Dusty: A Teleoperated Assistive Mobile Manipulator that Retrieves Objects from the Floor

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***Abstract*- Retrieval of dropped objects has consistently been ranked as a high priority task for assistive robots. We have previously presented a dustpan-inspired end effector capable of robustly grasping objects from the floor. In this paper, we present and evaluate Dusty, a complete mobile manipulator consisting of a new version of this end effector, a mobile base, a scissor lift, and a wireless interface. The interface consists of a joystick for driving, a button that triggers a grasping behavior, and a button that operates the lift. We first tested Dusty's ability to grasp objects from 25 object categories prioritized for robotic retrieval by people with ALS. Dusty succeeded in 97.6% of the 125 trials and grasped each object no fewer than 3 out of 5 times. We then tested Dusty's ability to grasp a small, thin cylinder (ca. 2.92cm diameter and 0.71cm height) placed at different locations. Grasping succeeded when the object was in a large region in front of the robot (ca. 15cm x 38cm), which we expect to improve usability. In preparation for testing with motor-impaired subjects, we conducted a pilot study with able-bodied subjects (n=10) in which each subject drove Dusty around an obstacle, picked up an object, and then delivered the object to him or herself, all while sitting in a stationary wheelchair. The subjects succeeded at this task in all 30 trials (3 trials each) with a mean completion time of 67.8 seconds (SD = 20.8 s). Our results suggest that assistive robots like Dusty could be useful for retrieving dropped objects and enhancing quality of life.**

***Keywords*- Assistive robotics, teleoperation, mobile manipulation**

I. INTRODUCTION

In 2005 the U.S. Census Bureau estimated that more than 2.2 million Americans have motor impairments [1], and that they frequently require assistance with activities of daily living (ADLs). People with motor impairments have consistently placed a high priority on the ability to retrieve out-of-reach objects, including objects on the floor [2]. Motor impairments can both increase the chances that an individual will drop an object and make recovery of an object difficult or impossible. In a survey we conducted previously, a group of 8 ALS patients reported dropping objects 5.5 times a day, on average [3]. Moreover, for the 22 specific reported cases of dropped objects in our study, recovery of the dropped object was reported to have taken 9.4 minutes on average with high variance (SD = 25.4 min). We estimated that the presence of a caregiver led to a recovery time of approximately 5 minutes, while the absence of a caregiver could lead to long recovery times including one report of a two hour wait [3].

Fig. 1. Picture during a demonstration of Dusty to an attendee at the ALS Association of Georgia Educational Symposium on February 6, 2010. A lab member was operating the robot. (Permission granted for use of photo.)

Assistive robots could potentially enable people with motor impairments to efficiently recover dropped objects, and thereby gain greater independence. Our lab, the Healthcare Robotics Lab at Georgia Tech [4], and other labs [5-7] have previously explored the possibility of general purpose, human-scale autonomous mobile manipulators to serve this and other assistive roles. In the long-run, this type of solution seems plausible and compelling, since a single robot might provide a variety of forms of assistance and be on call 24 hours a day, 7 days a week. However, general purpose assistive mobile manipulators are likely to remain complex, costly, and large relative to more specialized robots, and no one knows when affordable human-scale mobile manipulators will become a reality.

Within this paper, we explore the possibility of a relatively low-cost assistive robot with specialized capabilities that may be commercially feasible in the short term. Specifically, we present Dusty, a teleoperated assistive mobile manipulator designed to help people efficiently pick up objects from the floor (Fig. 1).

Dusty uses a dustpan-inspired end effector, which is a new version of the end effector we presented at ICRA 2009 [8]. As our experimental results in this paper show, this new version outperforms the old version even though it has a simpler design. Most significantly, the new end effector uses a simple rigid finger with a rotary joint instead of a compliant, cable-

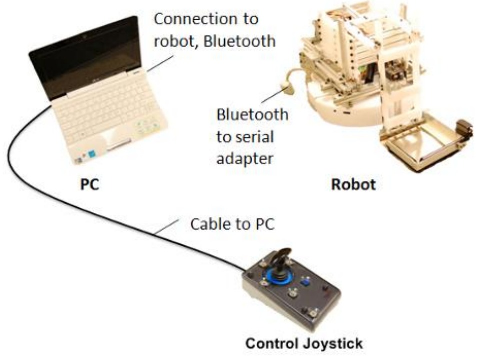

Fig. 2. For Dusty's user interface, joystick input is processed by the PC, which then transmits control information to the robot via Bluetooth.

driven finger with two joints and a flexible end. It also uses a rectangular plate made out of a simple rectangle of uniform material, rather than a complex piece of metal connected to a kitchen turner. In addition to using an improved end effector, Dusty integrates a scissor lift and a wireless interface via Bluetooth, so that the robot can be used as a complete system that moves to an object, picks it up, and delivers it (Fig. 2).

