Hand It Over or Set It Down: A User Study of Object Delivery with an Assistive Mobile Manipulator

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***Abstract*— Delivering an object to a user would be a generally useful capability for service robots. Within this paper, we look at this capability in the context of assistive object retrieval for motor-impaired users. We first describe a behavior-based system that enables our mobile robot EL-E to autonomously deliver an object to a motor-impaired user. We then present our evaluation of this system with 8 motor-impaired patients from the Emory ALS Center. As part of this study, we compared handing the object to the user (direct delivery) with placing the object on a nearby table (indirect delivery). We tested the robot delivering a cordless phone, a medicine bottle, and a TV remote, which were ranked as three of the top four most important objects for robotic delivery by ALS patients in a previous study. Overall, the robot successfully delivered these objects in 126 out of 144 trials (88%) with a success rate of 97% for indirect delivery and 78% for direct delivery. In an accompanying survey, participants showed high satisfaction with the robot with 4 people preferring direct delivery and 4 people preferring indirect delivery. Our results indicate that indirect delivery to a surface can be a robust and reliable delivery method with high user satisfaction, and that robust direct delivery will require methods that handle diverse postures and body types.**

I. Introduction

Service robots that robustly deliver objects to users could be valuable for a variety of applications. For example, a robot could assist a mechanic by delivering a tool, while a robot that prepares food could deliver a meal. Within this paper, we look at how an assistive robot can deliver an object to a motor impaired user.

People with motor impairments have consistently reported object retrieval as an important task for assistive robots [27]. At the Healthcare Robotics Lab at Georgia Tech, we have been developing the assistive mobile manipulator EL-E to perform assistive tasks such as object retrieval and door opening (see Figure 1). We have previously performed tests involving object fetching with able-bodied users [22]. In collaboration with the Emory ALS Center, we have also performed a study in which 7 patients with amyotrophic lateral sclerosis (ALS) and 1 patient with primary lateral sclerosis (PLS) commanded EL-E to approach and pick up an object using a handheld laser pointer, a head-mounted laser pointer, and a touch screen. In over 134 trials, the robot had a 94.8% success rate and the users reported high satisfaction [5].

In order to successfully retrieve an object, the robot must deliver the object after picking it up. Within this paper we report on our most recent study, in which 8 patients commanded the robot to either hand them an object or place the object on a nearby table.

Fig. 1. El-E handing a cordless phone to an ALS patient. Photos used with patient permission and IRB approval.

For this work, we assume that the user wishes to gain direct control of the object that the robot is carrying without the object falling on the floor or otherwise moving unfavorably. We further assume that at the end of a successful trial the robot must not be making contact with the object, and the user must be holding the object. For some severely motor-impaired users, it may be more appropriate for the robot to continue to hold the object so that the user can control the object through the robot, but we do not investigate this case in this paper.

Given these assumptions, the robot must somehow transfer control of the object to the user in a controlled and stable manner (e.g., not throwing the object). Humans frequently achieve this feat without difficulty. Waiters, in particular, serve as an informative example of successful strategies for delivering an object. Waiters typically hand an object directly to a patron, place the object on the table next to the patron, or present a tray from which the patron can grasp the object. Within this study, we compare two strategies for robotic object delivery: handing the object to the user and placing the object on a table next to the user. Our results show that these two methods have distinct implications.

During the development of EL-E, we have worked closely with patients and staff from the Emory ALS Center. ALS, also known as Lou Gehrig's disease, is a progressive neuro-degenerative disease that gradually takes away people's ability to move. Assistance provided by a robot could increase an ALS patient's quality of life by helping the patient achieve independence in daily activities. Furthermore, we believe this population serves as a valuable model for the many populations of motor-impaired patients who could benefit from this broadly applicable technology.

