ENHANCED TELEOPERATION EXHIBITING TELE-AUTONOMY AND TELE-COLLABORATION

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ABSTRACT

This paper presents enhanced remote manipulation of tools for D&D tasks by extending teleoperation with tele-autonomy and tele-collaboration. This work builds on a reactive, agent-based control architecture, which is 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 passive force-feedback control. Developed methodologies are tested using simulation, and then planned to be implemented using a structured light sensor and cobot hand controller on a dual-arm system to measure the enhanced performance of key tool operations that are tedious and difficult to perform purely by teleoperation. This work significantly leverages some 2000 hours of operational experience gained during the D&D of the CP-5 reactor at ANL using a dual-arm remote manipulator system, as well as DOE's investment in the dual-arm system itself, which will serve as a test bed for the proposed investigations.

I. INTRODUCTION

The liability for deactivation and decommissioning (D&D) of contaminated structures in the weapons complex is about $30 billion. Remote systems will be essential for this work to reduce risk to human workers from hazardous radiation and difficult work environments, while improving productivity and reducing costs. Nevertheless, the major drawback of currently available remote manipulation systems is that teleoperation is a slow and imprecise process, even after many years manipulator development. This was evident in ANL's experiences of deploying the teleoperated Dual Arm Work Platform (DAWP) system for dismantling the CP-5 reactor internals at Argonne National Laboratory. Despite significant improvements in productivity using robots over baseline (manual) methods, it was observed that nearly 90% of the robot operation time was spent in alignment operations, with the remaining time spent performing actual dismantling operations. Also, since the operation of the robot relies solely on human perception-action, precise motions easily achievable by the robot in programmed control become extremely difficult under teleoperation. Furthermore, due to the difficulty in manually commanding the two arms' simultaneous motions through teleoperation, the full task capability of the dual-arm system is seldom realized. What is required is a powerful aid that can effectively guide the operator through desired task motions. To this end, this paper presents an R&D effort to develop systems enhancements to facilitate efficient and precise teleoperation, yet demonstrate a system architecture that is flexible enough to adapt to the general scope of D&D tasks.

In this project, we explore two types of enhanced teleoperation: tele-autonomy and tele-collaboration, as depicted in Figure 1. In tele-autonomy, the robot is first instructed to perform some task by the operator (for example, "move to work piece") and the slave executes the proper motor behaviors to autonomously perform the given task. Human operator intervenes the process as a supervisor providing rough motion trajectory with unilateral input device. 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. The difference is analogous to a "path" being spatial and a "trajectory" being temporal. For example, in tele-collaboration, the operator's motion might be constrained to a particular path, but the motions or forces along that path are determined by the operator. Therefore, the opertor feels and controls the progress of what is happening at the same time.

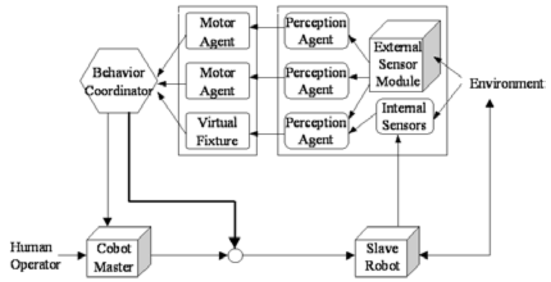


Figure 1. Structure of enhanced teleoperation sysetm

II. BACKGROUND

A. Reactive Robotic System

Tele-autonomy is achieved by blending human oversight with sensor-based autonomous operation. Such a semi-automatic robotic system can be implement based on either deliberative or reactive architecture. In this work, robot architecture refers to the discipline of building the software, rather than the hardware, of the robot control system. The deliberative architecture, characterized by the hierarchical control system structure, is well suited for structured and highly predictable environments. But it lacks the flexibility to cope with the unstructured and uncertain environments. On the other hand, a *reactive system* is composed of a collection of behaviors that tightly link sensory inputs to motor actions. The flow of control and communication between each behavior is less restrictive, and autonomous control emerges from the interaction of multiple behaviors. Therefore, a reactive system is more suitable for autonomy in unstructured and uncertain environment. Furthermore, due to its distributed nature, it exhibits incremental competency -- more complex behaviors can be built and tested incrementally from elementary behaviors.