The rest of this paper looks at related work, describes Dusty's design, and then presents the results of three experiments. The first two experiments demonstrate Dusty's ability to pick up a variety of important objects, and to pick up objects after only being coarsely positioned. The last experiment demonstrates that Dusty can successfully and efficiently perform navigation, grasping, and delivery when operated by able-bodied users.

II. Related Work

Current solutions for assistance in object retrieval include mechanical reachers, service animals, and wheelchair-mounted robotic arms. Mechanical reachers have a gripper or a sticky pad at the end [9], and can be used to recover a dropped object. Although it is a cost-effective solution, it requires significant dexterity and strength in a user's arms, hands, and torso. In addition, the operating range is limited by the reaching distance of the person, and retrieving heavy objects can be a challenge. Service animals, such as helper monkeys and service dogs, are trained to perform assistive tasks such as retrieving objects from the floor. However, service animals are expensive ($17,000- $35,000), have long waiting lists, and require care [10, 11]. In addition, service animals may not be suitable for some patients due to physical conditions such as allergies [12].

Research into assistive robots with manipulation capabilities has a long history going back to the 1960's [13]. This research has led to wheelchair-mounted robot arms [14-17], including commercially available products such as the MANUS ARM [18] and the Raptor arm [19]. However, these solutions are expensive ($12,500 - $35,000) [6], have a limited workspace, and can be an undesired attachment to a wheelchair. An independently mobile robot has potential advantages. For

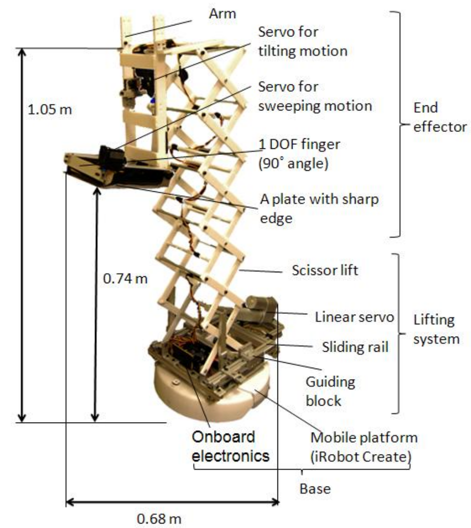

Fig. 3. Dusty consists of a mobile base, a lifting system, and an end effector

example, people could use wheelchairs that match their preferences with modest modification, and people who do not require a wheelchair, or are not currently in a wheelchair, could still benefit from the robot.

III. System Design

Dusty uses an assistive joystick connected to a control PC that wirelessly communicates with the robot over Bluetooth (Fig. 2). We selected an assistive joystick (Traxsys Roller Plus Joystick), which is designed to improve computer access for people with disabilities. For this work, we affixed the joystick to a wheelchair's armrest.

A. *The Dusty Robot*

Dusty is composed of three main components: an end effector, a lift system, and a mobile platform (Fig. 3). We use an iRobot Create as the mobile platform, and the robot receives control information from the control PC using a Bluetooth-to-serial adapter (RoboDynamics RooTooth). Moving the joystick left or right causes the robot to rotate counter-clockwise or clockwise, respectively. Moving the joystick forward or back causes the robot to move forward or backward, respectively.
The buttons for lifting and grasping result in commands that are relayed to an Arduino board, which controls the servos for the lift system and the end effector. The Arduino board and the servos draw their power from the iRobot Create.

End Effector

Our end effector consists of a rectangular plate with a leading wedge that slides under the object; a finger that pushes the object onto the plate; and a mechanism that tilts the plate to either push the leading wedge against the floor, or level the plate away from the floor in order to prevent objects from dropping out. The plate is a 15cm x 15cm square steel sheet, and is designed to be close (1 cm) to the floor surface when the scissor lift is lowered and the plate is held flat. The finger is made of aluminum, forming a 90˚ angle. When closed, the

