

# Recent Enhancements to Mobile Bimanual Robotic Teleoperation with Insight Toward Improving Operator Control

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**I**n a number of environments and scenarios where it is dangerous, impractical, or impossible to send humans, robotic teleoperation is used. It enables human-teleoperated robotic systems to move around in and manipulate such environments from a distance, effectively projecting human capabilities into those environments to perform complex tasks. Bimanual robots are equipped with two arms/hands and have the capacity to perform many tasks, particularly when integrated with mobile platforms. This article provides an overview of two mobile bimanual robotic system prototypes designed to be teleoperated by human operators to perform unmanned ground vehicle missions. It highlights limitations in robot sensing and control that were observed during the course of conducting research on improving the effectiveness of human operator control. System enhancements are discussed that are aimed at achieving this goal through robot sensor augmentation, increased operator situational awareness, and a robot control approach for facilitating human operator control. These enhancements are expected to improve human–robot capabilities for future unmanned vehicle applications.

## INTRODUCTION

Teleoperation refers to the direct human control of a machine from a distance. It is commonly associated with systems wherein the machine is represented by robotic mechanisms or mobile robots. Such systems are increasingly used on unmanned vehicles to enable a range of applications across a variety of domains including military, first responder, law enforcement, construc-

tion, hazardous material handling, and exploration of deep ocean, space, and planetary surface environments. The ability to affect environments through manipulation of robotic arms and attached end-effectors (hands and tools) lets human operators project their intent and capability from safe locations, facilitated by sensor feedback from a teleoperated system at a remote location,

providing a level of telepresence to the human operator. In some cases, the technology is necessitated by remote environments that are inaccessible or inhospitable to humans (e.g., space or planetary surface locations). In other cases, it is preferred to keep humans out of harm's way by providing them a safe standoff distance [e.g., military explosive ordnance disposal (EOD) missions and hazardous material sites]. To date, many teleoperated unmanned ground vehicles (UGVs) with single robotic arms have been deployed in most of the aforementioned application domains. As tasks become more complex or require additional capability, the demand has increased for UGVs with two robotic arms and added manipulation dexterity. Generally speaking, manipulation tasks requiring the application of torque or leverage tend to fall into this category. Particular examples of tasks for which dual-arm dexterity is required or preferred include lifting objects that exceed the lift capacity or balancing capability of a single arm, unscrewing the cap from a container (or other general screw assembly), operating a shovel or a similar tool, and separating objects (such as a blasting cap from an explosive). Robotic systems employing two arms and two hands are referred to as bimanual manipulation systems, in the same sense of the term as applied to humans; thus, many bimanual coordination tasks that humans can perform may also be performed by a bimanual robot, depending on its dexterity.

Bimanual teleoperation is an enabling technology for dexterous standoff operations, which are often preferred for telerobotic UGV missions that require human-like capabilities in environments or conditions that may put humans in harm's way. Bimanual teleoperation allows robots to manipulate certain objects and perform complex tasks that are not feasible with either single end-effector control or joystick-like control of two end-effectors. Although the feasibility and underlying capabilities of bimanual manipulation systems have been demonstrated, a number of challenges associated with accurately controlling such complex systems by using inputs from a single teleoperator remain and are discussed herein. This article focuses in particular on the use of bimanual teleoperation in the application domain of EOD and prototype research systems for bimanual teleoperation that comprise a mobile dexterous robotic platform and associated teleoperator/user interfaces. The content is also relevant to similar robotic systems and UGV applications.

After a discussion of related work from the broader research community, the APL research theme of human capabilities projection (HCP) is discussed. An overview of the APL prototype research systems for mobile bimanual teleoperation is presented next. System enhancements to address hardware limitations revealed during recent research at APL, and aimed at improving the ease and effectiveness of operator control, are then

described. Finally, we discuss insights gained toward a reduced-order control paradigm to manage complexities associated with human control of the many actuators comprising mobile bimanual teleoperation systems.

## RECENT RELATED RESEARCH

Fundamental problems of robotics and control theory that underlie telerobotics over communications links with and without appreciable time-delay were addressed decades ago and with considerable vigor during the 1970s and 1980s.<sup>1</sup> Bimanual teleoperation systems were subjects of some research during that time, although most systems involved a single teleoperated robot manipulator. With advances in computing, communications, sensing, and robotics technology, new implementations and enhancements of single and bimanual teleoperated manipulators have emerged and continue to evolve. Research at APL is addressing ways to improve operator control of such bimanual manipulators during teleoperation, as presented in later sections of this article. For broader context, this section provides a sense of the recent research related to bimanual manipulation, teleoperated or otherwise.

Research continues toward advancing the underlying issues in kinematics and control specific to bimanual robotic manipulators. Results representative of the state of the art include a generic control approach for highly redundant manipulator systems such as bimanual manipulators<sup>2</sup> as well as techniques for coordination and control of bimanual systems (with multi-fingered hands and finger-embedded force sensors) including contact variables (modeled as passive joints) for force control and feedback.<sup>3</sup> Other work advocates development of benchmarks for bimanual robotic manipulation that can be applied for different robots and hands,<sup>4</sup> signifying a sensitivity to the need for evaluating and comparing bimanual systems.

