Bio-inspired Assistive Robotics: Service Dogs as a Model for Human-Robot Interaction and Mobile Manipulation

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Abstract— Service dogs have successfully provided assistance to thousands of motor-impaired people worldwide. As a step towards the creation of robots that provide comparable assistance, we present a biologically inspired robot capable of obeying many of the same commands and exploiting the same environmental modifications as service dogs. The robot responds to a subset of the 71 verbal commands listed in the service dog training manual used by Georgia Canines for Independence. In our implementation, the human directs the robot by giving a verbal command and illuminating a task-relevant location with an off-the-shelf green laser pointer. We also describe a novel and inexpensive way to engineer the environment in order to help assistive robots perform useful tasks with generality and robustness. In particular, we show that by tying or otherwise affixing colored towels to doors and drawers an assistive robot can robustly open these doors and drawers in a manner similar to a service dog. This is analogous to the common practice of tying bandannas or handkerchiefs to door handles and drawer handles in order to enable service dogs to operate them. This method has the advantage of simplifying both the perception and physical interaction required to perform the task. It also enables the robot to use the same small set of behaviors to perform a variety of tasks across distinct doors and drawers.

We report quantitative results for our assistive robot when performing assistive tasks in response to user commands in a modified environment. In our tests, the robot successfully opened two different drawers in 18 out of 20 trials (90%), closed a drawer in 9 out of 10 trials (90%), and opened a door that required first operating a handle and then pushing it open in 8 out of 10 trials (80%). Additionally, the robot succeeded in single trial tests of opening a microwave, grasping an object, placing an object, delivering an object, and responding to various other commands, such as staying quiet.

I. INTRODUCTION

There has recently been a surge of interest in autonomous mobile manipulation in domestic environments [16], [22], [23], [10], [39], [9], [38]. Most of the research on robots for assistive mobile manipulation has focused on wheelchair mounted robot arms [8], [34]. Relatively little work has explored the possibility of assistive robots with autonomous manipulation capabilities that move independently from the user [14], [15], [35], [11], [32].

Autonomous mobile robots with manipulation capabilities offer the potential to improve the quality of life for people with motor impairments. With over 250,000 people with spinal cord injuries and 3,000,000 stroke survivors in the US alone, the impact of affordable, robust assistive manipulation could be profound [4], [5]. Moreover, as is often noted,

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Fig. 1. On the left, a service dog opens a door using a bandanna tied to the door handle. On the right, our assistive robot opens a door in an analogous manner.

the elderly population worldwide is increasing substantially as a percentage of overall population, and there are over 16,000,000 people currently over the age of 75 in the US [33]. This aging population creates a need for affordable, robust robotic assistance, since 20% of people in the US between 75 and 79 years of age have been shown to require assistance in activities of everyday living, and this percentage increases precipitously with age, with 50% of people over 85 years of age requiring assistance [1].

Currently, assistance for motor impaired individuals is most often provided by a human caregiver, such as a spouse or nurse, which reduces privacy and independence, and often places a heavy burden on a loved one or entails high costs. Highly trained animals, such as service dogs or helper monkeys, can also provide physical assistance, but they come with a host of other complications, including high costs ($17000-$35000), multi-year waiting lists, reliability issues, and their own need for care [2], [20].

Biological systems currently represent the state of the art in physical assistance. Researchers have implicitly used humans as a model for many research efforts that seek to create assistive robots. For example, members of the humanoid robotics community often cite assistance for the elderly as a motivation [6], [17]. These bio-inspired robots have human characteristics in form and function, but have yet to achieve success as reliable helpers. We have previously used helper monkeys as inspiration for our work on assistive robotics, which contributed to our development of a laser pointer interface for assistive mobile manipulation [21]. Helper monkeys have been successfully directed to perform

tasks, such as bringing a drink and operating light switches, by a mouth-held laser pointer and simple words [3]. This style of interaction helped inspire our design, and validate the feasibility of the interface from a usability stand point.

In this paper, we use service dogs as a model for assistive robotics, see Figure 1. Dogs have previously been used as models for bio-inspired robotics, but prior work has overwhelmingly focused on areas such as entertainment, companionship, and social interactions [19]. In contrast, this paper focuses on service dogs that assist people with motor impairments in activities of daily living. Unlike pet dogs, the primary role of service dogs is not social, but functional, with the goal of providing beneficial physical assistance to the owner. Although service dogs are likely to also provide companionship, we expect that a person with a robot assistant could also have a pet dog for companionship.

