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Dexterous Manipulation: Making Remote ManipulatorsEasy to Use

Raymond W. Harrigan and Phil C. Bennett

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Raymond W. Harrigan and Phil C. Bennett
Intelligent Systems and Robotics Center
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1004

ABSTRACT

Perhaps the most basic barrier to the widespread deployment of remote manipulators is that they are very difficult to use. Remote manual operations are fatiguing and tedious, while fully autonomous systems are seldom able to function in changing and unstructured environments. An alternative approach to these extremes is to exploit computer control while leaving the operator in the loop to take advantage of the operator's perceptual and decision-making capabilities. This report describes research that is enabling gradual introduction of computer control and decision making into operator-supervised robotic manipulation systems, and its integration on a commercially available, manually controlled mobile manipulator.

Key words: Robot, Manipulation, Operator-supervised, Shared control, Operator performance.

1. INTRODUCTION

Increasing numbers of hazardous environments, tightening controls on human exposure to the hazards, and increasingly effective remote technologies have driven the need for more remote and robotic systems in the field. Military and civilian explosive ordnance disposal (EOD) technicians, first-responders to chemical and biological devices, civilian HAZMAT teams, and radiation workers remediating and repairing nuclear installations all have a requirement to minimize exposure to bodily harm in the execution of their duties.

To remove the operators from the vicinity of the hazard, robotics technologists have typically tried to provide either remote manual (teleoperated) systems or completely autonomous manipulation systems. Effective teleoperated manipulation typically requires very extensive and perishable training, and frequently results in overly-demanding and tedious operation that is especially concerning in hazardous or high consequence environments. At the opposite end of the spectrum, computer-controlled autonomous operation in unstructured environments frequently fails to provide adequate response to the environment needed to build the confidence that the end users require for widespread adoption. Neither approach appears to fulfill the needs of most end users very well.

An alternative approach is to break the strangle hold that teleoperation places on the exploitation of computer control while leaving the operator in the loop to take advantage of the operator's perceptual and decision making capabilities. This report describes research that is enabling gradual introduction of computer control and decision making into operator-supervised robotic manipulation systems. The net effect is to make life easier for the robot operator thus gaining acceptance and trust. Building upon this trust, technology developers gain experience in how operators want to use the robots and the levels of technology with which they feel comfortable. Technology is then developed to address those operational desires and introduced incrementally to provide higher capability robot systems. Operating laboratory prototype systems are described as well as experiments involving end-users to measure improvements in performance. The path for incremental technology insertion based upon the functional needs of the user are discussed.

2. DIFFICULTIES

To better understand the problem and its potential solutions, let us first examine some of the inherent difficulties with remote manipulation.

2.1 Effective Work Volume

What positions can a manipulator reach? What orientations can it take in those positions? The answers to these questions define the effective work volume of a manipulator. Points in space that the manipulator can touch (ie. that are reachable) from the current manipulator base location are defined by its geometry and by its joint types and travel limits. The orientation that the tip of the manipulator can assume at those points in space is defined by the number, types and placement of the manipulator joints. At points near the joint limits, the orientation options may become severely restricted.

How does the operator know whether an object of interest can be reached with an orientation sufficient to complete a task? It is difficult for the operator to visualize the limits to position and orientation in a given situation. Time-consuming study of camera views can help the operator understand what is happening. However, operational pressures distract from such abstract thinking.

2.2 Control Type

A typical approach to control of remote manipulators is a joint-by-joint control. This is usually implemented either by matching switches in a switch box, or some type of joint angle measurement device on a master, with each joint. The operator must mentally visualize how he/she wants the manipulator to move and correctly translate this into orchestrated switch or keyboard strokes. The more capable manipulators have six or more joints; the resulting extreme difficulty for the switch box input approach has led to the use of kinematically-matched masters or more computerized coordination of joint movement, typically through one or more joysticks.

At the other extreme, total autonomy has rarely been successfully demonstrated in complex and changing environments. It requires sufficient sensory input, a priori knowledge, rules or reasoning capability, automatic error recovery, automatic path and trajectory planning, and speedy system response, all wrapped into a reliable package to carry out an autonomous mission.