In this work, a reactive control system is composed of motor agents that directly correlate sensory inputs to the manipulator's motor actions, whose structure is shown in Figure 2. As illustrated in the figure, the robot motion is determined as emergent response of multiple motor behaviors. For each motor agent, sensory inputs are tightly linked to motor actions. Embedded within each motor agent is a perceptual agent that provides the perceptual information customized for the respective motor behavior.

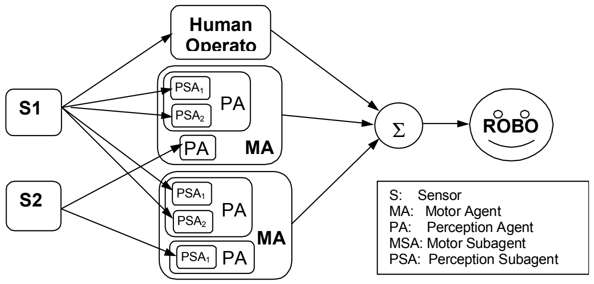


Figure 2. Reactive Robotic Atchitecture

B. Virtual Fixture and Cobot

In tele-collaboration, the operator is also passively guided by *virtual fixture*. Virtual Fixtures are defined by Rosenberg 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 (efference) and the subsequent changes in the sensations presented (afference)" [11]. 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. There is ample evidence in the engineering literature that virtual fixtures expedite operator training and improve operator performance in teleoperation tasks.

Unfortunately, the force-reflecting hand controllers necessary to implement these virtual fixtures are not, as a practical matter, commercially available. Therefore, this work addresses on the development of a hand controller based on the “cobot” technology. Cobots – collaborative robots – are a class of robotic devices that have been developed specifically for the display of virtual surfaces and fixtures. *Cobots* were invented in 1995 as a means of implementing virtual surfaces that would be strong, smooth, and highly robust. Cobots implement virtual surfaces by using mechanical transmissions - a wheel in contact with a flat rolling surface as shown in Figure 3. The wheel is free to turn on its axle. There is no motor to drive its rolling motion. Control of the steering angular velocity is accomplished by a conventional velocity controller. The resulting virtual surface relies for its strength and hardness not on actuators, but on the properties of a rolling wheel. In practice, many designs use Rollerblade® wheels, taking advantage of a technology that has been optimized for a sport requiring similar wheel properties. The presented work addresses design of cobot hand-controller with 6 d.o.f. motion.

III. STRUCTURED LIGHT SENSOR SYSTEM

In this work, a structured light system is adopted as environmental sensor that guides the robot motion, as shown in Figure 2. A structured light system consists of a camera and a patterned beam projector placed in parallel at a distance apart. By projecting a known geometry, the stereo correspondence problem is greatly simplified. The shape, size and orientation of the projected grid pattern can be analyzed to identify the location and shape of the environmental objects.

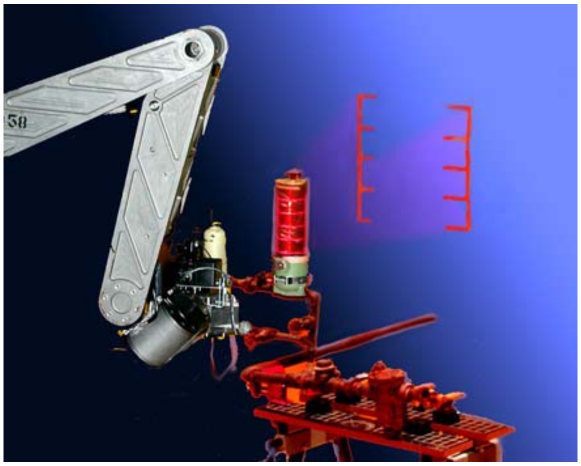


FIgure 2. Robot guided by structured light

In our implementation, a laser diode is used to project a grid beam pattern, and a CCD camera is equipped with optical band-pass filter to distinguish the beam pattern. Relatively simple image processing and computation is required to conduct range map generation. As illustrated in Figure 3, the image captured by the camera is converted to a binary image. Then connected component labeling and pattern matching is performed to segment the grid image. After thinning and pruning, the grid image of unit pixel width is prepared. Then the grid intersection points are identified by heuristic search for branching points. Missing points are estimated by interpolation. Then, based on parallex computation, the range data are computed for the grid points, and the surface normal vectors are computed from gradient information. The relevant image processing and geometric computation can be implemented in a firmware.