II. TWO SOURCES OF INSPIRATION

We have based the work in this paper on two aspects of service dogs. First, we have used a current list of service dog commands to select and develop a set of useful assistive behaviors for the robot and to develop a verbal interface for human-robot interaction. Second, we have developed a new way of augmenting human environments to help facilitate robotic assistance that is analogous to the way people augment human environments to help service dogs perform assistive tasks. In particular, we show that tying or otherwise affixing towels (e.g., via suction cups) to door handles, drawer handles, and other manipulable parts of the environment can simplify autonomous perception and physical manipulation by the robot.

A. A List to Assist

Service dogs must be trained to obey commands through extensive training programs that can last two years. In order to learn about service dogs, we have collaborated with Georgia Canines for Independence (GCI) a non-profit organization devoted to the training and placement of service dogs. At GCI, dogs learn to perform 71 distinct commands that have been found to be helpful to humans. GCI kindly provided us with a copy of their training manual [13], which includes a list of these commands. This list offers a distinct advantage for robotic development, since it represents both an explicit set of well-tested assistive behaviors and an example of how people can direct these behaviors.

As shown in Table I, a service dog owner commands the dog using short verbal phrases. In cases where the owner is capable, the commands are usually given in conjunction with hand gestures. For our robotic implementation, we combine these same verbal commands with our laser pointer interface.

Equipped with a laser pointer interface, our robot detects when a user illuminates a location with an off-the-shelf green laser pointer and estimates the point's 3D position. This enables a user to unambiguously communicate a 3D location to the robot using a point-and-click style of interaction, which, for example, provides a direct way to tell the robot which object to manipulate or where to go. Recent studies
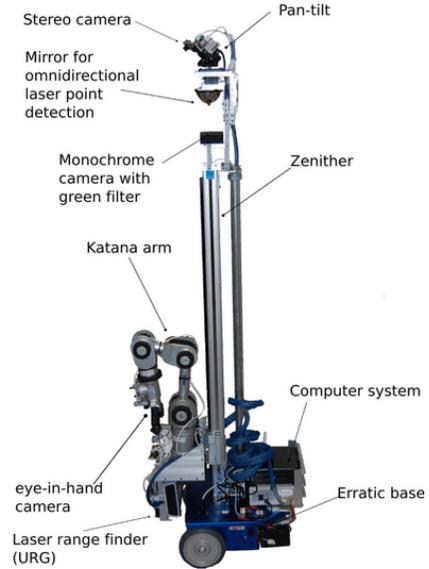

Fig. 2. An image of the assistive mobile manipulator El-E (pronounced "Ellie") used in this work. El-E has a 5-DoF arm (Neuronics Katana) on a vertical lift as well as a variety of sensors. In this work, El-E uses its gripper in a manner similar to the way a service dog uses its mouth. El-E also makes use of an eye-in-hand camera and force/torque sensors in its fingers.

performed in our lab (the Healthcare Robotics Lab at Georgia Tech) have demonstrated that motor-impaired patients can use this style of interaction to command a robot to pick up an object after less than 10 minutes of practice, with a 94.8% average success rate, and high satisfaction [12].

B. Functional Fabric

Through a presentation at our lab and a visit to GCI, we learned that GCI trains dogs to perform manipulation tasks using scarves or handkerchiefs that have been tied onto door handles and drawers, see Figure 1. People with motor impairments often engineer their environments in order to accommodate their needs. These alterations can be significant, such as when installing a lift system to help an individual move up and down stairs. With respect to these alterations, tying fabric onto handles is a comparatively small change.

Although we are uncertain of the exact reasons why the fabric helps a service dog perform these tasks, we have found that a similar method greatly simplifies analogous robotic manipulation. When opening a door or drawer, a dog grips the fabric with its mouth and proceeds to tug it. This tugging behavior is very similar to the tugging behavior that dogs often exhibit when playing with people. Our robot uses its 1 degree-of-freedom gripper, which has an eye-in-hand camera and force/torque sensors, in a manner analogous to the dog's mouth.

In our approach, we affix red towels to door handles, doors, and drawers by either tying the towel onto a handle or using a suction cup to hold the towel to a surface.

