

Human Capabilities Projection: Dexterous Robotic Telemanipulation with Haptic Feedback

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Human capabilities projection is the robotic manifestation of human-like dexterity and sensory perception through robotic telemanipulation. The goal of human capabilities projection is to leverage robotic systems to accomplish tasks that may not be practical or safe for human execution. Examples of such tasks include operations performed in inhospitable environments, operations—such as explosive ordnance disposal—performed under dangerous circumstances, and operations that pose high risk to personnel safety and require standoff distances. Human capabilities projection requires advances in robotic manipulation technologies, intuitive operator control modalities, immersive visual feedback, and effective haptic feedback. This article discusses past, current, and future research and development efforts in human capabilities projection.

INTRODUCTION

Warfighters, astronauts, and first responders must be able to perform challenging tasks for extended periods of time under stressful conditions. Such tasks include military operations that must be performed in life-threatening battlefield environments or are of long duration, as well as operations related to space and planetary surface exploration. These operational environments may contain hazardous conditions under which personnel must execute combat casualty care, engage improvised explosive devices, or investigate potential chemical, biological, radioactive, or nuclear threat con-

ditions. Many injuries and fatalities occur when highly skilled personnel such as explosive ordnance disposal (EOD) technicians and field medics are in harm's way within these conditions. Finally, there are repetitive or mundane tasks that put our warfighters and first responders at risk of letting their guards down; examples of these types of tasks include forward area logistics, manning security checkpoint stations, border monitoring, maintenance actions on nuclear reactors, and battlefield clearance. Effective teleoperation of robotic systems lowers risk to personnel by removing distractions experienced

by physically present personnel, allowing them to pay greater attention to operational tasks. In this article, we seek to define and outline work we have conducted in an area of internally funded research and development at APL, herein called human capabilities projection. Human capabilities projection focuses on leveraging robotic system design and control to enable safe and effective performance within operational contexts such as those described above through the remote projection of human-like dexterity, speed, and sensory immersion.

Using robotic systems with human-like manipulation capabilities in hazardous environments allows the user to avoid exposure and accomplish the operational task or scenario from a safe standoff range or location. Currently fielded systems available to military personnel have limited capability to address objects in a remote environment in a human-like fashion. These systems typically use low-dexterity end effectors [one degree of freedom (DOF)] and have a single manipulator arm. They typically provide operator control through a series of joysticks, switches, and buttons and lack direct user haptic feedback. Additionally, they typically provide a single video stream during object interaction, which results in poor depth perception when addressing target objects. Bimanual, high-dexterity limbs that are anthropomorphic in design and mounted to robotic platforms have the potential, if controlled effectively, to enable swift and accurate manipulation of objects and tools. Central to our hypothesis is the belief that the combination of high-resolution intent tracking of the operator's native limbs to control anthropomorphically designed robotic systems with haptic feedback and effective stereoscopic remote vision allows for effective manipulation of targets. Aside from the main benefit of such a system, which is to remove risk to human life, systems designed and controlled in this fashion have the potential to expand the operational contexts in which these systems can excel.

The central idea behind human capabilities projection is to project human-like dexterous manipulation of target objects in a remote environment in support of a wide range of threat assessment and mitigation techniques with the personnel safety benefits derived from removing the human from the hazardous environment. A key to our approach is to leverage the upper-limb and dexterous hand development activities from the Revolutionizing Prosthetics (RP) program.¹ We aim to explore the possibility that manipulation capabilities attainable through the use of highly dexterous manipulators and end effectors can enhance mission execution. The key enabler of effective human capabilities projection is the robotic system, which acts as a surrogate to the human operator for performing downrange operations. We focus development on core components of the robotic system most directly tied to achieving human

capabilities projection: platform mobility, bimanual dexterous manipulation capabilities, immersive stereoscopic vision, intuitive control modalities, sensor integration for operator feedback, and user-in-the-loop semiautonomy.

MOBILITY AND MANIPULATION

Our team developed multiple iterations of robotic systems at APL starting in 2007 in an effort to evaluate and study human capabilities projection. The early systems, referred to as “Segway Sally,” used a Segway Robotic Mobility Platform 200 series base platform providing system travel speeds of up to 10 miles/h with internal power, which is controlled through a USB interface to an onboard computer. The team chose the Robotic Mobility Platform 200 series because of its dynamic stabilization, appropriate form factor, and open programming interface. The team mounted a composite human-like torso atop the Robotic Mobility Platform to provide a human-like appearance. On the torso, a pan-tilt unit allows for horizontal and vertical panning of a pair of Internet Protocol cameras to provide stereoscopic visual spatial awareness to the operator. We chose a humanoid composite torso to provide an anthropomorphic mount-



Figure 1. Early human capabilities projection robotic system, Segway Sally, performing an EOD exercise at the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) in Indian Head, Maryland.

ing structure for prosthetic limbs to achieve human-like dexterity and range of motion.

