High Dexterity Robotics for Safety and Emergency Response – 17104

Jared Wormley *, Matthew Johannes *, David Handelman *, Rodrigo Rimando**, Christopher Dohopolski *, Reed Young *, Michael McLoughlin *
* Johns Hopkins Applied Physics Laboratory
** US Department of Energy

ABSTRACT

Recently, significant advances in robotics have led to increased use in industrial and military applications. For example, the military has used explosive ordnance disposal (EOD) robots to enable responders to remotely investigate hazardous environments. While EOD robots have saved many lives, their utility is hampered by: 1) limited ability to manipulate complex objects and mechanisms (e.g. open a car door, operate power tools or turn valves), and 2) the requirement for significant operator training using joystick-type interfaces. Most robots today have simplistic manipulators and cannot easily operate in environments designed for humans as evidenced by the recent Amazon Picking Challenge and the DARPA Robotics Challenge. Simple tasks that humans perform easily, such as picking up objects or operating a cutting tool, require customized rigs that are expensive and time-consuming to use. The specialized nature of these robots limits their utility in highly unstructured environments, for example during emergency situations where a robot may need to be rapidly repurposed for an unanticipated situation (i.e. the Fukushima nuclear disaster). Robots are needed that can perform complex human-like tasks and are easy to use for everyday and emergency tasks.

In 2005 the Defense Advanced Research Projects Agency (DARPA) initiated the Revolutionizing Prosthetics (RP) Program with the goal of creating prosthetics as capable as the human arm and a human-machine interface enabling highly intuitive operation. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) created the Modular Prosthetic Limb (MPL), originally developed for amputees and paralyzed individuals as part of the RP Program, to replicate the capability of the human hand and arm to the extent technologically possible. With 26 joints and over 180 sensors, it is one of the most sophisticated and fully integrated robotic arms in the world. We have also demonstrated human-machine interface techniques that are highly intuitive requiring minimal training. While the MPL was originally designed as a prosthetic, it has also been incorporated into mobile robotic systems to project human capability. Using tele-operation, we have demonstrated the ability to perform dual-arm remote operations in complex environments.

For nuclear facilities, high dexterity robots combined with teleoperation offer the potential to enhance worker safety, productivity and quality. Safety enhancements include enabling remote operation in hazardous environments, remote handling of heavy or dangerous materials, and elimination of injury due to repetitive motions. Because the MPL is designed to function like a human limb, the robot can work in environments designed for humans with limited need for specialized tools. When

used for routine operations, it can also maintain a level of familiarity and confidence that effectively accomplishes reinforcement training for use in emergency situations, unlike a specialized robot that might sit unused for months or years at a time.

In August 2016 we demonstrated the use of the MPL at the Portsmouth Gaseous Diffusion Plant in Piketon, Ohio. Two robotic platform technologies were demonstrated to familiarize the DOE Emergency Management's (EM) workforce on the potential benefits of this technology. Here we present the results of those efforts, highlight the lessons learned during "EM Week," and outline potential future developments that could further advance application of these technologies to enhance worker safety.

INTRODUCTION

Robotics solutions for repetitive and dangerous tasks are prevalent because of the influence of industry. One of the first widespread uses of robotic systems was in the automotive industry for production [1]. Recognizing the success of the automotive industry, the food and pharmaceutical industries sought similar robotic systems for their production lines to complete repetitive sorting and packaging tasks. This application required systems to interact with objects of various size and shape leading to an expansion in the intelligence of these systems [1]. The medical field explored capabilities of robotic manipulation for use in surgery and incorporated different levels of autonomy depending on the application. Some operations require surgeons to have full control over the system through teleoperation, other operations benefit from the robot completing tasks on its own (autonomy).

Vital to the human-machine team is the ability of the operator to receive feedback from the system to augment their control. For dexterous tasks this feedback requires a visual component so the operator can see how they interact with their environment [1]. Military applications for robots have sent them to perform missions ranging from scouting and bomb detection to explosive-ordnance disposal (EOD). Task requirements have increased development in ranged communications and sensing, also helping to influence the push for more modular systems [2]. In each of these fields the robotic system was built to complete specified tasks. The food and pharmaceutical industries expanded existing solutions to best fit their needs, medical robots balance autonomous and teleoperated control while providing feedback to the operator, and military robots exemplify modularity so a single system can be utilized for multiple applications. These varied applications help drive the need to create a system capable of performing highly dexterous tasks in undefined environments.