Taking the range data, the perceptual agents generate the perceptual information on need-to-know basis. To realize action-oriented perception, rigorous perceptual behaviors are designed incorporating sensor fission, fusion or fashion, as well as active perception, as will be described in the following section.

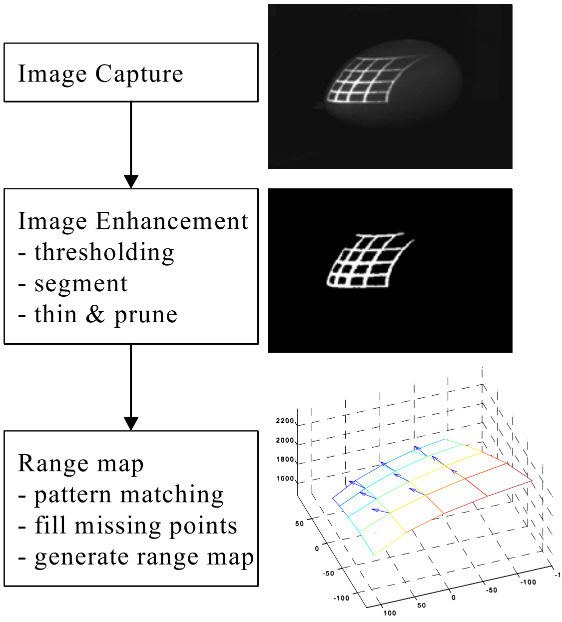


Figure 3. Image processing for range mapping

III. TELE-AUTONOMY

Our experience in robot operations revealed that most D&D tasks are composed of a few large-grain motor behaviors as shown in figure 4. Such high-level behaviors can be assembled from a few primitive reactive behaviors. The characteristics of these motor behavioral assemblages are described as follows:

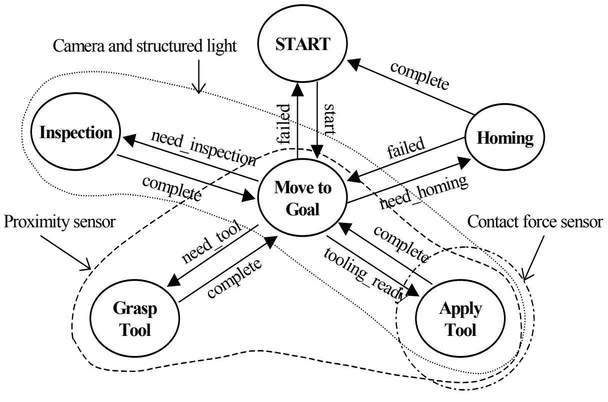


Figure 4. Motor behaviors for D&D teleoperation

A. *Move_to_goal* behavior

Move_to_goal moves the end-effector to a goal location. As can be seen in Figure 3, this behavior provides preliminary motions in between various tasks, which require transporting the tools. As shown in the finite-state diagram of Figure 4, it is constituted by a 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 workpiece. Also, the trajectory is further modified to avoid obstacles.

close_range_docking: When the robot is too close to the target workpiece, 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 workpiece until the end-effector touches the workpiece. Design and testing – circular saw

Due to the sequential nature of *move_to_goal* behavior, as shown Figure 5, its perceptual agent adopts 'sequencing' as the primary perceptual mechanism. The perception is accomplished by sequening the following perceptual behaviors:

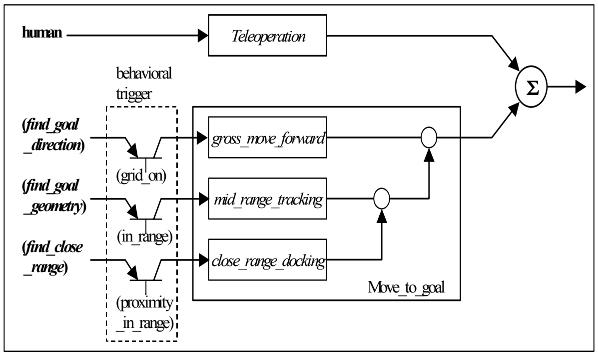


Figure 5. Perceptual sequencing in *move_to_goal*

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

find_goal_geometry: By analyzing the position and the distortion of the grid pattern, it determines the relative location and surface orientation of the workpiece.

find_close_range: It determines the close range distance and the surface orientation of the workpiece form the readings of the proximity sensors.

B. *Apply_tool* behavior

Figure 6 illustrates the various motor behaviors constituting *apply_tool* motor behavior, which performs the action of actually applying tools on workpieces. As can be seen, the tooling behavior requires moving the tool along a specified tool path, which is accomplished by two reactive behaviors, *stay_on_path* and *move_forward*. The motor agent, *stay_on_path*, directs the robot to follow the global path map stored in the long-term memory. The *move_forward* behavior is a local path modification that generates forward biased tool motion trajectory. Further tool dependent behaviors are also defined that maintain tool angle, depth and force.

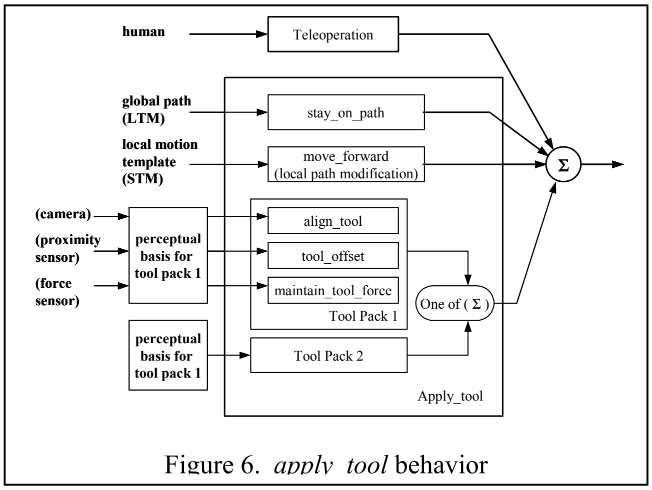


Figure 6. *apply tool* behavior

C. *Inspection* behavior

Reactive robots are built on spontaneous reaction to the current sensory inputs. However, if the environment is less dynamic and there is useful information that is accurate, durable and reliable, then it can be worthwhile in providing more persistent representations of environmental knowledge that encodes this information to the robot. The motor behavior, *apply_tool*, performs the actual operation of applying a tool onto the work piece. As can be seen in Figure 7, among its many constituent motor agents, *stay_on_path* moves the end-effector along a pre-specified tool path. Rather than accepting an instantaneous environmental perception, the *stay_on_path* acts on motion reference provided by a predefined tool path. Since a tool path needs to be fitted with a complex geometric shape and defined with reasonably high spatial resolution, the perceptual agent, *define_tool_path*, is designed as a relatively complex process that involves motor action as an integral part. As illustrated in Figure 7, the perception involves the following processes: 1) the sensor head is first moved and a patterned beam is projected onto the target workpiece, 2) the shape of the projected beam pattern is analyzed to estimate the shape and size of the workpiece, and 3) the sensor head is revolved around the workpiece and the projected beam patterns are analyzed and collected to from a tool path. Rather than continually regenerating the tool path at every control instance, the sensing routine is executed less frequently and the resulting path is stored in a long-term memory. This path data is referenced throughout the action of *apply_tool* behavior.

