

# Bimanual Haptic Teleoperation for Discovering and Uncovering Buried Objects

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**Abstract**—We describe an experimental system for the evaluation of teleoperation performance. The system was used in two experiments where operators were assigned the task of discovering a buried object while minimizing contact forces. The studies *i*) demonstrated the advantage of haptic feedback in the discovery task, and *ii*) compared different methods for haptic feedback, including our new bimanual method, Touch and Guide in Tandem (TAGIT). Results show that TAGIT enables the effective workspace of the teleoperator to be expanded while minimizing forces from exploration and contact, reducing their variability, and reducing task completion times.

## I. BACKGROUND

In many practical circumstances, there arises the need to uncover buried objects. For example, a utility worker must often dig up a lawn to expose buried wires to affect repairs, while taking care not to create inadvertent damage.

Manual demining is a procedure in which mines are manually detected and neutralized by a human deminer [1], [2]. The deminer first scans the ground with a metal detector. A prodder is then used in order to feel, locate and identify the object causing the signal, after which it is carefully uncovered.

Another important case is the care needed to dig out and uncover artifacts of archeological significance. Here, in addition to visual appearance, the ability to discriminate between levels of different firmness is often needed [3]. When these activities are performed manually, the innate human haptic sense can often provide exquisite discriminative ability upon encountering soft or hard buried objects. The sensitivity of haptic perception may enable objects to be discovered and even identified without damaging them upon contact.

Of course, in a number of cases the environment may be too dangerous or too remote to afford direct human intervention. Examples include disarming unexploded ordnance and improvised explosive devices (IEDs), mediating

hazardous materials, and operations conducted at the sea bottom. In these cases, remotely operated robots generally operated by switches and joysticks have been shown to be useful.

In most scenarios involving buried objects, there are few if any visual cues, and robots fall considerably short of the sensitivity and compliance of the human hand. In underwater operations, visibility is often obscured by muck and silt. In many situations, especially those involving explosives, contact forces must be carefully controlled. Therefore, remote robots equipped with force/torque sensing providing haptic feedback to operators has long seemed a promising approach, *e.g.*, [4], [5]. However, data from realistic experiments has been generally lacking.

The main goal of our research was to investigate the role of haptic feedback in teleoperation during detection and uncovering of objects buried in loose sand. We were interested in quantifying the difference between using visual only conditions *vs.* visual augmented with haptics. A secondary goal was to evaluate methods for effectively mapping the small workspace of the haptic master to the much larger workspace of the slave robot.

Section II introduces the experimental system; Sec. III introduces our newly developed TAGIT (Touch and Guide in Tandem) haptic interaction method; Sec. IV presents experimental results and statistical analysis from subject experiments in detecting buried objects in sand; Sec. V summarizes the results and draws conclusions; and Sec. VI briefly describes future extensions of the work.

## II. DEVELOPED HAPTIC TELEOPERATION SYSTEM

Figure 1 illustrates the connections between the main components of our experimental system. The RE2 slave robot arm is equipped with an ATI Mini45-US-120-160 6-DOF force/torque sensor. The 6-DOF haptic master is an impedance device with position/orientation input from the operator's hand while providing force/torque output to the hand via the Maglev 200 controller. Client programming and an operator's graphical user interface reside in the Haptic Control node. The main components communicate by means of Robot Operating System (ROS) nodes [6].

Figure 2 shows the main parts of our experimental setup with haptic master, slave robot arm, and sandbox.

