The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Large Scale Multi-Fingered End-Effector Teleoperation

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Abstract–Large multi-fingered end-effectors have promise to provide the added dexterity needed for manipulation while decreasing the amount of special fixturing required for tooling and object manipulation common to remote handling operations in hazardous and unstructured environments such as those in the nuclear domain. This paper presents the integration of a heavy-duty three-fingered articulated hand with a Schilling Titan hydraulic manipulator that is part of a comprehensive telerobotics test bed. Experiments demostrated that a multi-fingered end effector approach has distinct benefits and advantages.

INTRODUCTION

Remote handling using various types of mechanical devices was first addressed in the 1940's and 1950's to allow scientist and engineers to handle radioactive materials safely during the Manhattan Project. This work eventually lead to master/slave mechanical manipulators crudely approximating human handling skills, while operating across radiations shielding barriers. These results represented the first concepts of teleoperation using robotic manipulators. Initial designs were totally mechanical devices and were restricted to close proximity to the hazardous environment, on the order of ten feet.

Later, this physical proximity constraint was eliminated by using electrically driven manipulators at both the master and slave locations, making it possible to have 100's of feet of separation. Over the years, the fundamentals ideas generated in this work migrated to other hazardous applications such as undersea, space, and explosive ordnance disposal.

In the nuclear arena, remote handling and telerobotics has more recently been applied to environmental clean up operations, including the demolition of contaminated nuclear facilities.

High-fidelity teleoperation typically consists of 6 degree-of-freedom (DOF) slave manipulators operated directly by humans using a master controller, which is essentially another 6 DOF manipulator. Motions made with the master controller produce corresponding motions in the slave manipulator with good tracking between the two. Such master/slave teleoperators can be unilateral, or bilateral, meaning they are either solely position controlled, or they provide the human operator with a sense of the force interaction occurring with the slave manipulator in the remote environment.

Even though manipulator designs have gone through dramatic advancements over the decades, manipulator end effectors have not. End effectors are the mechanical mechanism that serves as the interface between the manipulator and the work environment, including tools. The vast majority of general-purpose end effectors are based on the single DOF parallel jaw gripper. Parallel jaw grippers use opposing fingers to allow objects to be handled by a pinching-type grasp, similar to the jaws of simple pliers. With this type of end-effector, any turning type moments that may exist between the object and the fingers can only be balanced through friction. In many cases, friction is insufficient and other arrangements such as additional grasping brackets must be added to the tools or objects to provide restraint. Often, these special provisions become complex and expensive. Over the years, users have desired to have different types of end-effectors that could provide sufficient grasping points for stability. In recent years, much robotics research has focused on multi-fingered end effectors and object grasping. Much of this research has involved complicated anthropomorphic hand designs not suitable for harsh nuclear work environments, but nonetheless provoked interest in possible variants suitable for high payload dexterous teleoperated manipulators, like the ones used in nuclear dismantlement operations.

Decontamination and dismantlement (D&D) of nuclear facilities that have been shutdown involves typical demolition-type operations such as sectioning and downsizing of metal structures, removing concrete, stripping paint and contaminated materials from surfaces, and leveling old building structures to the ground. Most often commercially available, off the shelf, tooling and techniques are used to do these tasks. Saws, shears, sheet metal nibblers, cutting torches, and all other sorts of tools are used to cut tanks/vessels, piping, and support structures. Jackhammers and CO_2 pellet pressure blasters are used on concrete and for material stripping. Tools normally used in

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construction, or demolition, may be needed in a D&D remote operation after being adapted for remote manipulation. These operations require a large inventory of tools, including replacement tools, to achieve the full spectrum of tasks. The complexity and cost of tooling modifications necessary to assure reliable remote operations is proportional to the number of tools required.

A suitable multi-fingered end effector with at least three-point contact could alleviate many of the modifications that are made to tools for parallel jaw gripping. Through a DOE small business innovative research contract, Barrett Technology (www.barrett.com) extrapolated their experience with the dexterous BarrettHand™ to a larger and more robust design suitable for D&D requirements. The BarrettWraptor™ is the result. As shown in Figure 1, it is of a size and configuration generally compatible with hand-held tools and high payloads.