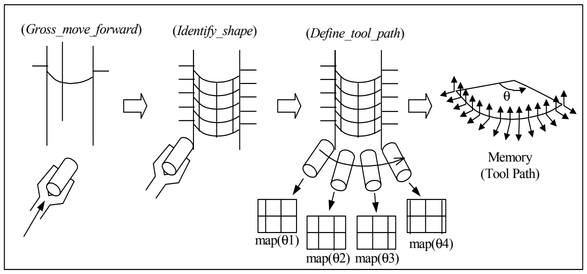


Figure 7. Inspection behavior

IV. TELE-COLLABORATION

Tele-collaboration is another enhanced form of teleoperation addressed in this work, where the operator continually controls the progress of what is happening via the master, while he is also passively guided by *virtual fixture*.

A. Hand controller design

The objective of this task is be to develop a force-reflecting cobotic hand controller. It is anticipated that the new device will have the benefits of cobots, including safety, stability, and high-quality virtual surfaces, along with the benefits of force-reflecting manipulators, including haptic effects such as programmable stiffness, damping and inertia.

Figure 14 is an illustration of the proposed design. This handcontroller is based on a parallel kinematic mechanism known as the Merlet platform[12]. The endpoint (handgrip) connects to a set of six pushrods via fixed-length legs. The legs connect via ball joints at their ends (or one end may be a universal joint, which keeps the leg from rotating about its own axis). By moving the pushrods back and forth, the handgrip may be positioned in six degrees of freedom.

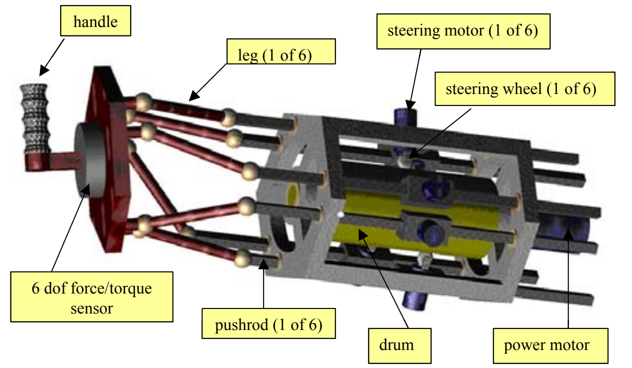


Figure 8. Cobotic Handcontroller Design

The Merlet platform has certain advantages relative to its better-known cousin, the Stewart platform. The workspace is typically somewhat larger for a comparably-sized mechanism, and the actuators may be placed in a fixed frame (in a Stewart platform, the six legs much change length, which is difficult to accomplish unless the actuators are mounted on the legs). For our purposes, however, the Merlet platform has a huge benefit in that it allows us to replace conventional actuators with a set of servo-steered wheels, all of which run on a common drum. This results in a cobot having the parallel CVT architecture[7]. As discussed earlier, this is a useful cobot architecture, because it eliminates singularities in the steering space, and it allows power injection through a single actuator.

The wheels in this cobot are somewhat akin to adjustable screw threads. The steering angle of a particular wheel determines whether the screw's pitch (i.e., the ratio of pushrod velocity to drum angular velocity) is zero (if the wheel's axis is parallel to the drum axis), infinite (if the wheel's axis is perpendicular to the drum's axis), or finite (Figure 9). The ratio of the set of six steering angles corresponds to a ratio of pushrod speeds, which then corresponds to a particular direction of

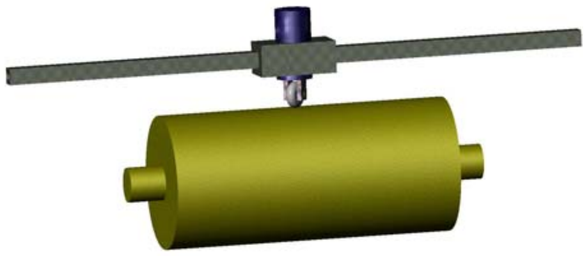


Figure 9. A single pushrod and steering assembly pressing against the drum. The steering angle is set for an intermediate pitch is set for an intermediate pitch

motion of the handle through six-space. This cobot has several features that make it appealing for the proposed research. To begin, it has six degrees of freedom, yet is mechanically rather simple. The six pushrod assemblies are all identical, as are the legs, which dramatically simplifies the design process when compared to a serial design.