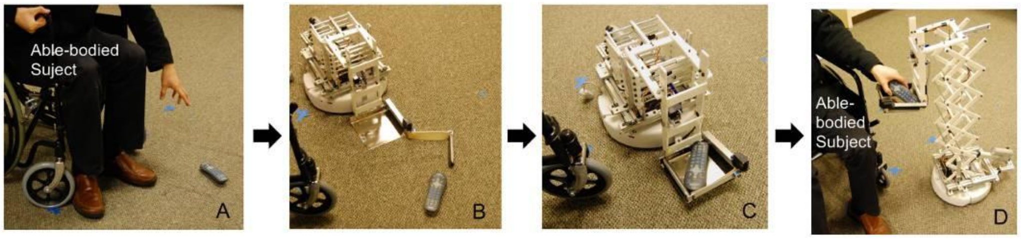

Fig. 4. This figure illustrates Dusty picking up a dropped object. An able-bodied user is pictured in this sequence.

finger covers the front and right sides of the plate. A fixed aluminum bar covers the left side (Fig. 4C). The joint between the finger and the plate is a servo mounted on the corner of the plate on top of this bar. When the finger is fully open, the angle between the finger and the aluminum bar is about 210˚ (Fig. 4B). We use the same model of servo (Hitec HS-7955TG) to sweep the finger and tilt the plate.

Lift System

The purpose of the lift system is to raise the end effector to a height for the user to comfortably retrieve an object. It consists of a base, a scissor lift, and a linear actuator. The base is built with extruded aluminum (80/20 Inc.) and is attached to the mobile platform. The scissor lift is made of acrylic using a laser cutter. Steel beams connect the corresponding joints of the two sides of the scissor lift. At the bottom of the lift, the two links in the front are connected to the base, while the two links in the back are connected to guide blocks on sliding rails (Fig. 3). A linear actuator (ServoCity HDLS) is connected to the back of the base. The other end of the actuator is connected to a beam at the bottom of the scissor lift. As the actuator moves, the guide blocks slide on the rails and the scissor lift extends. The end effector is screwed onto the top front of the lift, and is connected to the top back beam with slots that the beam slides within as the lift is extended and retracted. When the lift is fully extended, the end effector is 74 cm above the ground, which is within the guidelines for tables and counters provided by the United States Americans with Disabilities Act [20]. This enables the end effector's plate to serve as a tray which can deliver objects.

B. One-Touch-and-Grasp

Dusty has a *one-touch-and-grasp* feature that enables it to successfully grasp an object after coarse positioning and a single button press. We expect that this modest autonomous function can reduce the need for precise navigation of the robot, and may enable people with motor impairments to retrieve a dropped object more easily and efficiently. The algorithm for the *one-touch-and-grasp* behavior follows:

1. The finger of the end effector opens.
2. The end effector tilts down, so that its leading wedge touches the floor.
3. The robot moves forward at approximately 15cm/s for 2 seconds.
4. The finger then attempts to fully close at approximately 2.09 rad/s.

In an object fetching scenario, the user can use the joystick to perform the following sequence (Fig. 4): (1) navigate to a desired place; (2) pick up the dropped object; (3) navigate to the user; and (4) lift up the object to a comfortable height for the user.

IV. Methods

To evaluate the performance of Dusty we evaluated 1) the robustness of the grasping function over various object categories, 2) the area over which an object can be autonomously grasped by the robot, and 3) the ability of Dusty to perform a complete object fetching task when controlled by an able-bodied user (in preparation for tests with motor-impaired subjects).

Grasping Various Types of Objects

We first tested Dusty's grasping performance with objects from the 25 object categories ranked most important for robotic retrieval by motor-impaired users from the Emory ALS Center in our previous study [3]. We evaluated the previous version of Dusty's end effector with 34 objects in 5 orientations on 4 types of flooring, achieving an overall success rate of 94.7% [8]. We evaluated the new version of the end effector to find out if its simpler design provides comparable performance. We tested the top 25 object types from the prioritized object list [3] on a short-pile carpet floor. As shown in Table I, the objects varied in size and weight, allowing us to test the robot's ability to pick up a diverse array of objects. The experimenter placed each object about 37 cm in front of the robot at the center of the end effector, and then pressed the button to perform the *one-touch-and-grasp* function. The task was repeated five times for each object with varied orientations in a manner similar to our previous study [8]. As reported in detail in Table I, we performed a total of 125 grasp attempts for 25 objects and recorded the success rate of the end effector grasping the objects. We deemed a trial to be successful if the object was more than halfway on the plate after the finger closed on it and the robot had stopped moving. In our experience, this is sufficient for stable lifting of this set of objects, especially since the finger holds the object on the plate.

