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Bachelor of Science in Mechanical Engineering

Large-Scale Dexterous End-Effector Manipulation

A Senior Project

for the

Chancellor's Honors Program

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Abstract

Teleoperation has been used to perform manipulation in hazardous areas since the 1940s. The current standard system used for the dismantling and decommissioning (D&D) of inoperative nuclear facilities uses a parallel-jaw gripper end-effector. These operations also use many standard hand power tools. This end-effector apparatus requires that specialized fixtures be designed and fabricated for almost every tool that is used. The Department of Energy is in need of a way to provide versatile tool fixturing at a lower cost. This research investigates the implementation of Barrett Technologies, Inc.'s BarrettWraptor™ large-scale three-fingered end-effector as a replacement for the parallel-jaw gripper. The utilization of this end-effector can significantly reduce the tool fixturing costs and increase productivity by providing a way to use off-the-shelf power tools with fewer modifications.

Introduction

Teleoperation was created in the 1940's for the purpose of providing means to manipulate radioactive and otherwise hazardous materials from a remote location. It has also been used in space, undersea, search and rescue, military surveillance and surgical applications, among others. There are many types of teleoperation; remote-controlled vehicles are common types, including those that travel in air, water or on ground. In the case of nuclear facilities, the most common type of teleoperation system involves a slave arm with a parallel-jaw gripper on the "hot" side, and a replica master arm on the operator's side; the operator produces motion of the master, and it is copied by the slave. Only a simple variable input, such as a rotating disk or single variable switch, must be added to the master in order to control the parallel-jaw gripper. These systems are mature and have been used extensively in some of the more dangerous nuclear D&D operations. However, as a result of several factors, their productivity is in the range of ten times slower than human operators. And their operating cost is extremely high compared to that of equivalent human laborers [10].

One system that has been developed for these DOE nuclear D&D operations includes a very large slave robot named ROSIE, like the Jetsons' maid. This system uses Kraft Predator robotic arm, attached to the end of an extendable boom with a maximum extension of 20 feet. It is mounted on a mobile platform called a locomotor. A lifthook can be added as the end-effector, resulting in a system that can lift payloads of up to 1 ton.

Figure 1. Rosie with jackhammer end-effector [8]

During one test, this system, using a single operator, was used to remove a large portion of a nuclear reactor's structure and graphite shielding blocks in approximately 60 hours [8]. It was also tested using some other tools, including a jackhammer.

The telerobotic system used in this research works under similar concepts, but it is smaller and has no boom. It will use two hydraulic, non-redundant Schilling Titan II slave arms, mounted on a mobile platform.

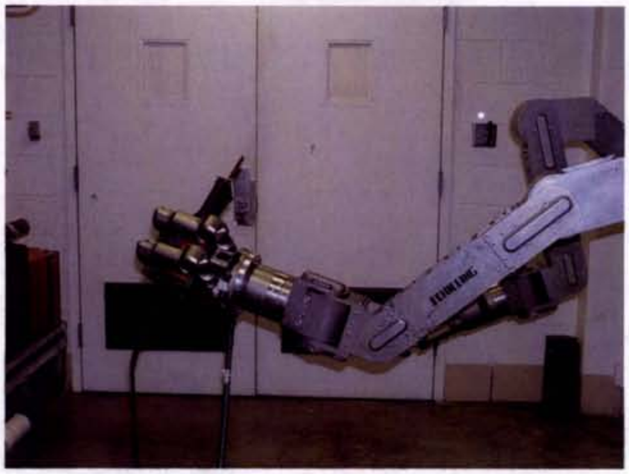


Figure 3. Schilling Titan II™ arms with Wraptor and reciprocating saw

These arms were designed for underwater use; they are constructed primarily of Titanium, have a reach of 78 inches, and have a payload capacity at full extension of 240 lb. The master controller is a cable-driven, redundant industrial robot arm called the BarrettWAM™, or Whole Arm Manipulator, which was designed to be used as an independent manipulator. Here, it is used in reverse; its position is controlled manually by the operator, so it functions as an active master manipulator for the Titan II. For this phase of development, we are assembling and testing the system without the mobile platform and with only one master-slave set of manipulators. An interesting aspect of this research, which is a separately funded project, is that the WAM master has seven degrees of freedom, while the Titan II has only six.

The system also includes a Compact Remote Console (CRC). This console includes four video monitors for viewing the remote task space, two computer monitors for monitoring system performance and a simulation model of the arm, the WAM master, and a touchscreen computer with graphical user interface (GUI) software. The CRC is shown in Figure 4.

Figure 4. Current CRC setup (right)

The decommissioning of a nuclear facility can generally be divided into two main components: dismantling and demolition. Dismantling refers to the disassembly of equipment such as piping, plumbing, tanks, etc. Demolition refers to the reduction of the building structure to rubble. Some tools commonly used in the dismantling stage are nibblers, saws, circular cutters, wall and floor saws, abrasive cutters, etc. Demolition is performed using controlled blasting, wrecking balls, core/stitch drilling, etc. This teleoperation system would be used primarily for dismantling and debris manipulation [2].

Many grippers other than the Wraptor are available. The most common types used for teleoperation are the parallel-jaw grippers. There are many different sizes and many different types of parallel-jaw grippers available. In spite of their inherent limitations resulting from their mechanical simplicity, they are the most popular type of end-effector in both industrial/manufacturing applications and in teleoperation because of their relatively low cost, reliability and simplicity of use.

The focus of this research project is the development of a teleoperation control strategy for a new BarrettWraptor™ end-effector. The Wraptor is described in detail in the next section.

The Wraptor

Barrett Technologies, Inc. has supplied us with one of only two existing prototypes of a new three fingered grasper called the BarrettWraptor™. Many other three, four and five fingered graspers have been developed, but none are powerful enough to work well in these types of tooling applications with high interaction forces. The tooling interaction forces with the Titan II were tested using a parallel jaw gripper and bandsaw to cut 2" steel pipe; forces higher than 70 lbf were recorded [7]. This is the first multi-fingered grasper of its kind that is durable and powerful enough to be considered for nuclear D&D operations. Figure 5 shows an image of the Wraptor holding a pipe.