### A. Robot Slave

The slave subsystem manipulator was a 5-DOF Auto Arm designed and manufactured by RE2, Inc. Its 5 DOFs

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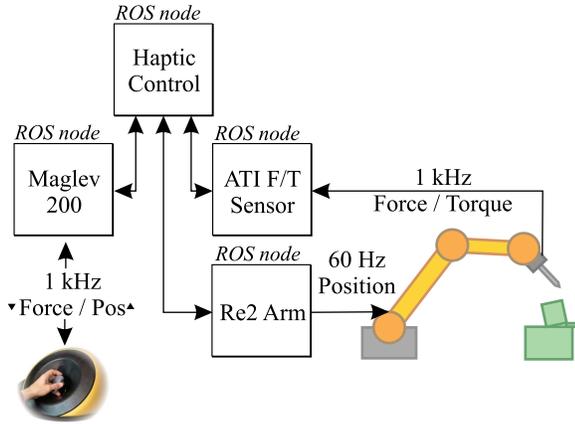


Fig. 1. Configuration of system for detecting and uncovering buried objects. The components communicate via ROS nodes.

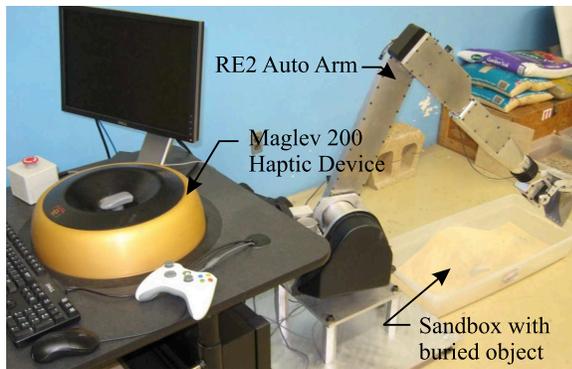


Fig. 2. Master and slave systems used in the experiments.

are torso yaw, shoulder pitch, elbow pitch, wrist roll, and wrist pitch, although for some of the experiments the wrist roll degree of freedom was mechanically locked. The manipulator has a 1.52 m reach and can lift 3.6 Kg at full extension. Each joint has an absolute magnetic position encoder with 12 bits of resolution. Higher level control software was developed to allow for Cartesian control along the  $z$  (up/down) and radial axes, crucial for integration with the Maglev 200. Several force-sensing end-effectors were developed, including a scoop and a blade for contacting buried objects.

### B. Haptic Master

The haptic master system featured a recently available Butterfly Haptics Maglev 200 magnetic levitation haptic device (MLHD) shown in Fig. 3. The device was chosen for its high position resolution, high bandwidth, high reliability, and friction-free operation affording extremely high fidelity since there are no motors, gears, bearings, cables, or linkages present as in conventional haptic devices. The haptic master behaves as an almost ideal “impedance” device, where handle positions and angles are sent to the remote robot, and pure forces and torques are displayed

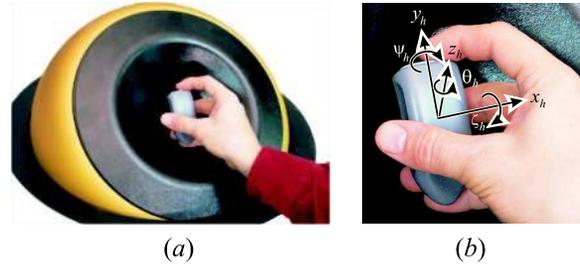


Fig. 3. 6-DOF magnetic levitation haptic device: (a) overall view showing the spherical swivel mounting in a desktop which allows re-orientation to suit users’ preferences, (b) closeup of the modular manipulandum with superimposed embedded coordinate frame.

TABLE I

ABBREVIATED PERFORMANCE CHARACTERISTICS OF MAGLEV 200 MAGNETIC LEVITATION HAPTIC INTERFACE SYSTEM.

Attribute	Value
Degrees of freedom	6 or 7
Maximum impedance	50.0 N/mm
Minimum impedance	0.002 N/mm
Translational workspace	24 mm sphere
Rotation range	$\pm 8^\circ$
Position bandwidth	140 Hz (-3 dB)
Position resolution	$2\mu\text{m}$ ( $1\sigma$ )
Levitation power	4.5 W
Peak force	40 N
Peak torque	3.6 Nm
Device pose	adjustable
Manipulandum	interchangeable

to the hand in return. Table I briefly summarizes its main performance characteristics.

