Behaviors for Robust Door Opening and Doorway Traversal with a Force-Sensing Mobile Manipulator

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***Abstract*— Fully autonomous robots will often need to open doors and traverse doorways in order to freely operate within human environments, and assistive robots that open doors on command would potentially benefit the motor impaired. In spite of these opportunities, autonomous manipulation of doors remains a challenging problem after more than a decade of research. Until recently, published research has focused on one or two aspects of door opening, and included results from only a small number of tests on a single door. Within this paper we present a set of behaviors that enable a mobile manipulator to reliably open a variety of doors and traverse doorways using force-sensing fingers and a laser range finder.**

With this system, a user only needs to briefly illuminate a door handle using a green laser pointer, after which the robot autonomously locates the door handle, finds the manipulable end of the door handle, twists the door handle, and pushes the door open while traversing the doorway. The behaviors use sensory feedback to continuously monitor task-relevant aspects of the world and respond to common forms of variation in the task, such as whether the door is locked or unlocked, is blocked or unblocked, opens to the right or left, or has a handle that twists down clockwise or counterclockwise.

We tested the robot in 30 trials with 6 different doors from an initial position over 1.6 meters away from the door handle. For the 24 trials with unlocked doors, the robot succeeded at the entire task in 21 trials (87.5% success rate). In the 6 trials with locked doors, the robot successfully detected that the door was locked in all 6 trials (100.0% success rate). For all 30 trials, the robot stopped in a safe manner without requiring human intervention after detecting failure or success at the task.

We conclude with a discussion of how this work relates to several broader issues for intelligent manipulation within human environments, including the use of 3D locations to select behaviors, the generality of serialized sub-tasks, task-relevant features, active perception, force sensing, and methods for scaling systems to handle more tasks of greater complexity.

I. Introduction

This paper makes two main contributions. First, it addresses the complete door opening task: the human illuminates a door handle using a green laser pointer and the robot moves up to the door handle, aligns itself with the door, haptically localizes the handle, detects the moveable tip, twists the handle, pushes the door, estimates the extent of the doorway and then passes through the doorway while opening the door to provide clearance.

Second, the robot uses sensory feedback to continuously monitor task-relevant aspects of the world and respond to common forms of variation in the task. The robot adjusts its actions in order operate doors and handles with varied dimensions and directions of operation. At the same time, it ignores many irrelevant features about the door, such as its color or the details of the handle's geometry, which enables the robot to open a variety of doors without additional programming or learning, see Figure 1. The robot constantly evaluates its progress towards completion of the task, and gracefully and safely stops if it detects failure due to a locked door, a door that must be pulled, lost contact with the door handle, and other common impediments.

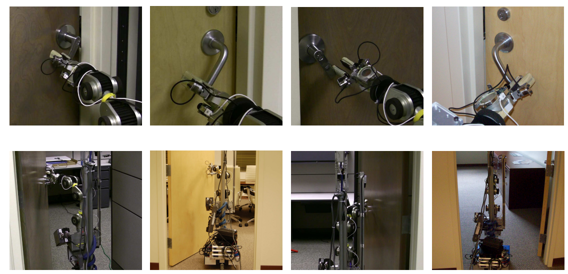

Fig. 1. Four of the six doors that the robot successfully opened and traversed. The first row shows the robot twisting the door handles and the second row shows the robot after it has traversed the doorway.

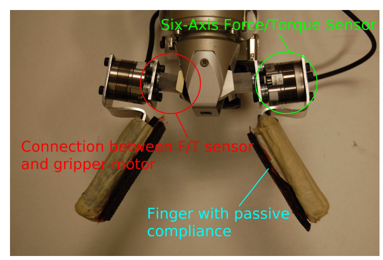

Fig. 2. Force sensing fingers

To accomplish both of these goals we have decomposed the overall task of opening a door and traversing a doorway into several sub-tasks, and developed behaviors that can accomplish each of these sub-tasks in series. These behaviors rely on high-fidelity force sensing at the end-effector, which is performed by two custom fingers we have developed, each of which has a six-axis force/moment sensor at its base, see Figure 2.