A recent survey paper<sup>5</sup> summarizes the state of the art and developments in bimanual manipulator control, modeling, planning, and learning. Research covering both bimanual manipulation (physical interaction with a single object) and goal-coordinated dual-arm manipulation (arms not physically interacting with each other but solving the same task, e.g., two-handed typing) is included in the survey. The survey projects that future research will address capabilities for performing complex, coordinated dual-arm tasks by building on the integration of these developments with computer vision, learning, and cognition in particular. The survey also projects a substantial increase in applications for collaborative human-robot manipulation. Robot learning of bimanual tasks is among the newest facets of this research topic area wherein a number of techniques are being pursued. An emerging theme is the use of models inspired by research on bimanual coordination

in human movement science and how tasks can be learned by robots using computational techniques of learning by imitation and programming by demonstration.<sup>6</sup> Such work seeks to address the challenge of robust execution of bimanual tasks by using machine learning techniques, which incurs the additional challenges of getting the motor system to reliably reproduce learned tasks and adapt to external perturbations. Future APL research seeks to address such challenges by building on the mobile bimanual teleoperation infrastructure described in this article.

With increased attention to the use of robots in environments designed for humans, a segment of the community is focused on robot manipulation technology that is effective for human environments, including bimanual systems allowing high-level teleoperation combined with onboard autonomous perception and autonomous control behaviors that can be overridden by a teleoperator.<sup>7,8</sup> Similar mobile bimanual systems have been considered for performing human-like tasks (e.g., using tools designed for human use) and to assist humans in remote, unstructured environments.<sup>9</sup> A common aim of such work is to reduce the human teleoperator effort or the cognitive load associated with successfully executing bimanual tasks while striking a balance between what humans and robots do best within the context of the task. The ongoing bimanual teleoperation research at APL contributes to these objectives using the bimanual systems described later. Additional challenges include reducing overall task completion time and developing a single human–robot interface that can be used for all modes of robot control from teleoperation to autonomous operations.

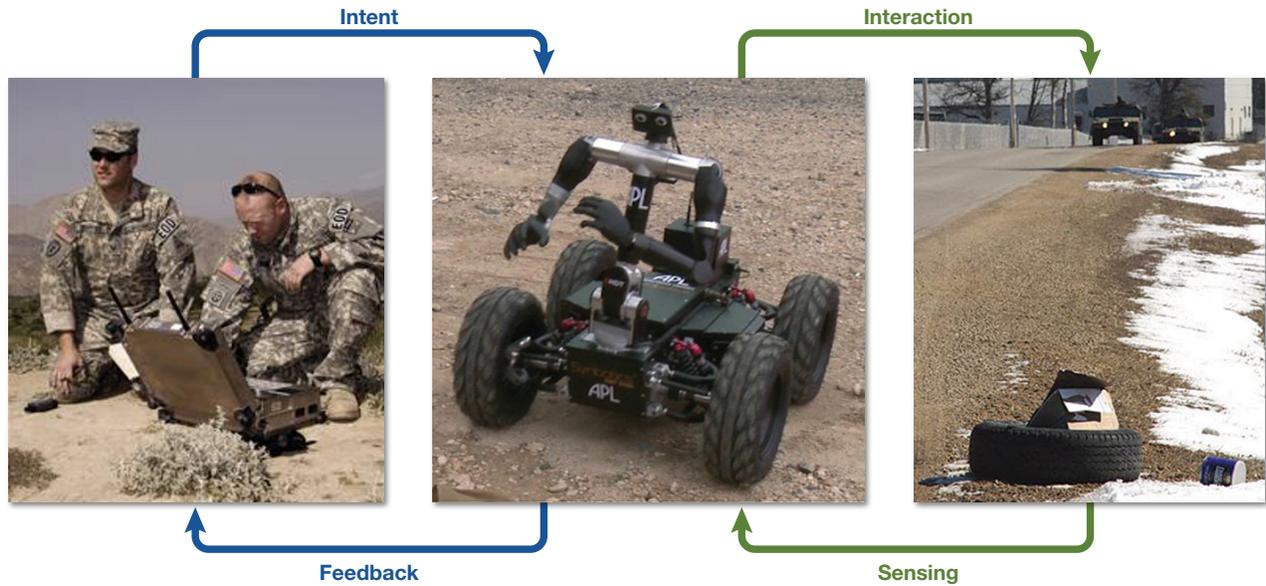
More germane to the primary application domain discussed herein, researchers are addressing challenges of teleoperated bimanual systems on UGVs for EOD operations. The research of Kron et al.<sup>10</sup> is representative of work using mobile bimanual teleoperation systems that are similar to platforms used at APL. Their work involves a bimanual manipulator system with haptic (tactile feedback) devices and a head-mounted display as a teleoperator interface that can ultimately be part of a larger system comprising a mobile platform and stereo vision system. The EOD task focus is tele-demining of anti-personnel mines. The research has similar motivations in its focus on bimanual teleoperation for EOD tasks facilitated by multiple modes of sensor feedback, a bimanual human–robot interface, and stereo visualization. More recent work seeks to advance the level of autonomy of dual-arm dexterity for inspection and EOD tasks in urban terrain by using a limb coordination system<sup>11</sup> that can be applied to autonomously control multiple dexterous manipulators for object grasping and manipulation. The limb coordination technology may enable task-specific capabilities such as dual-arm pick up and use of a shovel.