Category	Robot Command	Dog Command	Usage
Manipulation	Give	Give	tells dog to release item to your hand
	Bring it here	Bring it here	tells dog to bring item to you
	Take to	Take to	instructs dog to take item to drawer or another person
	Drop it	Drop it	dog should release item from mouth onto floor, table, or lap as directed
	Tug it/Tug it down	Tug it	instructs dog to pull on item with mouth
	Push	Push	tells dog to up on door and press closed
		Nose it	dog is to pres forward with nose; used to close drawers, activate life alert
	Get it	Get it	instructs dog to take hold of an items in his/her mouth
		Light	instructs dog to turn light on
		Switch	instructs dog to turn light off
		Pull	instructs dog to pull wheelchair (Pull right, Pull left, Pull easy, Pull hard)
		Hold	instructs dog to hold item until further directions
		Shake	dog gives you his/her paw
Administration	Quiet	Quiet	tells dog to stop vocalizing
	Stop	Stop	tells dog to stop pulling chair
	On/Off	Kennel	sends dog inside crate
		Get your leash	dog locates and retrieves leash
		Get your pack	dog locates and retrieves pack
		Go in	dog should go underneath table and lie down
		Settle	dog should remain in down position and remain calm and quiet
		Fix	dog lifts paw to allow leash to be untangled
		Dress	dog should put head through collar or pack
		Leave it	tells dog not to touch something or to ignore something
		Free dog	releases dog from work; he/she knows off-duty, can relax, play

This augmentation of the environment enables our robot to open a variety of doors and a variety of drawers using the straightforward behaviors "tug it" and "tug it down". This has a clear advantage over traditional approaches, since the robot is able to successfully use the same straightforward behaviors even though the appearance, structure, and kinematics of the handles and doors can vary dramatically. To make use of the towel, our robot El-E (pronounced "Ellie") first finds the red towel visually and segments it from the background using color image processing. El-E then grasps the red towel. Once grasped, El-E pulls the towel out or down depending on the command. The towel simplifies both the perception and physical interaction required to perform the task. With respect to perception, the robot primarily needs to perceive the red towel, which has a distinctive color and shape. With respect to manipulation, the robot can successfully grasp and pull on the towel with its single degree-of-freedom gripper without precise control. Cloth is both compliant and resilient to compression, so many grasp strategies result in a firm hold of the towel's material. The towel's material also forms a large target region with approximately uniform properties. After gripping the towel, the robot need only pull the towel such that the towel is in tension and applies sufficient force in the desired direction.

III. DESCRIPTION OF THE ROBOT

The robot, El-E, with which we performed the work in this paper is primarily constructed from off-the-shelf components as seen in Figure 2. Its mobile base is an ERRATIC platform from Videre Design. All computation is performed onboard. We have written most of our software with Python and some

C++ with the aid of open source packages such as SciPy, Player/Stage and OpenCV.

The ERRATIC base has differential drive steering with two wheels and a passive caster in the back. Attached to the center of the ERRATIC base is a 1-DoF linear actuator. This linear actuator, which we refer to as the zenither, raises and lowers an aluminum carriage with sensors and a 5-Dof Neuronics Katana manipulator in order for the robot to interact with objects at various heights. We have also mounted a Hokuyo URG laser scanner on a downward extension of the carriage.

El-E has a color, eye-in-hand camera with a $100°$ horizontal field of view. An omni-directional camera and a pan-tilt stereo camera sit on top of the zenither in order to detect when a location has been illuminated by a green laser pointer and estimate its 3D location.

For the work in this paper, the robot was tethered in order to connect the new force/torque sensors in the fingers to off-board boxes provided by ATI for power, signal conditioning, and digitization. We have recently completed changes to the robot, so that it now performs these functions onboard and is fully untethered.

More details about El-E can be found in our previous publication [21].