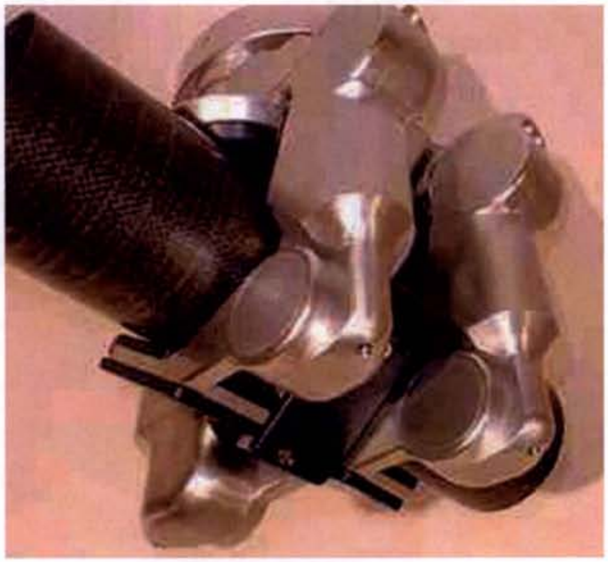


Figure 5. BarrettWraptor™ with pipe

Table 1 shows selected Wraptor specifications [4].

Table 1. Wraptor Specifications

Specification	Quantity
Load Limits	50 kg/finger
Dimensions	131mm x 640 mm x 192 mm
Mass	6.9 kg
Voltage Requirement	24 V
Current Requirement	Min 10A, Max 30 A
Environmentally Sealed	IP-65
Motor Peak Torque	65 N-cm (92 oz-in)

One recent technological advancement that has contributed to the development of this significantly stronger grasper is the advent of rare-earth Neodymium-ferrite (Nd-Fe) magnets, which are used in the rotors of the brushless DC servomotors of the grasper. As advertised in the BarrettWraptor™ Manual, these are "the smallest motors in the world for their torque range" [4]. If an Nd-Fe alloy is properly processed and pressed in the direction in which it is magnetized, it can be several times stronger than traditional ferrite magnets. This allows for significantly higher maximum torque to weight ratios of the motors. However, there are some problems inherent with these small motors. They produce a lot of heat, which is especially difficult to dissipate in an application that requires such strong sealing. Therefore, it is difficult to hold continuous torque without overheating the electronic components.

Figure 6 shows a CAD image of the Wraptor, with each joint labeled as M1 through M7.

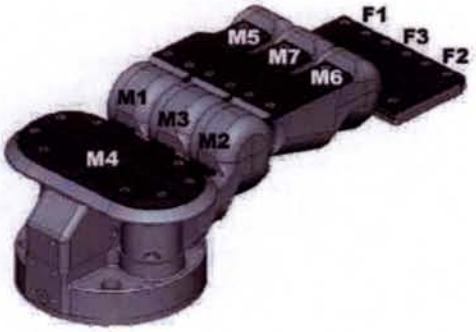


Figure 6. CAD image of the Wraptor

Each finger has two independently controllable joints labeled M1-M3 and M5-M7. Fingers F1 and F2 can rotate synchronously and symmetrically about the base, acting as two opposable thumbs. This spread motion is produced by a single motor, M4. Aside from the spread, all of the finger joints are non-backdrivable and independently controllable.

Problem Statement

The DOE's basic need is an intuitive, practical system to facilitate control of the Titan II arm and its end-effector by remote operations. For the purposes of this project, several aspects of this system are known. For instance, Barrett Technologies, Inc.'s WAM arm is used as the master controller for the Titan II. The Compact Remote Console (CRC), which was mentioned in the introduction, has also been developed, and it can be used in this system with very few modifications. Also, the Wraptor is provided from Barrett Technologies, Inc., with its own communication protocol which allows the user to specify joint positions, velocities, torques and internal controller parameters.

The focus of this project is the creation of a user interface to control the seven degree-of-freedom Wraptor. Eventually, the system will be expanded to include two sets of the Titan II/Wraptor. Therefore, the combined 13 DOF Titan II/Wraptor system must be controlled from one human hand. The development of a simple, intuitive control strategy for such a complex system is the most interesting component of this problem. Three major requirements listed in the proposal for this project are to develop a rugged robotic hand with the capability to:

1. Coordinate the arm and finger trajectories to obtain a secure grasp automatically in under 10 seconds.
2. Maintain the grasp of a power hand tool securely against strong kickback forces and torques.
3. Provide adequate dexterity to perform a variety of debris-handling and manipulation tasks in addition to fixturing cutting tools. [9]

Figure 7. The dual-arm system

A strategy has been determined that facilitates control of the Wraptor from a set of five grip force sensors mounted on the handle of the WAM master controller. A task-planning approach is used; before each operation, the operator selects from a list of predefined grasp types. This task planning stage requires only one button. A set of force sensors are mounted on the handle of the WAM master manipulator. Once the grasp type is selected, the commands needed to approach, grasp and release the object can be sent from the grip force sensors. Hence, aside from the selection of the grasp type, the operator can command all necessary motions on the slave side using only the WAM master controller and the sensors mounted on its handle.

Wraptor Control Strategy

There are several common master-slave control methods in telerobotic applications. The first is to map the position or velocity of an endpoint of the master controller to the position or velocity of the slave end-effector in space, using forward and inverse kinematics calculations. This method is used to control the Titan II arm using the WAM as a master. However, in the case of the Wraptor, the positions of the ends of the fingers are not of interest; we wish to manipulate the intermediate points along the links where they contact the object.