This research also has similar motivations to research pursued at APL in its focus on increased robotic autonomy for EOD missions. With that said, the bimanual systems used for each of these research efforts are less dexterous than the bimanual systems used for research at APL and described later in this article. In particular, they are limited in manipulation dexterity and mobility relative to bimanual systems used at APL, and the research was conducted for a partially integrated system (manipulation only) in one case<sup>10</sup> and in simulation in the other case.<sup>11</sup> As alluded to earlier, a goal of such research, despite the degree of system dexterity, is to enable autonomy within a system that is also applicable to mobile bimanual teleoperation wherein a proper balance is achieved that benefits from the best of human and robot capabilities. To this end, APL research discussed in this article is currently focused on improving human operator control during teleoperation.

## HUMAN CAPABILITIES PROJECTION

HCP is a research theme at APL that encompasses mobile bimanual teleoperation. Specifically, HCP refers to the robotic manifestation of human-like dexterity and sensory perception through robotic telemanipulation.<sup>12</sup> Our current HCP research is motivated by the notion that telemanipulation effectiveness is enhanced by combining intuitive teleoperator interfaces (based on high-resolution motion tracking of the human operator's native limbs) to control anthropomorphic robot manipulators with haptic feedback and with stereo remote vision. The key enabler of effective HCP is the robotic system, which acts as a surrogate to the human operator for executing downrange or remote operations. APL focuses its development on core components of the robotic system that are most directly tied to achieving HCP: bimanual dexterous manipulation capabilities, immersive stereo remote vision, intuitive control modalities, sensor integration for operator feedback, platform mobility, and user-in-the-loop semiautonomy.

The framework for HCP research on mobile bimanual teleoperation consists of human–robot elements as well as robot–environment elements, with relationships loosely shown in Fig. 1 for an example EOD application. The human–robot elements are concerned with operator intent via command and control using intuitive teleoperation interfaces and with feedback of information and sensor data from the robot to the operator. Operator intent is realized by using techniques of direct control of each degree of freedom (DOF) of the robot, reduced-order control (achieving comparable control performance considering a control model based on a reduced state-space), and supervised autonomy (commanding and guiding the robot via high-level commands executed using onboard autonomy). Robot–environment elements are concerned with the robot's sensing of its



**Figure 1.** Key elements and relationships for HCP depicted for an EOD scenario using mobile bimanual teleoperation.

internal state (e.g., positions and velocities of its joints and mobile platform) and external local environment, its physical interaction with and modification of the environment via direct manipulation and use of tools, and its mobility through its physical environment.

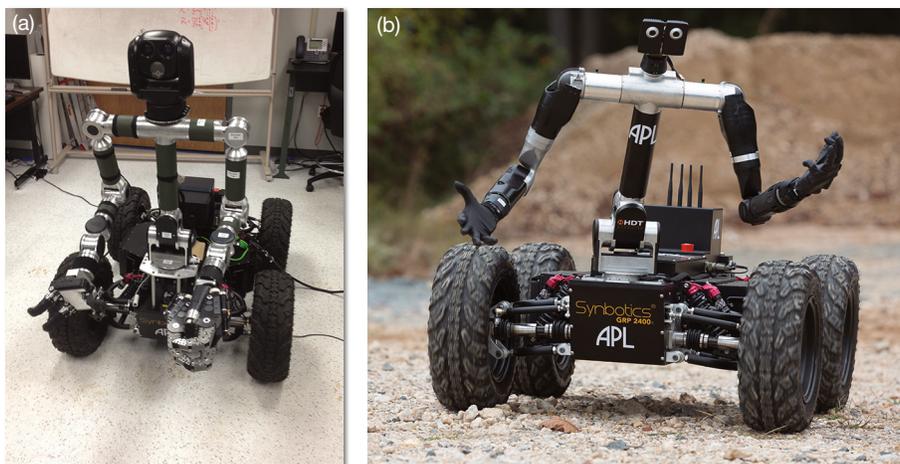
### PROTOTYPE SYSTEM OVERVIEW

Two prototype mobile bimanual teleoperation systems have been the focus of recent development at APL. They are referred to as Johnny-T and RoboSally and are variants of several dexterous robotic platform configurations used for HCP research to date.<sup>12</sup> Both robots comprise a dexterous bimanual manipulation subsystem mounted on an all-terrain mobility subsystem. They differ primarily in arm configurations and

dexterity for the bimanual manipulation subsystems, being more or less anthropomorphic, while sharing similar four-wheel mobility subsystems, as shown in Fig. 2 and further described in the following subsections. Each robot stands at a height of approximately 1.3 m and has a ground footprint of roughly 1 m by 1.2 m depending on the mobile platform used.