II. Related work

There is a long history of researchers developing robots to assist people with motor impairments. For instance, The Assistive Robotic Manipulator, known as MANUS, is a commercially-available, wheelchair-mounted robotic arm (WMRA) [17]. It can help individuals with various tasks including object fetching and retrieval by controlling the arm by joystick and keypad. Since the direct teleoperation of this kind of robotic device is often difficult, researchers have been developing autonomous capabilities for WMRAs [29]. The FRIEND II robot, another WMRA, includes an intelligent tray that serves as an object delivery location [18]. In general, WMRAs can place an object within the reach of the user without much difficulty due to the fixed configuration between the arm and the user. However, WMRAs require that the user drive the wheelchair system to the desired object in order for the arm to grasp it. Mobile manipulator platforms decoupled from the user's chair eliminate the need for the user to be at the site of object retrieval.

Researchers have attempted to characterize the mechanics involved when objects are handed between people or between a person and a robot. Shibata and colleagues [24] studied the motions involved when two humans hand each other an object to determine the trajectories and velocities of their hands during the task. Other researchers have used these human hand trajectories to simulate a human delivering an object to a robot using potential fields [15]. Another simulation study incorporated a controller to allow a robot to receive an object from a human while safely taking into account unexpected human movements [4]. Beyond simulation, a recent study used a 2D planar robot to assess human preference for delivery velocity and position during a human-robot object hand-over [14]. Analysis has also been done on the grip forces or torques used when passing an object [19], [20].

Several mobile platforms have been developed to deliver objects to able-bodied people. For instance, planning algorithms have been developed to find safe trajectories for handing objects as seen with Jido and Care-O-bot II [26], [25], [10]. A behavior-based approach that enables a robot on a fixed platform to hand objects to able-bodied people has been shown to allow intuitive human-robot interactions [8].

Autonomous mobile robots have also been developed to deliver objects to help the elderly and motor impaired perform everyday tasks. For instance, Mobile Assistant Robot for You (MARY) and Care-O-bot 3 are mobile manipulators that can fetch and deliver objects by placing them on a tray, which is attached to the robot's front panel, before moving closer to the receiver [28], [9]. Similarly, CERO delivered objects that had been placed on top of it to a motor-impaired individual [12]. However, none of these autonomous delivery systems has been tested directly with the elderly or the motor-impaired population whom their technologies aim to serve. The robot SAM has been tested with motor-impaired users in terms of object grasping, but studies of its delivery capabilities do not appear to have been performed [23].

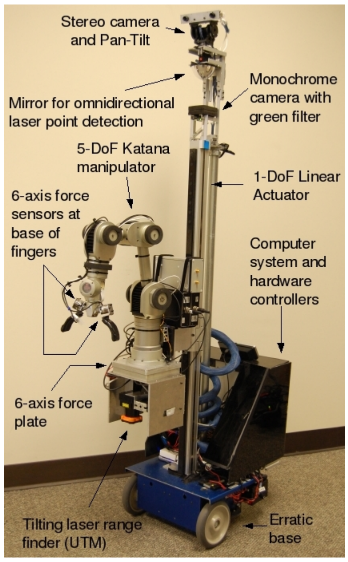

Fig. 2. The mobile manipulator EL-E used in this paper.

In designing the user study presented in this paper, we took into consideration prior work on user preferences during a mobile robot delivery task. Users tended to dislike when the robot approached them from the front, and preferred that it approach them from either their left or right side [7], [30]. We took these findings into account for the Experimental Setup.

Many previous researchers focused on one delivery method that researchers assumed to work for the users. In this paper, we developed two representative object delivery methods for an autonomous mobile manipulation robot. In addition, we tested the two methods with a specific user group of ALS patients.

III. Implementation

We describe the robot EL-E that we used in this paper in Section III-A. We then explain the safety mechanisms that we have implemented on the robot in Section III-B and the behaviors that implement the direct and indirect delivery in Section III-C.

A. The robot

The robot EL-E, is a statically stable mobile manipulator (shown in Figure 2) that consists of a 5-DoF Neuronics Katana 6M manipulator, an ERRATIC mobile base by Videre Design, and a 1-DoF linear actuator that can lift the manipulator and various sensors from ground level to 90cm above the ground [21]. El-E also uses the Festival Speech Synthesis System to give users feedback by speaking fixed sentences in English. For example, El-E asks the user to give it a laser command or to grasp an object from its gripper.