Extensive users of remote manipulators have recognized the need for hybrid advanced control systems. CEA in France has developed a use-specific system for repair of nuclear components[1] that incorporates trajectory planning for linear, circular and polynomial trajectories, and permits force feed-back to the operator. In Germany, remote master-slave manipulators with bilateral force feed-back were used to dismantle radioactive facilities[2], resulting in less than 4% of the originally expected worker radiation exposure.

2.3 Speed

In general it is desirable to move as fast as possible without compromising safety. Speed is limited by system hardware and any limitations of control software present. However, safety considerations will drive the use of available speed. The comfort level of the operator, the perception that he or she has the ability to understand what is happening and respond adequately will be the ultimate limitation of how quickly an operation will be completed.

2.4 Operator Interface

Limited information is available to the operator during remote teleoperations. Operators are typically presented with limited camera views, and sometimes with sound from microphones on the manipulator. Input typically involves some combination of switches, buttons, and joysticks or a "master" that is similar in geometry to the manipulator. The presentation, relationships and accessibility of both input and feed-back devices is important. For example, many systems require momentarily taking eyes off of the video image to find a switch, or taking hands off of a master to move a camera. These all distract the operator from critical tasks and add substantial amounts of time to their performance.

In an attempt to achieve operator "telepresence," a variety of feed-back technologies have been implemented in various combinations. The first and simplest response is to add more cameras; there never seem to be enough views. Stereo vision addresses the depth-perception problem inherent in remote systems. Audible queues have also been used, both from microphones installed on manipulation systems to listen to system components, and in more sophisticated systems, a variety of sound queues may be generated to call attention to one or more operating parameters. Force feed-back has long been scrutinized as a means of utilizing the operator's tactile perception. It can provide good resistance perception with good short-term operational results, as demonstrated on an ARTS vehicle by the Air Force Research Laboratory at Tyndall Air Force Base.

The problem with telepresence is the danger of giving the operator sensory overload. None of the sensory feed-back is quite the same as the human's, and the operator must interpret each slightly differently. More cameras require more switching decisions and operations. Stereo vision is known to cause fatigue, headache and vertigo in some operators, particularly noticeable during prolonged operation. Force feed-back is tiring. For operational periods extending to hours, operator fatigue from pushing against generated forces becomes a concern. Force feed-back also has high bandwidth requirements between base station and manipulator. The ARTS with multi-arms requires a separate video channel to transfer force data at sufficiently high speed. The result of too much telepresence is an array of sensory caucauphony that is fatiguing, potentially confusing, unsustainable, and could result in costly mistakes. One must ask: Does this make the operator's job easier, or simply overload him or her?

2.5 Pressure of the Operation

For most categories of remote manipulator users, the psychological pressure during remote manipulation operations is high. The physical or political consequences of mistakes, inadequate execution or speed, or uncontrolled movement can be severe. One need only think of the terrorist bomb at New York's World Trade Center or the bombing of the Murrah federal building in Oklahoma City to understand what may be at stake. Environmental factors also play a role in performance. Physical factors such as comfort of the operator's chair or excessive movement of arms, eyes and fingers to control the remote equipment impact operator effectiveness. Mental distractions such as command oversight may impact clarity of thought and the operator's ability to visualize the remote scene beyond the limited camera views.

These are but a few of the issues that should be considered when developing robotic systems for remote operations.

3. APPROACH

We approach the problem by first providing the operator with autonomous capability, then enabling operator command insertion where autonomy fails or is not yet trusted, and where sensory information is unavailable. The operator may then utilize all remaining automatic capabilities in a support role to relieve operational burdens. As new technologies are developed and implemented, they may then be used as "back-up" and for training purposes until the operator has gained a level of confidence in its performance and competence in its use.