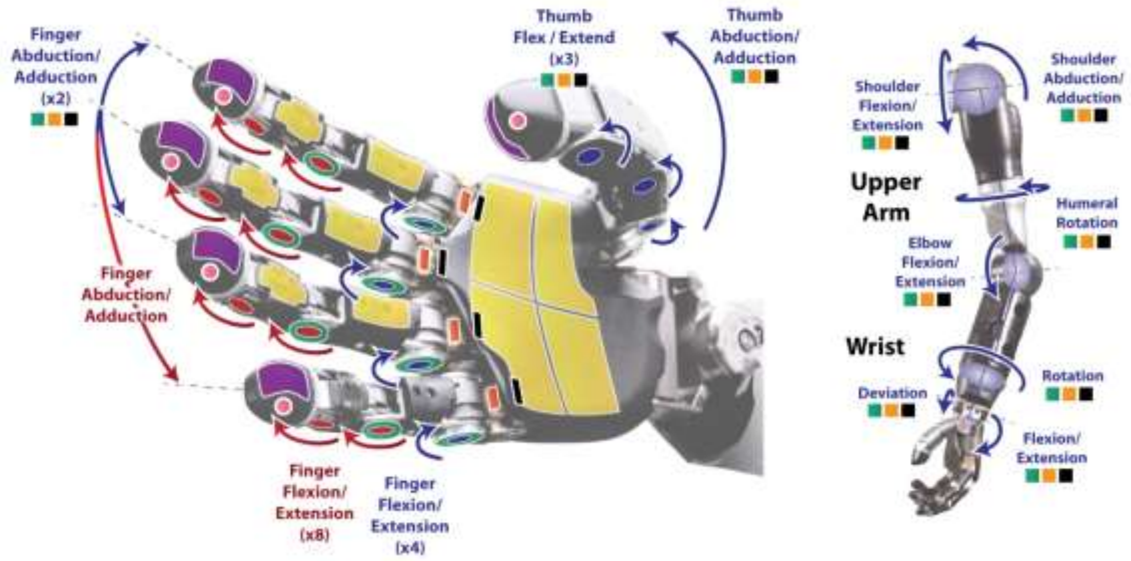
In order to perform highly dexterous tasks, a manipulator designed to interact with objects of variable shapes and sizes is warranted. It also helps if the manipulator configuration is familiar to the operator as it gives them an understanding of how to interact with various objects and yields a sense of one-to-one telepresence. With this in mind, we designed manipulation technology to restore human capabilities.

Modular Prosthetic Limb

Prosthetic technology suffered from a lack of development for decades, resulting in devices that could only restore a limited subset of capabilities. As soldiers returned from Iraq and Afghanistan with debilitating injuries, a better solution was needed. In 2005 DARPA started the revolutionizing prosthetics program to address this issue and create a robotic prosthetic device and associated Brain Machine Interface (BMI) strategies matching human capability [3]. One result of this effort was APL's modular prosthetic limb (MPL). The MPL (Fig. 1) was designed to match the size, weight, and strength of the 50th percentile military male. Housing a total of 17 motors controlling 26 articulated joints, the system contains position, torque and temperature sensors at each joint, contact sensors at finger phalanges, and optional pressure sensor arrays and load cells at the finger tips (Fig. 2). Of the 17 motors, 7 are in the Upper Arm and 10 are in the palm, thumb and fingers.

Figure 1: The JHU/APL Modular Prosthetic Limb

One of the most unique traits is the finger design where a single motor drives the finger assembly. The assembly contains a series of linkages. The first rigid linkage connects the motor at the knuckle to the proximal phalange and the second compliant linkage connects to the intermediate phalange. The output of the compliant linkage connects to the distal phalange completing the finger assembly. When pressed this compliant linkage causes the finger to bend at the proximal interphalangeal joint altering the unimpeded path of the distal phalange as the motor actuates. This allows for the fingers to conform to objects of different shapes when a force is applied to the intermediate phalange, a common occurrence when grasping objects. Abduction and Adduction is only achievable for the little, ring, and index fingers and the motion for the little and ring finger is coupled together. The thumb has an individual motor at each joint due its necessity for the dexterity of a hand [3].