IV. SYSTEM IMPLEMENTATION

In order to follow the biological model of the service dog, the robot uses a speech recognition front end for recognizing verbal commands. Each assistive behavior is triggered by the user speaking a phrase representative of the command used with service dogs. Since the robot would accompany and assist a single user at a time, speaker dependent recognition

TABLE II

AN EXAMPLE OF SUCCESSFULLY GIVING A VERBAL COMMAND

Speaker	Phrase
User	Robot arm give
Robot	I heard robot arm give. Is this what you said?
User	Yes
Robot	OK

of 71 phrases would be sufficient to support this assistive application with the full list of service dog commands. These 71 phrases use 82 distinct words and the phrase "go to X" can make use of words taught to the dog to denote names of particular persons. We use Sphinx-4 with a custom grammar and vocabulary, but default speaker-independent settings [26]. We implemented the command protocols to reduce the possibility of unintended commands being executed by the robot. Before speaking each command, the user is required to say either the word "robot" or the robot's name, "Ellie", which reduces the chance of the robot recognizing commands when the user is not speaking to it. To further reduce the chance of failure the user must prepend the word "arm" or "admin", where "arm" indicates a manipulation type of command and "admin" denotes an administration type of command as described earlier in this paper. For example, to give the command "tug it", which is a manipulation command, the user must say "robot arm tug it". Once a command is recognized, the robot is programmed to repeat the phrase it recognized back to the user for confirmation. An example of a successful dialog is given in Table II.

For this work we present results from implementing and testing the commands "tug it", "tug it down", and "push". We have also adapted the implementation from our previous work [28] into this new service dog framework, so that our previous assistive operations for object fetching, object delivery, and object placement can now be commanded using voice commands that are analogous to commands used with service dogs ("get it", "bring it here", "give", and "drop it"), as shown in Table I.

After a verbal command is given, the robot waits for the user to select a 3D location with the laser pointer interface [21]. If the location is less than 1 meter away, and the command requires the robot to move, the robot moves toward the location and performs the commanded action. Otherwise, El-E drives to within 1 meter of the selected location and asks the user to once again illuminate the location. This two step process reduces errors by ensuring that the robot has a good estimate of the selected 3D location.

A. Towel Detection

We detect the towel using visual segmentation with a Gaussian mixture model that represents color and texture and has been trained on the appearance of the towel. We trained this model using a single picture of the towel. After the robot has approached the location of the towel selected by the laser pointer, the robot is looking directly at the towel. At

this point, the robot visually segments the towel in a manner that is nearly identical to the method we use to visually segment objects for grasping in our previous work [28]. After segmenting the towel, the robot attempts to find the bottom tip of the towel. The towel hangs downward due to gravity and the bottom of the towel is far from the knot. In order to avoid grasping the knot, we take the top most pixel in the image that has been segmented as towel and the bottom most pixel in the image segmented as towel and finds the point that is 20% of the distance from the bottom pixel towards the top pixel. With this 2D coordinate we then calculate the 3D position of this pixel by assuming that the 2D towel pixel lies on the plane estimated by the laser range finder which typically corresponds with the surface of the door or drawer.

B. Force Guided Towel Grasping

To grasp the towel, the robot fully opens its gripper and then uses its arm to move the gripper forward towards the 3D point returned by the towel detector. The robot stops moving its gripper forward when it feels a force on the fingers as measured by the two 6-axis force/torque sensors or detects something in the gripper using the IR range sensor at its palm. After stopping, the arm then attempts to close its gripper while avoiding collisions between the tips of the fingers and the surface of the door or drawer, which requires backing up a bit while closing the gripper due to its rotary joint.

C. Service Dog Behaviors

1) Tug It: When given this command, i.e when the user says 'robot arm tug it', the robot first moves towards the 3D location selected with the laser pointer. Once the robot is within 1.2 meters range from this location it estimates the plane of the surface closest to the 3D point using its laser range finder. This estimation uses linear least squares and assumes that the plane is parallel to gravity. The robot then moves to within 1 meter of this estimated plane and orients itself such that it is directly facing it. At this time, the robot waits for the user to once again select the location of the towel using the laser pointer.

El-E then travels to this point and moves its linear actuator up so that the arm is at the same level as the 3D point. At this time, the robot uses methods for detecting and grasping the towel described above. Once the towel has been grasped, El-E uses its mobile base to drive backwards to pull on the towel. This backwards driving is performed in increments of 10 cm until the robot goes for a total distance of 90 cm or the force limit of 15 N is exceeded. Executed as is, this action results in a linear path for the end effector ideal for objects such as drawers.

Since doors and door handles move in arcs, adjusting this trajectory based on the forces sensed at the end effector can improve the robot's performance. At the end of each 10 cm movement, the robot uses the direction and magnitude of the force from the towel, now in tension, to adjust the trajectory of its end effector [30].