One possible method would be to use joint-to-joint mapping with a small master that could be controlled by a human hand. Some teleoperation systems use data gloves, exoskeletons or similar devices which are kinematically similar to the actual robotic hands. The use of a dataglove was investigated early in this project. However, these methods pose several problems, as noted by Michelman and Allen at Columbia [1]. Accurate calibration is difficult to achieve, complex force reflection is difficult, and even the most biomimetic robot hands have different capabilities than human hands. Additionally, this hand is especially kinematically dissimilar to a human hand; it has three fingers, two of which are opposable thumbs. And it would be difficult to use a dataglove while simultaneously controlling the Titan II arm.

In this project, it is desirable that the teleoperation system be competitive with a human worker in terms of productivity and capabilities. When a human worker decides to use a tool, the act of grasping the tool in a stable manner is trivial; the process is intuitive and very fast. However, if an operator needs to control seven independent links of a robotic hand with 10 inch long fingers, the simple act of grasping a tool could be difficult and time consuming. Additionally, the process needs to be intuitive in order to minimize the required operator training time [9].

Therefore, this teleoperation system requires a new method of controlling the end-effector. In order to determine the most effective and intuitive method, grasping operations were analyzed and divided into components. The execution of each component can be commanded from a single user input. For any tooling or pick-and-place operation, the movements of this end-effector can be divided into the following three stages:

1) *Approach the tool*

The fingers are commanded to an open configuration using position control. This enables the operator to position the end-effector relative to the tool. This configuration is defined such that the fingers can easily close around the object and form a stable grasp. At this stage, it is the operator's responsibility to make sure that the fingers can wrap around the desired object unobstructed and that the tool is centered in the robotic hand.

2) *Grasp and hold the tool*

The fingers are commanded to close around the object in the most stable manner. Once the fingers are in place and the motors stall against the tool, the motors must hold continuous torque in order to counter the tool vibration and interaction forces. The tooling operations are performed at this stage.

3) *Release the tool*

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

A task-planning strategy was adopted, utilizing these three stages of grasping. Before executing an operation, the operator selects the grasp configuration and type from the touchscreen graphical user interface (GUI).

A new touchscreen graphical user interface has been developed for this system. This serves as the only component of the user interface other than the master controller itself. As shown in Figure 8, the Wraptor functions are on the right side of the screen. The left side is devoted to the other parts of the system.

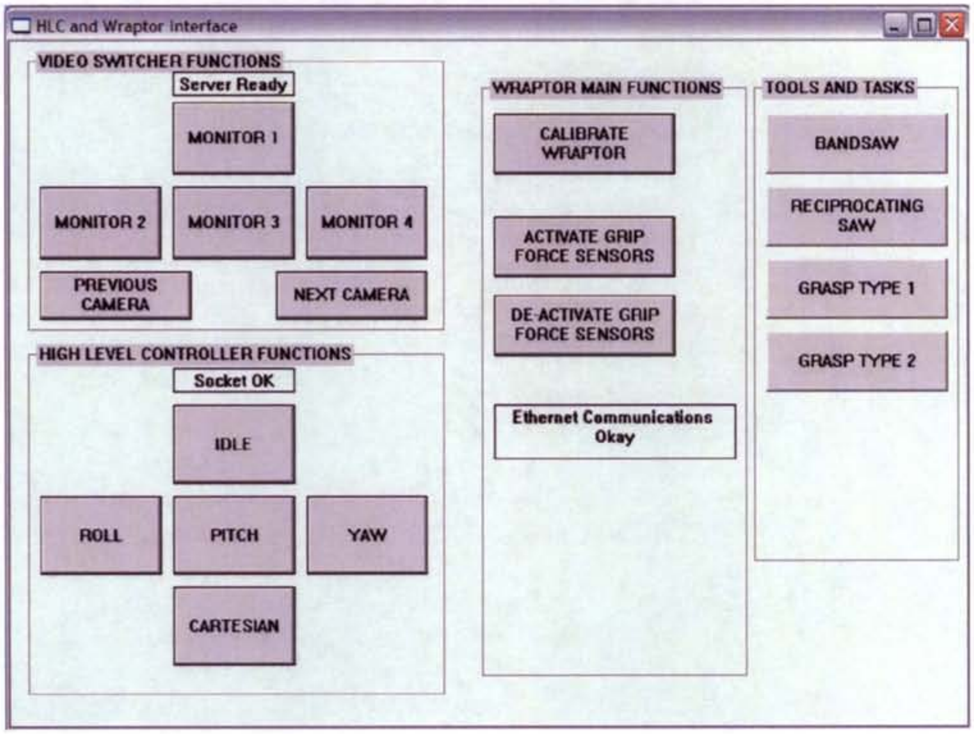


Figure 8. Graphical user interface (GUI) for Wraptor system

Each time the Wraptor is powered up, it must be calibrated; the user can send the calibrate command from the GUI. Aside from power and software startup, this is the only requirement to startup the Wraptor part of the system. The grasp type is selected from the vertical list on the right side of the screen. An image will be added to the bottom-right portion, giving the operator an indication of the functionality of each grip force sensor, and additional grasp types will also be added.

On the right side of the screen, there are two other sections. First is the video control region. The CRC has four video monitors, but the system can handle more than four video inputs. This gives the operator the ability to switch between camera views as needed. The second section provides means for the operator to change the control mode of the high-level controller for the WAM/Titan system. The position of the end-effector can be controlled in Cartesian mode, and the three wrist joints can be moved independently. Also, the system can be put in idle mode, so that the operator can reposition the WAM if needed without causing any motion of the Titan II.

This GUI software was written in C/C++ using Microsoft Windows Application Programming Interface (API). The touchscreen computer communicates with the high-level controller computer and Wraptor Linux computer via TCP/IP and with the video switcher via serial port. It does not send any commands directly to the Wraptor; it sends commands to the Wraptor controller computer, which in turn sends processes the inputs and sends the corresponding commands to the Wraptor. A diagram of the Wraptor network is shown in Figure 9.