Key	Sensor	Qty
🟩	Absolute Position Sensor	21
🟨	Contact Sensor	10
🟧	Torque Sensor	17
■	3-Axis Accelerometer	5
■	Capacitive Force Sensor	70
■	Additional Sensors	
	• Incremental Rotor Position	17
	• Joint Drive Voltage	17
	• Joint Drive Current (Upperarm Only)	7
	• Joint Temperature Sensor	17
	Total Sensing Elements	**181**

Key	Degrees of Freedom (DOF)	Qty
🟦	Active DOF	17
🟥	Passive DOF	9
	Total Articulating Joints	**26**

Figure 2: MPL Actuator Locations and Sensing Capabilities

The main microcontroller on the MPL, the limb controller (LC), communicates to each joint on the palm through serial based communication protocols. The Upper arm communicates with the limb controller through a controller area network (CAN) bus which is connected to a computer using a CAN to universal serial bus (USB) device. A front end application (VulcanX) processes inbound Universal Datagram Protocol (UDP) commands or Robotic Operating System (ROS) messages and translates them into the appropriate CAN messages. A common control method for the system is through use of MATLAB scripts which can be customized to send joint position commands to the MPL through the UDP interface. An endpoint position command can also be specified in MATLAB where the front end application will take the endpoint command and derive desired joint angles through inverse kinematics.

Impedance commands can also be sent which change the way the system reacts to external forces. These commands alter the torque generating characteristics of the joints, analogous to changing the spring constant of a spring. When a force is applied to the joint, depending on the stiffness setting, the joint will move, but once the force is removed, the joint will return to its original position. The various sensors on the MPL can also be read through MATLAB and up to two systems can be communicated with simultaneously.

For clinical applications where the MPL requires only a subset of its joints, the LC can be reprogrammed to communicate with specific nodes within the system. The modularity of the design also extends to the hardware, as joints on the MPL can be swapped out if damaged or if a different configuration is needed to fit the various types of upper arm amputees.

Integration of the MPL with patients is achieved through various configurations, some of which have allowed for patients to control the limb using surface Electromyography (EMG) through amplification of signals measured on electrodes integrated in a socket [4] and others through direct brain control [5]. Closed-loop control is the focus of recent efforts, where we have successfully provided users with sensory feedback using vibratory motors on re-innerved afferent pathways and directed microelectrode array based brain stimulation, enabling them to “feel” objects they are manipulating with the MPL [6].

Robo Sally

Due to the extensive dexterity and sensing capabilities of the MPL, the designers tested its potential for not only prosthetics, but also as a dexterous robotic manipulator. Outfitting a mobile robotic platform with MPLs would enable human-like manipulation through telepresence in dangerous environments without risk to personal safety. Additionally, since the MPL has an anthropomorphic design it can interface with hand tools and other devices designed for humans as well as create an intuitive and direct one to one proprioceptive sensation, which currently is not reproducible through sensory feedback modalities. This capability is essential because many robotic manipulators require customized end-effectors to perform different tasks and are usually limited to performing simple tasks due to fewer degrees-of-freedom (DOF). Many systems also lack the anthropometry necessary to create a direct proprioceptive sensation.

Initial development involved two MPLs mounted on a mannequin torso attached to a Segway. The design evolved to further mimic human capabilities by adding a 2-DOF torso which could both yaw left and right and pitch forward and backward. A Carnegie Robotics Multisense S7 camera and depth sensor system was mounted to the top of the torso equipped with stereoscopic vision creating the capability to project a 3D image to an operator. Similar to the torso, the Multisense camera gimbal developed by Telefactor Robotics can pan and tilt at high slew rates to aid in accurate and time lag free head tracking. The intent was to enable an operator to easily move the robot’s hands, torso, and head while receiving video feedback from the streaming stereo cameras. This would enable operators who typically work in dangerous environments to remotely complete tasks while leveraging their domain knowledge and expertise.