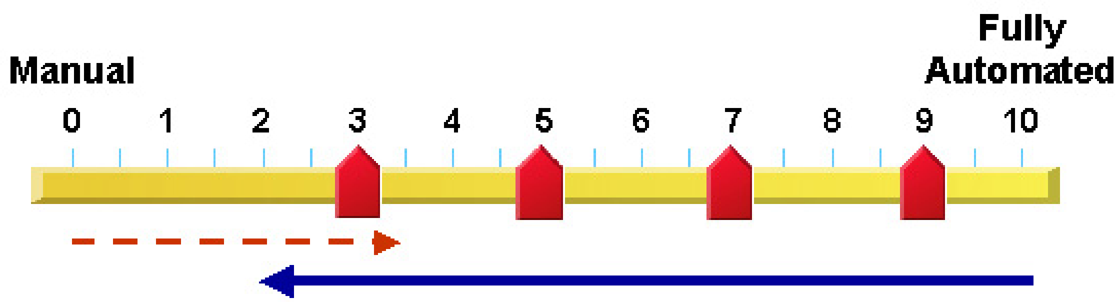

Figure 1. Approaching remote operations with fully automated capability enables a broader selection of autonomous assistance for the operator to choose.

3.1 Enable Automation

The first element of our approach is to provide a manipulator that is "*robotic*." According to Robotic Industries Association (RIA), a robot is "A reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks." A robotic manipulator has the ability to automatically pass through a desired series of specific points in space (x,y,z), with a specified orientation (roll, pitch, yaw), in a specified order, with selectable velocities. At some of the selected points, tooling may be activated to accomplish an effect (hence the term end-effector) such as grasping, cutting, welding, etc. This sequence of events is called the robot program.

One implication of the robotic definition is that the machine has the ability to determine what position and orientation it has achieved. This means that each of the joints of the robot has a device for measuring the joint angle or extension. Further, a kinematic model must also exist, mathematically describing the possible time-based motion of the robot given its geometric design. Forward or direct kinematics calculations determine the position and orientation of the tool tip from measurement of the current joint angles and extensions. Inverse kinematics determines what the joint angles or extensions should be to reach a desired position and orientation.[3]

A major advantage to a remote operator using a robot is that he or she can now command a tool change or other pre-programmed action at the push of a button. Another advantage is that robotic manipulators offer a variety of intuitive motion types, including straight-line motion and tool tip motion about a fixed point in space; each substantially ease manually-controlled operation.

The RIA estimates that some 110,000 robots are now at work in U.S. factories[4], most of which have these characteristics. In the event that an existing non-robotic remote manipulator is desired, modification may be possible by adding the critical measurement devices, kinematic models and appropriate computing and driver components.

Most commercial off-the-shelf robots are simply capable of teach-and-repeat operations. An operator typically stands near the robot, moves the manipulator to a desired position and orientation using a button box input device, then commits the point to memory in the program. When the program is run, the robot will return precisely to each point in the sequence as rapidly as possible. This approach to control has been most successful for manufacturing operations where the same program can be run many thousands of times and the required points do not change from one workpiece to the next.

Unfortunately, this approach is totally inadequate for the unstructured environments of emergency responders and combatants. What they encounter is nearly unique each time: different approaches, hazards, obstacles, orientations and targets of interest. A fully-automated response to each environment would require an extremely complex system. The system must be capable of sensing the environment, adequately reasoning about it, planning its activities both at high-level sequencing and low-level execution, executing, sensing and recovering from error, and successfully cycling this process. Much research has been carried out in these areas in the past few decades, and for some applications this may be possible. However, a system of this complexity does not immediately instill confidence in commanders and operators that the system will reliably operate in critical situations.

Our approach accepts that during such critical times, operators are much more comfortable with personal knowledge and skills. We therefore structure the robotic system to accept operator intervention at whatever level deemed necessary, providing automated functions such as tool changes and deploying or stowing a manipulator at less critical times.

By taking the first step of making the manipulator a robot, a vast body of robotic experience and technologies in hardware, control, sensor integration, and automated planning and programming becomes accessible to remote manipulation operations. These, in turn, can lead to expanded mission capabilities, more design and process solutions (a broader supplier base), less operator fatigue, and faster execution with fewer errors.

3.2 Use Flexible Architectures

The robotics field is replete with experiences where a new technology was desired in a robotic system, and a substantial engineering effort in control software as well as hardware was required to implement it. Such efforts are costly and time consuming, and to a large degree redundant. To best access the new technologies as they are needed and/or become available and minimize the costly redundancy, architectures that facilitate easy integration of the broadest range of technologies should be applied.