The ERRATIC platform has differential drive steering with two powered wheels and one passive caster at the back. A Mac Mini running Ubuntu GNU/Linux performs all computation on-board. We have written most of our software in Python with occasional C++ utilizing a variety of open source packages including SciPy, Player/Stage, OpenCV, and ROS (Robot Operating System).

For this work, EL-E uses three distinct types of sensors. First, EL-E uses a laser pointer interface that consists of an omni-directional camera with a narrow-band green filter that is designed to detect a green laser spot and a pan/tilt stereo camera that estimates its 3D location [16].

Second, EL-E uses a laser range finder (Hokuyo UTM-30LX) mounted on a servo motor (Robotis Dynamixel RX-28) at the bottom of the aluminum carriage attached to the linear actuator. The servo motor tilts the laser range finder about the horizontal axis. The robot uses this tilting laser range finder to obtain 3D point clouds of the environment.

Third, EL-E senses forces and torques using force-sensing fingers and a 6-axis force plate. We have replaced the Katana Sensor Fingers with our own custom fingers. Each finger is a curved strip of aluminum covered with elastic foam for passive compliance and is connected to the motor via a 6-axis force/torque sensor (ATI Nano25 from ATI Industrial Automation). This enables the robot to measure the resultant forces and torques being applied on each finger independently. In addition to force sensing fingers, we have mounted the Katana on a 6-axis force plate (HE6X6 from AMTI). The force plate allows the robot to sense forces applied to any point on the Katana arm.

B. *Safety mechanisms*

We describe three methods that we use to help ensure safe operation of the robot.

1) Obstacle detection using a safety screen: The Hokuyo UTM Laser Range Finder used in this study emits invisible laser light. It is a class 1 laser device [1] and is therefore safe under all conditions of normal use [2], [3]. Furthermore, no participants expressed any concern about their safety regarding the laser scanner during the experiments. When EL-E moves, it lifts the tilting laser range finder to a height of approximately 90cm off the ground and tilts it down. In this way EL-E can detect obstacles, such as table tops and people, that get close to its body. This helps to ensure that EL-E stops before colliding with anything. We refer to this as a "safety screen". For future versions of EL-E, we plan to place an actuated laser range finder that can pan and tilt at the top of EL-E. This will enable EL-E to monitor for potential collisions over its entire body, regardless of the direction in which it is moving (see Figure 3). For now, EL-E lifts its carriage to approximate this sensor configuration.

2) Collision detection using force sensing: When the robot moves the manipulator to hand the object to a user or to place it on a table, it monitors the force plate and the force sensing fingers and freezes the manipulator if it detects a collision.

3) General safety during user trials: The robot operates at relatively slow speeds to lessen the effects of undesired contact with the human. In addition, the experimenter can press an emergency stop button to turn off the robot's power during a user delivery trial to avoid unwanted contact.

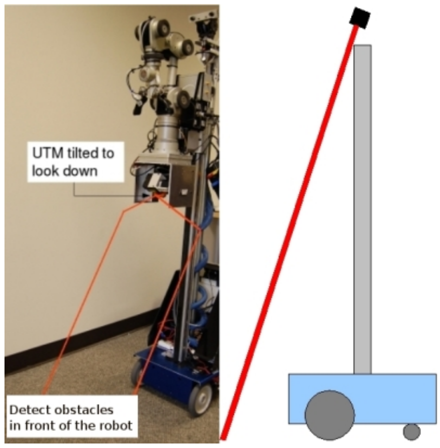

Fig. 3. **Left:** Our current implementation using a laser range finder for real-time obstacle detection in the form of a safety screen. **Right:** A sketch of our plans for a new actuated laser range finder that can pan and tilt in order to improve the coverage of the safety screen.

C. *The Behaviors*

In this paper, the experimenter chooses whether the robot will perform a direct or indirect delivery before the start of each trial. In the future, this could be inferred by the robot [22] or explicitly selected by the user, but we wanted to reduce the complexity of the experiment. To start the trial, the experimenter hits a key on a keyboard of a remote computer connected to the robot's on-board computer through Wi-Fi. Next, the robot asks the user to supply a laser command. The user then shines the laser pointer either at a location on or around him or herself (direct delivery) or at a location on a table (indirect delivery).