### III. TAGIT: TOUCH AND GUIDE IN TANDEM

A key issue with any haptic device is the mapping between its workspace and the environment it operates in or the slave device it controls. We refer to the haptic device’s multi-DOF workspace as the *master workspace* and the target interaction workspace, whether in a virtual environment or real environment via a robot, as the *slave workspace*.

The issue is that the available workspace of the haptic device is generally significantly smaller than that of the slave device. In the case of a mobile robot, the slave workspace may be considered infinite. This poses the natural question of how to best map hand position/orientation to the slave while mapping forces/torques back to the master under a variety of conditions.

#### A. Conventional master workspace expansion methods

In practice, a collection of methods can be employed to help solve this problem. *Scaling* can be used to scale up position/orientation of the master to cover the workspace of the slave. There is a limit to this scaling, however, because noise and hand tremor are scaled by the same amount. *Indexing* can be used to move by some non-haptic

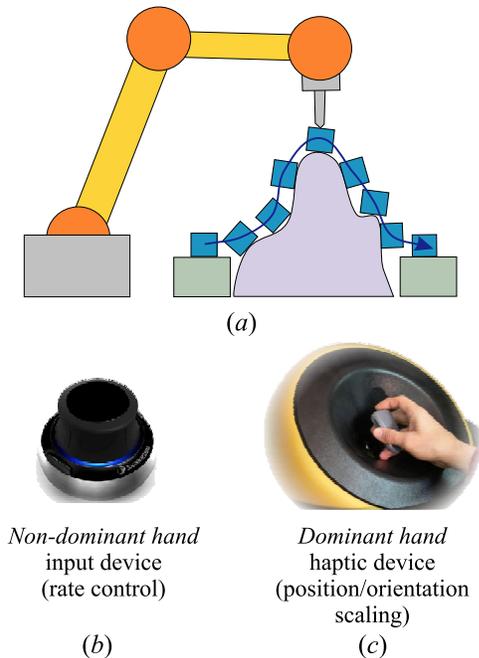


Fig. 4. TAGIT (Touch and Guide in Tandem) haptic interaction method. The dominant hand (c) interacts with a haptic device whose workspace is small relative to the size of the remote environment (a) while the non-dominant hand (b) controls the position/orientation of the robot using rate control.

means between sub-workspace regions of particular interest, such as the pick region and place region in a robotic pick-and-place operation. The principal disadvantage is the lack of any haptic feedback between regions. *Rate control*, where the slave's velocity is made proportional to the master's position/orientation, is the standard method used when interacting with a robot. However, haptic feedback during rate control is essentially low-passed filtered, giving an unrealistic feeling when tapping on a hard surface or moving along a rough surface which results in quick changes of direction. As a result, rate control reduces an operator's ability to perform tasks that require high-quality haptic feedback.

Recently, various *workspace drift* methods have been introduced [7], [8]. These methods seek to superimpose a gradual drift, which tends to re-center the master device within its workspace while allowing conventional scaling operation within the master workspace. The user is not supposed to notice the gradual drift. These methods work well when hand motions are small relative to the master workspace, but the target object of interaction must always be at least partially within the master's workspace or the algorithm will effectively behave like rate control. A downside of the Workspace Drift methods is that certain types of motions, for example long, straight movements similar to surgical wielding of a scalpel, are not always possible. Because of the constraints mentioned above, none of the currently available methods allow the seamless integration of haptic feedback in real-world robotic tasks

where the robots operate in large work spaces, which is true for a majority of applications such as telesurgery, remote bomb disposal, mobile robot control or robotic teaching systems.