An additional and quite critical issue is the integration and control of a multi-DOF end effector integral to a dexterous teleoperated master/slave system. Parallel jaw grippers are single DOF and can be controlled using trigger-like interfaces that can be readily integrated into the master controller without any risk of disrupting remote work efficiency. This is not the case with something like the BarrettWraptor™. The problem that immediately presents itself is that of what physical and control interfaces should be used to integrate the hand controller into the manipulator master controller. This paper presents our studies regarding control schemes and methods of integration with a prototypical telerobotic system.

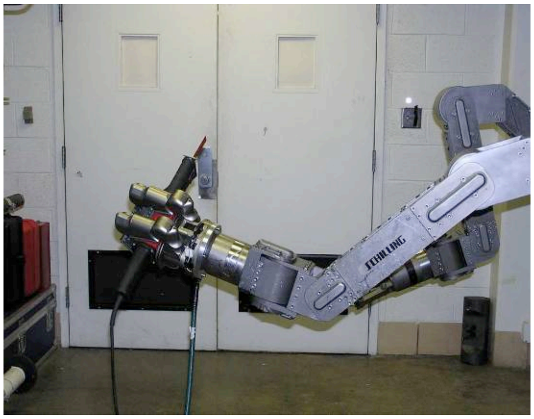


Figure 1. Wraptor holding a reciprocating saw mounted on the Titan II manipulator.

TELEROBOTIC TEST BED

The telerobotic test bed is located in the Robotics and Electromechanical Systems Laboratory at the University of Tennessee. The test bed has been used for extensive research into issues that influence the remote work efficiency of remote handling systems used in hazardous environments. Concepts of shared control, autonomous subtask control, and in situ task space geometric modeling have been explored. The test bed is a full-scale dual arm system with an integral prototypical operator controls station.

The slave manipulators are Titan II 6 DOF hydraulic manipulators made by Schilling Robotics®. Titan II's were originally developed for undersea operations, and are constructed primarily of titanium and weigh 225 pounds, with a reach of 78 inches and a payload at full extension of 240 lbs. The payload to weight ratio and robustness make this type of manipulator especially suitable for D&D operations. It has a serial chain wrist, pitch-yaw-roll, with considerable offsets (Figure 1). The manipulator incorporates a parallel jaw gripper, but provides a general-purpose mechanical interface that can readily accommodate the Wraptor.

Figure 2. The operator controlling the arm and the gripper from the CRC using the WAM.

The slave manipulators can be controlled with the standard Schilling minimaster, or with a haptic controller based on the Barrett Whole Arm Manipulator (WAM™). Another research project has focused on the use of the WAM™ as a somewhat universal force-reflecting master controller. The WAM™ is a 7 DOF lightweight cable-driven arm with minimal backlash and low friction joints. It has 4 active and 3 passive joints controlled through CAN-bus from a WAM PC at 500Hz. Its redundant kinematics, low friction, and gravity compensation are important properties for master control. The WAM and the Titan II have dissimilar kinematics which complicates both unilateral and bilateral control, making intuitive joint-to-joint control is not easy to achieve as discussed in [1]. A detailed discussion of the real time architecture of the test bed is presented in [2].

The operator workstation is based on the Compact Remote Console (CRC), Figure 2, originally developed by Oak Ridge National Laboratory and now manufactured by Agile Engineering, Inc. of Knoxville, TN. The CRC provides a comfortable workstation for viewing and controlling manipulators. It is equipped with four video monitors and two computer monitors. The CRC also has a touch screen computer, so that an operator can use it as a remote interface for computers or a video device interface to control camera views.

A Windows/C++ based GUI, with integral touch screen, has also been developed to control the camera displays on the CRC monitors and to select the control mode for the WAM teleoperation system. Figure 3 shows the section of the GUI that serves as an interface to the WAM/Titan high-level controller.