An example of such architecture is the Sequential Modular Architecture for Robotics and Teleoperation (SMART), developed and expanded over a decade at Sandia National Laboratories[5]. SMART's modular control approach allows each hardware or software technology to be wrapped in one or more modules represented graphically on a computer screen. The modules are then assembled with others by a controls engineer to provide a particular capability. Each capability is checked for completeness, then the control software is automatically assembled, compiled, downloaded and launched on the new hardware system. SMART deals elegantly with non-linear control, *and guarantees the stability* of the software control system when the modular architecture specification is followed.

An example of how SMART has been applied to generate new control capabilities is shown in Figure 2. Here, the Editor portion of SMART is used by the controls engineer to assemble a capability to robotically control a REMOTEC™ Wolverine vehicle manipulator. A 6 degree-of-freedom joystick marked as CIS2 was chosen as an input device. Next, a robot trajectory planner (TRAJ) module was inserted to program autonomous movement between points. The Wolverine_KIN module contains the kinematic model of how the manipulator can physically move, and converts the trajectory into a series of manipulator joint angles. If the operator attempts to move the robot faster than possible, the CLAMP module will modify the signal to match capability. All signals are then sent to the remote device through the remaining modules on the line.

Figure 2 also builds the ability for the camera to track the tool tip, which releases the user from having to continually adjust camera controls while operating. The PTU_TAP module watches the tool tip position coming from the KIN module. The tool position is then converted into a sequence of angles for the pan and tilt unit (PTU) by the PTU_KIN module that drive the camera's PTU to track the tool. The JOG module permits the operator to adjust the camera position as it follows the tool, such that the object of interest is in a particular part of the screen. A PTU_BASE_KIN module (not shown) gives the hardware designer the flexibility to mount the PTU on any of the moving joints of the manipulator. In the case of the Wolverine, it is mounted on the rotating waist.