### B. The TAGIT method

We have developed a new method for addressing the master/slave workspace problem which requires the use of *both hands*. We refer to this method as "Touch and Guide in Tandem," or TAGIT for short. In this method, both hands are used to interact with a single haptic tool or probe. The user's dominant hand operates the haptic feedback master with position/orientation scaling, while the non-dominant hand operates in rate control. This combination allows the user to seamlessly explore a large workspace while having high-quality haptic feedback at all times as illustrated by Fig. 4. In the figure, the block is moved for large distances along the curved surface while continuously interacting haptically. There are two variations. In the first case, the non-dominant hand can use a simple input device such as a 3Dconnexion SpaceNavigator™ or any other input device for rate control, while the dominant hand uses a haptic master for haptic feedback. In the second case, the non-dominant hand can use an additional haptic master for haptic feedback as well.

Previous research on haptic perception led us to develop TAGIT as a psychologically intuitive means of controlling exploration with a small workspace. Two critical features of TAGIT that support spatial representation and updating of effector position are *i*) it is active rather than passive, and *ii*) it constitutes coordinated bimanual control of exploration. Pertaining to the first of the features, systems that move the workspace for the explorer are passive, whereas TAGIT allows the user to actively control the workspace position/orientation. Gibson [9] noted that active control of exploration promotes focus on the external environment. Passive control of workspace position/orientation, on the other hand, may undermine users' ability to map haptically encoded features to their spatial origins [10]. The bimanual control that is fundamental to TAGIT is motivated by the finding that when people perceive an object haptically, they tend to simultaneously use one hand to control the object's position/orientation, while using the other hand to explore it [11]. TAGIT emulates this natural bimanual strategy, which, in contrast, is violated by systems that force users to treat spatial search and haptic encoding as separate modes of interface operation.

### C. Experiment Design and Test Plan

After several user studies were conducted simulating navigation of a contact point through a curved path with rigid walls under Position/Rate switching, workspace drift, and TAGIT, two experiments were designed and were conducted on the actual robotic system. The first assessed the effect on operator performance of adding haptic feedback to otherwise pure visual feedback. After the first

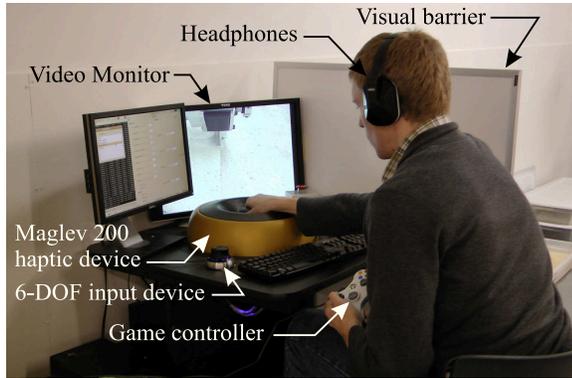


Fig. 5. Subject using experimental setup.

experiment showed that haptic feedback significantly improved operator performance, the second study compared the performance of the TAGIT method with the previously discussed rate control and Workspace Drift methods.

For both studies, we used the haptic teleoperation system described above to control a tool. A box (approximately  $.6 \text{ m} \times 1.2 \text{ m} \times .2 \text{ m}$ ) was filled with sand to simulate loose soil. Hidden in the box was a hard object with a mass of 2.7 Kg, completely covered with sand and therefore not visible to the robot's on-board camera. The exact location of the object was unknown to operators. The operator's goal was to control the robot with an attached tool in order to "find" the object (identify its location), while applying the smallest amount of force possible at contact. Arbitrary starting points for exploration across the width of the container were selected either  $.22 \text{ m}$  or  $.40 \text{ m}$  distant from the target (called short and long, respectively). Direct view of the work space was obscured, but a camera mounted on the arm provided an active view of the tool on a monitor directly in front of the haptic master as shown in Fig. 5. Once the target was detected, the operator self-terminated the trial.