The robot estimates the 3D location of the laser point in an ego-centric coordinate frame using the laser pointer interface. If the distance of the laser point is greater than 1.5m, the robot moves closer to the selected location and asks the user to repeat the laser command. Moving within 1.5m of the user selected location and repeating the laser command helps reduce the error in the robot's estimate of the location. We refer to the time from the start of the trial until the final laser command as the detection time (DT).

The robot then performs direct or indirect delivery depending on the type of trial that the experimenter chose. Figure 4 shows the behaviors that the robot executes for direct and indirect delivery, the actions that the human user performs for each trial, and the different time intervals that we measure and report in Section IV.

1) Direct delivery: After detecting a laser point within 1.5m, the robot turns to face the laser point, detects the user's face with the stereohead, and makes a 3D estimate of the location of the face. If the robot does not detect a face in a volume around the laser point, it stops and reports a direct delivery failure.

To detect faces, the robot first uses the Viola-Jones face detector as implemented in OpenCV to generate multiple

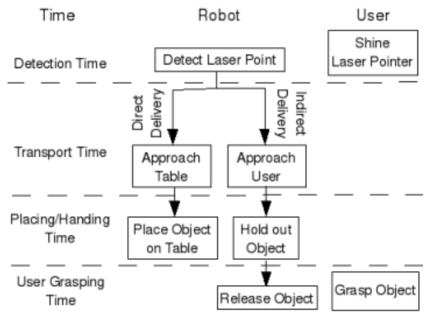

Fig. 4. This figure shows the different time intervals, robot behaviors, and user actions involved in both direct and indirect delivery. Note that the user actions are identical for both delivery methods. Robot behaviors and user actions are shown in boxes.

face hypotheses for the left and right camera images independently. The robot then uses a Gaussian Mixture Model for skin color [31] trained on an online database of faces [11] to remove false positives from the Viola-Jones face detector. Finally, the robot triangulates each pair of remaining hypotheses from the left and right camera images to generate 3D face hypotheses. The robot rejects 3D face hypotheses that are either smaller than 13cm or larger than 25cm, or are at a height of less than 1m or greater than 2.2m above the ground. The robot then selects the 3D hypothesis closest to the robot as the estimated location of the user's face.

After detecting the user's face, the robot approaches the user in a straight line path. It stops when it is either 1m from the user's face or it detects an obstacle, such as the user's feet, using the safety screen.

Once the *Approach User* behavior as described above completes, the transport time (TrT) ends and the robot executes the *Hold out Object* behavior. To do this, the robot uses the linear actuator to move the laser range finder 20cm below the estimated height of the face and rotates it so that it scans parallel to the ground. The robot then performs a 2D connected component labeling of the points in the resulting scan. When two points are less than 2cm from one another, they are considered to be connected. The robot then selects the connected component closest to itself as the user's body.

Let P_{face} be a 3-tuple representing the estimated 3D coordinate of the user's face and P_{body} be a 2-tuple representing the 2D coordinate of the centroid of the user's body in the planar scan. The coordinate of the direct delivery location is $(P_{body}[0]-0.25m,\ P_{body}[1],\ P_{face}[2]-0.25m)$ where the X axis points out from the robot, Y axis is to the robot's left, and Z axis is vertical. This corresponds to a point backed off a quarter meter from the estimated body, laterally at the center of the estimated body, and below shoulder height. If possible, the robot then moves the manipulator so that the object is at this location. After holding out the object, the robot asks the user to grasp the object which marks the end of the placing/handing time (PHT).

Next, the robot monitors its force sensing fingers and releases the object after the user has grasped it. It adds the force vectors measured by both the force sensing fingers to estimate the resultant force between the manipulator and the object. If the robot detects a change greater than 1.4N in the magnitude of this estimated resultant force, the robot releases the object, marking the end of the grasping time (GrT).

