Robotic Grasp Assistance for Decontamination and Decommissioning Tasks: Initial Applications with RoboGlove – 17310

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ABSTRACT

RoboGlove, developed by NASA and General Motors, is a wearable robotic grasp assist device designed to augment human strength and endurance during manual tasks. Recent testing as part of the U.S. Department of Energy Office of Environmental Management's (DOE-EM's) Science of Safety Initiative has provided the opportunity to explore the glove's use within the context of decontamination and decommissioning work. Capable of providing a wearer with an additional 65-90 N (15-20 lb) of additional continuous grip strength, RoboGlove has the potential to decrease fatigue during long duration tasks, thereby reducing the risk of repetitive stress and other work related injuries. While current work at NASA focuses on integrating robotic grasp assistance with space suit gloves, the effort described herein focuses on the terrestrial application of RoboGlove to DOE-EM's cleanup mission. Following a brief technical description of RoboGlove, testing by United Steelworkers Union personnel at the Portsmouth Gaseous Diffusion Plant is described. Members of the workforce, in collaboration with NASA technologists, studied RoboGlove utility and performance while using tools common to the nuclear decontamination and decommissioning efforts at the plant. Results and feedback from this testing aim at identifying candidate activities for which RoboGlove holds particular promise as a workforce tool, in an effort to facilitate the infusion of robotic technology into routine workflow and processes across the DOE complex for the benefit of worker safety and health.

INTRODUCTION

A significant number of wearable devices designed to impart force on the human hand have been developed in recent years. These systems, both prototype and commercial, find utility across many applications. Haptic feedback, for example, is of particular interest in virtual reality and remote tele-manipulation, and devices such as the CyberGrasp® from CyberGlove Systems LLC [1] use powered exoskeletal mechanisms to resist finger motion and provide users the sensation of touching virtual objects. The need for hand rehabilitation due to disease or injury has compelled the development of powered orthoses and other wearable robotic devices (e.g. [2], [3], and [4]), while increased grip strength and improved endurance during dexterous tasks are desired in a variety of work settings (e.g. [5] and [6]).

Augmenting grip strength during the performance of strenuous work is the primary motivation behind RoboGlove [7] (Fig. 1). Developed jointly by NASA and General Motors (GM), RoboGlove is a wearable robotic grasp assist device derived from the tendon-based finger actuation system of Robonaut 2 (R2), a dexterous high degree-of-freedom robot developed by NASA and GM for human-scale manipulation and task

Fig. 1. The NASA/GM RoboGlove (shown here holding an example tool).

performance in unstructured, human-engineered environments [8]–[10]. Like R2, RoboGlove is designed for direct interaction with human interfaces, but unlike a purely robotic solution, the glove assists rather than replaces the effort of the human operator. And in contrast to many other hand-worn robotic devices, RoboGlove is designed to impart significant forces on the environment, work surface, or tool being used rather than the human hand itself. When wearing the glove, external grasp loads are transferred from the user's hand to the glove's actuation system with the intent of relieving worker fatigue and reducing repetitive stress or other related injuries.

Originally targeting repetitive assembly line tasks with an eye toward future integration into space suit gloves, RoboGlove's rugged yet comfortable design and power-dense, lightweight package make it well suited for the difficult tasks associated with decontamination and decommissioning across the nuclear sector. To that end, NASA and the U.S. Department of Energy's Office of Environmental Management (DOE-EM) recently partnered to expand RoboGlove testing in this domain as part of DOE-EM's Science of Safety Initiative. The balance of this paper provides a brief background on the design and development history of RoboGlove before focusing on initial application-specific, workforce-driven testing at DOE's Portsmouth Gaseous Diffusion Plant in Piketon, Ohio. Preparation for these tests and the forward work inspired by resulting lessons learned aim to facilitate DOE-EM efforts to infuse robotic technology into routine workflow and processes across their nuclear complex for the direct benefit of workforce safety and health.