As limitations of the initial mobility design became clear, the designers looked for a more robust solution. The company AMBOT had created a four-wheeled ruggedized platform capable of traversing rough terrain and carrying high payloads, an ideal upgrade as the robot's mobility solution. The payload capacity allows for the storage of onboard computers, a network switch, an integrated radio for wireless communications, cable routing, and additional power. The fully integrated system is known as Robo Sally (Fig. 3). The control interface for Robo Sally utilizes ROS and allows computers to be connected to its network to stream commands to the system using UDP transferring ROS messages between the system and the Operator Control Unit (OCU).

Figure 3: Early variant of the Robo Sally Platform

Bimanual Robot Control

Coordinated control of multiple manipulators is a difficult task for an operator. If the control interface is unintuitive, simple tasks become cumbersome, but if done well, the operator can use the manipulators to extend their natural capabilities. Two different control modalities for Robo Sally allow operators to use natural movements as a control medium. The first modality (Fig. 4) shows an operator outfitted with a Sony Head-mounted Display(HMD), two Cyberglove II's, and six Xsens MTw sensors.

The Sony HMD provides the operator with a 3D black and white visual feed from the Multisense camera. This enables the operator to have a sense of depth aiding in picking up objects. The Cyberglove II's integrated piezoresistive sensors detect the bend on the glove at each joint. The angle of the joint can be calculated and then sent to the MPL as a position command. These sensors are highly accurate but require calibration each time they are worn.

Because the Cybergloves capture only the angles of the finger joints and the wrist deviator, another sensor is used to detect upper arm motion as well as the remaining two wrist DOFs. The Xsens MTws measures orientation angle along three axes. By securing these sensors to the head, torso, left bicep, left wrist, right bicep, and right wrist, the position and orientation of the operator's limbs can be measured in real time and used to command the MPL. This allows intuitive control for the operator as they control the robot the same way they control their own hands. Control of the platform can also be done through use of a Nintendo Wii balance board or through an additional operator, the latter of which typically has better control.

Figure 4: Operator wearing Sony HMD, Cybergloves, and Xens MTw

The second control modality for Robo Sally uses a novel input device and real-time inverse kinematics to enable an untrained operator to easily "fly the grippers" without wearing sensors and without calibration. Behavior Development Studio (BDS) software provides full-body motion planning and a 3D graphics visualization tool that simulates how the robot should move when provided endpoint movement commands (Fig. 5). BDS integrates with real sensors to simulate a robot's response to the sensor data.

This real-time motion planning capability was used to integrate the Leap Motion controller which tracks hands and fingers for virtual reality gaming. Using the data from the sensor as a controller for the simulated robot, an operator can simply move their hands above the sensor and the simulation moves the robots hands to a relative position in its space that matches the operator's hands. This approach incorporates inverse kinematics to not only calculate the robot arm joint positions, but also the torso as well which increases the full workspace of the system. Desired joint angles are sent from the BDS simulation to the ROS computer through UDP packets. The ROS node then translates and communicates those joint commands to

Robo Sally. This setup allows operators to control the platform with no calibration and provides full-body motion planning with a single sensor.

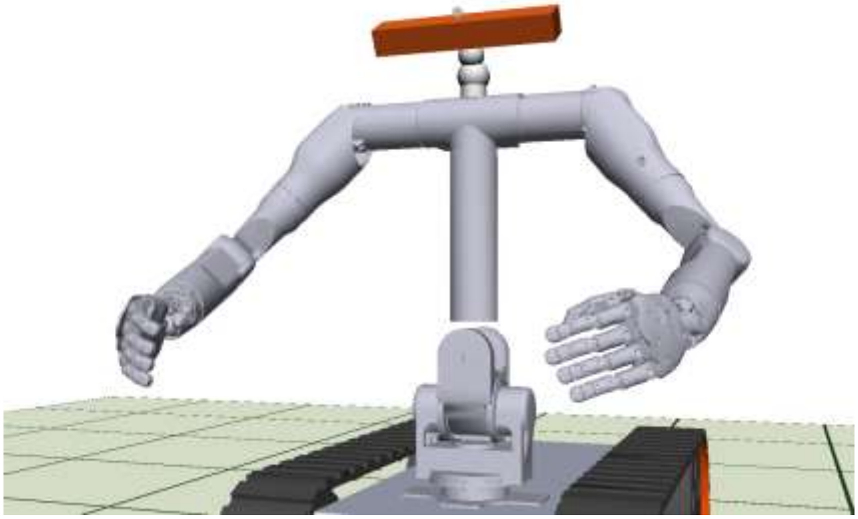


Figure 5: Robo Sally modeled in Behavioral Development Studio (BDS)