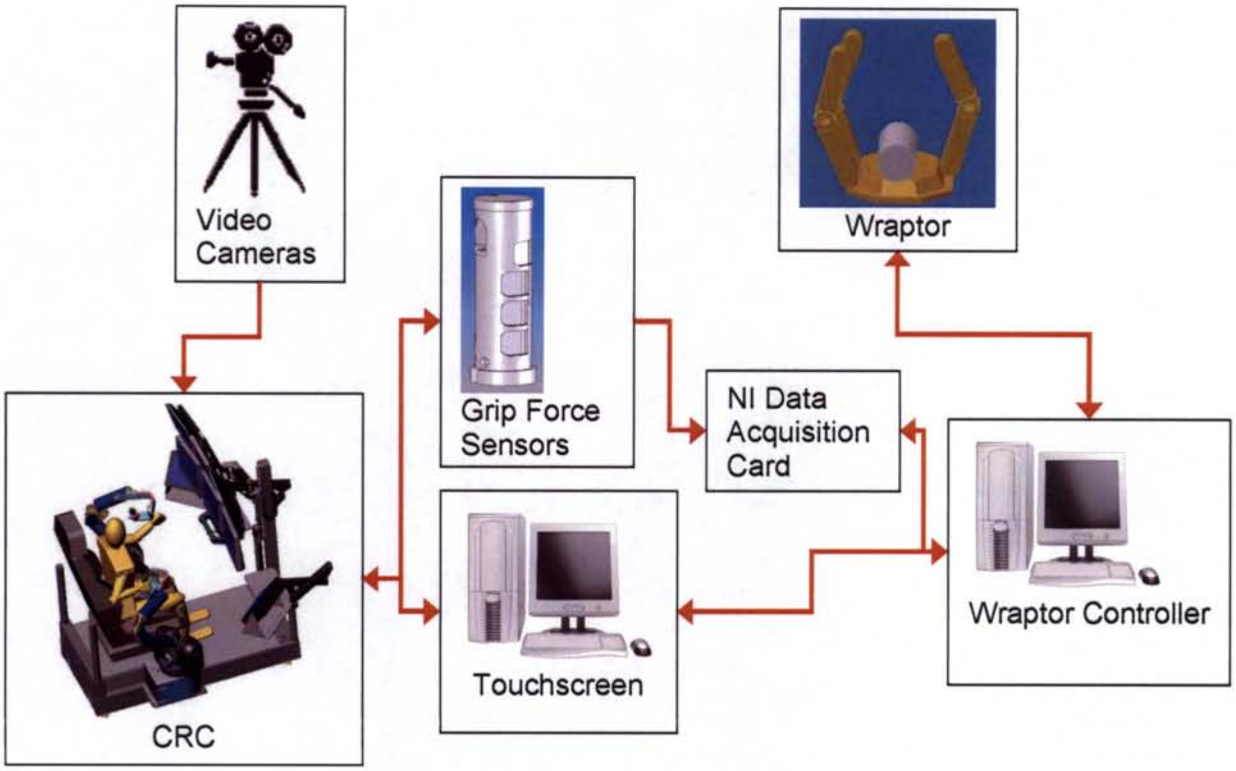


Figure 9. Wraptor Network

The Linux/C based Wraptor controller software acquires the data from the analog grip force sensors using an open-source Comedi® driver with a National Instruments NI-6036E data acquisition board. The acquired sensor data is analog, although it is currently used as a digital input. The Linux computer communicates with the touchscreen computer via TCP/IP. The Wraptor controller processes all user inputs for the Wraptor and sends the corresponding commands to the Wraptor via serial port.

An op-amp force-to-voltage circuit is required to convert the force exerted by the operator's fingers into an analog signal that can be read by the Wraptor controller's data acquisition system. This circuit is shown in Figure 10.

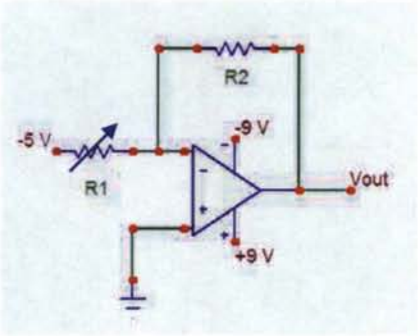


Figure 10. Force sensor circuit diagram.

The variable resistor shown on the left side of the circuit is the force sensor. This circuit produces a linear relation between output voltage and applied force. The circuit calibration is achieved by adjusting the feedback resistance, R2. A new handle for the WAM manipulator has been designed in order to mount the FlexiForce™ sensors. Figure 11 shows the sensor for the thumb, mounted on the new WAM handle.

Figure 11. FlexiForce™ sensor mounted on WAM handle

Figure 12 illustrates how the force sensors are used in this system.