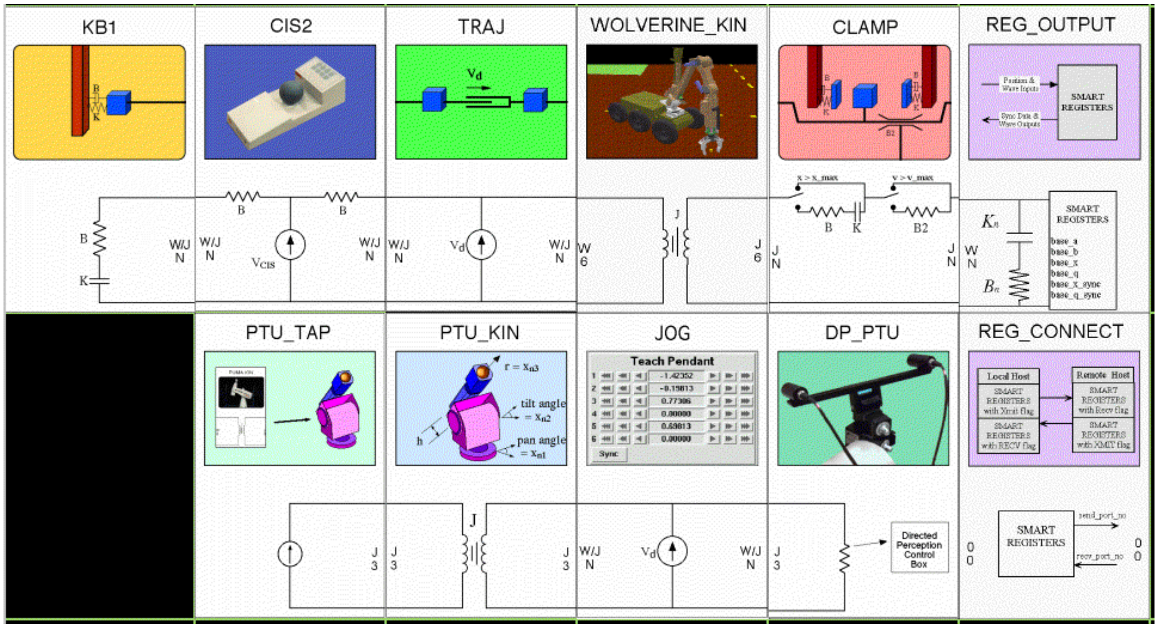

Figure 2. SMART Editor GUI building a Wolverine capability

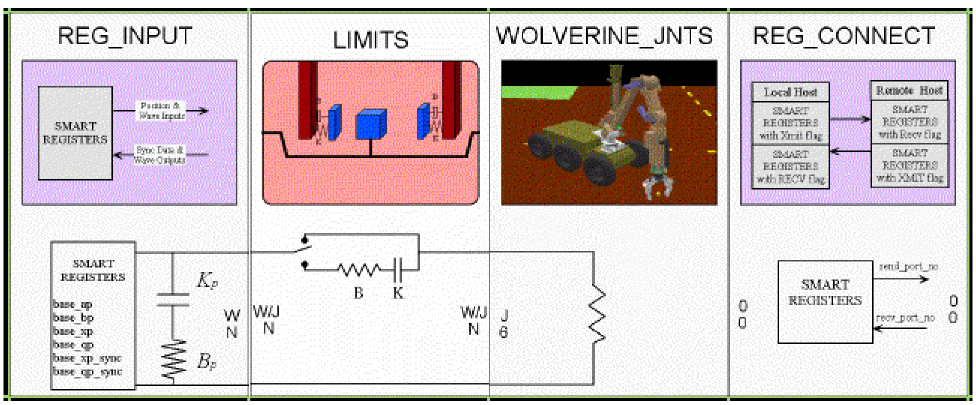

Figure 3. SMART control build for the Wolverine vehicle processor

Figure 3 illustrates the part of the control directly on the vehicle processor. It first connects to the command processor, then runs the commands through a LIMITS module. This module will prevent motion beyond the physical capability of the robot, as well as any other limit set to prevent collision, singularity issues, etc. The WOLVERINE_JNTS module then takes the joint angle commands, and executes the motion with the hardware. Joint angles and other discreet information are shared with the rest of the system through the REG_CONNECT module.

Once the controls engineer is satisfied that a sequence embodies the desired capability, it is checked, assembled and compiled automatically by SMART. The whole capability is then accessed by the operator by a simple button on SMART's Supervisor graphical user interface, which is discussed in the next section.

Within SMART there are nearly 300 modules representing various types of input devices, manipulators, kinematics, sensors, motion planning, communications, and Supervisor GUI elements. The result of a decade of applications development, they are continuously extended to new technologies, then mixed to provide a vast array of capabilities.

3.3 Use An Effective Operator Interface

An effective operator interface will provide sufficiently complete systems operation information in a quickly understandable format, and input capability that most efficiently interprets human intent into system action.

In our example of the Wolverine robot, the developmental user interface is divided into functional areas. On the left of the graphics screen in Figure 4 a series of buttons provides the operator with automatic operations such as deploy the arm, grasp a pipe and retrieve a tool. The ability to start from any arbitrary position and move to a desired location to perform a function such as grasp a pipe depends upon knowing the current set of joint angles, what the final set of joint angles should be, and what sequence of joint angles should be followed to get there. The first is supplied by measurement devices, the second by the kinematics model, and the last by a trajectory or path planner. All this is contained in the function of a single button in the interface.

To the right of the function buttons is a motion control button group. For ease of understanding, these are configured much like a VCR control, with arrows for forward and backward motion, as well as pause. Additionally, the speed may be adjusted with the slider bar below the arrows. If the operator chooses to grasp a pipe, the motion can simply be reversed by pressing the reverse arrow in this panel. Logically, if a manipulator has safely reached the pipe, it should be able to reverse the movement with reasonable chance of success. However, if the pipe protruding from the gripper is about to make contact with some obstacle, the operator can pause to examine the situation, then maneuver the pipe into a safe position before pressing the forward button to complete the operation. Alternatively, the operator can simply perturb the motion with an input device while the automated movement continues.