The original end effector designed for the user studies was a digging scoop. While the scoop was very useful for moving larger amounts of soil, it was not well suited for the task of identifying an object hidden in sand because it had a large surface area that moved in the same direction as arm motion. When the arm moved toward an object hidden in the sand, compacting of the sand against the object caused the force applied to the operator's hand to gradually increase making it difficult to recognize the point of contact. Therefore, a blade-like end effector was designed that did not compact sand while moving, but rather "cut" through it. The resulting force was small until the actual impact, which operators could then discriminate well. After contact, the object could be uncovered by sweeping the blade sideways.

Figure 6 shows the blade-like end effector being pulled through the sand and encountering the buried object. (As the blade moved through the sand, even friction and impact with small pebbles could be felt by the operator through

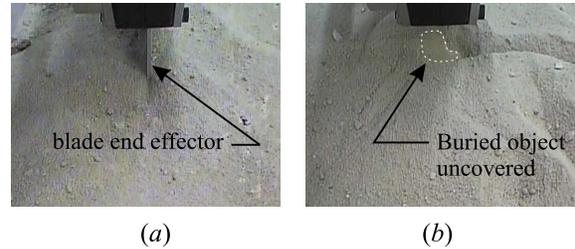


Fig. 6. Uncovering an object buried in sand. (a) End effector blade moving through sand; (b) object is uncovered (highlighted by dashed line).

the haptic device.)

## IV. RESULTS

### A. User Experiment 1: Visual Feedback vs. Visual + Haptic Feedback

The first study evaluated the effect of haptic feedback by comparing three interaction conditions: In the *Maglev haptic* condition, the Maglev 200 haptic master was used with the bimanual TAGIT method so that vision and force feedback were both present. The *Maglev no haptic* condition was similar except that haptic feedback was disabled, and only vision was available. In the *Joystick no haptic* condition, the slave was rate-controlled with a video game controller (the usual default controller for bomb disposal robots) and only visual feedback was available from observing the motion of the sand and the responsiveness of the effector.

The subjects were eight adults associated with a robotics firm, who gave informed consent. The experiment used a within-subject design in which the operator experienced all conditions, which were administered in a counterbalanced order across participants. Each participant performed 12 trials (2 repetitions per combination of target distance and mode).

The measured forces obtained from the wrist sensor included the force on contact with the target and several measures derived from the 2-s window before contact: maximum force, mean force, minimum force, and force variability (standard deviation of force measurements within the window). Statistical analysis was performed with Analysis of Variance (ANOVA), including factors of condition, target distance, and repetition. The level for statistical significance was set at  $p < .05$ .

In brief, the *Maglev haptic* condition was significantly superior to the other conditions by every force measure. Effects of other factors (repetition and target distance) were minimal and did not alter this pattern. The advantage of haptic feedback is clearly illustrated by the following two figures. Figure 7 compares resulting forces measured at the end effector at the moment when the operator was able to detect contact with the unseen buried object. The plot shows that across all trials and across all subjects, the contact force with the object is substantially lower when

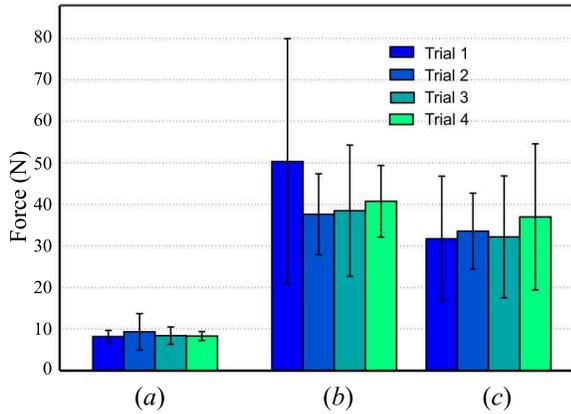


Fig. 7. Force (average over the 2-s window preceding contact) across 8 subjects during buried object detection using three different conditions: (a) TAGIT haptic feedback (our new method); (b) TAGIT without haptic feedback, (c) hand-held game controller. The four trials represent combinations of target distance and repetition. Error bars are one standard deviation.