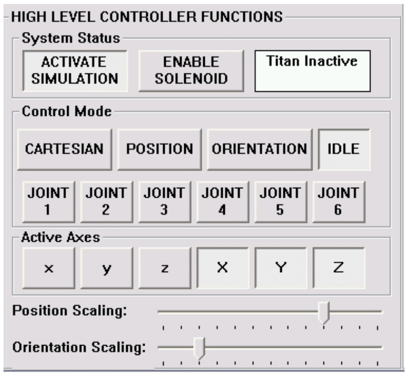


Figure 3. WAM/Titan high-level controller interface

WRAPTOR INTEGRATION

The Titan II arm with the standard parallel jaw gripper was tested using a bandsaw to cut a 2” diameter steel pipe. The tooling interaction forces, as measured with a force/torque sensor, were shown to reach values higher than 70 lbf [3]. These tests showed that end-effectors, including the Wraptor, must be able to withstand high tooling interaction forces common in tooling operations.

The Wraptor is generally able to grasp off-the-shelf tools without modifications, and was expected to handle the tooling interaction forces generated by large tools necessary for D&D. This end-effector has three finger-like mechanisms with a total of 7 DOF, and is able to create more points of contact, thus providing more stable grasps. [4]

The Wraptor design is depicted in Figure 4. Fingers are labeled F1, F2 and F3, and the drive motors are labeled M1 through M7. Fingers 1 and 2 are able to rotate synchronously and symmetrically about the base, acting as two opposable thumbs. Aside from this spread motion, each finger features two independently controlled joints, labeled M1-M3 and M5-M6. All seven motors are brushless DC servomotors. Except for the spread joint, the finger joints are non-backdrivable, a design simplification made in the interests of cost and compactness [4].

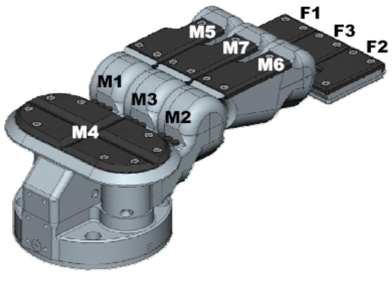


Figure 4. The Wraptor.

TABLE I. Wraptor Specifications

Specification	Quantity
Load Limits	50 kg/finger
Dimensions	131mm x 640 mm x192 mm
Mass	6.9 kg
Power	
Voltage	24 V
Current	10 – 30 A
Environmentally Sealed	IP-65
Motor Peak Torque	65 N-cm (92 oz-in)

Barrett developed Wraptor with its own particular data communication and control protocol. This allows the user to specify joint positions, velocities, torques and internal controller parameters.

The fundamental issue associated with integrating multi-fingered end effectors into dexterous telerobotic systems is preservation of the intuitive teleoperation characteristics that are central to high remote work efficiency. The operator must be able to use the multi-dof attributes of the end effector without disrupting the workflow of the overall system. The human hand has over 20 dof, but we seldom think about what is happening with the control of individual fingers during routine tasks. This form of control transparency must also be present in a telerobotic system.

Consequently, the major challenge with the Wraptor is the determination of a control strategy for the combined master controller for both the arm and hand used in this system, while sustaining overall teleoperation dexterity and performance. The combined master controller necessitates Wraptor control from a single human hand, the same hand that is controlling the motion of the slave manipulator itself. In order for an operator to be able to simultaneously control the Titan II arm and the Wraptor, the Wraptor control user interface needs to be as simple and intuitive as possible. Some teleoperation systems use data gloves or similar devices to control robotic hands [5]. These methods would be problematic for this case, because the Wraptor is kinematically dissimilar to a human hand; additionally, these could also make it difficult for the operator to simultaneously control the Titan II arm. We chose to approach the Wraptor control problem by integrating additional sensors into the conventional manipulator control handle, the same handle used with parallel jaw gripper end effectors. These sensors would serve as control channels that the operator could change with individual fingers or thumbs while simultaneously controlling the manipulators.

