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MIMIC'D ABILITIES – TOOLS, TOOL CHANGING, AND ROBOTIC CONTROL

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ABSTRACT

Research is currently underway to improve controllability of high degree-of-freedom manipulators under a Phase II SBIR contract sponsored by the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC). As part of this program, the authors have created new control methods as well as adapting tool changing technology onto a dexterous arm to look at controllability of various manipulator functions. In this paper, the authors describe the work completed under this program and describe the findings of this work in terms of how these technologies can be used to extend the capabilities of existing and newly developed robotic manipulators.

INTRODUCTION

Fielded robots and robotic manipulators are rapidly becoming more capable, allowing them to complete more missions than ever before. As the capabilities of the robotic arms become greater, they must be accompanied by a corresponding advancement in tool development and manipulation control. This control of high degree of freedom robotic arms is a focus of the Modular Intelligent Manipulation and Intuitive Control (MIMIC) project currently underway. This Phase II SBIR contract is studying optimal methods for enabling users to interact with and intuitively control high degree of freedom manipulators and the early results of this effort has been presented at various technical conferences. [1, 2, 3]

One of the important early efforts of the Phase II SBIR was to develop a robotic manipulator that could be used to study intuitive control of arms using various degrees of freedom and to explore the ability to control different types of end effectors to complete a variety of missions. This paper presents the results of development, some of the early test results of the system, and some of the tools developed to interoperate on the system.

In order to make the most efficient use of available funding, the project team determined that the best approach to creating a generic arm to test various degrees of freedom and tools would be to leverage an existing manipulator and outfit it with a tool changing ability whereby different end effectors, including end effectors containing additional degrees of freedom could be developed and attached. The base arm selected for this was iRobot's Warrior arm (Figure 1). This large arm was selected because of its dexterity and available development environment. With this as a base platform, the team modified existing tool changing technology originally developed under a separate TARDEC sponsored SBIR contract to create an extension for the Warrior arm. The tool changing technology leveraged for this work allows not only electrical power to be transmitted to the end effector, but also allows mechanical power to be transmitted to the end effector. The number of electrical connections to the end effector is sufficient to enable control of an additional degrees of freedom. A two degree of freedom attachment is currently under development.

Figure 1. Warrior tool change technology outfitted with TARDEC-developed door opening end effector

In addition to being a test platform for the technologies under development on the MIMIC program, the development team hopes to harden this tool changing technology to be a secondary technology transition success for the SBIR program.

The project team has successfully developed and tested the Warrior tool change technology and has demonstrated this technology to Marines at Camp Pendleton. This paper will present the feedback from this demonstration as well as the test results.

Figure 2. Warrior platform outfitted with gripper showing "toolbelt" to carry additional end effectors

There are many long-term benefits to the U.S. Army in the development of the tool changing ability, the advanced tools available for the tool changer, and the control logic being developed under this program. In particular, the tool changing technology will accelerate the rate at which missions can be conducted downrange by enabling tools to be changed remotely, will enable custom tools to be developed that increase safety and speed on missions, and will enhance modularity of systems by defining a standard tool interface. The control logic will enable more accurate and faster control of robotic manipulators – providing accurate control of high degree of freedom manipulators and faster control of existing manipulators.

MIMIC

In the field of unmanned ground vehicles with dexterous manipulators, current control systems require a high cognitive load and training to properly position the manipulator and have it effectively interact with its environment. This level of control requires careful attention of the various knobs and buttons on the control station – taking an operator’s attention from the robot and greatly reducing the overall speed of an operation. Based on our interviews with bomb squad members, robots can be used effectively for simple operations, but when complex tasks or maneuvering is required, the squad has a technician “suit up” and conduct the operation.

The complexity in the user’s interaction is an issue with currently available robotic arms. However, as robotic manipulators grow more capable through additional degrees of freedom and as Explosive Ordinance Disposal (EOD) robots are developed that take advantage of multiple manipulators on the same platform, the demand for more intuitive control and enhanced situational awareness will also increase.

MIMIC seeks to research, design, and develop technologies that will allow a user to intuitively control multiple degree of freedom robotic arms and maintain better awareness of the operating environment through haptic feedback. In addition to reporting resistance, haptic feedback can help make operators feel like they are actually there with the robot. Coupled with intuitive controls and advanced video feedback, MIMIC will provide users with the sensation that robots are an extension of their bodies.