2) Indirect delivery: To deliver an object to a table, the robot moves toward the 3D location selected by the laser point, raises the laser range finder 20cm above this selected location, and takes a 3D scan with the tilting laser range finder. It performs a subset of this scan around the laser point to detect a flat surface and approaches the laser point in a direction normal to the boundary of this surface.

Once the robot is close to the flat surface it takes another 3D scan and uses that information to refine its estimate of the height of the surface. It then navigates such that the location for placement, specified by the laser pointer, is within the workspace of the robot's object placing controller.

After approaching the table, the transport time (TrT) ends and the robot executes the *Place Object on Table* behavior. It takes a 3D scan to determine if the object placing controller can operate without a collision and then executes it. More details about the flat surface detection algorithm and the object placing behavior can be found in [13]. After placing the object on the table the robot asks the user to grasp the object from the table. This marks the end of the placing/handing time (PHT). When the user successfully grabs the object, the grasping time ends (GrT).

IV. METHODS

We describe the methodology of this user study beginning with participant recruitment. Next we describe the experimental design and setup. Lastly, we describe the procedure we performed for each trial.

A. Participants

We recruited the eight participants in this study by visiting the Emory University ALS Center three times. As they did their rounds seeing patients, a staff nurse or physician first asked patients whether they would be interested in participating in our study where some upper limb mobility is required. Then, either one or two researchers from our team explained the delivery capabilities of the robot as well as usage of the laser pointer interface to the patients. We emphasized that using the interface would require some squeezing or pressing ability with at least one hand, and that some arm movement would be required to grab the object from either a table or the robot itself. After a short question and answer period, the user then told us whether they were comfortable and interested in participating. We contacted the patient who participated in the previous user study through mail and telephone communication and explained the hand and arm movements required to operate the robot in a similar fashion. We provided 50 US dollars to each participant for compensation. Table I shows the demographic information.

The population of people with ALS exhibit varying degrees of motor impairment ranging from limited hand gripping capability to paralysis below the neck. Thus, we do not claim that the group of participants in this user study

TABLE I

DEMOGRAPHIC INFORMATION

Gender	Male (6), Female (2)
Ethnicity	White (7), African American (1)
Age	37 - 70 (average 59.8) years
Diagnosis	34.9 months ago (average)

TABLE II

MASS AND SIZE OF OBJECTS

Object	Mass	Length	Width	Height
Cordless phone	116 g	15.0cm	4.8cm	2.9cm
Medicine bottle	99 g	8.2cm	4.4cm	4.4cm
TV Remote	90 g	17.0	4.7cm	2.8cm

is a representative sample of the entire ALS population. We believe that the form of object delivery that we developed would be most useful for those with some level of upper limb and gripping capabilities. We did not include those with severe upper limb motor impairments in this study.

B. Experimental design

The independent variables of this study are the method of delivery (direct and indirect delivery) and the object type. We used the following three objects in this study: 1) cordless phone, 2) medicine bottle, and 3) TV remote control with masses and dimensions as shown in Table II. We selected these objects from the top four objects in the list of everyday objects prioritized by ALS patients described in [6]. We did not select the medicine pill (whose rank is #2 in the list) as one of the objects for this study due to manipulation limitations of the robot.

The quantitative dependent variables are detection time (DT), transport time (TrT), placing/handing time (PHT), user grasping time (GrT), and total time (TT), which are defined in Section III. For qualitative measurement of the users' experiences, we conducted several surveys which we describe later in Section IV-D.4.

Each patient participated in 18 object delivery trials using the robot. These trials consisted of all possible combinations of: the two delivery methods, three object types, and three repetitions (2x3x3 = 18 trials). We conducted the trials in a counter-balanced fashion.

C. Experimental setup

The study took place in a simulated living room environment with dimensions of 3.64×4.4m (see Figure 5).

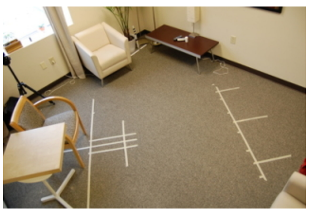

Fig. 5. Experimental setup. The desk chair and table used in the experiment are shown in the bottom-left. The robot start positions are shown to the right.