### Dexterous Manipulation Subsystem

The Johnny-T configuration uses a Highly Dexterous Manipulator (HDM) integrated with wrist-attached end-effectors and a head that houses cameras for stereoscopic vision. The HDM mechanism is a prototype dual-arm system developed as a technology demonstrator for the Advanced EOD Robotic System (AEODRS) program of record.<sup>13,14</sup> (The HDM is a product of HDT



**Figure 2.** Prototype mobile bimanual robots: (a) Johnny-T; (b) RoboSally.

Robotics, developed with funding from the Joint Ground Robotics Enterprise for the AEODRS program, which is sponsored and led by the Naval Explosive Ordnance Disposal Technology Division.) A “T”-shaped torso with 3 DOFs at the waist (roll, pitch, yaw) and two 7-DOF arms comprise the HDM. Each robotic arm has a fully extended reach of 65 cm (shoulder to wrist) and terminates in an interface to which a variety of robotic hands or end-effectors (having the proper mating interface) can attach. This common interface enables using interchangeable end-effectors designed for various manipulation purposes. To date, several types of end-effectors designed for EOD dexterous manipulation tasks have been used on Johnny-T, including robotic hands from Contineo Robotics (now Telefactor Robotics; see right hand in Fig. 2a), RE2, Inc. (left hand in Fig. 2a), and HDT Robotics; each of these end-effectors add 4 DOFs. The integrated stereo head is a commercial off-the-shelf unit produced by Telefactor Robotics that adds 2 DOFs to the assembly (excluding the zoom capability of its embedded cameras).

The RoboSally manipulation subsystem configuration is an integration of the same HDM torso and stereo head used on Johnny-T, along with more dexterous manipulators in the form of two Modular Prosthetic Limbs (MPLs) developed by a multi-institutional team led by APL as part of the Defense Advanced Research Projects Agency Revolutionizing Prosthetics program.<sup>15</sup> Each MPL is highly anthropomorphic in form factor and weight relative to the human arm, providing 7 DOFs from shoulder to wrist plus 10 DOFs in its five-fingered anthropomorphic robotic hand, resulting in 26 articulating joints in total (4 DOF of which are in the thumb for dexterous grasping and hand shaping). With its many DOFs, along with fingertip-embedded sensors for tactile perception and haptic feedback, the overall MPL design allows for demonstration of human-like dexterity and feedback to a human teleoperator.

### Mobility Subsystem

The ground mobility subsystem transports the bimanual dexterous manipulation subsystem throughout the operational environment to sites for performing manipulation tasks. The mobility subsystem for the Johnny-T and RoboSally configurations is a high-mobility, heavy-payload UGV available commercially from Synbotics—two model varieties from its Ground Robotic Platform (GRP) Series have been used to date, namely the GRP 2400x and the GRP 4400x models. These fully electric UGV models feature four wheels with independent drive motors and independent passive suspension as well as active four-wheel steering. The GRP 2400x model is capable of four steering modes (crab, rear-only, front-only, and skid steer for turns in place) wherein the front and/or rear wheels are oriented

at the same angle within the steering range of motion. The GRP 4400x is capable of the same steering modes plus an additional steering mode wherein all wheels are maximally oriented toward the central longitudinal axis of the UGV, enabling a four-wheel turn-in-place capability. With multiple steering modes and ground clearance of approximately 20 cm and 45° slope traversability (without payload), the mobility subsystem provides high maneuverability on various ground surfaces, from indoor floors to paved roads and natural off-road and rough terrain. Such high maneuverability is essential for accessing varied terrain to bring the next work site within reach of the bimanual dexterous manipulation subsystem.

### Teleoperation Interfaces

Controllable DOFs of both mobile bimanual teleoperation system prototypes can be teleoperated via a variety of user interfaces and devices. Provided with visual imagery from cameras in the robot’s stereoscopic head, and in some cases haptic feedback from sensors on the robot’s manipulators, a human operator can teleoperate the robot to perform tasks by using any of the HCP control modes mentioned above. To achieve this, appropriate interfaces are required to deliver visual and haptic feedback to the operator and to deliver motion control inputs to the robot, all over a wireless communications link. An operator of the Johnny-T or RoboSally system wears a head-mounted display to receive stereo views of the robot’s local environment as seen by cameras in the robot’s stereoscopic head and transmitted over the communications link. This provides the operator with a degree of visual immersion or telepresence in the remote environment, which facilitates effectively executing teleoperated tasks. Teleoperation of the mobility subsystem for both robots is achieved by using a separate remote control device enabling the operator to drive and steer the platform between manipulation work sites.