Under Phase I of MIMIC, the SBIR program achieved three main technical objectives:

1. Determined the feasibility of using various control input devices with integrated feedback to more intuitively and effectively control robotic arms.
2. Characterized the control fidelity of commonly fielded platforms and investigated the practicality of countering coarse-control manipulation via dynamic modeling techniques.
3. Demonstrated the practicality of using a dexterous end-effector with embedded force feedback sensing, improved visual feedback, multiple fingers, and wrist compliance for use on a representative robotic arm for the purpose of performing complex maneuvers such as cutting wires.

The results of the MIMIC Phase I analysis are available through the project’s final report. A summary of results is also available in various conference papers presented on the subject [1, 2, 3].

Phase II of the MIMIC project is currently underway and is focused on implementing the leading control technologies to control highly dexterous arms. The first portion of this phase of the work was to identify an appropriate manipulator technology that could be used to integrate the MIMIC technologies onto for detailed testing. For this effort, the MIMIC program is using the iRobot Warrior arm due to the availability of a capable Application Programming Interface (API) that was under development and its ability to accurately and finely control movement for each joint.

In order to explore the control requirements of various end effectors, the MIMIC program then added a modified tool changing ability that allows us to rapidly change end effectors. This tool changing technology is based on an earlier TARDEC sponsored SBIR topic on Small Robotic Tool change. This technology is currently being fielded for manual tool change, but the system used on MIMIC allows automatic tool changing based on control logic developed under the NAVEODTECHDIV SBIR titled AUTOmated Manipulator Tool Inter-Change (AUTOMATIC). This tool change technology is also similar to the tool changing technology that has been developed for the Advanced EOD Robotic System (AEODRS) program of record.

Because the tool changing technology was based on a current standard tool changer, we were able to re-use many tools that were developed under other programs for usability testing.

To get a basic understanding of the usefulness of these technologies as well as to set a baseline for controllability of the system, the MIMIC system was shipped to Camp Pendelton for evaluation by the MarForPac Experimentation Center (MEC) under an Operational User Assessment (OUA) in late November 2011. The feedback from this testing is discussed later in this paper.

MIMIC TOOL CHANGE TECHNOLOGY

Automatic tool changing provides robotic operators with significantly increased capabilities in the field. This technology allow a robot to be equipped with a number of tools appropriate for completing an assigned mission and dynamically change to the most appropriate tool based on actual field conditions. Since research on the first tool changing technology for mobile manipulators was begun in 2005 by RE2 [4], the concept of both manual and automatic tool change has been adopted by both the military and civilian communities.

Recently, through the development of a standardized input for the Advanced Explosive Ordnance Disposal Robotic System (AEODRS), the military has shown a clear path forward for manual and automated tool change on future robotic systems. Having this standard interface not only provides the operator with the potential of having multiple tools down-range, it also allows specialized tool development to progress without ties to a specific robotic manufacturer.

The iRobot Warrior arm is a capable robotic arm with 6 degrees of freedom, including

- Continuous shoulder yaw
- Shoulder pitch
- Elbow pitch
- Wrist pitch
- Continuous wrist roll
- Gripper actuation

For the MIMIC research, RE2 added tool change ability by replacing the existing wrist mechanism with a new mechanism that replicates the wrist roll but also adds new capabilities to enable communication and control of arbitrary tools that can be connected to the end of the arm. The new additions include the software and firmware to read and understand the embedded control of arbitrary end effectors as well as an additional motor that enables mechanical power to be transferred to end effector elements in addition to the standard electrical power supply.

The mechanical power take-off provides a single capable motor to enable moving end effectors without the need for each end effector to have its own motor. This feature has several distinct advantages over an electrical-only connection. With the mechanical power take-off, end effectors can be much simpler in construction since they do not need motor controls or motors. These are typically the most expensive parts of the end effector as well so having mechanical power available through the connection enables much less expensive end-effectors to be created. In addition, by having a single motor for multiple end effectors, the overall system weight is reduced when carrying multiple end-effectors. Finally, since the motor is integrated into the tool change mechanism on the arm, it allows shorter and lighter end effectors which increases the overall capacity of the arm since there is less weight farther out on the arm.

Every actuated tool that can be attached to the Warrior arm is equipped with a tool change board that contains information that the arm can read to set motor controls and customize the user interface to the specific capabilities of the attachment.