The first generation of the Segway Sally system incorporated the Prototype 1 (P1) limb system. The P1 system was designed to have seven independently actuated DOF: shoulder flexion/extension, humeral rotation, elbow flexion/extension, wrist rotation, wrist flexion/extension, and two actuated hand grasps. In this original system prototype, the P1 system served as the right arm. A year later, the Prototype 2 (P2) limb was developed and demonstrated as part of the RP program. The P2 prototype incorporated 22 DOF in contrast with P1's 7 DOF. The team incorporated the P2 upper arm (4 DOF) coupled with a duplicate P1 wrist and hand to form the left arm of a bimanual Segway Sally system. Figure 1 depicts Segway Sally performing an EOD activity at a testing range at the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV) at Indian Head, Maryland.

The early human capabilities projection effort found in Segway Sally enabled early insight into some of the challenges and needs associated with developing robotic systems to have human-like dexterous manipulation, useful mobility, and effective visual feedback for situational awareness. The Segway Sally system has many components that take on a human-like appearance and motion capabilities. There is a torso, two anthropomorphic robotic arms, a neck that can pan and tilt, and two Internet Protocol cameras to provide stereoscopic visual feedback. One of the challenges with this early platform was the reliance on the two-

wheeled Dexterous Robotic Platform (DRP)'s dynamic stabilization algorithms. This characteristic became problematic when attempting dexterous bimanual manipulation tasks, as the platform necessarily sways fore and aft to dynamically stabilize the inverted pendulum-type control challenge that it poses. Responding to feedback from the EOD robotics community gathered through a variety of demonstrations and field tests, we began integration of the prosthetic systems onto a new platform—the iRobot PackBot—and transferred over to that platform the bimanual manipulation, situational awareness, and fully wireless control capabilities. The PackBot is currently used as part of the Navy's Man-Transportable Robotic System fleet of EOD robots. The PackBot is a tracked vehicle with skid-steering capabilities, a single 4-DOF manipulator arm coupled to a single-DOF gripper, and integrated sensors. Because this system does not rely on dynamic stabilization, it provides a better platform for fine manipulation tasks. The further appeal of such a system is that it is field ruggedized and has been proven an effective mobility design for current EOD operations. Once a new platform was adopted, a new name was given to the system—DRP. The DRP was fitted with the Modular Prosthetic Limb (MPL) v1.0 from the RP effort (Fig. 2, left), which extends the platform capabilities for demonstration of advanced human-like functions in extreme environments by adding more controllable DOF. The MPL v1.0 system and the P2/P1 hand combination were mounted to the first link of the system through mounting brackets spaced anthro-