To achieve bimanual teleoperation, human operator motions expressing intended motions of the robot’s DOFs must be transmitted to the robot. Likewise, to benefit from haptic feedback, the forces/torques or physical contact measured or detected by sensors on the robot manipulators must be interpreted and transmitted to the human operator via suitable haptic devices. Two sets of different teleoperation interface types have been used thus far to deliver motion control inputs to the robots and haptic feedback to the operator. These sets are referred to herein as human-joint mimicry (HJM) interfaces and joystick endpoint control (JEC) interfaces. As noted earlier, our HCP research advocates the use of intuitive teleoperator interfaces based on high-resolution motion tracking of the human operator’s native limbs to achieve enhanced telemanipulation effectiveness. HJM inter-

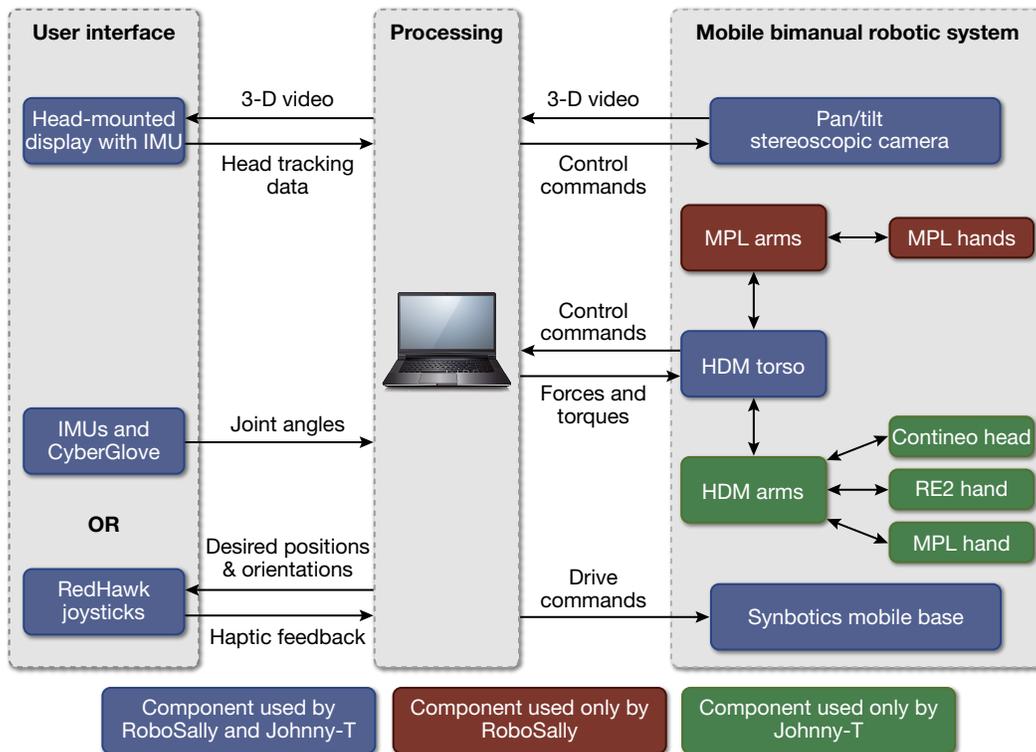


**Figure 3.** The Harris RedHawk dual controller.

faces embody this approach with 3-D motion tracking devices (from Xsens Technologies) worn by the operator to track the operator’s arm and torso movements and a CyberGlove (from CyberGlove Systems, LLC) worn on each of the operator’s hands to track hand and finger movements. Positions and/or orientations of the operator’s arms, torso, hands, and fingers are tracked by these devices, mapped to the equivalent DOFs on the robot, and transmitted to the robot for execution, thus mimicking the motions of the human operator. To receive haptic feedback from the robot’s fingertip sensors, the operator can also wear small electromechanical actua-

tors (also known as tactors) on his/her fingertips that physically convey haptic information in the form of pressure or vibratory sensations.<sup>16</sup> HJM interfaces have been used for both the Johnny-T and RoboSally systems.

A second approach to bimanual teleoperation uses advanced multi-DOF joystick-like devices to provide motion control inputs to the robotic manipulators and to apply forces/torques to the operator’s hand(s), representing haptic feedback received from the robot. JEC interfaces embody this approach with Harris RedHawk intuitive haptic controllers (Fig. 3). The operator’s left and right hands each manage a single haptic control-



**Figure 4.** Overview of the various system components, connections, and signals. IMU, inertial measurement unit.

ler to provide motion inputs to the robot for positioning its respective left and right arms. Each haptic controller can control 6 DOFs as well as end-effector grip motions. Hand-controlled motions are mapped to the controllable DOFs on the robot and transmitted to the robot for execution, thus mimicking the intended motions of the human operator. The operator receives interpreted feedback of forces/torques experienced by the robot's manipulators via the haptic hand controllers for the six controllable DOFs and the grip control. JEC interfaces have been used for the Johnny-T system. Figure 4 depicts a high-level block diagram of the overall mobile bimanual teleoperation system.