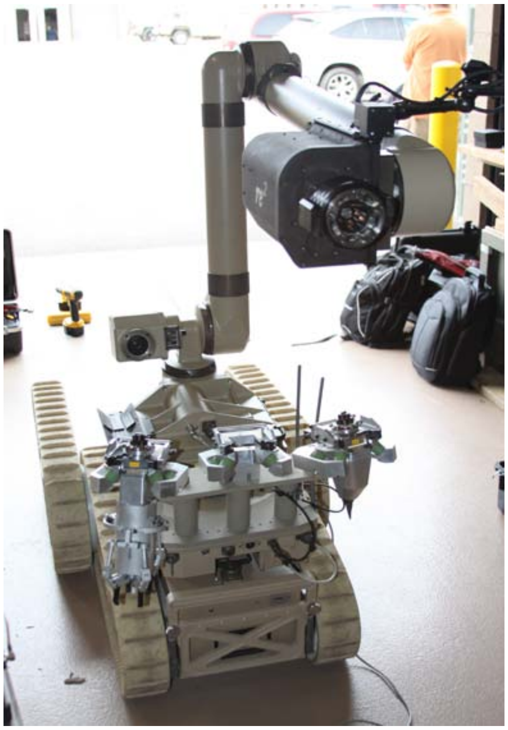

Figure 3. Warrior tool change technology showing tool interface to arm and tool belt mounted to platform

Figure 1 shows a side view of the tool changer developed as part of the MIMIC program utilizing tool change technology developed under the TARDEC-sponsored SBIR titled Small Robotic Toolkit. This tool change interface can be seen more clearly in Figure 3. In addition, Figure 4 shows the “tool belt” attached to the Warrior platform. This tool belt allows three different tools to be carried downrange to conduct operations.

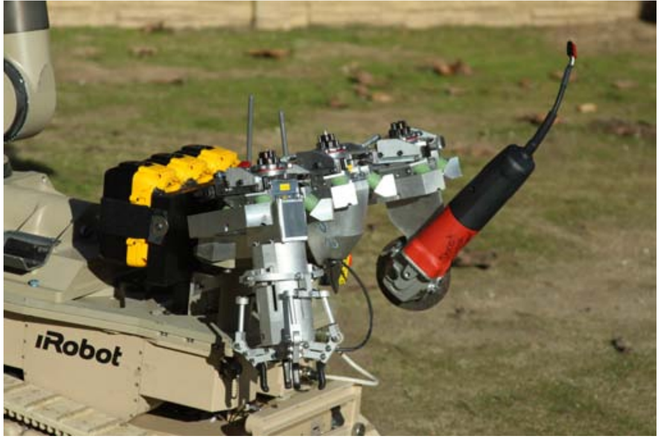

Figure 4. Warrior tool change technology showing tool interface to arm and tool belt mounted to platform

TOOLS

Figure 4 shows a close-up view of the three tools used to demonstrate the MIMIC tool change technology at a recent user trial for the MEC. These tools include (from left to right) a highly dexterous end effector known as the Modular Universal Door Opening End-effector (MUDOE) that was jointly developed under a CRADA agreement between RE2 and TARDEC, a sheet metal cutter powered by the mechanical power take-off developed under a research effort sponsored by the Technical Support Working Group (TSWG), and a modified COTS cutting tool for grinding through metal and other materials developed under funding made available through the Center for Commercialization of Advanced Technology.

With these three tools, the Warrior platform was able to complete a variety of missions as well as provide the operator with multiple options for completing a given mission. For example, during a door breaching operation at the MEC user evaluation, we demonstrated cutting through a door lock, opening the door using the door knob, and hanging a charge from the door knob using a two-fingered gripper. Figure 5 shows a series of images based on these tests.