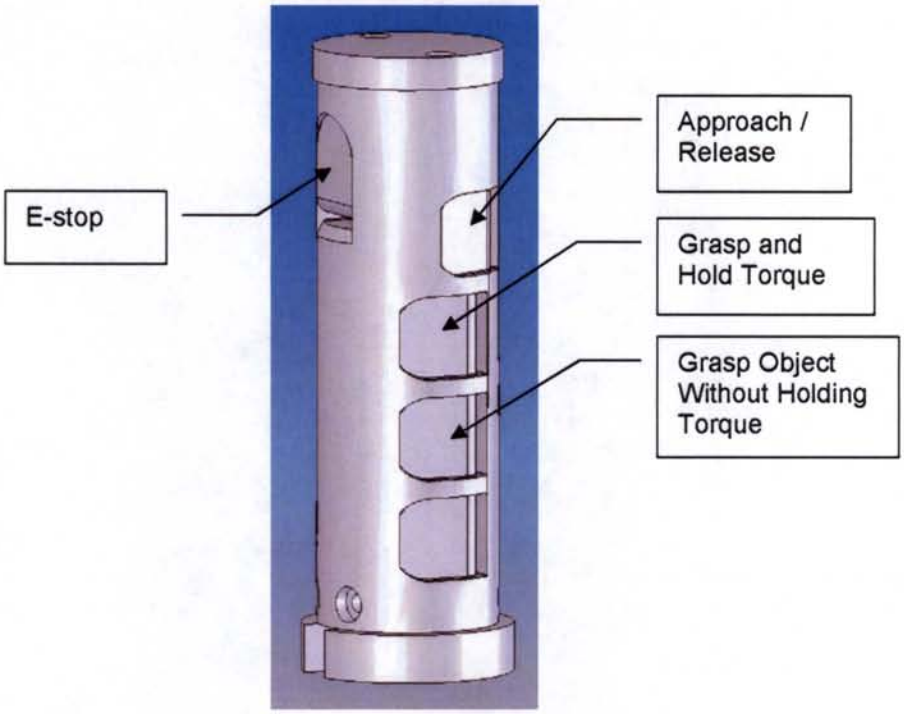


Figure 12. Sensor functions

The instructions to go to the approach position, grasp the object and release the object are commanded from three of the the force sensors. A fourth sensor is used as a stop/idle button; this can be used to idle the motors for the purpose of lowering the temperature or for cancelling an unintentional or incorrect command during execution. The fifth sensor is available for an additional function to be added in the future.

Predefined Grasp Configurations

In the late 1980s and 1990s, considerable research work focused the determination of grasp configurations for complex multiple-degree-of-freedom robotic hands. In *Mechanical Hands Illustrated,* the following chart was created for classification of grasp types of human hands.

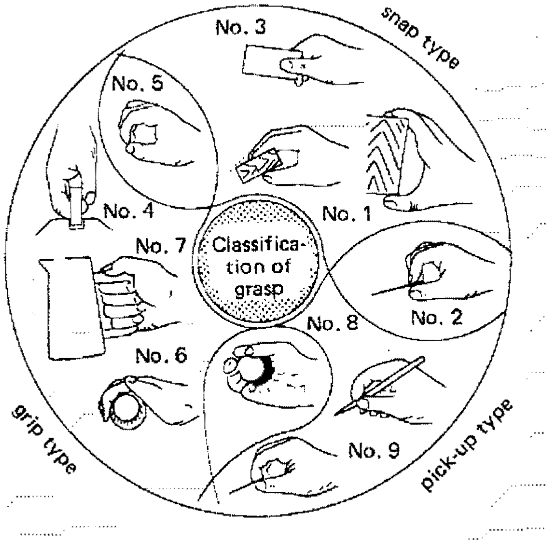


Figure 13. Human grasp classifications

Some of these grasp types can be used with the Wraptor; however, in general, the Wraptor grasps objects in manners that are significantly different from a human, especially considering its much larger size; this is especially true in the case of the power tools used in this research.

Elaborate algorithms have been produced for the determination of optimal grasp types in the dexterous manipulation of objects. As part of his dissertation research at Columbia, Dr. Miller produced software that determines the optimal grasp configuration for a CAD model of a given object, using several leading mechanical hands, including the BarrettHand™ and the Utah/MIT hand [6]. However, this work is not useful in teleoperation where the object is unknown. Drs. Michelman and Allen at Columbia produced a method for teleoperated control of the Utah/MIT hand that is based on the concept of “supervisory control”, in which they use a joystick to control the motions of the manipulated object rather than the motions of the robot hand. They also produced a method which enabled the Utah/MIT hand to remove a childproof bottle cap [1]. However, their strategies are far too complex and slow for this application.

A group of researchers at the University of Southampton, UK, have developed a three-fingered hand with a control strategy based on a set of high level commands for orientation of the gripper with fuzzy logic for controlling the fingertip force. Their strategy is intended for automatic grasps of objects in unstructured, unknown environments. They produced the set of three-fingered grasp primitives shown in Figure 14, which is the basis of the strategy proposed for this project.

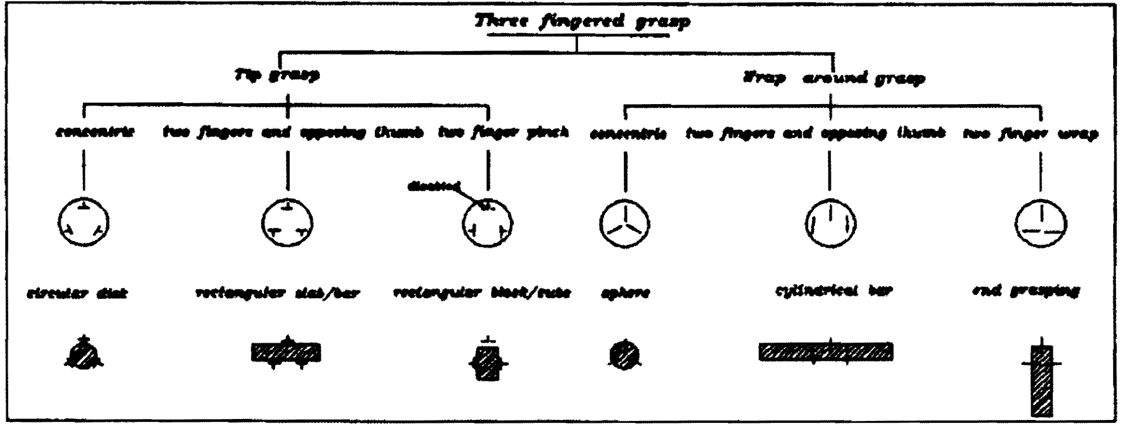
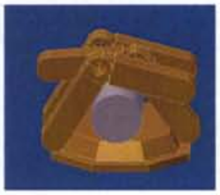


Figure 14. Crowder, Dubey, Chappell and Whatley's three-fingered grasp types [5]

For a three-fingered hand, there are two main components of the grasp configuration that can be varied. One is the spread angle, and the other is the contact type. For the Wraptor, the spread angle is continuously variable. The spread angle of the two opposable fingers is not independent; it is controlled by a single motor. Table 2 shows a proposed set of predefined grasp types for this system.