2) Push: As with the "tug it" command, the robot first moves to the laser selected 3D location and orients itself with respect to the plane. The robot then reaches out to the 3D location that was selected with the laser pointer until it makes contact as measured by the force/torque sensors in the fingers. After making contact, the robot moves forward in a straight line with its mobile base while keeping its arm extended. It continues to move forward until the measured force exceeds 15 N or it has moved forward a total distance of half a meter.

3) Tug It Down: For this command, the robot grasps the towel using the same method as the "tug it" command. Once it has grasped the towel, the robot moves its linear actuator down to exert a downward force on the towel. The linear actuator then moves in 1.5 cm increments up to a maximum distance of 10.5 cm or until the force pulling the fingers upwards exceeds 15 N. This distance is appropriate for the door handles in our lab. However, it should be possible to increase this total distance and stop once the force exceeds the threshold. As with the "tug it" command, the robot senses the force at its end effector and adjusts its trajectory.

After the robot has finished pulling the towel down, it pushes forward until the measured force exceeds 15 N or it has moved forward a total distance of half a meter. We incorporated this pushing forward motion, so as to open doors without requiring an additional command.

4) Other Commands: For manipulation commands such as "get it", "bring it here", "give", and "drop it", we use the behaviors from our previous work. The "get it" behavior grasps the object if the object is on a table or the floor. When the user gives the command "bring it here", the robot moves toward the object closest to the laser selected 3D location, as segmented by the laser range finder. After being issued the command "give" the robot moves its linear actuator up to a person's height and extends its arm if it has an object in hand. With the command "drop it" the robot simply opens its gripper allowing the object to fall out.

We have also implemented minor administration commands such as "on", "off", "quiet", and "what is happening". As previously mentioned, when saying these commands the user must append "robot" or "Ellie", followed by "admin", and then the command phrase. For example, the user might say, "Ellie admin on". The commands "off" and "on" toggle the command recognition system into and out of a mode that only recognizes the command, "on". "quiet" turns off the robot's voice and "what is happening" turns it back on. This can be useful since the robot is programmed to narrate its actions and give feedback.

V. EXPERIMENTS AND RESULTS

A. Experiments

We first evaluated the efficacy of the commands "tug it down", "tug it", and "push" by testing each command 10 times for manipulating the same object under the command of a human operator. Each trial starts with the robot positioned next to the operator with the operator giving the voice command followed by use of the laser pointer to designate

(a) White Drawer   (b) Grey Drawer

(c) Door

Fig. 3. A door and drawers manipulated by the robot during the experiment. In the case of the grey drawer, which does not have a protruding handle, the towel was attached to a suction cup, which enables a towel to be attached to smooth surfaces.

the appropriate location. In each trial, the operator used the verbal protocol described to command the robot. If the robot executed the wrong command due to a failure with its speech recognition system, the trial would be recorded as a failure. However, the verbal communication protocol was not the cause of any failures. It is worth noting that when commanding a service dog, the user will often repeat the same command multiple times while gesturing to a relevant part of the world. Although our robot requires more verbose commands and more complicated verbal protocols, we believe that it is competitive with canine speech recognition in this context. Furthermore, we expect that a speaker-dependent speech recognition system specifically trained for the user would improve performance and reduce the need for verbose commands and protocols. The main difference that would be likely to persist is the need for the user to speak into a microphone when commanding the robot. We used a lavalier microphone for this work, although one could imagine a single device that combines a microphone, laser pointer, and other components with which to command the robot.

1) Tug It: To test the command "tug it", the user instructed the robot to tug on a towel attached to a white drawer, as shown in Figure 3. The robot started out at the user's side, which was a distance of 210 cm from the drawer and perpendicular to the plane of the drawer. After the voice

command was given, the user gave the first laser command providing the robot with the 3D coordinate of the towel. Then, after the robot had driven closer to the selected location and oriented itself with respect to the plane of the drawer, the user gave the second laser pointer click providing a more accurate 3D location of the towel. In this case, a trial was successful if the robot pulled the drawer fully open.

2) Push: With the command "push", we instructed the robot to push the drawer closed. This drawer was the same drawer used when testing the command "tug it". The physical location of the robot and the command process was exactly the same but with the success criteria being defined as closing the drawer completely.