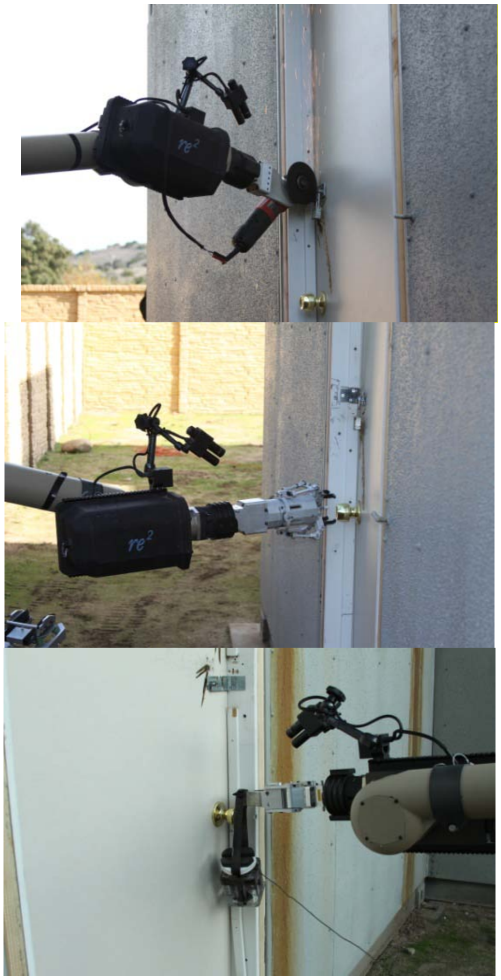

Figure 5. Tool changing technology demonstrated effectiveness at conducting various breaching operations

MUDOE

One of the more novel end effectors demonstrated on the tool changing system is the MUDOE. When opening a door, current two-fingered grippers pinch the doorknob with two to four points of contact, relying on the friction coefficient between the claw and the doorknob and the pinching force applied by the gripper to secure and maintain a firm grip on the doorknob. This method is ineffective, as the gripper fingers tend to slip off the doorknob.

Human hands possess a capability to grasp their object and conduct complex movements and rotations which are required to open a door. The process to open a door encompasses a grasping like motion that can maintain the positions of force and rotate the doorknob without interfering with its grasping hold on the doorknob. Functionally, the human hand always applies a nearly equal force to all points of contact when the hand is closed and grasping an object (Figure 6).

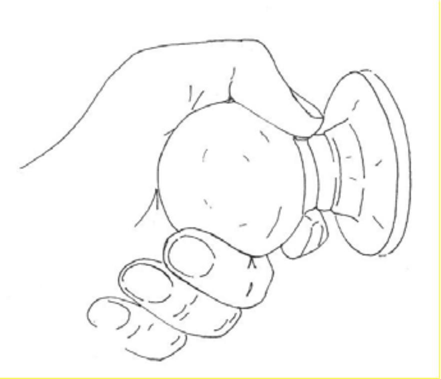

Figure 6. Hand grasping a round doorknob [6]

Through multiple Degrees of Freedom (DoF), the human hand can also conduct this range of motion at a high degree of an off axis angle relative to the center axis of the doorknob (Figure 7). Once the doorknob is rotated and the bolt is disengaged, the human pushes or pulls the doorknob, again using a grasping hold and movements of the wrist, arm, and shoulder to maintain a firm grip on the doorknob as the door swings inwards or outwards. Most robotic actuated end effectors do not have the distinct capability to apply equally distributed forces to all points of contact, and maintain that distribution of force throughout the desired range of motion.

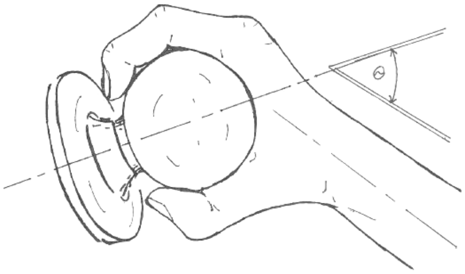

Figure 7. Human hand offset to doorknobs center axis [6]

With a detailed understanding of the interaction between a human hand and a doorknob in mind, the mechanical equivalent may be extrapolated. Like a human hand grasping a doorknob, the end-effector must have multiple points of contact with the doorknob that apply equal forces to the doorknob, even if the end-effector is not perfectly aligned with the doorknob. Just as the hand, wrist, arm, and shoulder work in concert to open a door, the operation of opening a door robotically may be shared between the end-effector and the robotic arm to which it is mounted.

In order to achieve the equal distribution of force across multiple points of contact that may be misaligned, the Modular Universal Door Opening End-effector (MUDOE) employs the whiffletree concept of force distribution to conform its self to the doorknob/handle. As illustrated in Figure 8, the Whiffletree mechanism distributes force evenly through a series of linkages that pivot at or near the center of the applied force. Each of the loads (Load 1, 2, and 3) are balanced from each side of the load, preventing the load from tugging alternately on each side. The Whiffletree can be used in both tension and compression. Common applications of the whiffletree mechanism include the harnesses of draught animals, such as horses pulling plows, and windshield wipers.