Grasping an Object at Different Locations

In order to evaluate the spatial sensitivity of Dusty's grasping behavior, we used a similar experiment to our previous paper [8] (Fig. 5). The performance of our old end effector design when grasping a small cylinder (ca. 2.92 cm

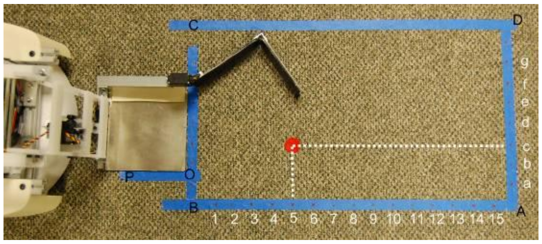

Fig. 5. Testing grasping area. Rectangle ABCD encircles the testing field. There are 7 markers on tape AD, and 15 markers on tape AB. The testing cylinder is placed on the mesh grids formed by these markers, e.g. the coordinate of cylinder shown in the figure is (5, c). Line BC and line OP are perpendicular to each other, and they define the starting position of the robot. The test is run with finger opened in the beginning.

diameter and 0.71 cm height) was poor. We tested our new design by moving this same cylinder over a 15 x 7 grid covering a 55 cm x 30 cm area (Fig. 5 and Fig. 7).

As in our previous work, we ran the test with the finger opened at the beginning. This is in contrast to the algorithm executed by the *one-touch-and-grasp* function during the object type test and the pilot user study, which keeps the finger closed until the *one-touch-and-grasp* button is pressed. As shown in Fig. 7, Dusty is able to robustly pick up the cylinder over a large area and significantly outperforms our previous work. In this experiment, we deemed a trial to be successful if the cylinder was fully on the plate after the trial.

Pilot Study with Able-bodied Users

In order to begin evaluating the complete system and prepare for user studies with motor-impaired subjects, we performed an object retrieval test with able-bodied subjects. The purpose of this pilot study was to evaluate the feasibility and safety of the current system. In addition, we solicited feedback that may help us refine our design. A total of 10 subjects (age range 20-43 years), which consisted of male (n=9) volunteers and female (n=1) volunteers participated in the study. All subjects were members of the Healthcare Robotics Lab at Georgia Tech and have no clinical history of motor impairments.

In this study, each subject performed three trials of the object retrieval task. In the object retrieval task, shown in Fig. 6, an able-bodied subject sat in a wheelchair and used the armrest-mounted joystick to control the robot. We used a cardboard box (35.6 cm x 28.0 cm x 21.6 cm) as an obstacle placed between the subject and the robot. The box was 1.07 m from the subject. We included this obstacle to simulate a situation in which a user needs to drive Dusty around household furniture to retrieve an object. For example, the robot might sit in a corner of the room waiting to be called upon. We placed a target object 61 cm in front of the wheelchair because we anticipate that dropped objects would be close to the user. We used a remote control as the target object for retrieval because it ranks as the number one object category in our prioritized object list [3].

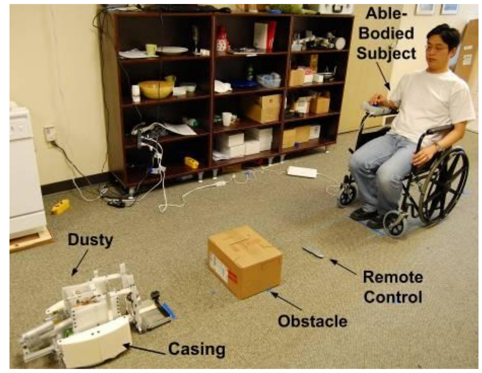

Fig. 6. **Experimental Setup:** Dusty (with protective casing) is in front of an able-bodied subject on a wheelchair, and an obstacle is placed in between the subject and the robot. The subject navigates the robot to avoid hitting the obstacle, fetches the remote control on the floor, and delivers it to himself.

We asked each subject to navigate the robot around the obstacle, pick up the remote control from the floor, and then deliver it to him or herself. We conducted this experiment on the same short-pile carpet floor as the other object grasping tests. We solicited user feedback from each subject upon the completion of three trials. We also recorded the following data during each test: time to complete the task, number of times that Dusty collided with the obstacle, number of times that Dusty failed to grasp the object, number of times that the object dropped from the end effector during the delivery, and the number of times the robot collided with the subject during delivery. We defined a grasping attempt as successful if the object was on the plate of the end effector after the robot completed the *one-touch-and*-grasp action.