DESIGN

RoboGlove relies on electromechanical actuators and synthetic tendons to augment a user's hand muscles and reduce the physical effort required to close fingers during repetitive or long duration grasps. Three linear actuators, located on the palmar side of a gauntlet covering the user's forearm (Fig. 2a), pull tendons which assist finger flexion. When actuating all five fingers, RoboGlove can exert approximately 222 N (50 lb) of momentary grasp force while continually providing 65-90 N (15-20 lb) of

(a) (b)

Fig. 2. (a) RoboGlove actuation layout including conduit anchor and sensor placement and (b) tendon finger mounting details.

steady-state force. Only three actuators are used to assist all five fingers by pairing certain fingers. A single actuator drives both the index and middle fingers, a second is used for the ring and little fingers, and a third actuator is reserved exclusively for the thumb.

The body of the glove is constructed using lightweight, elastic materials to fit a variety of users, minimize weight, and avoid significant reductions in dexterity. High friction material is added to the palm to assist with maintaining grasps and material thickness is doubled in key locations to improve durability. Available in three hand sizes, each with adjustable zippered sizing bands and a Velcro wrist strap to accommodate a wide range of users, RoboGlove weighs approximately 0.8 kg (1.7 lb).

Tendon Routing

Tendons in RoboGlove route from the linear actuators in the forearm to the fingers through a flexible conduit. In this Bowden cable mechanism, the conduit serves to react loads from the tendon and prevent actuation forces from being transmitted through the user's wrist. Each of the five conduits (one corresponding to each finger) terminate at the conduit anchor, a rigid 3D printed part sewn into the palm of the glove near the metacarpal interphalangeal joints of the fingers. Each tendon, however, continues through the conduit anchor and along the palmar side of its corresponding finger to a mounting location along the medial phalange of the finger (Fig. 2b). The thumb tendon terminates at the thumb's distal phalange. To terminate each tendon an eye-splice is used to create a loop that encircles the phalange around a rigid saddle that distributes force comfortably around the user's finger.

Sensing and Control

All of RoboGlove's power, control, and motor drive electronics reside on a single board mounted inside a case on the glove's forearm. This main controller board receives power from a commercially available power tool battery pack worn on the user's belt. Power is converted to the various voltages required by the control and drive electronics and processors read force sensor data from the glove fingertips as well as motor temperature, position, and current data. The controller board also features a three-position mode selector switch and various LEDs to communicate system status to the user.

Force sensitive resistors (FSRs) located within the fingertips of the glove detect contact and provide external force measurements when the user interacts with tools or the environment. These thin film piezoresistive devices change resistance inversely proportional to the force applied, and these feedback signals, once linearized, are used to control RoboGlove's actuated response. Individual thresholds can be pre-configured for each sensor to vary glove responsiveness and customize control modes.

The simplest RoboGlove mode treats each finger's FSR as a straightforward on-off switch. If pressed beyond its programmed threshold the signal from an FSR initiates actuation of its corresponding finger (or fingers). When force drops below the threshold the glove responds by relaxing tendon tension on that finger. Control is completely modular and force sensors within the glove can also be mapped to trigger or release different actuator combinations for an array of custom modes designed around specific tasks or tool grasps. Control mode development, like many of RoboGlove's other features, is often application driven. The specific control modes adopted for the decontamination and decommissioning tasks examined in this work are outlined in greater detail during discussion of DOE-EM's Science of Safety Robotics Challenge.

DEVELOPMENT HISTORY

With potential applications across many domains (e.g. construction, manufacturing, space, etc.), RoboGlove is intentionally designed to be easily programmable and versatile to provide useful grasp assistance in a variety of settings. Throughout RoboGlove's development history, design decisions and the glove's resulting functionality have been driven by desired candidate tasks and the application-specific challenges associated with reducing workforce strain and fatigue in different settings.