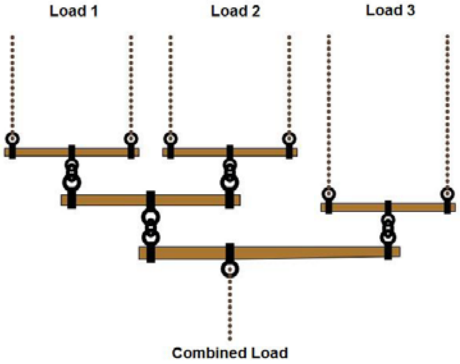

Figure 8. Whiffletree load distribution concept [6]

In the case of the MUDOE, the whiffletree concept of force distribution is used in compression. Instead of multiple loads under tension resulting in one combined pulled tension force, a single force is applied and is distributes it evenly to its appendages (Figure 9). Ball joint swivel bearings and pins are used as pivot points between the linkages. This underlying design allows the MUDOE to utilize a single actuator to apply equally distributed forces to each of the four finger-like appendages, while maintaining multiple DoF.

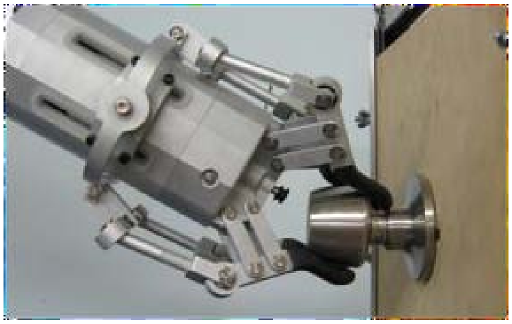

Figure 9. MUDOE prototype [7]

MUDOE uses both the available Electrical Power Take-Off (EPTO) interface and the Mechanical Power Take-Off (MTPO). The MPTO provides the linear motion to the first set of three linkages, via an outer collar. The outer collar creates a pivot between the second set of linkages, the top and bottom sets of finger-like appendages of the end-effector. The second set of linkages, mirrored on the top and bottom of the outer collar, act as pivots between the left and right fingers on the top and bottom of the end-effector. The third set of linkages connects each finger to one side of either the top or bottom cross-bar. Figures 10 and 11, respectively, illustrate the open and closed positions of the fingers of the end-effector without a resistive load. The pinned pivots are spring-loaded to maintain their unloaded alignments (Figure 9). If equal forces are applied to all four fingers, each linkage bar maintains position and forces each finger to simultaneously close.

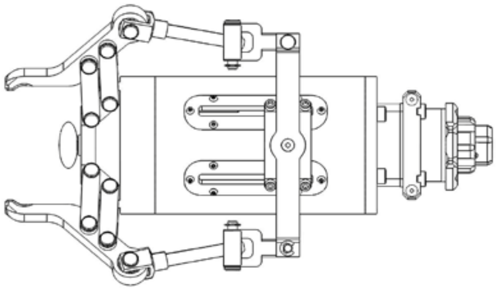

Figure 10. MUDOE side view, open position [6]

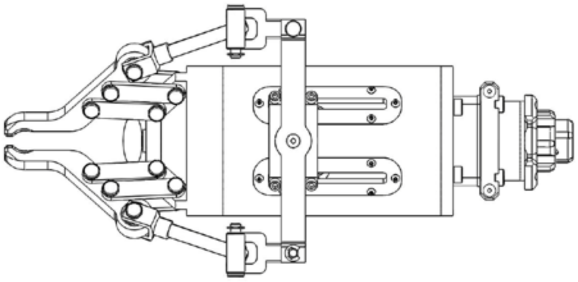

Figure 11. MUDOE side view, closed position [6]

When the fingers encounter uneven resistance, such as when grasping a doorknob without precisely aligning the central axis of the doorknob and end-effector, the applied force is distributed through the linkage system and the fingers adjust their relative positions accordingly. Figure 12 illustrates the first linkage, the outer collar, rotating to compensate for a greater force applied to the top two fingers of the end-effector. The bottom fingers are rotated forward until the forces are evenly distributed. Figure 13 illustrates the second linkage, the cross bar, rotating to compensate for a greater force applied to the two right fingers of the end-effector. Again, the opposing fingers are rotated forward until the forces are evenly distributed. Both of these cases allows MUDOE to conform to the object off axis regardless of position, and it then can maintain constant force and conformity while the MUDOE tool is being rotated by the manipulator's arm to generate the "opening" feature required for doorknobs. This feature also allows the end-effector to encompass movements that are normally conducted by a human hand and wrist capabilities into the grasping connection to the doorknob.