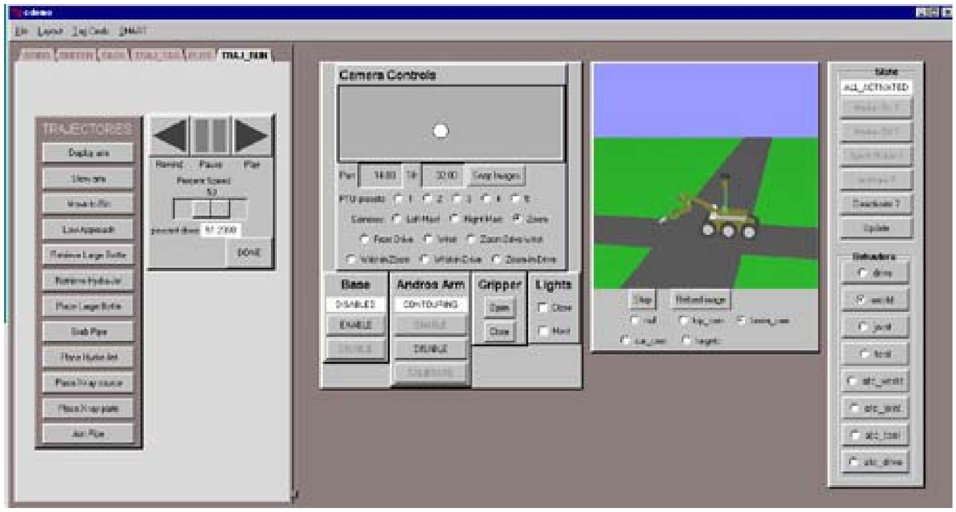

Figure 4. Developmental interface generated by SMART for the Wolverine robot.

The elements in the center of the screen in Figure 4 are the camera controls. In this version, the operator may select a camera view. For cameras mounted on PTUs, preset positions may be selected, or the camera guided through the available panorama by dragging the white dot in the box at the top to any position in the box. Below the preset and camera select buttons are options for picture-in-picture, which allow display of one or more camera views inset on the selected master view. Just below the camera controls are base and manipulator enabling buttons. To the right of those are the gripper controls and the camera lighting switches.

The next element of the screen to the right of the camera controls is a newly-developed graphical presentation of the robot configuration. The operator can spin about the robot in this window to gain any desired view, or select a preset view. During robot movement, this view is updated in real time from the measured position of the robot, but is also used to preview an automated move as necessary. The individual joints of the robot will change color if a joint travel limit is reached, indicating to the operator why motion may have stopped. The graphical view is executed using Open GL, permitting inexpensive implementation without specialty graphics programs.

The last set of buttons on the right of Figure 4 is the motion type selection. This is where the operator can access the straight-line motion, cylindrical motion, tool motion, and joint motion for telerobotic operation. Straight-line motion is the most intuitive way to approach objects and retreat. All joints are moved in a coordinated fashion to create a smooth straight line at the tool tip in the direction the operator commands. Tool mode permits the operator to move the tip of the tool about a point in space. This is especially valuable when rotating the manipulator about a point, such as changing impact angle while aiming a weapon at a particular target point.

Another important aspect of the operator interface is the physical input device. To demonstrate the modular flexibility of SMART architecture for input devices, the motion types described above were mapped into two different devices controlling the Wolverine. The first is a set of two 3-DOF joysticks in a commercial product from UK Robotics. The 6-DOF CIS or Spaceball provides sufficient degrees of freedom to control the entire manipulator with a single hand. Both devices work well for certain operations. Experimentation to determine which is most intuitive to optimize operator performance is easy within the context of SMART: simply replace the input device module with another, and the balance of the system operates as before.

3.4 Insert Technologies Incrementally

With a truly robotic system established under a flexible and robust architecture, a program to experiment with the world of newly-accessible technologies can be efficiently pursued.

In our example, a basic form of reachability analysis was implemented. This enables the robot system to evaluate a command to go to a location in terms of its physical ability to get there. If it is unable to reach the commanded point and orientation, it prevents motion from beginning and alerts the operator. It also serves to prevent collision with the robot itself, disallowing motion if joint limits would be exceeded.