Table 2. Wraptor Predefined Grasp Types

	Contact Type		
Spread Angle	**Fingertip** **(one contact point per finger)**	**Finger Pad** **(surface contact along the outer links)**	**Wrap** **(2 contact points per finger)**
0°	**---**	**---**	
120°			**---**
180°			

Using the Wraptor protocol, the commands required to achieve these grasp configurations are simple. It provides the ability to send either velocity commands or position commands. For the position commands, the Wraptor system can execute trapezoidal moves, in which the velocity versus position is approximately a trapezoidal curve; this allows for lower accelerations and consequently smoother starts and stops. For all grasp types, the same position commands can be used for the approach position and release position. Also, in general, for operations using power tools, it is imperative that the Wraptor can hold constant torque to counter tool vibration and interaction forces.

For pick-and-place operations, it will most likely be acceptable to allow the motors to cease to provide torque upon stalling and rely on the non-backdrivability of the fingers to prevent the object from slipping.

The most stable and powerful grasp type is the cylindrical power grasp, which corresponds to the 180° wrap grasp shown in Table 2. This grasp type would be used for almost every tooling operation. The main advantage of the wrap configuration is that it locks the object in place mechanically, rather than relying solely on friction. It could also be used for pick-and-place operations. However, this grasp type generally requires palm contact before the fingers wrap around the object; this can be a significant problem, which will be discussed later. Figures 15 and show the stages of the wrap grasp types.

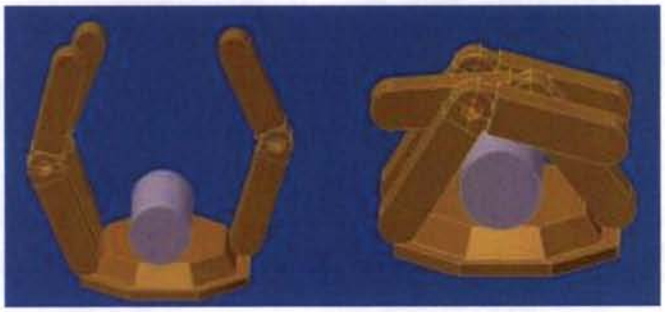


Figure 15. Stages of 180° wrap grasp

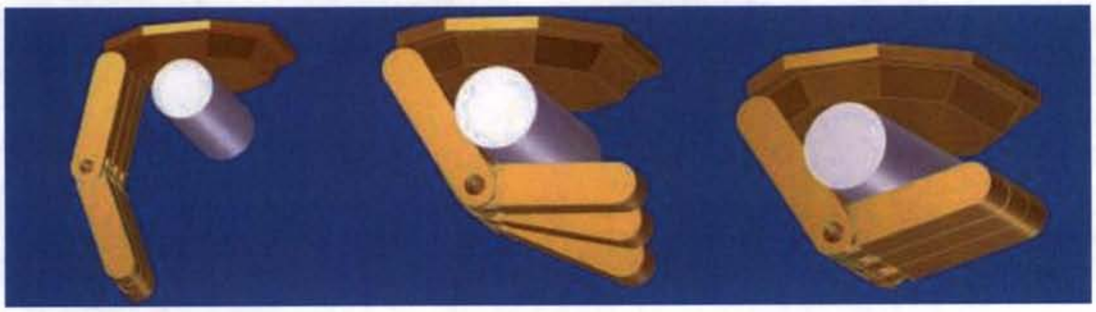


Figure 16. Stages of 0° wrap grasp

The following sequence of commands is required in the software in order to achieve the 0° and 180° wrap grasps. Once the grasp type is selected, each step is commanded from a force sensor on the WAM handle.

1. Approach: position commands to open position, currently 100 halls for all six finger joints and spread angles of 180° and 0°, respectively
2. Grasp: simultaneous velocity commands to inner and outer links
3. Release: same position commands that were used for the open position

The surface contact grasps would be used primarily for pick and place operations. These types rely on friction to hold the object in place; nonetheless, this should be sufficient without holding contant torque, considering that the Wraptor fingers are covered in a soft rubber. One advantage of the surface contact configurations is that they do not require initial palm contact. The 180° finger pad grasp would be well-suited for moving blocks of concrete or graphite.

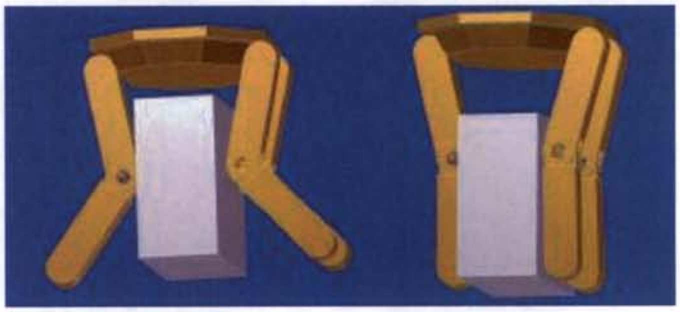


Figure 17. Stages of 180° finger pad grasp

Figure 18. Stages of 120° finger pad grasp

The following is the command sequence for the 180° and 120° finger pad grasps.

1. Approach: position commands to open position; unlike the other grasp types, initial shape of the inner and outer links must be convex rather than concave
2. Grasp: velocity commands are sent to the inner links; upon motor stall, commands can be sent to the outer links
3. Release: same position commands that were used for the open position

The fingertip grasp configurations would be used primarily for pick-and-place operations with light objects. They also rely on friction to hold the object and do not require initial palm contact. In some cases, these may require that the finger motors hold torque upon stalling. For fingertip grasps, the inner links are locked in a position; in the grasping stage, only the outer links move inward toward the object.