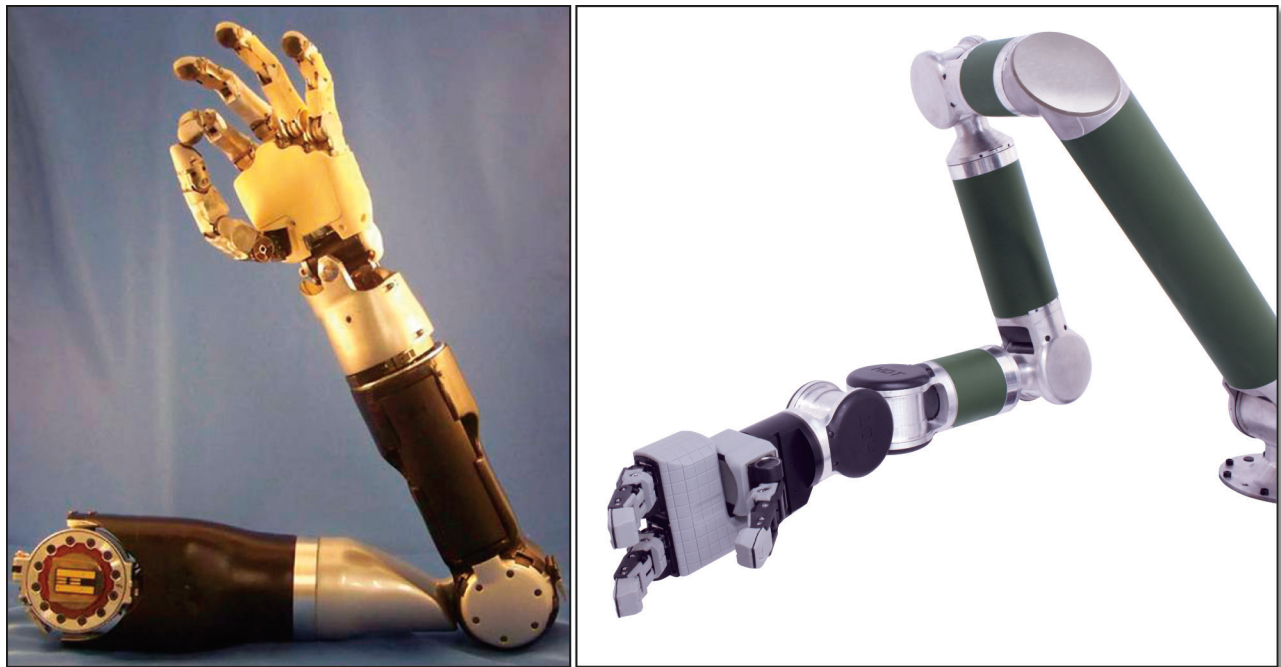


Figure 2. The MPL v1.0 manipulator (left) and the MK1 manipulator from Hunter Defense Technologies (right).

pomorphically; this first link acted as a torso for the DRP, providing rotation and pitch DOFs. The v1.0 MPL system allows for four controllable DOF in the upper arm and 10 DOF in the hand, including 4 DOF in the thumb for dexterous grasping and hand shaping. It should be noted that a 3-DOF wrist is part of the complete MPL system; however, one was not available for use in the context of this work. Additionally, the fingertip sensor nodes provide a source of tactile perception, enabling haptic feedback to the user. We save discussion of the description and use of these sensors for later. Within the framework of the DRP the team also integrated the Hunter Defense Technologies MK1 manipulator, which is based on derivative technologies from the RP program. The MK1 system uses simplified versions of the MPL (upper-arm drives and fingers) for intermediate dexterity and robust manipulation specifically tailored to military field use (Fig. 2, right).

IMMERSIVE STEREOSCOPIC VISION

One of the most important aspects of the system for dexterous object manipulation is the ability to provide effective visual feedback to the operator. Two cameras, which act as the robot's "eyes," are anthropomorphically spaced and mounted to the pan-tilt neck. The video feeds are then streamed into an immersive display unit that provides stereoscopic video feeds to the operator, giving the perception of 3-D vision of the remote scene. This system provides a visually immersive experience that is critical for teleoperation effectiveness when executing manipulation tasks. This capability provides a degree of depth perception not attainable with monocular vision and aids in the execution of bimanual tasks.

FEED-FORWARD CONTROL

We believe that to achieve true human capabilities projection, highly dexterous robotic manipulation systems require a level of control that is not offered through traditionally used joystick and button control units. Throughout the course of our research efforts, the team has focused on providing one-to-one joint-level mapping for control of anthropomorphic manipulators and the pan-tilt unit. The advantage of anthropomorphic robot linkages and manipulators with a range of motion and speed commensurate with the natural human limb is that teleoperation of the high-DOF system though joint mapping is intuitive because of the system's one-to-one correspondence with the user's native limbs. Because of this correspondence, the operator has an innate proprioceptive sense of his own body position, which maps directly to the position of the manipulators. For control over the pan-tilt unit, the operator's head movements

are tracked with inertial measurement sensors to provide one-to-one mapping of operator viewpoint through the DRP's two cameras. Inertial sensors track the operator's upper-arm motions, which are mapped to the DRP's anthropomorphic manipulators. Similarly, the operator's hand and wrist motions are tracked using a combination of inertial sensors for the wrist rotator and piezoelectric bend sensors (CyberGlove II, CyberGlove Systems) for the finger joints and the wrist flexor and deviator (Fig. 3). Because both hands are occupied controlling the manipulators on the platform, some other method for platform control is required. We implemented hands-free platform control using a Nintendo Wii Balance Board to enable simultaneous bimanual motion tracking and platform control.

To further aid the user in command and control of the DRP, the team uses the Virtual Integration Environment (VIE) framework from ongoing RP efforts.² The VIE serves as an overarching framework for the command, control, and visualization of the DRP system. The VIE provides a manner of prototyping new control scenarios, with a virtual representation of the entire DRP system for integration and test efforts. Additionally, it provides a software framework through which commands are sent and feedback is received from the system.

There are additional control modalities that the team has investigated under the purview of our research efforts. These include approaches that rely on tracking the user's eye motion while within the immersive contextual view of the DRP system (Fig. 4). Within the framework of the VIE, the team has developed and prototyped a training and evaluation software module for eye-tracker-based control of the platform, manipulators, and system context. This software module allows for a multimodal control approach in addition to the mapping of the user body segments for system control. The eye tracker is able to control a cursor over the



Figure 3. One-to-one mapping of the operator's hand movements using CyberGlove control inputs.