V. Results

The area over which Dusty successfully grasped the small object is shown in Fig. 7. The current end effector was able to grasp a low profile object over a much larger area than the previous version [8]. The black area in the figure represents places where grasping succeeded 3 out of 3 times.

Table I shows the results of our tests to evaluate Dusty's ability to grasp objects from the top 25 object categories [3]. Dusty achieved an overall success rate of 97.6% across all the objects with various sizes, shapes and weights.

The results of the object retrieval study are shown in Table II. All subjects successfully retrieved the object in all trials, and the overall average time to complete the task was 67.8 sec

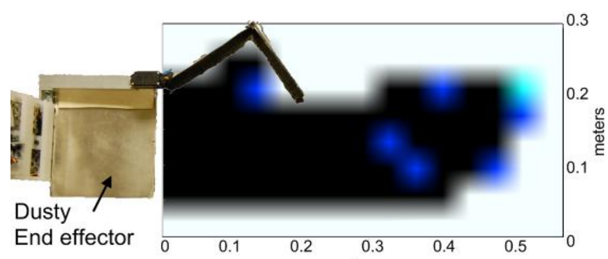

Fig. 7: Results of grasping a small cylindrical object at points on a grid. Black represents a grasping success rate of 3/3, dark blue represents 2/3, light blue represents 1/3, and white represents 0/3.

TABLE I
RESULTS OF THE OBJECT GRASPING TESTS – VARYING OBJECT AND ORIENTATION

Rank [3]	Object class [3]	Weight* (g) [3]	Max size* (cm) [3]	Success rate
1	TV Remote	90	18	5/5 = 100%
2	Medicine Pill	1	2.2	5/5 = 100%
3	Cordless Phone	117	15	5/5 = 100%
4	Prescription Bottle	25	7	5/5 = 100%
4	Fork	39	18	4/5 = 80%
6	Glasses	23	14	5/5 = 100%
7	Toothbrush	15	19	5/5 = 100%
8	Spoon	38	17	5/5 = 100%
9	Cell Phone	76	9	5/5 = 100%
10	Toothpaste	160	20	5/5 = 100%
10	Book	532	24	5/5 = 100%
10	Hand Towel	65	58	5/5 = 100%
13	Small Envelope (Mail)	22	24	3/5 = 60%
14	Cup/Mug	267	12	5/5 = 100%
15	Soap	116	9.5	5/5 = 100%
16	Disposable Bottle	500	13	5/5 = 100%
17	Shoe	372	30	5/5 = 100%
17	Dish Bowl	154	13	5/5 = 100%
19	Keys	24	8.5	5/5 = 100%
20	Dish Plate	182	18	5/5 = 100%
21	Pen/Pencil	3	14	5/5 = 100%
22	Table Knife	76	24	5/5 = 100%
22	Credit Card	5	8.5	5/5 = 100%
24	Medicine Box	25	10	5/5 = 100%
24	Bill	1	13.5	5/5 = 100%
		Overall Success Rate		**97.6%**

* Estimated average weight and maximum dimension for each category [3]

(SD = 20.8 sec). This is significantly lower than our coarsely estimated time of 5 minutes for object retrieval by a caregiver, although we do not know how far Dusty would need to move in practice, nor how cluttered the environment might be.

There were a total of 15 times that the robot failed to grasp the object; 8 cases occurred when the finger of the end effector pushed the object away as it opened, and the remaining 7 occurred when the end effector missed the object due to the position of the robot prior to the *one-touch-and-grasp* button being pressed. There were no examples of the robot colliding with the subject, although the robot did collide with the obstacle a total of 10 times. This error mainly occurred with one subject (5 times). In addition, the object was not dropped during delivery. This indicates that once an object has been grasped, it tends to be stable even as the robot carries it and lifts it. However, we observed that the finger of the end effector occasionally had a tight grip on the object that made the object more difficult for subjects to retrieve from the end effector.

TABLE II
RESULTS OF THE OBJECT RETRIEVAL TESTS

Subject	# Trials Complete	Avg. Task Completion Time (sec)	Total # Obstacle Hit	Total # Fetch Failed	Total # Object Drops	Total # Subject Hit
A	3	58.0	0	1	0	0
B	3	75.0	0	3	0	0
C	3	54.0	0	0	0	0
D	3	61.0	1	1	0	0
E	3	47.3	0	0	0	0
F	3	46.3	0	2	0	0
G	3	78.3	5	3	0	0
H	3	67.0	2	1	0	0
I	3	73.3	1	2	0	0
J	3	117.7	1	2	0	0
Avg.	3	67.8	0.3	0.5	0	0
Total	30		10	15	0	0

The subjects' feedback provided us with valuable information on how to improve the user interface. Subjects reported a noticeable latency between the joystick control and the robot's motion, and indicated that this caused them to overshoot the desired rotation or position for the robot. Some subjects stated they would prefer simultaneous control of the rotation and forward/backward motion of the mobile platform rather than independent control. Some subjects suggested that a finger with flexible links can be used to reduce robot's tight grip on the object.