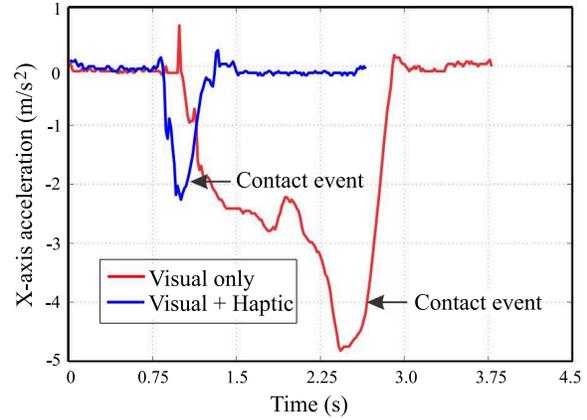


Fig. 9. Typical acceleration values measured by a wireless accelerometer node embedded in the buried object. Observations are taken during the subject's efforts to detect the buried object during conditions of visual only and visual combined with haptic feedback.

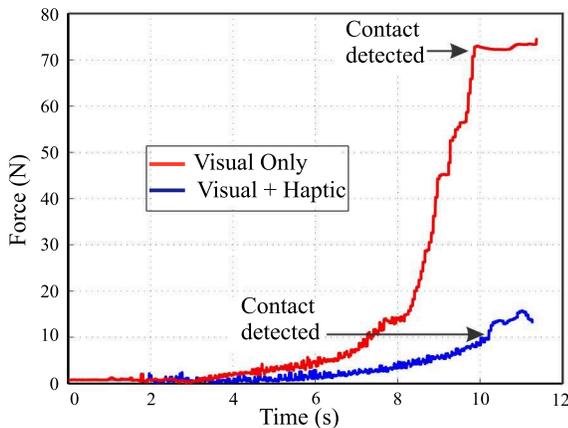


Fig. 8. Typical subject force profile contacting a buried object measured by the robot end effector's force/torque sensor; comparison between visual only feedback vs. visual combined with haptic feedback.

haptic feedback is present. In most cases the contact force was 3 times to 4 times smaller with haptic force feedback; in some cases haptic feedback reduced impact force by a factor of more than 10. A typical contact force vs. time plot is shown in Figure 8.

The contact force experienced by the robot end effector, and hence the operator's hand via haptic feedback should, after suitable geometric translations, be the negative of the force experienced by the buried object. In cases where the object is a bomb with a sensitive trigger, it will be important to minimize these forces. In a separate series of tests, the advantage of haptic feedback for reducing contact forces was confirmed by using an instrumented object consisting of a weighted hollow wooden box containing a wireless accelerometer node. Figure 9 shows typical ac-

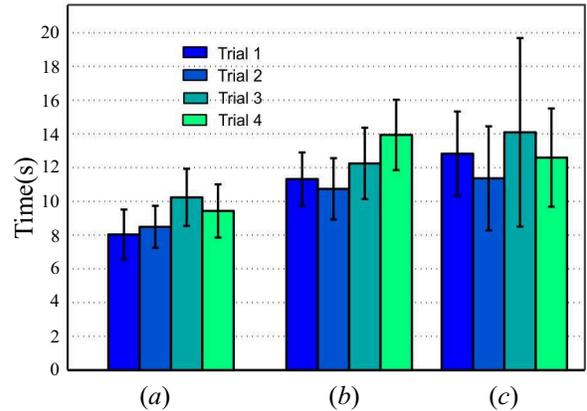


Fig. 10. Time (average) across 8 subjects required to detect a buried object using three different conditions: (a) TAGIT haptic feedback (our new method); (b) TAGIT without haptic feedback, (c) hand-held game controller. The four trials represent combinations of target distance and repetition. Error bars are one standard deviation.

celerations experienced by the instrumented object during conditions of visual only and visual combined with haptic feedback.