Industrial Applications

Originally developed as a partnership between NASA and GM, RoboGlove's first terrestrial applications targeted the automotive manufacturing sector. At the General Motors Technical Center in Warren, Michigan, several ergonomically difficult tasks have been explored with RoboGlove. Wire harness crimping for prototype vehicles requires 180 to 400 N (40 to 90 lb) of grasp force (highly dependent on the size of the wire) with hundreds of crimps required per vehicle. RoboGlove was originally designed to exert peak forces suitable for this application, adding approximately 180 N (40 lb) to the user's grasp to significantly reduce the required effort (Fig. 3a).

(a) (b)

Fig. 3. Examples of (a) crimping and (b) door glass installation using RoboGlove (illustration only).

Another candidate task investigated at the GM Technical Center is the installation of side door glass. Held between an operator's four fingers and palm, a majority of the glass weight is carried by one hand as the worker aligns the pane with the door for installation (Fig. 3b). A specific RoboGlove control mode was developed to assist the four fingers while leaving the thumb free. Following initial flexion triggered by a force sensor on one of the fingers, all four fingers are actuated and maintain their grasp until the operator releases the actuators by pressing down with the thumb's force sensor. This use of RoboGlove provided an early example showing the glove's promise for reduced worker effort while manipulating large, heavy objects.

Space Applications

Recent work at NASA has focused on the integration of RoboGlove technology with a Phase VI Extravehicular Activity (EVA) space suit glove to provide grasp augmentation and reduced fatigue during astronaut's suited operations [11]. The Space Suit RoboGlove (SSRG) integrates the robotic actuators and synthetic tendons of RoboGlove into this current generation glove used on the International Space Station, while also incorporating modifications for the space suit application including revised electronics, stronger actuators, and additional sensing to enable continuous assistance when closing the glove [11]. Using a glovebox to simulate the pressure differential between a space suit and the vacuum of space, engineers tested SSRG against other prototype gloves leveraging novel construction techniques but not robotic augmentation (Fig. 4). While quantitative results from these tests are still under analysis, comments from test subjects indicate a feeling of less fatigue after executing tasks with SSRG versus other gloves. The space suit application has motivated further design improvements in environmental survivability, sealing, control methodology, and sensor design. While this progress and the described tests target future space exploration applications, it is worth noting that SSRG's usage in NASA gloveboxes closely mirrors the handling of high consequence materials common to glovebox operations across the DOE complex. In addition to the tool use described in the next section, RoboGlove has obvious promise as an aid to glovebox-related maintenance, processing, decontamination, and decommissioning work.

Fig. 4. Glovebox Testing of the Space Suit RoboGlove.

DOE-EM SCIENCE OF SAFETY ROBOTICS CHALLENGE

From August 22-25, 2016 the U.S. Department of Energy's Office of Environmental management, in cooperation with site contractor Fluor-BWXT Portsmouth (FBP) and the United Steelworkers Union (USW), hosted the DOE-EM Science of Safety Robotics Challenge at the Portsmouth Gaseous Diffusion Plant in Piketon, Ohio [12]. Twelve unique teams of technologists participated in the event by delivering to the plant robotic systems relevant to DOE's ongoing decontamination and decommissioning efforts. Rather than being a demonstration by the visiting technologists, however, the Robotics Challenge was designed as a "proof of application" event in which FBP's USW workforce operated each robotic system themselves under relevant conditions or in conjunction with site-relevant tools. The workforce-driven nature of the evaluation offered a unique opportunity to assess the merits of assistive robotic technology as perceived by those whose health and safety the systems are intended to benefit.

In partnership with DOE, NASA provided four new RoboGloves for testing during the Robotics Challenge event with the intent of evaluating RoboGlove utility when operating tools common to nuclear decontamination and decommissioning tasks, identifying and developing design features and control modes to enhance glove performance, and assessing qualitative workforce feedback in an effort to identify candidate tasks for which RoboGlove holds particular promise as a workforce tool. These objectives were addressed during the application-specific design work leading up to the event and during the on-site tests themselves, and they continue to be considered as part of NASA's follow-up efforts to continually improve RoboGlove performance for both terrestrial and space applications.