3) Tug It Down: For the command "tug it down" we attached the towel to a door handle and instructed the robot to pull on the towel to open the door. This experimental setup is shown in Figure 3. In this case the robot stood at a distance approximately 178 cm away from the door and facing the direction parallel to the plane of the door. After giving the voice command, the operator used the laser pointer to select the towel. After the robot drove to within 1 meter of the selected location, it requested that the user select the location again. After selecting the location, the robot performed the action. In this experiment, a trial was successful if the robot opened the door. Opening the door required that the robot unlatch the door by operating the door handle and then push the door open.

4) Tug It (with second drawer and microwave using suction cup): Not all drawers have handles to which a towel can be tied. For this test, we used a suction cup to affix a towel to a drawer with a recessed handle, see Figure 3(b). We found that when fully shut, the force required to open this particular office drawer was more than 25 N, which is beyond the maximum rating of our robot. This large force is by design to keep the drawer securely shut. Prior to each trial, we slightly opened the drawer in order to present the robot with a situation within its physical capabilities. This test was performed in a smaller room with the robot standing 152 cm away from the drawer. A trial was deemed successful if the robot fully opened the slightly ajar drawer. We also performed a single trial with the towel affixed to the door of a microwave.

5) Other Commands: We only performed informal trials for the object grasping, fetching, and delivery commands. We have previously reported the performance of these behaviors using the laser pointer interface by itself. Likewise we only performed informal tests of the administration commands to make sure that each command puts the robot in the correct state. The robot successfully performed all of these commands at least once.

B. Results

In the "tug it" trials using the white drawer, the robot was successful in 9 out of 10 trials (90%). In the one failure case (trial 5) the robot's pose was too close to the drawer causing the manipulator to be unable to fully close its gripper around the towel due to collisions between the fingers and
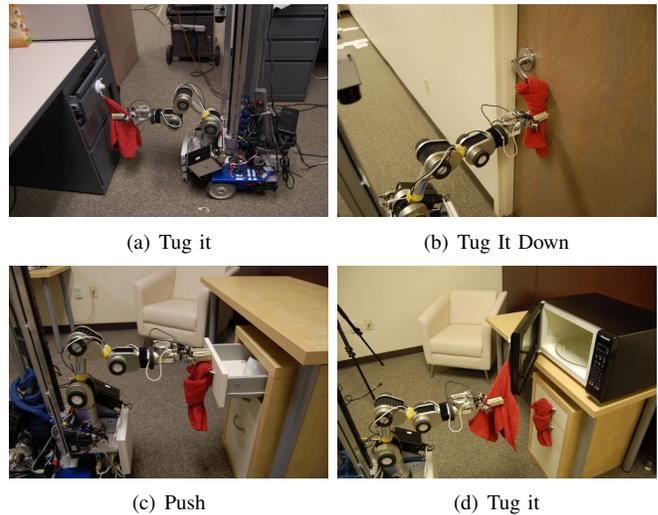

(a) Tug it

(b) Tug It Down

(c) Push

(d) Tug it

Fig. 4. El-E manipulating these doors and drawers using the attached red towel.

TABLE III

EXPERIMENTS SUMMARY

Command	Number of Trials	Success Rate
Tug it (white drawer)	10	90%
Tug it down (door)	10	80%
Push	10	90%
Tug it (grey drawer)	10	90%
Microwave	1	100%

the drawer. This error was due to the imprecise backwards motion of the robot using the mobile base and should be correctable with better integrated control of the end effector and base.

With the "push" command the robot was successful in 9 out of 10 trials (90%). The one failure case (trial 4) was due to a failure in the identification of the plane of the drawer which caused the robot to align itself with the side of the drawer instead of the front.

In the "tug it down" trials the robot was successful in 8 out of 10 trials (80%). In the first failure case (trial 6), the failure was the same as in trial 5 of "tug it" since the gripper was not able to close completely around the towel due to the mobile base being too close to the door's surface. In trial 7, the robot successfully grasped the towel and was able to turn the door handle, but not enough to open it.

With the "tug it" command using the office files drawer, we were able to pull the drawer open in 10 out of 10 trials (100%).

Finally, we performed the same "tug it" command on a microwave oven with a towel attached using a suction cup. In the single trial attempted the robot successfully opened the microwave.

In all of these trials, the robot performed the intended command. Even in cases where the user said the wrong command there was an opportunity to cancel the command when the robot asked for confirmation. In the 41 trials, there

were 8 instances where the command had to be repeated more than once, including one instance where the "yes" confirmation was repeated 4 times.