Figure 4. Menus for eye-tracking-based interaction with robotic system. (Left) Contextual mode. (Right) System main menu.

operator's view; in an effort to provide more than just cursor control, one can indicate a selection modality through a fixed-duration gaze on an object of interest. For this approach, the operator is regularly interacting with a computer screen showing live video streams, so the location of the operator's gaze highlights targets of interest. Using these approaches, the control modality can be used for menu-based navigation during contextual switching or as a method to indicate objects of interest based on fixed-duration gaze to cue semi-autonomous grasping algorithms. To accomplish the visual feed overlays—for instance, to switch between a contextual menu versus video feeds from the robot—we simultaneously run two different windows within the immersive display unit. Test and demonstration with head-tracker and arm motion has indicated an effective manner for system control. The system functions such that manipulator-based control streams are disabled automatically whenever exiting immersive mode (manipulator and head-tracker motion scenario) or when at the main menu.

HAPTIC FEEDBACK—SENSORS AND ACTUATORS

Feed-forward control and immersive stereoscopic vision are a large part of the control solution when teleoperating bimanual robotic systems; however, there is another component that plays a powerful role in manipulations. It is potentially challenging for an operator to rely solely on visual feedback when executing complex tasks in a fine bimanual manipulation scenario. In human beings, part of a manipulation task is executed through visual feedback and the other part is through haptic sensation feedback. To achieve true human capabilities projection, we feel that both elements must be present. Haptic feedback can be subdivided into sensations delivered to the skin (tactile) and those that are due to a sense of location in space (kinesthetic or

proprioceptive). These sensations are extremely important when conducting manipulation tasks. Studies have shown that the execution of even the most fundamental activities of daily living are markedly more difficult in the absence of these sensations.³ We believe that when conducting teleoperated robotic manipulations, the absence of similar sensation for the user has a similar effect. Kinesthetic feedback in experimental teleoperated EOD robots can improve manipulations required for disabling explosive devices. Reports have shown that increasing psychological immersion into the remote task serves to increase the operator's capability at performing EOD-type maneuvers, such as the unscrewing of detonators and insertion of retaining elements into detonators.⁴

We hypothesize that as the dexterity of the end effector increases, such as with the MPL, the need for haptic feedback for all DOF in the end effector becomes increasingly important. The MPL contains a number of sensing elements, called fingertip sensing nodes, that provide the necessary source of information for haptic feedback. Specifically, there are sensors at the fingertip that detect force and vibration at primarily the thumb, index, and middle fingers. These strain gauges are capable of detecting both static and dynamic forces in three axes (normal, lateral shear, and longitudinal shear) with 24-bit resolution up to a maximum load of ± 64 N (14.4 lb). Vibration is measured by commercial three-axis accelerometers, which are configurable for a ± 2 -g or ± 8 -g dynamic range with 8-bit resolution and can achieve accuracy of ± 40 mg in the ± 2 -g range and ± 60 mg in the ± 8 -g range. For kinesthetic feedback potential, there are sensors to detect joint angle, velocity, and torque for each joint. As mentioned previously, the goal of the haptic feedback system is to display information from sensors such as these to the operator in an intuitive manner to enable successful telemanipulation.

Once the sensory input pathways are established, focus can turn to effective ways of displaying this stimulation to the user in an effective manner. The CyberGrasp (VRLOGIC) is a force feedback exoskeleton device that can provide individual reactive forces to the fingers of the user. The CyberGrasp contains five individual tendon-like cables that apply a variable tensile force (to 12 N) to each finger via actuators. The forces sensed by the finger torque sensors are mapped in a one-to-one fashion to the CyberGrasp. Furthermore, vibratory sensation from the MPL can be displayed using a sine wave overlay on the DC reactive force. This feature could be especially useful in displaying a slip event to the user. To surpass the bandwidth limitations of the CyberGrasp (50 Hz), the team is considering the inclusion of a secondary device (e.g., eccentric motor) to handle higher frequencies.

To further the effective display of tactile information to the user, the team has developed a novel actuator to provide stimulation to multiple areas on the fingertip.⁵ The custom motor-driven fingertip tactile feedback device uses four DC motors that individually drive corresponding stimulating pins (Fig. 5). During activation, the appropriate motor is supplied a pulse-width modulated voltage from COTS motor controllers, which causes the deflection of a spring flexure through the winding of a cable. As the cable is wound, the flexure bends toward the finger and the stimulator pin within the flexure engages the operator's finger. The force applied to the finger increases as the motor continues to turn, eventually saturating when the motor reaches its stall condition. By varying the pulse-width modulated voltage, the force applied operator's finger when the motor stalls can be controlled and made proportional to the sensed force in the fingertips of the MPL. Additionally, we can deliver a vibratory sensation to the user; we have verified operation of the device up to 500 Hz in this manner.