DESCRIPTION

With the development of these different control modalities the next step is twofold:

1. To make sure that operators without experience can quickly adapt to the two control modes
2. To see if the control allows for the completion of dexterous tasks.

To test the first step, the system was taken out to the Portsmouth Gaseous Diffusion Plant in Piketon Ohio where the team set up the system and a few objects to see how well inexperienced operators could manipulate the system. This testing was intended primarily with the Cyberglove controller as it more accurately projects the operator's motion to Robo Sally. BDS control of Robo Sally through the leap motion sensor was examined to see how this new control modality compared to the older method based off user feedback. To test the second objective a team of experienced Cyberglove operators was formed to demonstrate how a platform like Robo Sally could be used to accomplish dexterous tasks in a scenario similar to those found during nuclear power plant disassembly.

The demonstration involved one operator driving Robo Sally to a simulated debris pile while a second operator (outfitted with the Sony HMD, Cybergloves, and 6 Xsens MTws) controlled the platform by picking up a wooden dowel rod from the debris. The first operator would then drive Robo Sally to another location where an additional MPL system was setup. After placing the debris in two vice grips the second operator would tighten the vice grips and the first operator would drive Robo Sally back to its starting position. A third operator (outfitted with a single

Cyberglove and 2 Xsens MTws) controlling the standalone MPL system would then pick up a handsaw and cut the rod.

RESULTS

At the Portsmouth Gaseous Diffusion Plant the experienced operators setup the demonstration to exhibit the capabilities of the system. Prior to the demonstration several trial runs performed by the experienced operators demonstrated the difficulty of the task. The stereoscopic camera on Robo Sally provided a 3d video feed only in black and white. This worked well most of the time but occasionally if the hands needed to interact with dark objects it would blend in with the hand and the operator would not be able to tell where Robo Sally's hands were located. Due to this the objects in the debris pile were optimized to have different shades when viewed in the camera feed which made picking up the dowel a more attainable task for the operator (Fig. 6). Additionally the MPL had trouble fully grasping the handle for the vice so only a single finger was used to tighten each vice (Fig. 7).

Figure 6: Operators when Robo Sally is being driven at start of operation; left: Robo Sally placing wooden dowel in vice

Figure 7: Robo Sally tightening vice with single finger

A different set of issues arose with the saw operator. The first hand saw experimented with proved difficult for the MPL to pick up off the table. This was mainly due to the workspace of the limb when on a table mount. Even when the MPL could grab the tool it was difficult to orient it in a way that the MPL could engage the trigger. Since the MPL fingers curl in at an angle, applying linear force to press a button becomes difficult so the hand saw need to be oriented at an angle to accommodate for the MPL kinematics. The solution was to simply hand the tool to the MPL and have the operator only control the engaging of the saw and the motion to cut the dowel. When the saw would begin cutting it would sometimes get bound in the dowel rod and kick back at the MPL causing the limb to lose grip on the saw. When this would happen the MPL would continue to hold on the saw but be in an orientation where the operator could not press down on the trigger due to the MPL finger kinematics. To remedy the difficulties in pressing the saw’s trigger, the trigger button was padded down to see if it helped with the stability and repeatability for cutting the dowel. Though it did help a little, it was not significant enough to be a reliable solution. Another saw with a different trigger mechanism was procured and replaced the original saw. With this saw the operator could more reliably cut the dowel, and even though it would sometimes bind, the handle design increased the reliability of the MPL pressing the trigger. The result was a more repeatable solution to cutting the dowel (Fig. 9).

Figure 9: MPL cutting through dowel with hand saw

The adjustments to the demonstration helped increase operator performance and demonstrated the difficulties in fully projecting user capability through a robotic system.