WRAPTOR CONTROL

Clearly, a telerobotic system with multi-fingered end effectors such as the Wraptor requires a new method of control. In order to determine the most effective and intuitive method, grasping operations were analyzed and divided into basic stages. These basic stages represent end effector motion sequences that can be chained together to accomplish overall behaviors necessary to accomplish tooling and object handling operations. The execution of each stage can be commanded from a single operator input through a discrete sensor that is integrated into the manual controller handle. The functional analysis showed that for any tooling operation, the movements of this end-effector can be divided into the following three stages:

1) *Approach the tool*

The fingers are commanded in a coordinated fashion to an open configuration using position control. This enables the operator to pre-position the end-effector relative to the tool. From this configuration the fingers can easily close around the object to form a stable grasp.

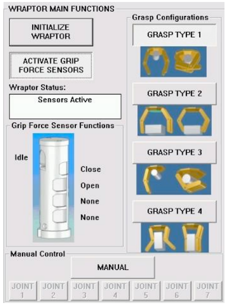
2) *Grasp and hold the tool*

The fingers are commanded in a coordinated fashion to close around the object. Once the grasp is complete, the Wraptor drive motors are commanded to apply a continuous torque in order to assure a firm grasp that can counter the tool vibration and interaction forces. The desired tooling operations are performed with the Wraptor in this configuration.

3) *Release the tool*

Once the operation is complete, the tool is returned to its original position and released. This stage can use the same position commands that were used to approach the tool, with the inverse trajectories.

It is believed that these stages are quite general, and can also be applied to operations for removing debris or moving objects other than tools. A task-planning strategy was adopted, utilizing the three stages of grasping. First, the operator chooses the tool or grasp type from a touch screen GUI, Figure 4, in the CRC. Then, the commands to approach, grasp and release are commanded from force sensors on the handle of the WAM master controller. The specific position and velocity commands for these three stages depend upon the selected tool or grasp type.



Wraptor Status: Sensors Active

Figure 4. Wraptor section of touch screen GUI.

The tool or other object type is selected on the right side of the screen. The "CALIBRATE" button is used to calibrate the Wraptor's position control. The bottom left window provides current system status information.

A set of grasp types based on shape primitives is included, allowing the Wraptor to grasp a wide variety of objects. Extensive research has focused on determining and analyzing the most stable end-effector grasp configurations for different types of objects. Most of these methods are based on the assumption that the geometry of the object is known [6]. However, in teleoperation, the object geometries are not necessarily known. Some methods have been determined for teleoperation and grasping objects of unknown geometries, such as groping and vision-based methods [7], [8]. These methods would not be efficient or effective for this teleoperation system. A small set of basic grasp types were determined for a three-fingered end-effector [9]. This set was modified and tested for use with the telerobotic system.

Preliminary experiments were performed with a number of different objects to determine which grasp configurations are most useful. The set of standard grasp configurations used in this software is shown in the GUI in Figure 4, and are discussed below.

Grasp Type 1: This grasp is called the cylindrical power grasp, and is the most powerful and most common configuration. It is used for almost all tooling operations. However, this grasp configuration generally requires palm contact before the fingers wrap around the object. This can be a problem because in many cases there is no space for the fingers to go past the object, as in the case of an object sitting on the floor or mounted against a wall. Therefore, this grasp type is more often used with tool racks that are designed to allow space for the Wraptor fingers to reach around tools.

Grasp Type 2: This grasp is most useful for small, light pick-and-place operations. In this case, the fingertips are fixed. Only the inner links move. Since palm contact is not necessary, this grasp configuration can be used to grasp objects that are resting on surfaces.

Grasp 3: This grasp can be used in similar situations as the Grasp Type 1, but space is only required for the fingers to wrap around the object from one side. For the same reasons, it can also be somewhat easier to release objects from this 180° configuration, especially in cluttered task environments.

Grasp 4: This type is especially useful for grasping flat-sided objects. It can also be used to grasp objects that extend past the length of the fingers, as in the case of grasping a pipe from the end. Like the second configuration, palm contact is not required.

Once the operator completes task planning and setup, all other necessary Wraptor functions can be controlled solely from the control sensors integrated into the handle of the WAM. Most importantly, the operator can control the Titan II and the Wraptor simultaneously from the master controller without returning to the graphical user interface. Therefore, aside from the initial setup, the operator has the ability to simultaneously control both the Titan II and the Wraptor using a simple, intuitive, integrated master controller.