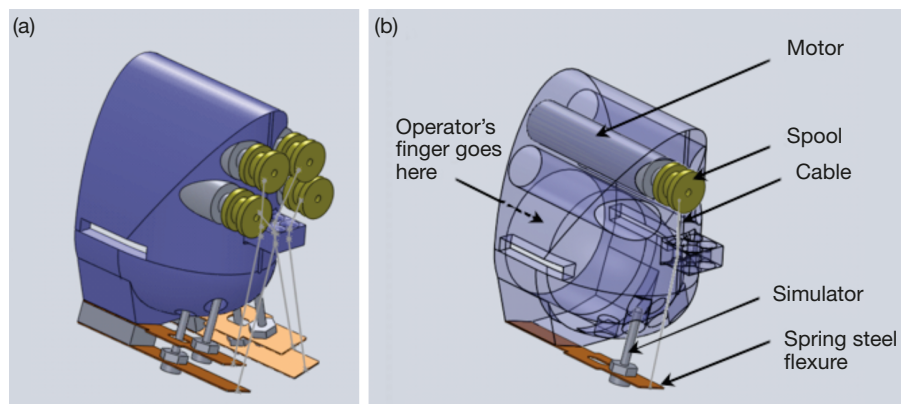


Figure 5. (a) A 3-D model of motor-driven device for tactile feedback showing all components and (b) a simplified version showing only one stimulating element for improved visibility.

SYSTEM EVALUATION STUDIES

In 2008, the team evaluated functional and comparative performance of Segway Sally in a series of tests both at APL and at a remote explosive ordinance disposal test facility, NAVEODTECHDIV, at Indian Head, Maryland. These tests included evaluating the mobility and manipulation system as well as obtaining user feedback on the system and potential improvements.

Mobility Evaluation

Mobility was evaluated for the DRP in the Segway Sally configuration both as a comparison to existing fielded EOD units (iRobot PackBot and QinetiQ TALON), as well as across the control input space for a single platform. The team evaluated platform control using both conventional (joystick) and novel (Wii Balance Board) control by driving Segway Sally through an obstacle course.

In the first test, a course was navigated by a series of operators using joystick-based control, and the time was recorded. The navigation course for evaluation consisted of a series of traffic cones set up with the spacing as shown in Fig. 6. The users' task was to remotely navigate the robots around and then through the course in a slalom fashion, eventually returning to start. Across four trained operators who had previous experience in operating the Sally platform, the average time for completing the course was 1 min, 38 s. For a comparison, the average times for a trained operator using the QinetiQ TALON system was 1 min, 20 s, and for the iRobot PackBot system, 1 min, 14 s. This indicated that the Segway platform version of the DRP was not appreciably less maneuverable or slower through this test course than currently fielded ground robotic systems. Additionally, a number of untrained operators also completed the test. These operators have experience in EOD robotics operation but had never been

exposed to the unique vehicle dynamics of Segway Sally. The average time for the untrained operators was markedly slower, at 2 min, 59 s. The results indicate that a level of training and familiarity with the system probably aided the operator in the completion of the task.

For evaluation of the Wii control interface, an additional course was established (Fig. 7) that the team felt maximized the necessity for more precise control of the platform. This evaluation course considered only the Segway Sally system.