Another important comparison metric is the time taken to detect the buried object. Experiment 1 found that in addition to larger and more variable forces being produced if haptic feedback is omitted, there is also a statistically significant increase in completion time, as shown in Fig. 10.

### B. User Experiment 2: Comparison of Workspace Expansion Methods

After demonstrating that haptic feedback significantly improves operator performance, Experiment 2 compared the TAGIT method with two other haptic workspace expansion methods frequently used for haptic teleoperation

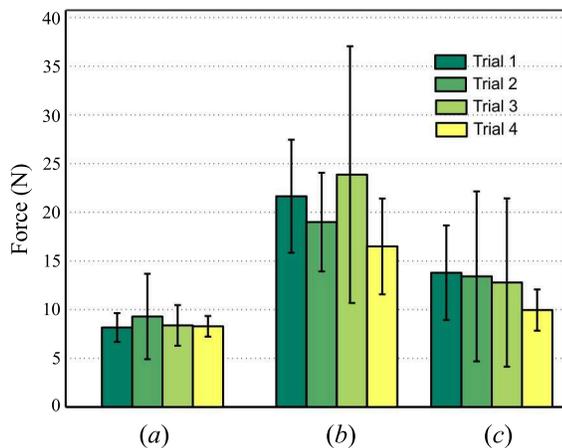


Fig. 11. Comparison of contact force with buried object using three different haptic workspace expansion methods: (a) TAGIT (our new method); (b) rate control; (c) Workspace Drift [7]. The four trials represent combinations of target distance and repetition. Error bars are one standard deviation.

and/or simulation, described previously: *rate control* and *Workspace Drift*. Haptic feedback as well as visual feedback were present with all of the methods. The basic test setup was the same as before, including the goal of identifying the location of a hidden object with as little contact force as possible.

The subjects were eight adults from the same pool as Experiment 1. As before, the experiment used a within-subject design in which the operator experienced all conditions, which were administered in a counterbalanced order across participants. Each participant performed 12 trials (2 repetitions per combination of target distance and mode).

As in Experiment 1, forces were measured at contact and the 2-s window beforehand. The ANOVAs on all measures showed a disadvantage for rate control, which produced significantly higher and more variable forces than the other methods. As shown in Fig. 11, the force on contact was on average more than 10 N lower when using TAGIT vs. rate control, and slightly (3-5 N, not significant) smaller when using TAGIT vs. Workspace Drift. An important disadvantage of Workspace Drift is that operators were forced to move the haptic master in a “zig-zag” motion, as when coloring an image with crayons; straight smooth motions are not possible. This constraint on exploration may contribute to the finding that Workspace Drift was inferior to TAGIT in eliciting greater maximum, mean, and variability of forces in the 2-s window before contact.

## V. CONCLUSIONS

The present experiments clearly show that the addition of haptic feedback to a challenging teleoperation task substantially enhances performance. Without such feedback, operators must rely on small, visually observable changes in the behavior of the robot or soil in order to identify the point of contact. This tends to happen considerably later

than the physical contact and elicits much larger and more variable forces. The effect of haptic feedback on operator performance for this type of task is clearly of practical importance.

Moreover, our results show that not all uses of haptic feedback are equally beneficial. TAGIT offers clear advantages in reducing contact forces and enhancing their consistency. We believe that the TAGIT haptic workspace expansion method has the potential for significant impact in the field of telerobotics and haptics. In addition to the current findings related to buried object discovery, data collected in several other user studies indicates that TAGIT significantly outperforms other state-of-the-art methods in robotic teleoperation and exploration of virtual haptic environments.

This paper is accompanied by a short video illustrating the operation of the system.

## VI. FUTURE WORK

Future work is intended to enhance the domain of application in which the TAGIT method is applied. TAGIT has an additional advantage not discussed here, namely, to improve the stability of a teleoperation system by effectively lowering loop gains without sacrificing haptic fidelity. Studies are planned with the goal of quantifying and optimizing this stability gain.

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