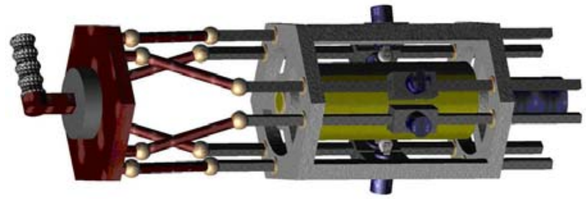
Even more important for the proposed work, this design eliminates virtually all sources of compliance and backlash except for the steered wheels themselves. Moreover, the steered wheels is the simplest and most robust form of CVT. In this design, we even have the option of rubberizing the drum and using steel or aluminum wheels. This is an advantage because the wheels themselves can be designed with very low rotational inertia, yielding very high bandwidth steering control. Owing to these factors, there is every reason to expect that the cobotic hand controller will be capable of implementing high fidelity virtual surfaces and haptic effects.

It is important to note that this design may also be used as not only a force-reflecting device, but also a six-axis motion-sensing joystick and a six-axis force-sensing joystick. As illustrated in Figure 10, this does not depend upon feedback control; in other words, we are not simulating these two types of joystick. Instead, this is achieved mechanically by steering all six wheels to either infinite pitch or zero pitch. In the former case, the pushrods are all mechanically decoupled, and the cobot becomes a motion joystick. Motion is detected by linear position sensors on the pushrods. In the latter case, the pushrods are all mechanically locked, and the cobot becomes a force joystick. Forces and torques are measured by the force/torque sensor at the endpoint. The result is an extremely high level of versatility in a single device.

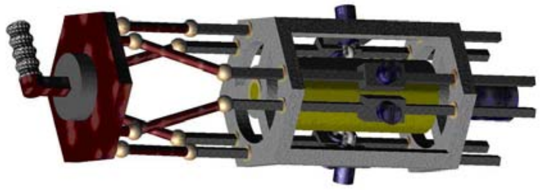
B. Hand controller integration

In this task, the cobotic hand controller will be integrated with the DAWP. Successful integration will require the selection and implementation of an appropriate system architecture. Hannaford provides a good discussion of the most common teleoperator architectures, including the "classical" architecture based on position errors, the "forward flow" architecture in which the master commands slave motion and the slave commands master force, and the "bilateral impedance control" model in which force and impedance commands are exchanged between the master and slave in a symmetric manner [10].

In this work, the selection of architecture will be driven in part by the electromechanical characteristics of the cobot hand controller and the DAWP, and in part by the need to introduce virtual fixtures that constrain the motion of both devices. Fortunately, these considerations are consistent with one another:



(a) cobot is configured as a motion-sensing joystick by aligning wheels with axis of drum



(b) Cobot is set as a force-sensing joystick by aligning wheels perpendicular to drum

Figure 10. Configurations of cobotic hand controller

- The DAWP is an admittance device: it senses force and accepts motion commands.
- The cobot may be treated as either an admittance or an impedance device, but the former is generally preferable.
- Virtual fixtures are most readily modeled in terms of motion constraints (as opposed to forces).

Thus, it seems logical that the control architecture should provide position commands to both the cobot and the DAWP. In the case of free motion, these position commands may be derived from a position error, as in "classical" teleoperator control. In the case of constrained motion, these position commands may be modified consistent with any virtual fixtures. Such a design might be termed a "bilateral admittance controller with virtual fixture overlays."

Software will be written to coordinate not only master and slave motions, but master and slave reactions to motor behaviors and virtual fixtures. The system to be developed will also be flexible enough to allow the master to be operated in either a position mode or a rate mode.

V. Conclusion and Further Works

Both types of 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. A synergistic advantage can be achieved by combining both tele-autonomy and tele-collaboration. The choice between the two must ultimately be related to the quality of sensory information available to computer controller, versus that available to the human operator. More work is expected in this area.

ACKNOWLEDGEMENTS

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