A member of the United States Steel Workers with no prior experience operating Robo Sally was outfitted with the Sony HMD, Cyberglove, and 6 Xsens MTws to test the system’s ease of use. The operator first adjusted to the system through moving their arms and hands and seeing the projection of those motions onto Robo Sally through the HMD. Seconds later the operator felt comfortable with the control and attempted to grab some conformable objects. After a few tries the operator was able to grasp a conformable object and eventually worked towards grabbing one with each hand (Fig. 10). The only task that proved difficult was grabbing the dowel rod as it required some bimanual coordination. If coordination is not perfect, this task could cause excess torque on the MPLs, possibly damaging components. The operator was able to pick up the dowel with a single hand then secure both hands on it. Once held, coordinated bimanual manipulation of the limbs to move the dowel rod proved difficult resulting in excess torque on the right limb.

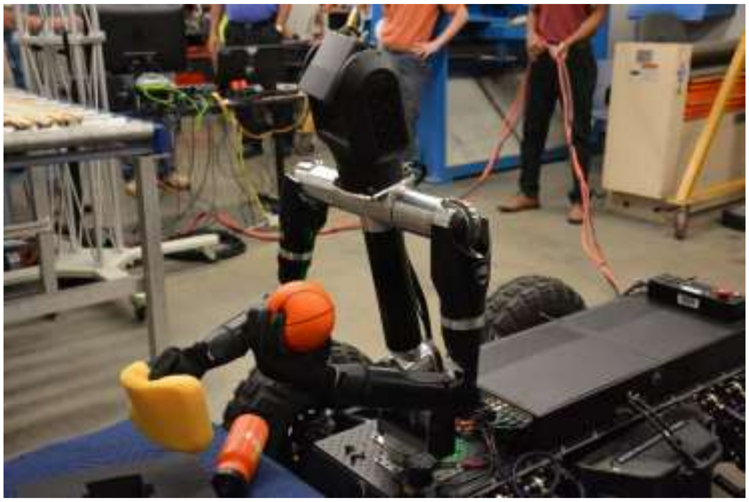


Figure 10: First-time operator showing bimanual control of Robo Sally

Multiple operators controlled Robo Sally with the leap motion controller through BDS (Fig. 11). Operators found it to be a very intuitive form of control. Due to less complexity in setting the system up and the lack of calibration, more users were able control this system and saw this as a more attractive solution for development. Operators were able to pick up items with this interface which showed it as a viable method of control. With some improvements, it could match and eventually exceed the control provided by the Cyberglove.

Figure 11: Leap Motion sensor capturing operator hands for Robo Sally Control

CONCLUSION

Working with both experienced and inexperienced operators revealed areas of improvement in our current control architecture. The BDS' abilities to integrate new operator intent sensing capabilities and test out various forms of autonomy make it the more appealing option for developing dexterous control. The system also has the benefit that any control methods developed can be switched over to different platforms modeled in the software. Based on the inability of the experienced operator to reliably pick up the hand saw and the inexperienced operator's struggle to balance control of both arms, more autonomy is being developed to simplify grasping and manipulation. For single objects the system needs to be able to recognize the object, grasp it, and have the operator then resume control of the manipulator once it grasps the tools. With the tool in hand the operator should be able to limit the motion of the end effector to specific planes, and to do a simple gesture to turn the tool on or off. For grasping tasks involving both hands, the operator still needs to be able to autonomously grasp an object, but once grasped, be able to move the combined linkage of the two hands and the object with a single hand to simplify control. Autonomy could also be applied to the robot's locomotion which could reduce the necessity for a second operator.

Though autonomy can help reduce human error involved in the system's control, augmentation of the operator's feedback gives them better situational awareness. Data from the MPLs sensors can be provided to the operator in two ways. The sensor data could be added as part of the operator's display allowing for them to see more information about the status of the system. In addition to having visual access to the sensor data, a haptic system could be developed to provide the operator with a feeling of how external forces are interacting with the system as well as giving a sense of touch when interacting with objects.

Combining autonomous grasping, autonomous navigation, and sensor feedback with teleoperation, dexterous robots can be made more capable to deal with unknown dangerous environments.

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