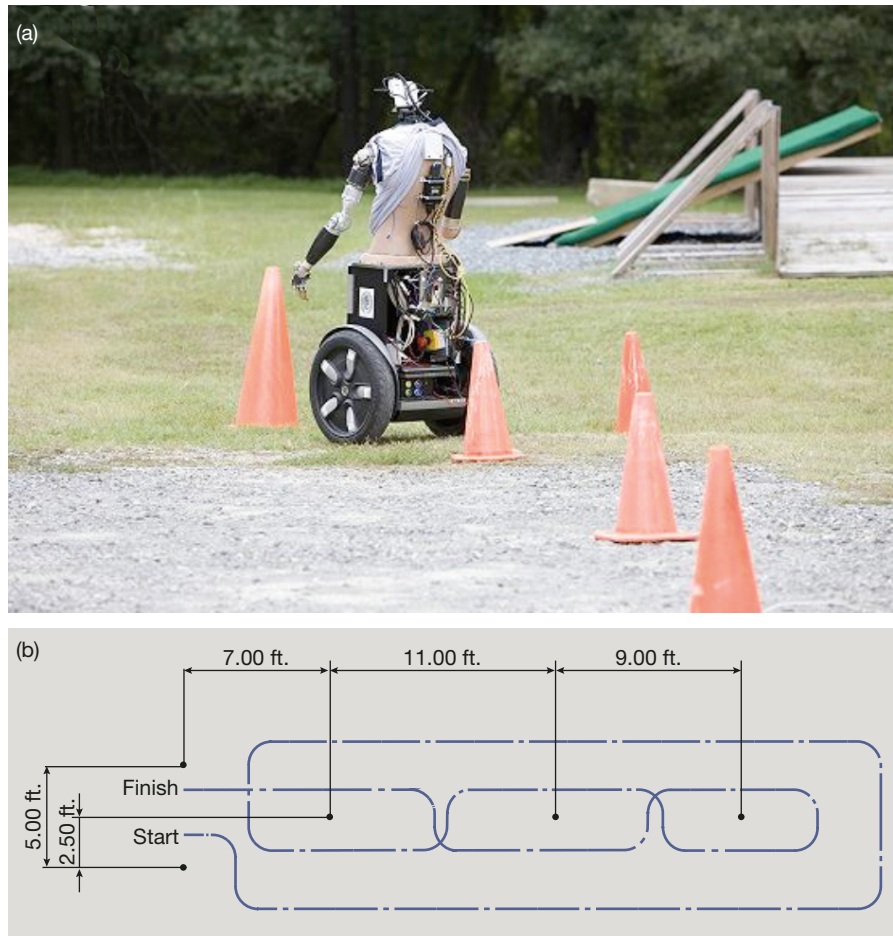


Figure 6. (a) Robotic dexterous robotic system completing mobility evaluation at NAVEO-DTECHDIV in Indian Head, Maryland, on 22 September 2008. (b) Robot control course layout (course no. 1). Note: Solid black lines denote reference distance markings.

Each black circle marks a cone location, and a solid blue line indicates an upright shipping palette forming part of a corridor. The square with the circular arrow marks where the robot must rotate 360° at zero turn radius before continuing.

The Segway Sally platform was controlled with the joystick and the Balance Board under either direct visual observation (third-person perspective) or immersive stereo vision (first-person perspective). The results indicate that the course could be completed with both the hands-free (Wii) system as well as using manual control with a joystick (Table 1). It should be noted that in each case (joystick or Wii board control), there is approximately a doubling of

execution time when in first-person viewing as opposed to third person. We attribute this to an inability to execute path planning due to reduced spatial awareness, a result of the limited field of view of the immersive cameras. It is also noteworthy that for a given view, the execution times also approximately double when switching from joystick control to Wii control. We attribute this doubling to the relative inexperience during platform-based navigation using the Wii control approach. We believe that through refinement of control tuning via the Wii board, the separation times between the two methods may be minimized. Remember, the inclusion of the Wii-based control enabled the users to simultaneously execute mobility as well as one-to-one teleoperation of a bimanual robotic system using their native limbs.

Incidentally, the stereoscopic vision seemed to hinder the ability to drive the system compared with third-person viewing; however, one must remember the context. A user will not always have line of sight to the robot to engage in visual maneuvering, so incidentally, camera-based navigation is a necessity for human capabili-

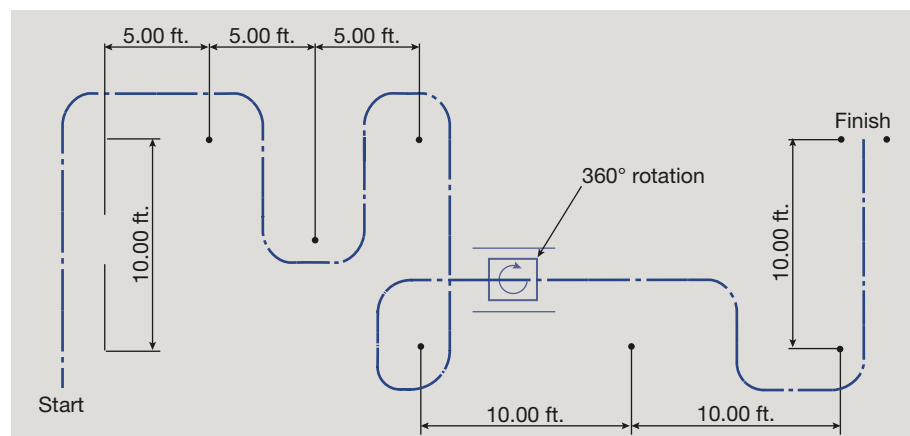


Figure 7. Advanced robot control evaluation test course (course no. 2). Note: Solid black lines denote reference distance markings.

Table 1. Mobility control results for DRP tests varying the visual modality and input method

Course No.	Controller	View	No. of Trials	Time (s)
1	Wii Balance Board	Third person	7	88.3
1	Wii Balance Board	First person	2	168.5
1	Joystick	Third person	7	43.3
1	Joystick	First person	5	97.2
2	Wii Balance Board	Third person	1	115.0
2	Wii Balance Board	First person	2	193.5
2	Joystick	Third person	4	66.0
2	Joystick	First person	4	137.8

ties projection. Additionally, the primary role of the stereoscopic vision system is to aid in functional dexterity-type tasks.