VI. Discussion and Conclusion

As our results show, Dusty can robustly pick up a variety of objects from the floor with only coarse positioning, and can be effectively controlled by able-bodied users to fetch objects from the floor. We have taken a user-centered approach to Dusty's design by focusing on object fetching, which is a well-documented task of value, and by evaluating Dusty with respect to objects relevant to this task. We have also received positive informal feedback through demonstrations at the Abilities Expo Atlanta on November 7-8, 2009, and the ALS Association of Georgia Educational Symposium on February 6, 2010. Based on the results of our pilot study with able-bodied users, we plan to refine our design and take the essential next step of performing a user study with subjects who have motor impairments. We are anxious to discover the limitations of our current design when used by subjects from the target population. Many options exist for further development of the robot, including the incorporation of greater autonomy, remote operation by a call-center, and video-based teleoperation by the user. Likewise, the possibility of long-term use is both exciting and daunting. We expect user studies to help point the way towards productive research and design.

Given the high level of grasping success (97.6%) across varied objects in both this experiment and our previous work [8], we are confident in the efficacy of our end effector design. Nonetheless, further refinement is necessary. The performance across diverse floor types could vary. Many failed fetching attempts occurred because the finger sweeps outward when opening at the beginning of a grasp. Also, the rigid finger occasionally has a tight grip on the object and requires dexterous and strong intervention by the user, a prospect that is not well-matched to the target population. Although there was no instance of collision between the robot and the subject in this study, we wish to be especially careful about the possibility for the wedge of the rectangular plate to collide with the user. Given the large compliance in the scissor lift, the low speeds and torques of the base, and the dull leading wedge, we do not expect any problems. However, we feel it is extremely important to carefully address potential safety issues prior to long-term deployment. We hope to look at all of these issues in our future research.

From Fig. 7, we can see that the grasping area of the current end effector is approximately the area the plate covers while moving forward (plate width x travel distance), plus the sweeping area of the finger. This interpretation should allow us to optimize the design of the end effector and the *one-touch-and-grasp* behavior for the needs of real users. There appears to be a tradeoff between the ability of the robot to handle clutter and the ease with which it can be commanded to pick things up. If the floor is highly cluttered with unmovable obstacles or objects that the user does not wish to grasp, then a wide plate and long distance of travel in the grasping behavior could be problematic. On the other hand, if the robot is operating on a clutter-free plane with a single isolated object desired by the user, then a wide plate and a long distance of travel could simplify control of the robot. This tradeoff merits further investigation and may justify the use of a variable-width end effector and a variable travel distance. Of course, the size of the end effector also impacts the size of the objects that it can grasp. The current end effector size and payload capacity appear to be well-matched to the top 25 object categories we used in our tests.

Due to consistent complaints about the latency of the system during the pilot study, we subsequently estimated the latency of the system to be around 700 ms, which is very high. Reducing latency will be an important goal for future versions.

Dusty is a low cost solution relative to other assistive robots. The total material costs to construct the current prototype are less than $3,000, and include various low-volume, research-grade components that could be substituted or eliminated through cost-engineering. As such, we believe there is the potential to commercialize this technology in the near term.

While Dusty has been specifically designed to retrieve objects from the floor for motor-impaired users, similar robots may be able to perform a variety of assistive tasks, such as delivering pills, operating household devices, and providing telepresence capabilities. We expect that the future may bring many different forms of assistive robot, both big and small, in a manner not unlike computers today, which can be found in desktops, laptops, mobile phones, and more. We look forward to seeing how future robot designers tradeoff factors such as complexity, size, cost, and capabilities. We are optimistic that small, specialized assistive mobile manipulators can be useful and affordable in the near future.

ACKNOWLEDGMENT

We thank Tiffany L. Chen, Travis Deyle, and Marc Killpack for their help in this project. We gratefully acknowledge support provided for this work by the National Science Foundation (NSF) under grants IIS-0705130 and CBET-0932592.

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