The operator input commands to execute the motions to approach, grasp, and release an object are commanded from the FlexiForce™ grip force sensors mounted on the handle of the WAM master controller. Five sensors are mounted on the handle, one for the thumb and one for each finger. These sensors can function as analog inputs to the system since their output level is proportional to the digit pressure applied by the operator. The sensor functions handle layout is shown in Figure 5. As shown, the thumb and first two finger sensors are assigned to Wraptor state control. The remaining two sensors can be assigned to other functions as appropriate.

Figure 5. WAM operator handle and sensor functions.

The Wraptor can hold objects with the motors de-energized by relying on the self-locking nature of the non-backdrivable finger joints, but this is usually insufficient for countering tool vibrations and interaction forces. In our initial work, the third finger sensor was used to provide temporary hold torque through the finger drives to command additional grip force for counteracting sporadic tooling movements. The operator can release this command as necessary in order to prevent drive motor overheating. The software also provides over-temperature warnings and automatically cuts power to the Wraptor motors if the temperatures reach specified limits. Figure 6 shows a close-up of one of these sensors mounted on the handle of the WAM.

Figure 6. FlexiForce™ sensor.

The sensing area of the FlexiForce™ sensor is made of a pressure-sensitive ink [10] whose resistance varies with applied force. These sensors can also serve as digital inputs as in the case of idle, close and open, using a software threshold.

Regardless of how the general set of grasp types is defined, there will be some objects that do not work with the predefined set. In some other cases using the predefined grasps, it is also useful to be able to adjust the approach positions online. Therefore, it is desirable to have the ability to control individual joints, even though the process is slower than the semi-automated option. An additional manual control mode is included, in which the operator can manipulate any combination of joints. At the bottom of the Wraptor section of the GUI, the operator can select "MANUAL" mode. The grip force sensors function in a slightly different manner than with the predefined grasp types. Still, three sensor functions are defined as open, close and idle. The Wraptor is controlled in velocity mode, and the commanded velocity is a linear function of the force exerted on the grip force sensor. One grip force sensor is used to command velocity in the open direction, and another is used to command velocity in the close direction. When the operator releases a sensor, or if the grip force drops below a threshold voltage, then the Wraptor is commanded to servo to a velocity of zero. Hence, as the operator presses harder on a sensor, the selected Wraptor joints move faster, and when the sensor is released, they stop moving.

EXPERIMENTAL RESULTS

A set of experiments was designed to demonstrate and evaluate the Wraptor-based task execution. The tools and tasks were selected to emulate real D&D operations.

Debris Handling Operations

To emulate basic debris handling operations, three types of building materials were picked up from the floor and placed in a bin: a 2 ½" diameter pipe section, a wood block, and a cinder block. Grasp types 2-4 were used in these operations. For the cinder block, it was found that the approach position for grasp type 2 needed to be adjusted in order to slide the fingers through the holes in the cinder block. The manual mode was used to slightly close the inner links prior to approaching the block.

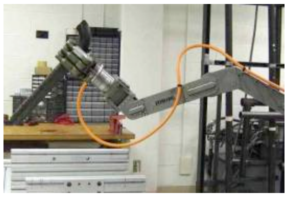


Figure 7. Debris handling operations

As mentioned earlier, the Wraptor has non-backdrivable finger joints drives without slip clutches. Therefore, the experiments were designed to prevent the fingers from encountering any type of hard contact. Operations involving close proximity to rigid surfaces were performed slowly and carefully in order to protect the Wraptor. If the Wraptor were backdriveable, it is believed that most of the tooling operations could be performed faster. Images from the three operations are shown in Figures 7-9.

Typically, once the Wraptor is in position to initiate a grasp, a stable grasp can be formed in less than four seconds. Likewise, releasing an object can also be performed in less than four seconds. These experiments were performed slowly in order to protect the prototype Wraptor from damage from impact. During debris handling, the Wraptor was reverted to the idle state at every opportunity, and no temperature warnings occurred.