A further development for tool movement is the ability to move in the coordinate frame of the video screen. When the operator switches to tool, cylinder or world mode, the input device is automatically registered to the video frame of reference. In this way, the operator is assured that "left" on the joystick produces motion toward the left of the screen, relieving him of another source of stress during telerobotic operation.

Another of the new technologies identified as potentially greatly enhancing system utility is Visual Targeting. Fundamentally, visual targeting is a means of using two calibrated cameras on the manipulator and/or vehicle, together with features marked on the camera images by the operator to triangulate the position and orientation of an object of interest. That information can then be used by the robotic system to execute a number of tasks. Initially, Visual Targeting has been implemented in a simple form that effectively uses operator knowledge about the object without extensive machine vision software.

To facilitate operator input, another interface technology developed by SNL called Active Sketch was adopted. In Active Sketch, the operator draws points and lines in two camera views on the object of interest. These points and lines indicate features of the object to the system, which interprets them depending upon the command next received from the operator.

To illustrate the combination of Visual Targeting and Active Sketch technologies, Figure 5 shows a line drawn on a pipe that is to be retrieved. The operator chooses two features on the pipe, draws a line between the two points in each of two views, then presses the Grab Pipe function button described in the previous section. The system now understands that the line has been drawn on a pipe. It has been pre-programmed that to grab a pipe, a vertical approach that bisects the line is desired. It then activates the trajectory generator to execute a path to the pipe, which it then grips at its center. This has been expanded to manipulation of other types of packages, door latches and knobs, and generalized to assist the approach to virtually any type of object.

It is important to note that during any of the automatic operations, the operator is capable of stopping the motion, adjusting the speed, or adjusting the position as the robot continues to move. This adds a degree of confidence to operations and enables the operator to deal with uncertainties such as loose manipulator gearing, sag due to gravity or sinking of wheels and tracks.

Figure 5. Using Visual Targeting and Active Sketch the operator indicates position, orientation and location for the robot to grasp a pipe.

Interactions with user community were extensive during the development and implementation of the above technologies. Community participants included the inter-agency counter-terrorism Technical Support Woking Group (TSWG), Albuquerque Police Department Bomb Squad, US Armed Forces, and DOE/NNSA emergency response personnel.

In experiments, operators have required approximately 4 minutes on average to execute the grasping operation under teleoperated (fully manual) control of a Wolverine manipulator from a fully-stowed position. Under robotic control with the Visual Targeting /Active Sketch combination, execution takes just under 1 minute. In another experiment, operators required from 5-15 minutes to carefully aim a disruption weapon at a pipe. Using the same Visual Targeting, it was complete in less than 2 minutes.

In other experiments, improvised explosive devices were recovered from building and car situations and placed in mock containment vessels for removal from the vicinity. Disruption weapons were aligned with target devices and proper placement verified by users. Breaching charges were placed on doors for forced entry. X-ray equipment was emplaced, x-ray recordings made and recovered in approximately 4 minutes without direct human intervention, approximately 5 times faster than baseline capability. Car and building doors were opened to access devices placed in indoor and outdoor scenarios, then confined space searches conducted, including access to glove boxes. Computer-assisted key insertion and turning to gain access to car trunks and doors was accomplished. Automated and computer-assisted tool changing was consistently carried out in the course of all demonstrations. The aggregate effect of the use of these advanced technologies is a reduction of operational times by factors of 2 to 5.

In the course of these interactions, other candidate technologies that have been identified for future insertion include advanced path planners, advanced reachability analysis, grasp analysis, and a number of fault recovery technologies including kinematic model reduction and visual servoing.

Advanced path planners can be used to move a robot through complex paths and around obstacles. Linked with sensors and available models, the path planners enable such actions as passing a manipulator through a car window and around a seat, or placing tools and weapons next to objects without collision with the target.

Reachability analysis determines whether a robot is capable of reaching points and orientations required to execute a task from its present base location. This was implemented successfully in a mobile multi-manipulator system used to replace coatings on the F-117 stealth fighter. It uses information gathered from a sensory system about the position and orientation of the target object, runs the kinematic model through a sequence of required moves, and determines if physical limits are exceeded. In our example, Visual Targeting would provide the target object position and orientation, and the function command button would provide the context for action. If the system determined the desired action could not be performed with the robot, it would display to the operator where to move the manipulator base in order to achieve success.