Functional Dexterity

In addition to mobility testing, we compared the Segway Sally system to existing EOD robot systems performing a number of functional dexterity tasks. For the first functional dexterity test, we used the robots to open an unlatched car door from a fixed position (Fig. 8) using time to completion as a comparative metric. In this test, Segway Sally was controlled by a trained operator who posted times of 2 min, 45 s using Sally's right arm (RP2009 P1) and 1 min, 6 s using Sally's left arm (RP2009 P2). A conventional EOD robot (TALON) with a trained operator completed the test in 47 s.

Finally, dexterous mobility was evaluated in a task that combined grasping, manipulation, and mobility. The goal was to grasp a water charge disruptor from a pickup location and then deposit it at a destination 9 ft away (Fig. 1). A trained operator controlling Sally and using the Proto II Arm was able to complete the task in 3 min, 45 s. For comparison, a trained operator controlling the TALON system completed the task in 1 min, 12 s.

It should be noted that although these results indicate faster execution times for each scenario examined for conventional EOD robots, an advantage of the DRP lies in bimanual manipulation, which was untested. This was untested because conventional EOD robots would have been unable to complete the task. Bimanual manipulations are important for the forensics analysis potential gained through disarming in place and recovery of improvised explosive devices. Operations seeking this advantage are limited by current EOD robots because of their single manipulator arm and 1-DOF end effectors.

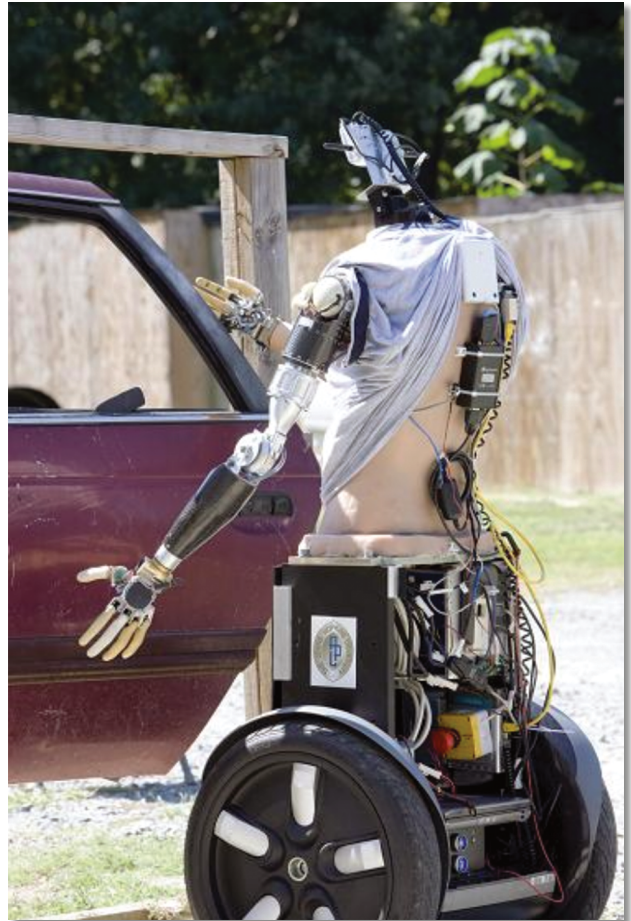


Figure 8. Segway Sally executing the car door functional dexterity task.

ONGOING AND FUTURE WORK

Autonomous or semiautonomous control strategies are an important aspect of robotic control and currently span a significant portion of robotics research. Autonomous and semiautonomous control modalities would hypothetically reduce the cognitive and physical burden on the operator when performing bimanual manipulations. Imagine a scenario where a user could, instead of precisely controlling every DOF in the DRP system, select a target object and where the system would then automatically determine the effective motion to execute a specific function with the target object. To accomplish this, we plan to base local autonomous control capabilities primarily on a combination of two sensor modalities: computer vision and MPL-based tactile object interaction. Information from these combined sensor modalities will provide feedback to a local autonomous algorithm framework (Fig. 9). High-level commands from the operator (e.g., maintain grasp on object or select an object in the environment) will be used to cue low-level hand control to conform around target objects and maintain object stability.

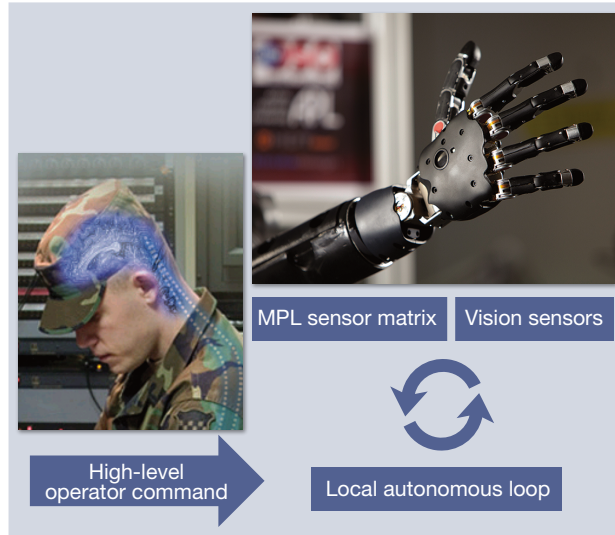


Figure 9. Overview of local autonomous control algorithm receiving high-level operator inputs to operate the limb system in a user-in-the-loop autonomous control approach.