Application-Specific Design

In anticipation of the Robotics Challenge, design updates were made to RoboGlove to improve glove fit and comfort for long duration use. The conduit anchor, or palm bar, fixed in the center of the glove was originally a thin, flat aluminum bar. This was replaced with a more conformal piece designed to follow the contours of the hand and improve support, providing for a more natural grasp. Additionally, added curvature at the ends of the new palm bar address undesired migration of the anchor with respect to the hand.

Taking advantage of the modular and programmable sensing architecture of the glove, multiple new control modes were developed to target the specific hand tools of interest (as described in the following section). Prior to on-site testing, preliminary work was done to identify useful modes for each tool. These changes included modifying the specific sensors that trigger glove behaviors and adjusting which fingers are actuated in response to various external force inputs. The glove has the ability to store three unique control modes on board at any given time and is easy for the user to switch among them. The candidate suite of modes programmed for the Robotics Challenge (summarized in Table I) includes: a powered secondary finger grasp with free trigger finger (Mode 1), a full hand grasp-assist mode (Mode 2), and a four-fingered power grasp with unactuated thumb (Mode 3).

Tool Use for Decontamination and Decommissioning

Decontamination and decommissioning work at the Portsmouth Gaseous Diffusion Plant involves a great deal of manual labor to disassemble, inspect, and remove large equipment and structures once used as part of the plant's Uranium processing operations. RoboGlove's grasp assist ability holds great promise as a means to reduce

Table I. RoboGlove control modes used during on-site testing at the Portsmouth Gaseous Diffusion Plant.

Mode	Actuation Trigger	Actuation Release	Finger Behavior	Notes
1	Index or middle finger force sensor	Thumb force sensor	Only secondary fingers actuated	index and middle fingers remain free to manipulate tool triggers
2	Index or middle finger force sensor	Both index and middle finger force sensors fall below the force threshold	All five digits actuated	Requires no overly intentional release motion by the user
3	Index or middle finger force sensor	Thumb force sensor	Four fingers actuated, thumb remains unactuated	Originally developed for glass assembly in automotive applications

worker fatigue, increase endurance, and reduce work-related injuries. To test the glove’s utility across a range of plant operations five specific tools were selected for RoboGlove testing by FBP personnel. These include a reciprocating saw, a power drill, a six-foot spud bar, a handheld grinder, and an HMS4 sodium-iodide radiation detector. As illustrated in Fig. 5 and Fig. 6, these tools were all manipulated and/or actuated by a RoboGlove-assisted operator during testing. Both dual-hand and single-hand manipulation was explored, and a variety of control mode combinations were tested by USW workforce personnel to assess RoboGlove performance.

Looking first at single-hand tasks, the DeWalt power drill (Fig. 5b) is operated in Mode 1 where the user’s grasp intent is sensed by a force on either the index or middle finger, which causes the glove to power both secondary fingers closed. This action maintains a firm grip around the drill handle but keeps the index finger free to actuate the drill trigger. By intentionally exerting force with the thumb tip on the back of the drill handle the user can signal RoboGlove to release. The HMS4 radiation detector is also held by a single hand (Fig. 6). During inspection and measurement tasks significant fatigue can be experienced by holding the detector in position for extended period of time. Here, Mode 2 is used to reduce the grasp force burden on the user across all fingers and thumb.