VI. DISCUSSION

We started this paper with two main forms of biological inspiration, which we discuss here.

A. What are useful commands for assistive robots?

Great efforts have been made to try to determine what functionality assistive robots should have in order to best meet the needs of users [37]. By modeling the capabilities of the robot on service dogs, we immediately have a proven model for assistive manipulation that has been shown to be highly beneficial and cost effective [7].

We have found that the 71 commands used by GCI can be roughly divided into six categories which we have named manipulation, administration, movement, people following, communication, and reinforcement, a subset of which is presented in Table I. Manipulation includes commands that direct the dog to manipulate the world using its mouth, nose, paws and body. Administration commands direct the dog to perform tasks that are not immediately assistive and have more to do with preparation and maintenance of the dog. Movement commands primarily direct the dog in navigation activities. People following commands direct the dog to position itself with respect to the user or the user's wheelchair. Communication commands help the user tell the dog what to expect and help the user to better understand the dog's state of mind. Reinforcement commands provide positive and negative feedback to the dog with respect to its actions.

We believe that these commands can serve as a valuable guide for the future development of assistive robots.

B. How do towels help?

Our straightforward approach to opening doors and drawers in domestic settings contrasts dramatically with previous approaches. Roboticists have worked on door opening for well over a decade [27], but have yet to develop methods that successfully generalize across the great variety of doors and drawers found in human environments. As suggested by the results we present in this paper, minimal augmentation of the environment might enable a robot to operate robustly on this diverse array of doors and drawers using just a few simple behaviors that can be commanded by a user.

Many previous approaches have focused on methods for physically manipulating the door once in contact with the handle using kinematic estimation and control [30], or force or impedance control, such as recent work with advanced arms with torque controlled joints [29]. Other researchers have worked on the challenging problem of finding the handle or other appropriate locations at which to make contact [25]. Recent approaches to these perceptual problems have used machine learning and statistical estimation with both visual and haptic sensing [24], [31]. Work on opening drawers and doors has been rare [36], as has operating

Fig. 5. A service dog operating a light switch with a small flexible tube attached.

distinct doors [24]. Our approach is more similar to manipulation research that makes use of fiducial markers [18], but our method requires no calibration, is inexpensive, is easy to install, has proven precedents, and simplifies both the physical and perceptual aspects of manipulation. For some applications, the simplification of the physical interaction may be as important to autonomous manipulation as the perceptual simplification.

The straightforward success of our approach appears to derive from several factors. First, making appropriate contact with an unaltered door or drawer will typically involve a small target area with dramatic variations in appearance. In contrast, the towel presents a large, readily identifiable region for contact. Likewise, unaltered handles, doors, and drawers usually require that constrained trajectories be followed by the robot's end effector in order to continue to apply the appropriate forces and moments as they are opened. Following these trajectories has typically involved either advanced kinematic, force, or impedance control [30], [29] or carefully scripted actions [24]. In general, handles, doors, and drawers are rigid and undergo constrained motion, either rotary motion around a pin joint or linear motion along a rail. In contrast, our approach allows for slow motions over imprecise trajectories with a relatively simple robot arm. Additionally, when pulling down on a handle, the towel tends to move to the end of the handle which helps maximize the moment arm and reduce the force that the robot must apply to the towel.

VII. CONCLUSIONS AND FUTURE WORK

This work makes three main contributions. First, with respect to human-robot interaction we have demonstrated that verbal commands and a laser pointer can be used to direct a robot to perform assistive tasks in a manner similar to service dogs. Second, we have demonstrated that an assistive mobile manipulator can perform assistive behaviors that are comparable to those performed by service dogs. Third, we have presented a novel, inexpensive way to engineer the environment to help assistive robots perform useful tasks with generality and robustness.

In this work we only utilized red towels, but we believe there are other opportunities to develop inexpensive, easy to install mechanisms that enhance robotic performance both in terms of perception and physical interaction. Some of these opportunities are already used by service dogs and

trainers. For example, people attach small flexible tubes to light switches in order to help service dogs operate the lights, see Figure 5. In the long run, we believe that by using these methods to simplify the environment we will be able to implement the full set of relevant service dog commands. This could lead to valuable new assistive robots that enhance the lives of the motor impaired.

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