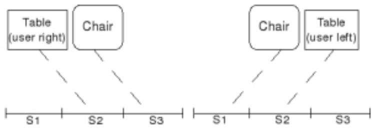

Fig. 6. **Left:** Starting positions when the user prefers the table on his right. Indirect: S2, Direct: S3. **Right:** Starting positions when the user prefers the table on his left. Indirect: S2, Direct: S1.

Fig. 7. **Left:** Hand-held laser pointer. **Middle:** Ear-mounted laser pointer. **Right:** The three objects used in this study - TV remote, cordless phone and medicine bottle.

The participants were seated for the entire experiment. When participants brought their own wheelchair, they used it for the study. If they did not bring a wheelchair (e.g., used a walker), but used one at home, we provided a standard wheelchair for them to use for the experiment. For two participants who did not use a wheelchair in their daily lives, we provided a desk chair.

For the indirect delivery method, we placed a height-adjustable table adjacent to and at the height of the armrest of a standard wheelchair. We allowed the user to select the side on which the table was placed for the entire experiment, depending upon which side was more comfortable for the user to reach for an object.

At a distance 2m away from the front face of the chair, we marked three robot initial positions (S1, S2, and S3) with tape on the floor. For indirect delivery trials, we placed the robot at the center position S2 and and then it traveled along a diagonal path to place the object on the table to the side of the user's choice (either user left or user right). As shown in Figure 6 (Left), if the user preferred the table to be on his right, then the robot started at position S3 for direct delivery. On the other hand, if the user preferred the table on his left, the robot started at position S1 for direct delivery.

This starting position scheme prevented the the robot from approaching the user in a direct, frontal path. We took this precaution since Walters and colleagues reported that more users preferred that a robot approaches them from the side compared with the front during object delivery [30]. In addition, the scheme enabled the robot to approach the user at the same angle for both delivery methods.

D. Procedure

1) Initial paperwork: When a participant visited the lab, we welcomed them and asked them to be seated in either a wheelchair or a chair positioned as shown in Figure 6. They then read and signed the appropriate consent forms and completed a demographic survey.

2) Selection of laser pointer: After the paperwork, we introduced a hand-held laser pointer and an ear-mounted laser pointer (see Figure 7) and asked the participant which would be more comfortable to use.

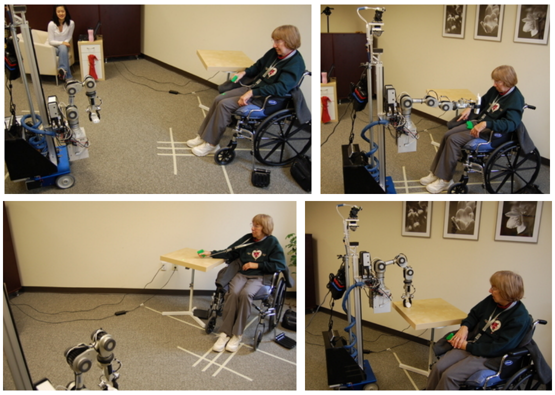

Fig. 8. **Top:** The user shines the laser point onto her lap, the robot delivers the object to user (direct delivery). **Bottom:** The user shines the laser point onto the table, the robot delivers the object to the table (indirect delivery).

3) Delivery trials: After the users completed all pre-task assessments, we explained the two object delivery methods. Then we asked the participant to practice using the laser pointer and conducted one trial run of each delivery method before the experiment began. Each participant conducted a total 18 trials as described in Section IV-B.

4) Satisfaction surveys and final interview: After a user completed a set of 6 direct and indirect delivery trials with one object, we administered a brief survey regarding their experience. The same survey was administered again after 6 trials were completed for the second object and then again for the third object. The survey contained the following statements which had response choices graded by a 7-point Likert scale from strongly disagree (1) to strongly agree (7):

Q1) I could effectively use the system to accomplish the given tasks.
Q2) It was not physically burdensome to use the system.
Q3) Overall, I was satisfied using the system.