## HARDWARE LIMITATIONS AND ENHANCEMENTS

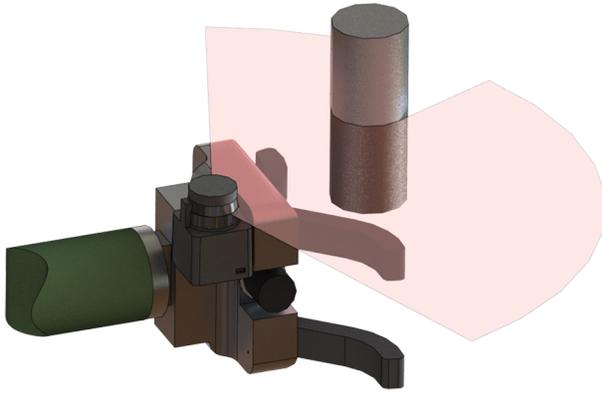
Through the course of conducting recent research at APL with the types of bimanual teleoperation systems described herein, as well as particular robot hardware components associated with them, we have observed limitations in the achievable quality of manipulator state estimates and haptic feedback as well as a need to improve visibility for reaching and grasping occluded objects. The robot's onboard estimates of its bimanual manipulator joint positions, and thus the overall posture of the manipulation subsystem, are important for accurately tracking operator motions under direct teleoperation control. The same is true for accurately executing any automatic or autonomous motions under reduced-order or supervised (operator-assisted) autonomous control. Uncertainty in manipulator joint positions associated with the actuators used in our work has been found to be a limiting factor in bimanual manipulator state estimation. More specifically, backlash in the drive train of the manipulator actuators, coupled with errors in encoder alignment and motor control, causes a divergence of the estimated state from the true state as the system is operating. This divergence is a direct consequence of actuator design, which in the MPL and HDM systems has favored high speed and torque in a lightweight and low-profile package traded for ultimate precision. Although an experienced operator may be able to compensate for such divergence during direct teleoperation, the need to do so unnecessarily adds to the physical and cognitive load associated with operating the system. Without knowledge of bimanual manipulator state via precise sensor measurements or adequate state estimates, robust implementation of automatic control functions (e.g., gravity compensation) and autonomous control behaviors (e.g., sensor-based avoidance of self-collision and designated keep-out regions) would clearly be a major challenge.

Haptic feedback in the form of forces, torques, and contact indicators provides information about the physical nature of the robot's interactions with its environment and enhances the operator's telepresence. The

quality of such feedback affects the robot's ability to successfully execute teleoperated tasks. Torque feedback from the bimanual manipulators described herein is currently derived from dedicated strain gauges within the joints of the upper arms. However, the location of these sensors and the drivetrain friction inherent in the joints can lead to inaccurate readings, limiting the quality of haptic information fed back to the operator. It is anticipated that sufficient experimental calibration could serve to overcome some of these issues. With that said, certain limitations would remain as impediments to accomplishing tasks such as manipulating objects occluded from operator view. For example, certain EOD tasks require reaching into cavities or behind obstructions to retrieve objects. Although a rich set of haptic information may enable an operator to explore within the occluded area and "feel" for the object, our current prototype configurations do not provide an adequate level of haptic feedback.

The authors are considering a variety of design and implementation enhancements for the bimanual systems described herein to address their limitations and improve manipulator state estimation, haptic feedback, or both. One approach would incorporate a dual-encoder system, adding a high-count encoder before and after gear trains. In this way, the amount of divergence in joint angle positions from the true states can be measured and used to estimate joint torque. This approach has been designed into recent industrial robot manipulators available on the commercial market. The drive torque measurement challenge can be addressed using other specially designed sensors or intelligent control techniques.<sup>17,18</sup> Another approach to enhancing state estimation as well as contact detection for haptic feedback would integrate accelerometers into each link of the bimanual manipulator. Low-frequency portions of the signal provide additional information that can be used to improve the accuracy of the system's state estimation. High-frequency response can be used to provide the user with feedback related to sudden contact with objects or obstacles.<sup>19,20</sup> Accelerometer elements in the fingertip sensors of the MPL system and on the limb controller of the MPL in the RoboSally configuration provide this frequency response.

To enhance the operator's visibility for reaching and grasping occluded objects, the sensor suite for the right hand on the Johnny-T bimanual manipulator was augmented with a lidar sensor (Hokuyo URG-04LX-UG01) and auxiliary camera with LED illumination. These sensors were located on the end-effector and provided visibility during the end-effector's approach to and within occluded areas, thus compensating for limited haptic feedback from the hand and facilitating guidance during the reach and grasp actions. Figure 5 illustrates the position and orientation of the lidar sensor and the type of planar distance information that it provides. As shown



**Figure 5.** Illustration of end-effector-mounted lidar sensor detection profile intersecting a cylindrical object to be grasped.