Two vision sensors that operate either complementarily or independently will be integrated within the mobile robotic system framework: a more advanced and resolved stereoscopic vision system in addition to a scanning light detection and ranging (lidar) sensor. The advantage of using both technologies in a complementary fashion is that it provides the operator with native vision feedback as well as computer vision for object detection.

A system running the Robot Operating System (<http://www.ros.org>) within a Linux-based operating system will process the autonomy algorithms. The Robot Operating System provides a central environment for communicating with peripheral devices, visualizing

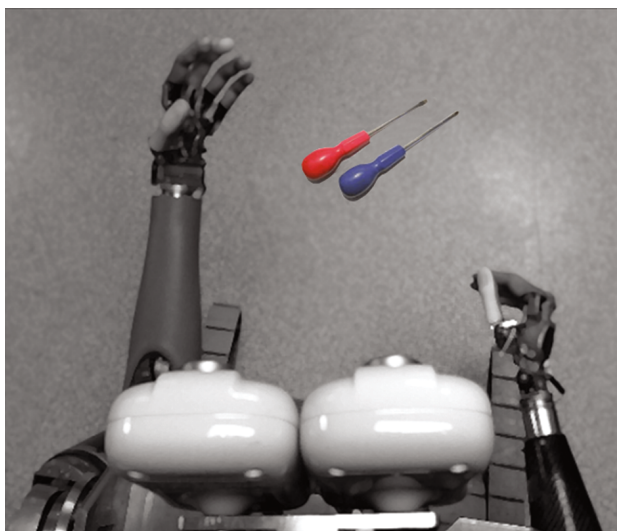


Figure 10. Example robotic workspace view with selectable objects for autonomous grasping.

component relationships, and handling messages. Additionally, developing in this environment enables access to an open-source community that provides thousands of libraries for image processing, navigation, object segmentation, visualization, autonomy, manipulation, and localized control. Once the Robot Operating System development environment is established and peripheral devices integrated, we will pursue parallel paths to develop object pose detection from sensor data hybridized with arm path and grasp planning. Path planning is involved in determining the optimum combination of joint angles to realize a particular location and orientation of the end effector, whereas grasp planning pertains to the positioning of elements of the end effector in contacting and stabilizing an object of interest.

Path planning will be based on the kinematic relationship of the detected object coordinate frame relative to the vision sensor coordinate frame as well as the arm, hand, and fingertip coordinate frames with respect to the robot base frame. The MPL currently supports a variety of grasp patterns and movement macros to obtain reproducible hand conformations. We plan to use an object library to set an appropriate grasp for interaction with a target object. For each grasp, a kinematic approach vector defines the prehension and pose required to interact with the target object. A path-planning module will either position the hand and wrist into the desired pose or direct the user to adjust the mobile platform pose and/or torso position to achieve the desired grasp location through direct or assisted teleoperation. Once the system achieves the prehension position, the system will begin an object interaction mode with the target object. Information from the sensor matrix of the MPL can indicate successful object interaction and can be used to trigger trajectory correction if unexpected contact forces are encountered. The end-to-end implementation of this grasp planning and execution algorithm will allow the operator to provide a high-level command such as clicking on the screen or fixing their gaze on an object through eye tracking to select a target object and initiate autonomous grasping (Fig. 10).

CONCLUSION

We have developed an approach for robotic system design and control that focuses on human capabilities projection downrange. The ultimate goal of this approach is to provide the operator with the ability to perform necessary actions, manipulations, and tasks downrange at safe standoff distances in harmful or dangerous scenarios. The team has been able to investigate and compare a variety of control modalities through the integration of bilateral advanced anthropomorphic robotic limb systems (MPL and prototypes) onto com-

mercial (Segway) and military-fielded (PackBot) mobility platforms. Additional testing with EOD technicians provided valuable feedback to help define the needs for future systems. To make effective use of the breadth of sensor information provided through the MPL system, we have developed a tactile feedback device to feed these signals back to the user when performing robotic telemanipulation tasks. We seek to continue our efforts by reducing cognitive load through development of autonomous and semiautonomous manipulation techniques, which further expand the effectiveness of our approach. We feel that continued advancements in the work described here will help advance the team to the ultimate goal, which is to realize true human capabilities projection through the enhancement of operational effectiveness downrange.

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