When the user completed all the trials, we administered the final satisfaction surveys for direct and indirect delivery methods over their experiences with all three objects with following questions also by 7-point Likert scale:

Q1) I could effectively use the system to accomplish the given tasks.
Q2) I am satisfied with the time between I gave command and the robot delivered object.
Q3) It was easy to point with the interface.
Q4) It was easy to learn to use the system.
Q5) It was not physically burdensome to use the system.
Q6) Overall, I was satisfied using the system.

After the final satisfaction survey, we conducted an interview to ask participants questions regarding their experience using the robot and as well as to gather suggestions for improving the technology. Specifically, we asked them their preferred method by asking which delivery method they felt more comfortable using.

V. Results

All 8 participants reported that their dominant hand was their right hand and preferred the table to be placed on their right side. Although most participants showed some level of difficulty moving their arms and fingers, all of the participants were able to reach for and grasp objects from the robot gripper or from the tabletop.

TABLE III
MEAN TIMES BY DELIVERY METHOD IN SECONDS

Method	Detection (DT)	Transport (TrT)	Placing/ Handing (PHT)	Grasping (GrT)	Total (TT)
Direct	13.76	89.33	30.94	1.2	135.3
Indirect	12.17	183.93	65.8	1.6	263.6

A. Quantitative performance measures

We conducted an analysis of variance (ANOVA) using a general linear model to determine the effects of the two independent variables on the dependent variables. The statistical analysis showed that the delivery method and object type do not have significant interaction effects with each other, which enabled us to separately analyze the effects of the two independent variables. The object type does not show significant effect on any of the time measures, so we can focus on analyzing the differences caused by the delivery method alone. The delivery method had significant effects on TrT, PHT, and TT with $p<0.001$. However we found no significant effect on times which required user interaction: DT (p-value of 0.084) and GrT (p-value of 0.109). Table III shows comparisons of the means of each time measurement by object type. Overall, indirect delivery was slower than direct delivery. Direct delivery was only slightly slower in detection time, but the difference was not significant. The delivery success rate was higher for indirect delivery with 97% success rate (70/72) than for direct delivery with 78% success rate (56/72), while the overall success rate was 88% (126/144).

B. Failed trials

We observed 18 failures in 144 total trials. Two of the failures occurred during indirect delivery and 16 during direct delivery. One of the indirect delivery failures was due to a laser detection failure which occurred when the user was using the ear-mounted laser pointer. When the user turned his head to the right in order to shine the laser point onto the table, a portion of the hooded shirt the user wore obstructed the laser beam, causing it to split into two laser points. One laser point shone on the user and the other on the table. The robot detected the laser point on the user's body, which caused the experimenter to stop the trial. In the second case, the robot failed to release the object after attempting to place it on the table.

15 of the 16 failures during direct delivery were due to the same flaw of the direct delivery implementation. The failures occurred when the robot estimated a direct delivery location outside its workspace after observing a connected component that was relatively close to the robot. 9 of these failures occurred with one user who had a relatively large mid-section which explains the source of the close connected component. The other six instances of this failure occurred

TABLE IV

MEAN SATISFACTION BY OBJECT AND METHOD

Method / Object	Q1	Q2	Q3
Direct Delivery	6.86	6.82	6.96
Indirect Delivery	6.89	6.81	6.96
Phone	6.90	6.85	6.95
Medicine Bottle	6.83	6.83	6.94
TV Remote	6.89	6.72	7.00
Total	6.87	6.8	6.96

TABLE V

MEAN OVERALL SATISFACTION BY METHOD

Method	Q1	Q2	Q3	Q4	Q5	Q6
Direct Delivery	7.00	5.88	6.75	6.88	6.88	7.00
Indirect Delivery	6.88	5.75	6.75	7.00	6.88	7.00
Total	6.94	5.81	6.75	6.94	6.88	7.00

with three other users and we suspect that the users' posture and size may have been involved, but have not been able to determine the exact causes. The other direct delivery failure occurred when the force torque sensors stopped providing readings possibly due to a server communication error.