Grasp analysis techniques currently under development could enhance the ability of a system to move objects larger than the available gripper, or ensure a firm grip in the gripper. Enveloping grasps can be analyzed for their level of security in the presence of uncertain loading. Both geometric and frictional considerations may be included. Figure 6 speculates how grasp analysis may be used for a multiple-DOF manipulator securely grasping large objects.

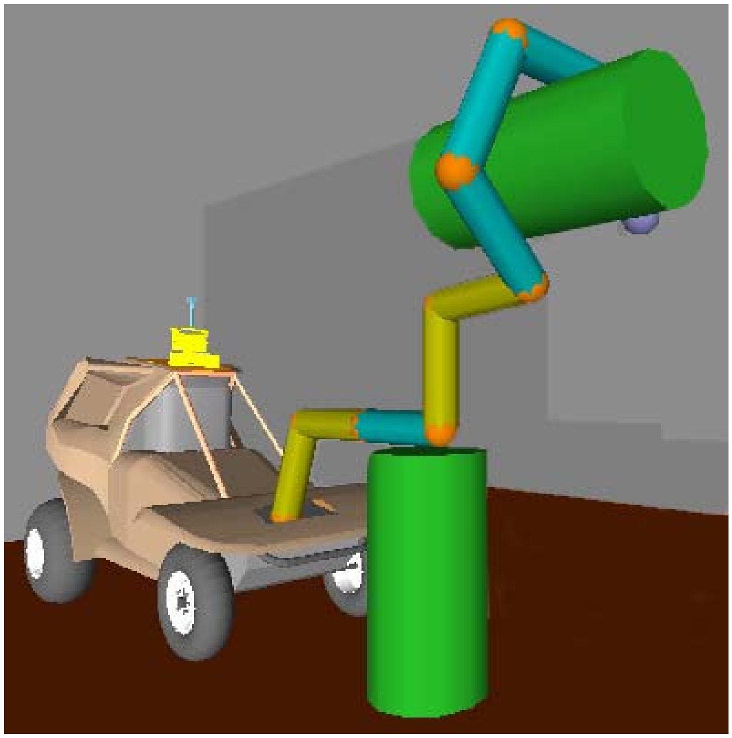

Figure 6. Secure grasping with a manipulator driven by grasp analysis.

Fault tolerance will be increasingly important in the application of field robotics. Whether an equipment failure occurs or other limitations surface due to operational conditions, the ability to complete a mission and recover will be critical. Research is being conducted to respond to a joint failure with an automatic re-forming of the kinematic model. This would enable the manipulator to execute a controlled move without the need to control the failed joint. Linked with the graphical feed-back, the operator can decide whether to return or to continue the operation.   Visual servoing is another recovery technique whereby a vision system automatically tracks visual targets on the manipulator components and deduces the actual joint angles from the position of the targets. In conjunction with a new kinematic model, this would permit near-normal operation if an encoder or potentiometer in a joint were to fail.

In addition to technologies that can be inserted into the mobile manipulation system, the SMART framework upon which many of these capabilities are built can be connected to the simulation world. This will provide access to design and performance evaluation tools, including wargaming networks, where modular systems can be evolved and tested for operational impact prior to actually being built. Recommended future work includes such a connection to UMBRA, an SNL-developed, military High Level Architecture (HLA)-compatible simulation environment.

4. CONCLUSION

An approach to remote manipulation has been described that exploits computer control while leaving the operator in the loop to take advantage of the operator's perceptual and decision-making capabilities. By first making the manipulator programmable with position control (ie. a robot), the operator can insert himself at any level of control deemed necessary. Further, a very broad range of developing robotic and supporting technologies can be accessed. To facilitate integration of these new technologies, a flexible modular architecture was described that enables efficient insertion and deployment. Finally, incremental integration of new technologies was described, each building on the capabilities of others. Each of these steps enhance operational capability, simplify control of the system, and speed execution of the operations, thus maximizing efficiency in the field.

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