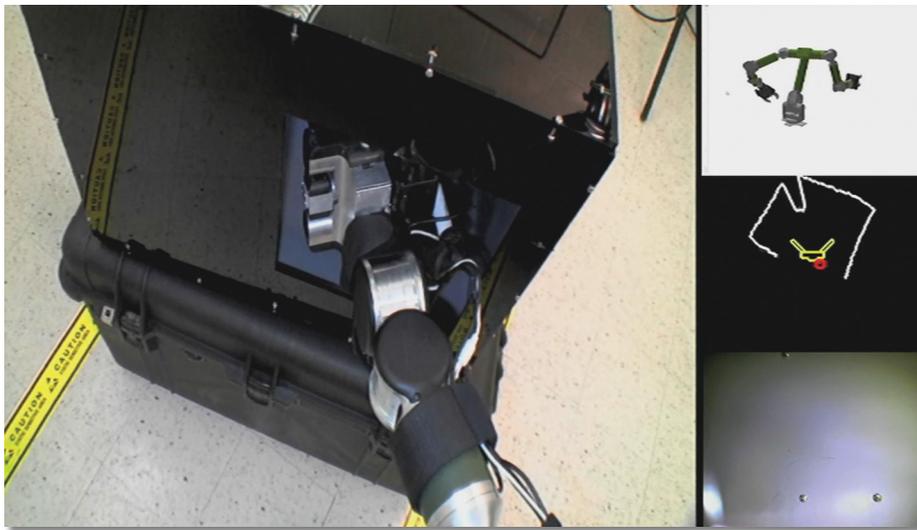
in Fig. 6, this information is provided to the operator through an augmented view window within the operator's head-mounted display, showing the hand-camera view and lidar range data. In Fig. 6, the lidar range data view indicates the detected presence of an object inside an enclosure reached into using the right hand of Johnny-T. With this approach, visual information presented to the operator enables the operator to see within the occluded area, locate an object within, and consider object orientation (and other obstructions) in deciding how to grasp it directly or otherwise manipulate it to ensure an effective grasp. This is an improvement on limited haptic feedback, which would at best allow the operator to blindly “feel” around within the occluded area while inferring information about object presence, location, orientation, and spatial relationship to other obstructions within the occluded area. The gain in increased situational awareness provided by the hand-

mounted lidar, camera, and illuminator is expected to increase efficiency of the reach and grasp task. Such enhancements to manipulator state estimation, haptic feedback, and visibility for grasping occluded objects increase teleoperation effectiveness and capabilities for the Johnny-T and RoboSally systems.

## REDUCED-ORDER MODELING CONSIDERATIONS

While the hardware enhancements identified in the preceding section can improve the controllability of the bimanual manipulation hardware, enhancements are also considered for improving the operator's capability to teleoperate the overall system. In this regard, the aim is to manage the complexity of controlling the many DOFs of highly dexterous robotic platforms via human interfaces limited to control of fewer DOFs. A related aim is to reduce the burden on the human operator by obviating the need for direct, serial control of each DOF. A further enhancement that can address such issues is the application of reduced-order models of highly dexterous robot manipulators.<sup>21</sup>

Considering the number of controllable DOFs for the Johnny-T and RoboSally systems and their associated observable states, the fundamental complexity involved is due to an extensive control space (29–42 independent active joints and 27–74 available sources of sensor feedback as indicated in Figs. 7 and 8, exclusive of the aforementioned end-effector camera plus lidar enhancement). APL research experience to date has identified a number of problems with accurately controlling such complex systems by using inputs from a single human operator's limbs or common handheld operator control units. These insights have led to consideration of techniques



**Figure 6.** Operator head-mounted display during a teleoperated reach into an enclosure to grasp an occluded object, showing hand inserted into an opening in the enclosure (left), bimanual manipulator kinematic posture (top right), hand-lidar range data (middle right), and hand-camera view (bottom right).

to control our systems on the basis of reduced-order models as a means to manage bimanual teleoperation complexities as well as the physical and cognitive burden associated with the teleoperation experience.

The mobility subsystem is already teleoperated in a reduced-order manner in that only 2 DOFs (i.e., the gross UGV direction and speed) are controlled by the human operator as opposed to additional DOFs for each individual wheel speed and steering control. Similarly, a reduction in operator-controlled DOFs is desired for

bimanual teleoperation of the dexterous manipulation subsystem considered in combination with the mobility subsystem. This is achieved by using the redundancy in the system and the associated null space of the Jacobian matrix<sup>22</sup> to optimize secondary aspects of the system while achieving the desired goals (Wolfe, K., Kutzer, M., and Tunstel, E., “Leveraging Torso and Manipulator Redundancy to Improve Bimanual Telepresence,” unpublished manuscript, 2013). Note that, for this system, the dimension of the Jacobian matrix is

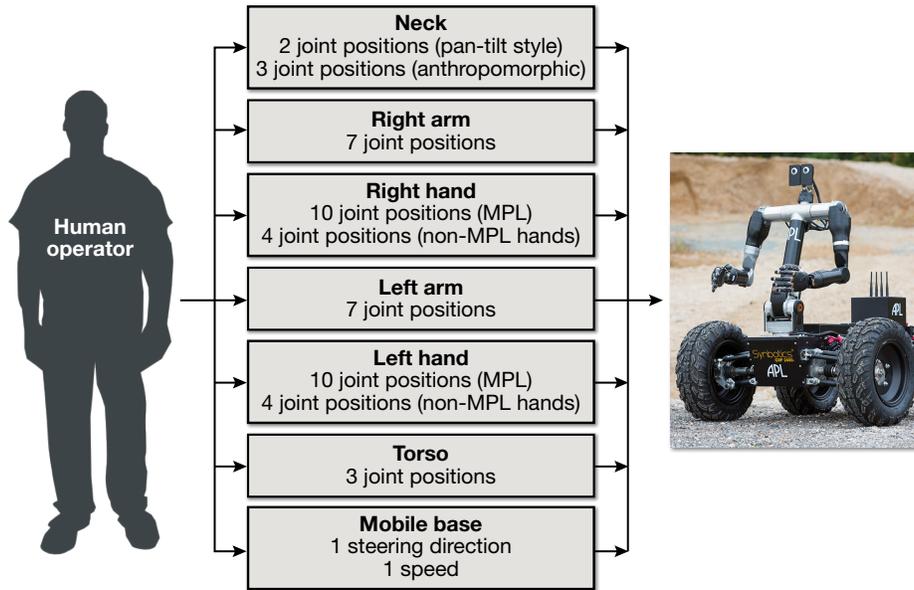


Figure 7. Control state-space breakdown assuming 1:1 mapping between user and system.