Working with the spud bar (Fig. 5c) also leverages Mode 2 on both the left and right RoboGlove because the nature of impacts and prying actions with the tool require the worker to provide varying amounts of grip strength over the course of their motion. (This is to protect from excessive shock loads that would be experienced across the arm if impacts occurred with a firm, rigid grip on the bar.) Because it is triggered off by dropping below force thresholds on the glove’s sensors, Mode 2 allows for seamless release and regrasp without the need for extra intentional motions. The reciprocating saw (Fig. 5a) and the angle grinder (Fig. 5d) are unique in this set of tools in that they both require two-handed operation, but left and right hand functions differ significantly. Thus, the individual RoboGloves on each hand rely on different control modes. For the saw, the right glove is used in Mode 1 to allow for tool trigger actuation, much like the power drill example. The left glove which supports much of the tool weight during operation is used in Mode 2 for grasp assistance across the whole hand. When operating the angle grinder, the left glove is used in Mode 3 to provide a firm four-fingered grasp on the tool’s support handle while keeping the thumb free to stabilize the tool as seen in Fig. 5d. Because the grinder has a trigger paddle actuated by the full right hand it was recommended by the USW users to leave this glove unpowered during tool use. This ensures no unintended actuation of the grinder by the user and provided an additional level of safety and comfort while the workforce personnel gained familiarity with the RoboGlove. Given more workforce experience with RoboGlove and the potential to modify control modes further in the future, this choice might be revisited. Regardless, the ease at which RoboGlove can adapt to given task requirements speaks to its utility in the unstructured environment of decontamination and decommissioning work.

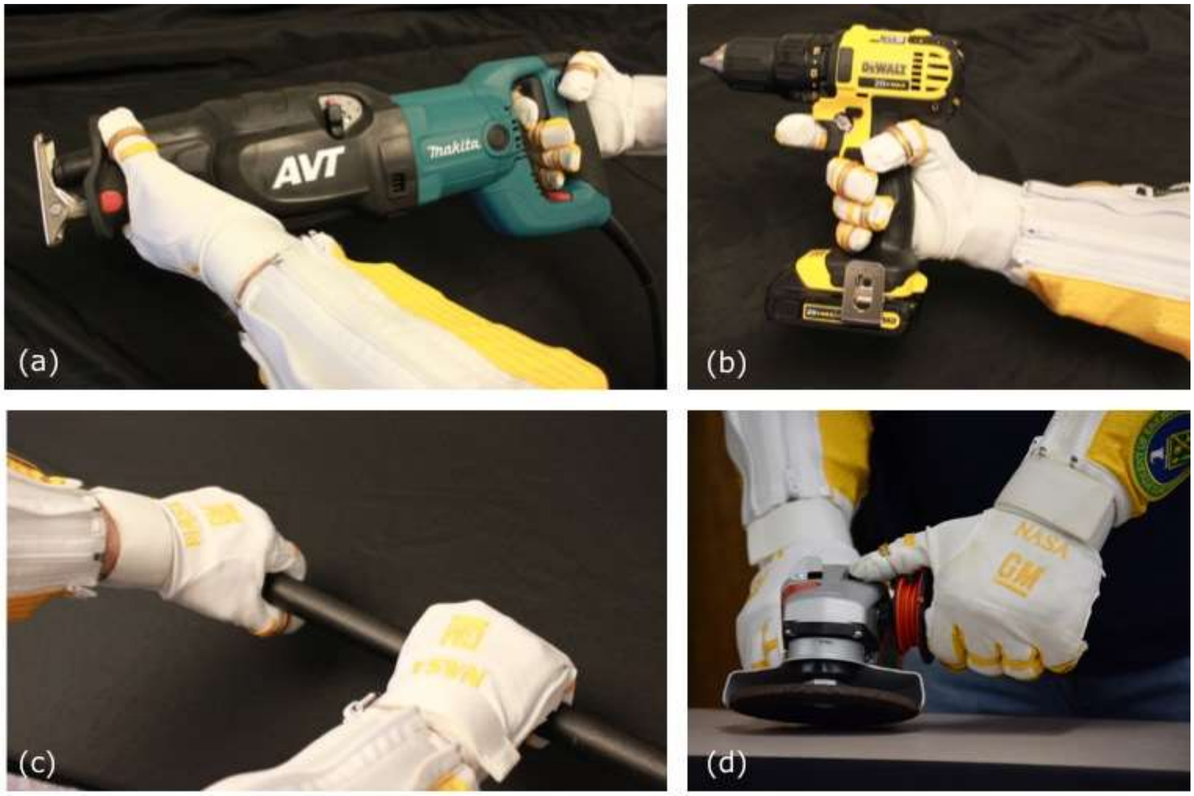

Fig. 5. Standard hand tool manipulation at the Portsmouth Gaseous Diffusion Plant using RoboGlove. Tools tested include (a) a Makita brand reciprocating saw, (b) a DeWalt compact power drill, (c) a six-foot spud bar, and (d) a Metabo brand handheld angle grinder.