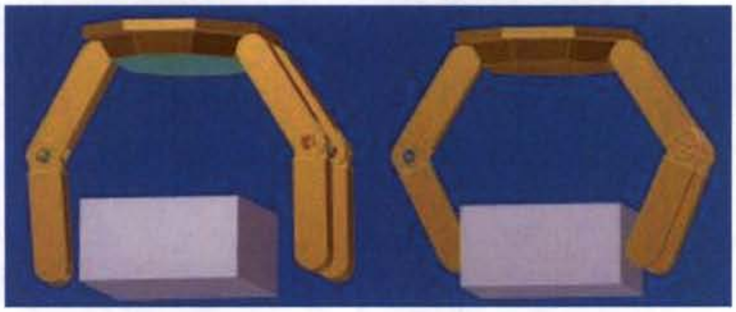


Figure 19. Stages of 180° fingertip grasp

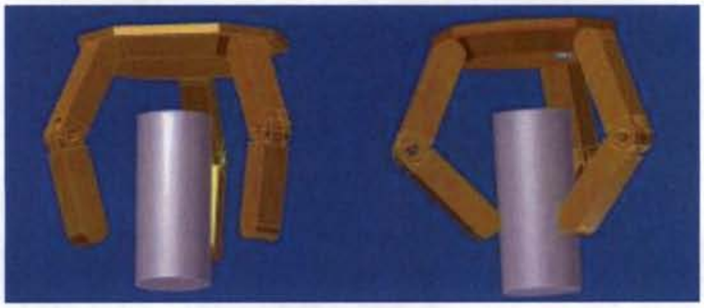


Figure 20. Stages of 120° fingertip grasp

The following command sequence is used for fingertip grasps.

1. Approach: position commands to open position
2. Grasp: velocity commands are sent to the outer links only
3. Release: same position commands that were used for the open position

For the wrap configuration grasps, it is feasible to send simultaneous velocity commands to all six of the inner and outer finger link joints; however, the velocities of the outer links should be slower than those of the inner links for the fingers to wrap around the object properly. The finger pad grasp configurations may require that the velocity commands be sent to the inner and outer links separately; it is essential that the inner links stall before the outer links. Because the Wraptor sends a response back to the host computer upon a motor stall, the software can automatically send commands to the outer links after the inner links have stalled

So far, only the cylindrical power grasp type is included in the software. However, the necessary GUI widgets and communications are set up to allow the addition more grasp types with little more than copying a few functions and changing the strings that are sent to the Wraptor. However, the new version of the Wraptor protocol has not yet been completely defined by the manufacturer.

Experiments will show whether or not this set is sufficient; some additional grasp types may need to be added and others may prove to be unnecessary. For instance, it may be useful to add a set of grasps with a spread angle of 90°. Also, the Wraptor protocol and programming capabilities are not yet completely defined; modifications may be needed in order to work within the protocol capabilities. If the Milwaukee bandsaw is needed, a specialized grasp type will be necessary. In order to grasp the bandsaw, the fingertips must bend inward first, in order to avoid contact with the blade; then the inner and outer links can close together, wrapping around the body of the saw in a 180° wrap grasp.

Joint Control Mode

Regardless of how general we make the set of grasp types, there will be objects that do not work with the predefined set. In these cases, it would be desirable to have an additional manual control mode, in which the operator can manipulate joints individually. There are several possible sensor mapping configurations, using the current components of this system. The analog force sensor inputs could be used to control velocity, assuming that the next version of the Wraptor firmware includes the necessary real-time mode. One method of reducing the complexity of such a mode and enabling the use of the current force sensor setup would be to couple degrees of freedom. One option would be to couple the three outer finger links together with one input and couple the three inner finger links with another input. Another option would be to couple the two links of each finger with a single input; this is how the BarrettHand™ is controlled.