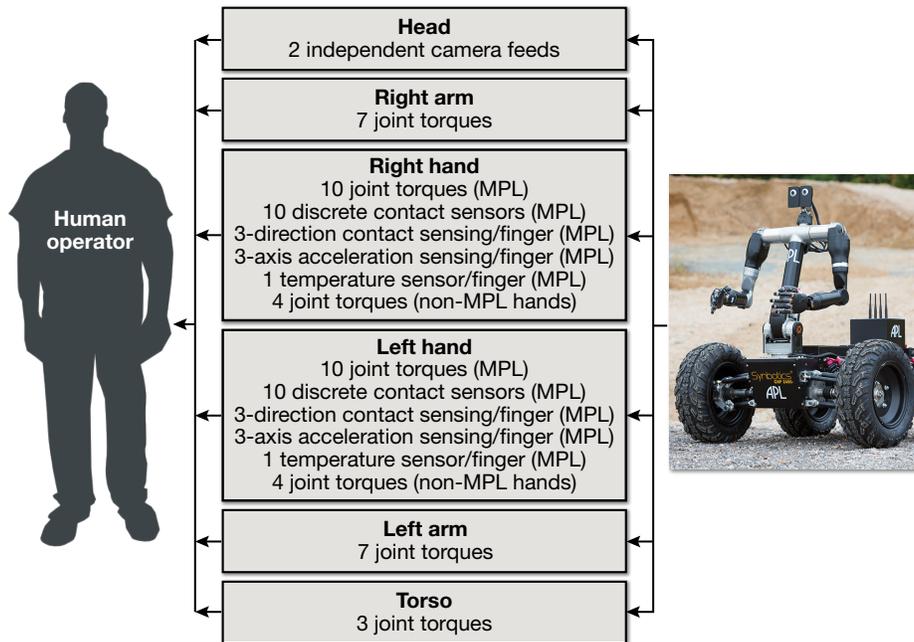


Figure 8. Sensory feedback options for hardware variants of the dexterous manipulation subsystem.

12 rows by 17 columns because of the redundancy in the number of joints when compared to the minimum DOFs required to describe the position and orientation of the two end-effectors. This dimension results in a null space with a minimum dimension of five, which means that at any point in the workspace (ignoring joint limits), at least five joints or combinations of joints can be moved without changing the position or orientation of either end-effector. The approach enables smooth and natural teleoperation of single-handed and bimanual manipulation tasks via self-governing torso control.

A distinct attribute of the approach is a deliberate human-centered design aimed at immersive telepresence for the human operator achieved through careful choice of cost functions that place value on aspects of performance affecting the immersive experience. These secondary cost functions include reducing camera motion and jitter that can result in the operator feeling disoriented, increasing the future range of motion of the system by avoiding joint limits, and improving the lifting capabilities of the manipulators by configuring joints so that the moments and torques applied to the motors are minimized. Results demonstrate the effectiveness of the approach for next-generation EOD robot prototypes such as Johnny-T and RoboSally (Wolfe et al., unpublished, 2013) and can be extended for application to other high-DOF robotic systems and dexterous telemanipulation applications.

## CONCLUSIONS

Enabling technologies for mobile bimanual teleoperation and improvements on existing approaches are impacting teleoperated UGV systems and their operational techniques. As advances continue to occur in parallel, it is important to reassess the synthesis of integrated system solutions and component technologies to achieve desired effects for increasingly complex UGV tasks. With an aim toward advancing the effect of HCP for dexterous standoff operations, we have concentrated on improving the effectiveness of the human operator by using intuitive teleoperation interfaces to control many robotic DOFs.

Recent enhancements described herein aim to address limitations encountered through teleoperation experience at APL with two high-DOF prototype mobile bimanual robotic systems. The use of high-count dual-encoders and the integration of accelerometers into all links of the bimanual manipulator are considered for improving the quality of manipulator state estimates and haptic feedback. The integration of optical ranging, imaging, and illumination sensors into robot end-effectors, with associated presentation of the sensor data in augmented head-mounted display views, has proven effective for improving the capability to reach for and grasp objects otherwise occluded from the operator's

view of the remote scene. Techniques for controlling the many DOFs of mobile bimanual systems via reduced-order modeling offer an effective and more manageable teleoperation approach and experience for the operator than direct serial teleoperation of each DOF.

Incorporating such enhancements into existing and future mobile bimanual teleoperation systems is expected to improve the human-robot capabilities for executing complex and increasingly dexterous tasks associated with future UGV applications. The expected impact is increased utility and deployment of highly dexterous UGVs for military, first responder, law enforcement, construction, hazardous material handling, and exploration missions.

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