C. Satisfaction survey

Refer to Section IV-D.4 to recall the questions asked in Tables IV and V. As shown in Table IV, all participants expressed high levels of satisfaction close to "strongly agree" (score of 7). For all three questions, the average satisfaction scores did not differ much by delivery method or by object type. Similarly, the overall satisfaction scores shown in Table V did not differ much by delivery method either. However, we note that the satisfaction score of Question 2: "I am satisfied with the time between I gave command and the robot delivered object" was below 6 which was lower than the other questions. We believe that this is due to the slow performance of the robot.

D. Final interview

During the final interviews, we asked whether the users thought the robot was useful for object delivery and all the participants gave positive answers. All participants agreed that the robot gave enough feedback on its progress through speech output, but one participant thought the speech was difficult to understand. Most participants said they did not have any difficulty using the laser pointer, but one user who used the hand-held laser pointer said that the grip was not very good. Some participants wanted the hand-held laser pointer to be bigger and easier to squeeze while one participant who used the ear-mounted laser pointer wanted it to hook onto the ear more securely.

To compare the preference of delivery methods, we asked which delivery method they felt more comfortable using. 4 participants chose indirect delivery and 4 preferred direct delivery. The participants who preferred indirect delivery said that it gave them more flexibility in when and what manner they grabbed the object. Several users slid their hand and arm along the table surface to grab the object. The participants who preferred direct delivery said that it required less arm movement for reach the object. It is important to note that none of the participants who preferred direct delivery said that the speed of delivery was the reason they preferred that method, even though direct delivery was much faster. One participant said he preferred indirect delivery because of the 9 failures he experienced with direct delivery as described in Section V-B.

(a) (b) (c) (d)

Fig. 9. Posture and body size variation. (a) and (d) show more reclined postures. (b)-(d) show varying wheelchair foot rest heights and extensions.

One participant experienced difficulty in direct delivery because the object was obstructed by the robot gripper which made it difficult for him to grasp the object. He suggested that the robot grasp only one end of the object to make it easier for him to grasp. Another participant experienced difficulty using the laser pointer when the laser light was incidentally blocked by and reflected on his clothing. Other suggestions to improve direct delivery included bringing the object closer to the user and improving the speed of delivery. No one reported difficulty using the indirect delivery method.

VI. Discussion and Conclusion

The results show that the robot could accomplish the delivery task with an overall 88% success rate. Although the success rate was high for indirect delivery (97%), we observed a relatively high failure rate in direct delivery. We plan to fix the causes of the failed trials to improve robustness. Specifically, for direct delivery, we will implement changes to allow El-E to back up and re-try the *hold out object* behavior in the event a close connected component is detected. While indirect delivery was more reliable, it was much slower because it required additional laser scanning to detect the edge of the table.

As found in the results of the satisfaction surveys and final interviews, participants showed very high levels of satisfaction regarding the robotic delivery methods. However, we found less favorable responses regarding the time it took to complete the delivery tasks. We also found that the preferences of delivery methods were equally divided. The preferences were mostly related to the manner in which the user could grab the object. Indirect delivery provided users with greater flexibility in the manner and time of grabbing the object, while direct delivery reduced the arm movement needed to grab the object. The apparent differences in task time did not affect users' preferences of delivery methods.

With the current system, we believe that robust, autonomous delivery of objects to flat surfaces is achievable. Although user preferences were divided, delivery to flat surfaces showed very high satisfaction rating and all the participants could reach and grasp an object in every trial. This indicates that functional robotic assistance might be provided prior to fully solving complex issues related to autonomous direct delivery. In contrast, further research will be required to make direct delivery robust to the large variations we encountered in posture and body size. This is an especially significant issue with motor-impaired individuals who can be more vulnerable to robotic error and can have more varied postures due to weakness and wheelchairs (see Figure 9). When a suitable solution to this problem is found, providing direct delivery in addition to indirect delivery would be beneficial to some users with motor impairments who prefer direct delivery. Additional possibilities that fall between our direct and indirect methods would be for the robot to hold out an object and have the user approach the robot to grasp it, or for the robot to place the object on a tray and present the tray to a user. Given our results and the many options available, we are confident that object delivery should not be a limiting factor for future assistive robots.

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