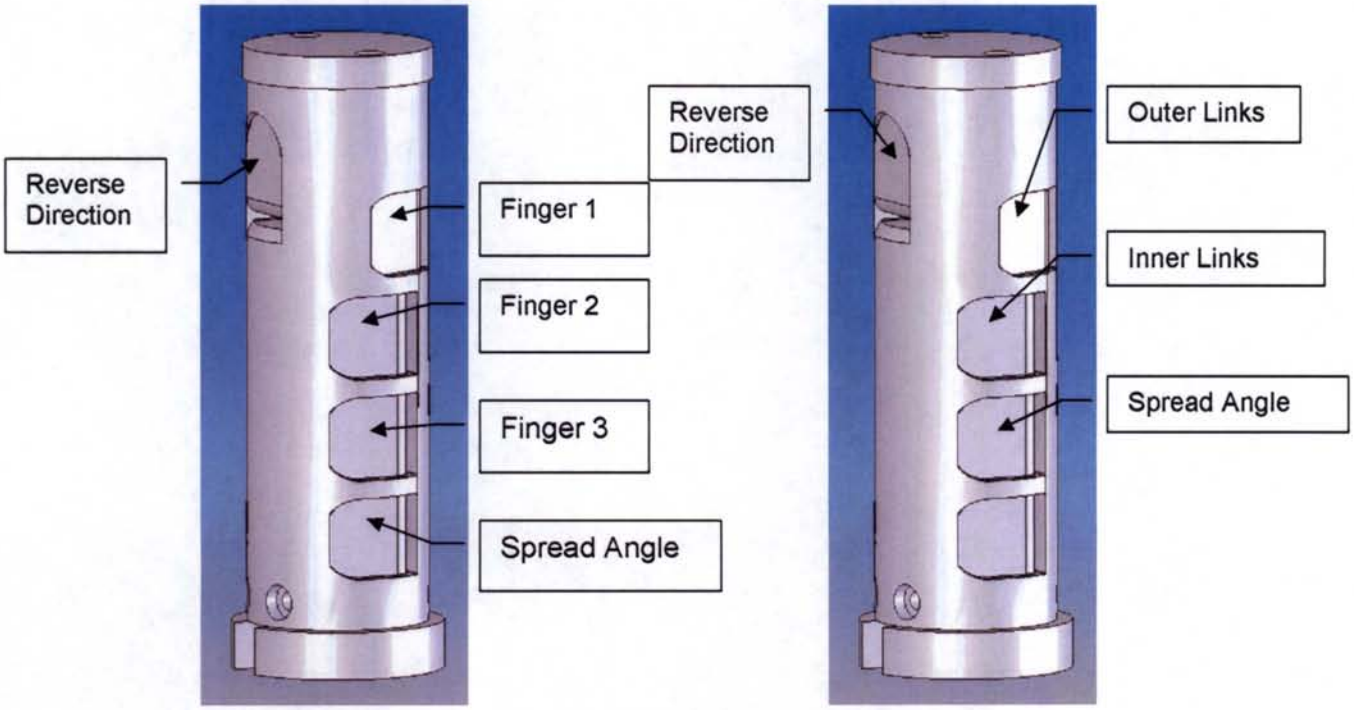


Figure 21. Possible sensor functions for manual control in velocity mode

Another possibility would be to control all seven joints independently by adding widgets to the GUI to allow switching between sets of joints. Manual control with the force sensors could be investigated at a later stage in the project.

Other Important Considerations

Several important considerations regarding this application of the Wraptor system have been observed through previous sets of experiments.

In general, objects are not placed in positions that allow the fingers to wrap around them unobstructed. In all of the previous testing, a pipe, a bandsaw and a reciprocating saw were used, with the cylindrical power grasp. The tools and pipe were placed in the testbed such that the ends were supported and the centers of the objects were free from obstructions. With the Wraptor, the cylindrical power grasp requires initial palm contact. However, in debris manipulation operations, the debris will not be positioned in such a manner; it may be against the floor, in a stack or against a wall. Obstructions to the Wraptor's long fingers can be problematic. This means that the stronger wrap configurations will generally only be available using the tool rack. The tool rack will have to be designed such that the 10 inch fingers can easily wrap around the tools unobstructed.

Ergonomic power tool designs can cause difficulties for the Wraptor. Many power tools have handles that extend out from their casings, like the handle on a milk jug. While these handles work well for a two-handed human grasp, they can be cumbersome for the Wraptor. Common pistol grips can also be problematic because they are too small for the Wraptor fingers to wrap around in a stable manner. Figure 22 shows a few tools that may not work well with the Wraptor.

Figure 22. Difficult tool geometries

The off-the-shelf tools will have to be carefully selected in order to use the Wraptor. However, Figure 23 shows a reciprocating saw, bandsaw and circular saw that work well with the Wraptor.

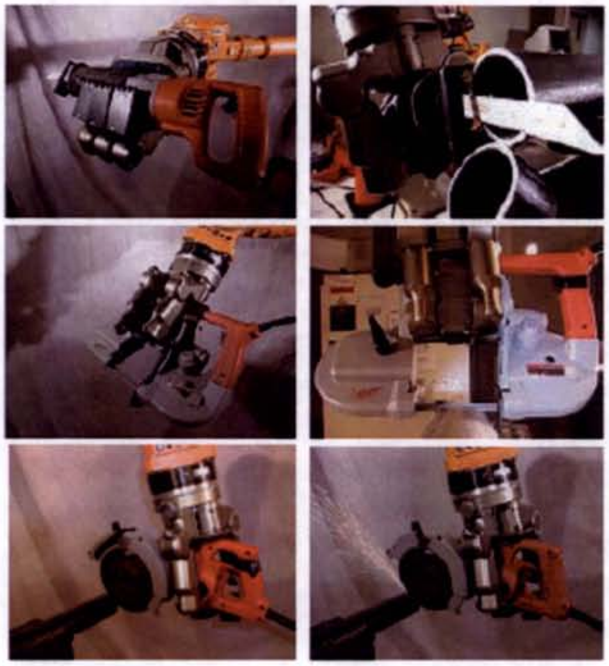


Figure 23. Off-the-shelf tools that work with the Wraptor

Previous Testing

Some full-system testing has already been performed with this system. A successful cutting operation was performed, using an earlier version of the graphical user interface and the grip force sensors mounted on the modified WAM handle. Figure 24 shows images from this testing.

Figure 24. Test results

The Wraptor was able to grasp the reciprocating saw in a stable manner. However, it was found that the Wraptor has some problems with overheating when it is continuously powered near its maximum torque; continuous torque is necessary to counter the tool vibration forces.

Experimental Evaluations

The following is a list of items to consider in the final testing of this system.

- What objects/tools can the Wraptor work with easily? What objects are difficult to deal with?
- Do the problems result from difficulties with controlling the Wraptor or do they result mostly from the Wraptor dynamics/kinematics?
- How does the Wraptor compare with the parallel jaw gripper?
- How long does it take for the Wraptor/Titan to perform a cutting operation? How long does it take for a human to perform a cutting operation? What causes the teleoperation system to be slower?
- How well can the Wraptor handle a well-defined task (i.e. pick up a tool from a specified tool rack, perform a simple operation, put the tool back)
- How well can the Wraptor handle general objects in unknown environments?
- How does the Wraptor compare to the parallel jaw gripper in tooling operations?
- How does the Wraptor compare to the parallel jaw gripper in pick & place operations?
- Is this set of general grasp types sufficient? Should more be added?

- Can any generalizations be made about the types of objects that are difficult for the Wraptor? Why?

Conclusions

Overall, the use of the Wraptor has proved to be feasible for tooling and pick-and-place operations in nuclear D&D applications. However, there are some design issues that must be resolved before the system is put into operation. The Wraptor must be able to hold constant torque in order to counter tool vibration and interaction forces; the temperature rise issues must be alleviated. And the Wraptor firmware must be more robust than the current version. Additional testing will be performed over the next five months.

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