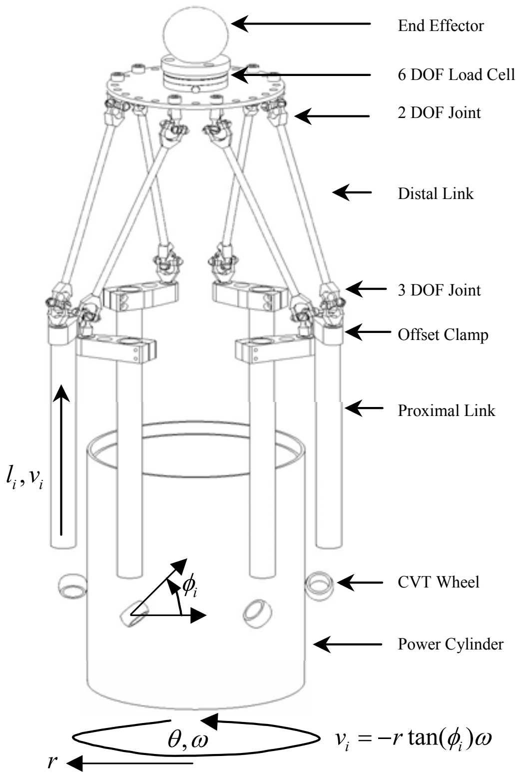


Fig. 12. Kinematics of a Merlet-cobotic parallel platform

As mentioned before, an operator can interact with the cobot in a "free mode" in the full dimensional six-space, or while constrained to a one to five dimensional virtual-surface. In Fig. 13, a trajectory on a four-dimensional constraint surface is shown. The user's force input in two dimensions is followed via a mass-damping model. The operator is constrained to zero rotation about all three axes, and to the surface of a 17 cm diameter sphere, which provides a good representation of the available translational workspace. At the center of the Cobotic Hand Controller's translational workspace, ± 40 degree rotations about x, ± 45 degree rotations about y, and ± 85 degree rotations about z are feasible.

The test operation revealed that active six-degree-of-freedom Cobotic haptic display with workspace resolution of approximately 25 μm, force transmission capabilities exceeding 50 N, structural stiffness ranging from 20-400 kN/m. Based on the authors' experience with haptic interface devices, the feeling of this device is quite remarkable. The crisp distinction between free and forbidden directions of motion is striking. This performance arises not from elaborate control algorithms, but from the inherent physical characteristics of the device due to the utilization of non-holonomic constraints.

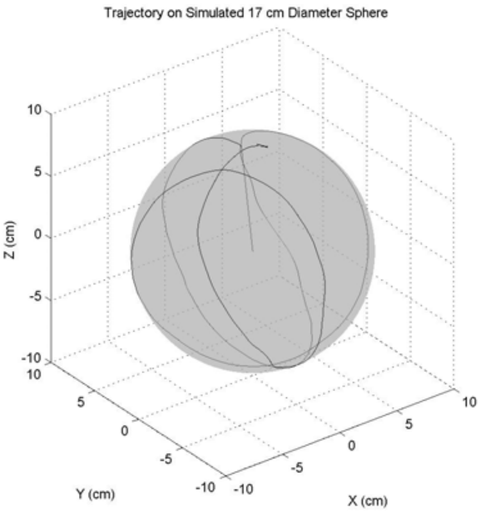


Fig. 13. Spherical kinesthetic virtual constraint implemented with 6 d.o.f. cobotic hand controller

VI. CONCLUSIONS

To aid in teleoperation of D&D tool manipulation, two types of semi-automatic teleoperation methods are developed, namely tele-autonomy and tele-collaboration. Tele-autonomy is accomplished by blending automation and manual operation, in such a way that precise motion is accomplished by the robot while human provides rough motion. By adopting reactive robotic architecture, the system is capable of adapting to unstructured environment. Furthermore, it is possible to build and reconfigure various autonomous behaviors incrementally from basic building blocks - motor agents. The perceptual basis is configured with structured light sensor and perceptual agents, which provides perceptual information targeted for the motor agents. Tele-collaboration aims at providing virtual fixture that passively guides human motion. Building upon Cobot technology, a new hand controller is developed to provide its kinesthetic implementation.

Both types of enhanced teleoperation serve a useful role. Tele-autonomy is particularly useful for routine operations where the operator does not require sensory feedback. Tele-collaboration may be more useful for situations where the operator needs such feedback, such as feeling the vibration from the saw cutting action to guard against binding. Experimental studies revealed the effectiveness of each method. A synergistic advantage may be achieved by combining both tele-autonomy and tele-collaboration.

ACKNOWLEDGMENTS

This research was sponsored by the Environmental Management Science Program of the Office of Environmental Management and Office of Science, U. S. Department of Energy.

REFERENCES

1. R. C. Arkin, "Reactive Control as a Substrate for Telerobotic Systems," IEEE Aerospace and Electronics System Magazine, Vol. 6, No. 6, pp. 24-31, June, 1991.
2. O. Faugeras, Three-Dimensional Computer Vision: A Geometric Viewpoint, MIT Press, 1993.
3. Y.C. Shiu and S. Ahmad, “Calibration of wrist-mounted robotic sensors by solving homogeneous transformation equations of the form AX=XB” IEEE Trans. Robotics Automat., vol. 5, pp.16-29, 1989.
4. C. Wang, “Extrinsic calibration of a vision sensor mounted on a robot” IEEE Trans. Robotics Automat., vol. 8, pp.161-175, 1992.
5. Park, Y.S., Boyle, J.M., Ewing, T.F., "Agent Based Dual-arm Motion Planning for Semi-automatic Teleoperation," Proc. of ANS 9th International Topical Meeting on Robotics and Remote Systems, Seatle, Washington, March 4-8, 2001
6. Y. Park, "Structured beam projection for semi-automatic teleoperation," Proc. of SPIE 2000 ISAM Conference on Opto-Mechatronic Systems, Boston, MA, Nov. 5-6, 2000
7. J. V. Draper, and Blair, L.M., "Dual arm work platform performance estimates and telerobot task network simulation," presented at American Nuclear Society Seventh Topical Meeting on Robotics and Remote Handling, Savannah, GA, 1997
8. L. B. Roseberg, "Virtual fixtures: perceptual overlays enhance operator performance in telepresence tasks," in *Mechanical Engineering*: Stanford University, 1994
9. M. A. Peshkin, Colgate, J.E., Wannasuphoprasit, W., Moore, C.A., Gillespie, R.B., and Akella, P., "Cobot architecture," *IEEE Transactions on Robotics and Automation*, vol. 17, pp. 377-390, 2001.
10. E. L. Faulring, Colgate, J.E., Peshkin, M.A., "A high performance 6-DOF haptic cobot,"submitted to IEEE International Conference on Robotics and Automation, 2004
11. J. P. Merlet, "Direct kinematics and assembly modes of parallel manipulators.," *International Journal of Robotics Research*, vol. 11, pp. 150-162, 1992