Fig. 6. Two images of RoboGlove-assisted manipulation of the HMS4 sodium-iodide radiation detector.

Workforce Feedback

The active involvement of USW personnel at the Portsmouth Gaseous Diffusion Plant provided valuable feedback on RoboGlove's design, operation, and application. In addition to assessing the overall utility and comfort of RoboGlove during typical tasks, workers suggested control mode refinements, potential enhancements to fit, and ideas concerning optimal force sensor mounting locations. There was also candid discussion about more intangible aspects of wearable robotics and the use of robotic augmentation to accomplish work in a safer, more efficient manner. Much of this feedback will lead to targeted improvements in both RoboGlove and other wearable robots in the future.

Many of the design suggestions made were environment-related. A need to make the glove more robust by incorporating cut-resistant material was recognized, further dustproofing was mentioned, and replacing zippers with Velcro to ease donning and doffing was suggested. These ideas are, in part, being investigated within the space suit RoboGlove effort and represent a natural progression from laboratory prototype to fielded system that will greatly enhance RoboGlove's practical utility in the workplace. Fit and comfort received both positive feedback and their share of constructive criticism. The two glove sizes used during on-site testing did not offer enough variability to accommodate all hand sizes and additional size adjustment in the glove forearm was also recognized as desirable. As a result, research has already begun on techniques to make glove and finger size fully adjustable for the user.

Insight concerning control modes and use cases was particularly valuable coming from workers intimately familiar with decontamination and decommissioning tools and processes. On-site changes were made as application-specific issues were identified. For example, during spud bar work it was noticed that the glove was not releasing its grip fast enough to avoid undesirable shock loads during impact. Force sensor thresholds were adjusted and task performance and worker comfort were significantly improved. The layout of force sensors across the fingers and palm of the glove was also discussed. Due to variability in tool grasps, additional locations along the medial phalanges and inside the palm were identified as useful locations for force sensors. Mapping secondary finger sensors to trigger secondary finger motions was suggested to improve the tool trigger grasp of Mode 1, and separating actuator coupling between fingers so they all can move independently was discussed. While this design change might prove useful it would likely require additional actuators, thus introducing mass to the system.

Additional candidate applications were identified as USW personnel recognized the utility of RoboGlove beyond the current scope of hand tools. It is believed that leveraging RoboGlove will benefit carrying buckets and pulling wagons, common tasks in the plant, and all workers involved in this study saw a potential benefit to iterating on past GM-related work and modifying force sensor locations to target RoboGlove assisted wire crimping and tin snip use. Formal trade studies of new candidate tasks and further quantitative analysis of the initial applications explored here are needed to fully determine overall benefit, but preliminary results and the qualitative feedback from the workforce (all overwhelmingly positive) suggest the significant benefit to be had from leveraging RoboGlove during decontamination and decommissioning work.

CONCLUSION

Originally developed with automotive assembly tasks in mind, then expanded to examine space suit integration for the benefit of future NASA exploration, RoboGlove has now been demonstrated within the context of decontamination and decommissioning of nuclear facilities. As a result of U.S. Department of Energy sponsored field testing at the Portsmouth Gaseous Diffusion Plant and the active involvement and feedback of the USW workforce, the early promise of RoboGlove in this regard has been established and avenues for further technology advancement have been identified. Research and development is ongoing to build upon the progress of recent field tests and establish RoboGlove, and more broadly wearable robotic grasp assist technology, as a viable tool to improve safety, reduce injury, and increase efficiency within the DOE workforce, the astronaut corps, and a variety of other applications.

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