Figure 8. Cutting aluminum rod and steel pipe

Cutting Operations

Cutting operations were performed with a reciprocating saw, a common cutting tool that is also difficult to use remotely. Several materials were cut, including a ½" diameter brass rod, a 1½" diameter aluminum rod, a steel bar 1/8" thick and 1½" wide, and a 2 ¾" steel pipe with a 1/8" wall thickness. We found that Grasp type 1, the cylindrical power grasp, works very well for the reciprocating saw. The tool rack was designed such that palm contact can be established before closing the fingers around the tool.

Reciprocating saw operations do require that the tool be held with significant torque, in order to counter the tool vibrations and interaction forces. This meant that the finger drive motors were active most of time, and therefore, high temperatures were an issue. In most cutting operations, the maximum recorded temperatures were between 60°C and 65°C. Typically, only a few cuts could be performed before temperature warnings occurred.

Table II. Operation Times for Two Consecutive Cuts of the Brass Rod

Operation Status	**Time (min:sec)**
In position for grasping	0:00
Fingers closed	0:04
Begin cut 1	3:15
Finish cut 1	3:50
Begin cut 2	4:25
Finish cut 2	5:20
Replaced saw	7:35

These elapsed times include the bulk manipulation movements necessary to acquire and return the tool. This could be reduced considerably with improvements to the current master/slave control limitations present with telerobot.

Impact Wrench Operations

An impact wrench was used to remove three ½" bolts from the test stand. Grasp type 1, the same cylindrical power grasp that was used for the reciprocating saw, was also used to grasp the impact wrench. However, in order to provide room for the handle to easily slide between the fingers, the approach position of the fingers was modified slightly using the manual mode. The sequence of grasping the tool and removing the first bolt is shown in Figure 9.

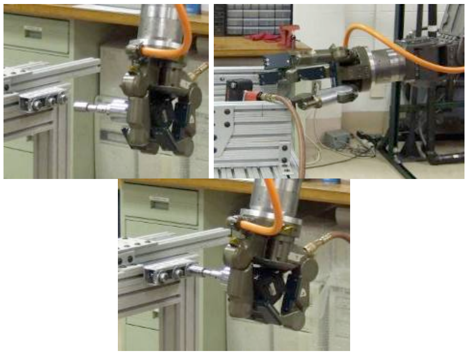


Figure 9. Removing a bolt using an impact wrench

All three bolts were consecutively removed in one successful operation, while holding constant torque. Some motor temperatures did exceed 60°C, but none exceeded 65°C.

SUMMARY AND CONCLUSIONS

We feel that this limited set of D&D operational emulations has demonstrated the potential merits of multi-fingered end effectors versus parallel jaw grippers. All tests in the experimental plan were performed successfully. The Wraptor was able to grasp and hold both the reciprocating saw and the impact wrench throughout respective tooling operations. Operators found that the impact wrench and reciprocating saw are easier to use with the Wraptor compared to experience with parallel jaw grippers, because of the closer physical coupling to the slave manipulator.

A few issues are apparent with regard to the current Wraptor design that should be considered in future design revisions. The kinematic architecture is effective but the physical size is too large. In the perspective of this application domain, tooling devices and objects are those designed for humans. The finger and thumb lengths are nearly double large human size. It is believed that more stable grasps of off the shelf tools could be achieved with more anthropomorphic-sized fingers. Telerobotic operations in hazardous and unstructured environments are extremely difficult and more often than not result in undesired impacts between the handling equipment, tools and task objects. The non-backdrivability of the finger drivetrains would not survive under such conditions. The incorporation of slip clutches or backdrivable drivetrains would be a major design change that could impact compactness and cost. Nonetheless, a multi-fingered end effector used in this class of telebrobotics must have a robustness that can withstand substantial impact loading.

The most important conclusion of these studies is that multi-fingered end effectors can provide more effective tooling handling and operations while drastically reducing requirements for special tools and fixtures compared to techniques based on parallel jaw grippers.

ACKNOWLEDGEMENTS

Authors thank Dr. Bill Townsend and Dave Wilkinson , along with their colleagues at Barrett Technologies, Inc., for their work on the development of the BarrettWraptor™. This work was supported by the U.S. Department of Energy through a sub-contract with Barrett Technologies, Inc.

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