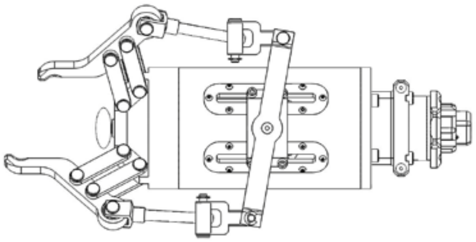

Figure 12. Resistive force applied to the top fingers, rotating the outer collar (first linkage bar) [6]

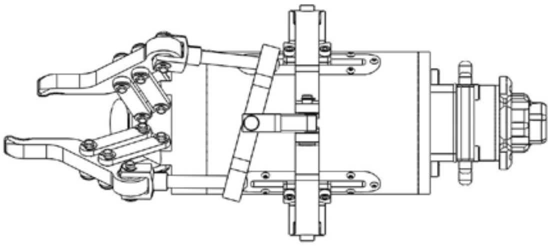

Figure 13. Resistive force applied to the right fingers, rotating the cross-bar (second set of linkage bars) [6]

Unlike a human hand using its four fingers and opposable thumb to produce the grasping force into the center of the palm, MUDOE contains an extendable center appendage to mimic this behavior. The center palm reactionary force and the four fingers generate five points of contact that create a grasping motion that is similar to a human hand. The combination of a material with a high coefficient of friction applied to the fingers, and the angled ends of the fingers prevents the palm from pushing the doorknob out of the end-effector's grasp. Once the doorknob has been turned, the palm may also apply the pushing force necessary to open outward-swinging doors without the fingers losing their grip on the doorknob. Figure 14 illustrates the five forces vectors applied to the center point of gravity for the doorknob by the end-effector's fingers and palm.

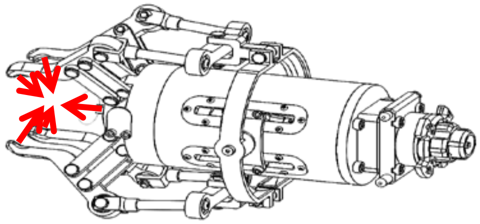

Figure 14. MUDOE Diametric View –Force Vectors [6]

USER TESTING

In November/December 2011, the Warrior tool changing technology, various tools, and MUDOE were tested by the MEC. The results of this testing were detailed by the MEC data collectors and released to TARDEC as a report of findings [5]. The MEC developed two Critical Operational Issues (COI):

1. Do End Effector technologies effectively support CIED missions?
2. Is the End Effector suitable for use by the Warfighter?

The testing was completed by Marines from the 1st Explosive Ordnance Disposal Company and was independently assessed by the U.S. Marine Corps Forces, Pacific Experimentation Center.

The majority of the information gathered to support the testing was subjective data collected from the 1st EOD Warfighters via questionnaires and interviews. In addition to this subjective data, the Marines also completed two operationally realistic scenarios using the provided equipment. The operational scenarios focused on Vehicle Bourne Improvised Explosive Device (VBIED) Response and an Urban Structure Search and Render Safe.

The conduct of the experiment enabled a side-by-side comparison of the iRobot Warrior equipped with the automatic tool change technology compared to a QinetiQ Talon robot.

The results of the user analysis led to several useful recommendations that will be addressed before the Warrior system with tool change is released. Some of the critical findings and recommendations relating to the tools described above and the tool change technology include the following:

- The MUDOE gripper needs more strength to effectively open arbitrary building and car doors. This is likely because of a critical tool element breaking early in the testing, but there was a clear indication of the importance of a highly capable gripping tool.
- Marines noted that the ability to change tools onboard instead of making multiple trips down range was beneficial and that the time required to change tools was sufficient to meet mission requirements.
- Generally, the Marines felt that the tool changing system on the Warrior required additional development and in its current stage of development was not better than the currently fielded solution.
- Marines felt that the tool changing user interface was easy to configure and intuitive to operate. Further, they thought that the system could be easily learned via on-the-job training with manuals. The users did not feel that the MUDOE was easy to use.

CONCLUSIONS

Through the course of work described in this paper, the authors have created automatic tool changing hardware and control logic for the iRobot Warrior arm, have developed a specialized tool for opening doors, and have conducted user testing on the prototype systems. While the user testing showed that the prototype was not ready to be deployed for CIED operations, it did indicate that there are substantial potential merits in the tool changing technology and the users provided many useful recommendations to make the tool changing techniques useful for their operations.

The authors hope to implement these recommendations to create a solution that provides Warfighters with an ability to carry multiple tools downrange to quickly adapt to unexpected situations in order to efficiently complete their missions and improve individual safety.

ACKNOWLEDGEMENTS

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DISCLAIMER

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