Within this paper, we first give a brief overview of related work. We then describe the robotic platform. Next, we describe the component behaviors and how they are combined into a complete control system. Then, we present quantitative, empirical results for the robot's performance in a variety of situations. Finally, we conclude with a discussion of how this work illustrates several broader themes for intelligent manipulation within human environments.

A. Related Work

For well over a decade, the operation of doors has served as a challenge problem for mobile manipulation within human environments [1, 2]. Until recently, published research has typically focused on one or two aspects of door opening in isolation, such as navigating to a door, locating or twisting a door handle, or navigating through an open doorway [3, 4, 5, 6]. Presentations of more integrated systems have often lacked details or included results from only a small number of tests on a single door [7, 8, 9]. Due to a lack of empirical validation and the use of specialized geometric models, maps of the environment, and assumptions specific to particular doors, the generality and robustness of most previous methods is unclear [1, 2, 10, 11, 12, 13].

Rhee *et al* [8] present a robot which grasps a door handle using map matching, vision, and tactile sensing and then pulls open the door. The size of the door, and direction of opening are fixed and results are shown for only a single door. Petersson *et al* [14] present an admittance controller that allows the robot to estimate the radius and axis of rotation of the door. It assumes that the robot starts out with a firm grasp on the door handle and that the door can always be pushed open. Niemeyer *et al* [15], propose estimating the velocity of the end-effector (and also the object) and applying a force in the direction of this estimated velocity, which also requires a firm grasp on the door handle.

Schmid *et al* [11], present a static manipulator for opening cabinet doors and drawers. It assumes that the handle does not need to be twisted. The 3D model of the handle is known and grasp analysis is performed prior to opening doors or drawers. Petrovskaya *et al* [12, 13] describe a method of determining the position and orientation of a door handle by estimating a Bayesian posterior based on force measurements. A 3D model of the door handle is assumed to be known in advance and the robot executes a pre-planned trajectory to twist the handle. Ott *et al* [9] use an impedance controller for flexible joint robots to make a mobile manipulator open a door. The paper presents results on one door only and assumes the direction of twisting of the door handle. Unlike previous approaches, the controller for pushing open the door does not require a firm grasp on the handle and is similar to the door pushing behavior that we present.

Klingbeil *et al* [16] use a vision-based learning algorithm that can detect and locate door handles and elevator buttons and visually decide the direction in which door handles should be turned. Once the vision system has estimated these properties, a pre-planned trajectory is executed for twisting the handle. Due to lack of force feedback, it is unclear whether the robot can respond to mis-classifications (e.g. trying to twist the handle in the wrong direction) and unexpected situations such as locked doors or the door handle slipping out during twisting.

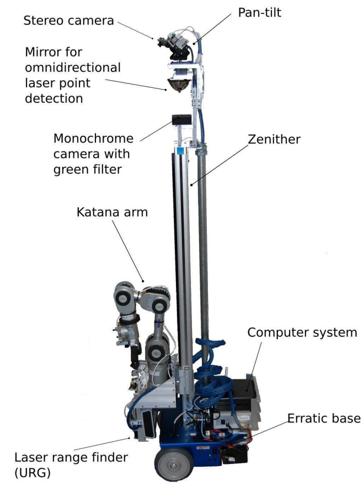

Fig. 3. The mobile manipulator, El-E (pronounced "Ellie"), used in this paper.

Brooks *et al* [17] present Cardea, a mobile manipulator that visually detects doors while navigating through corridors and shoves open slightly ajar doors using impedance control. Like our work, Cardea uses behavior-based control. However, Cardea assumes the direction of opening of the door and does not operate door handles. The article only reports on a single trial with a single door.

II. The Robot

The robot, El-E (pronounced "Ellie"), with which we performed the work in this paper is a statically stable mobile manipulator, shown in Figure 3, that consists of a 5-DoF Neuronics Katana 6M arm, an ERRATIC mobile base by Videre Design, and a 1-DoF linear actuator we call the "Zenither" that can lift the arm and various sensors from ground level to 90cm above the ground [18]. The ERRATIC platform has differential drive steering with two powered wheels and one passive caster at the back. All computation is performed onboard with a Mac Mini running Ubuntu GNU/Linux. We have written most of our software in Python with occasional C++ and make use of a variety of open source packages including SciPy, Player/Stage and OpenCV.

For this work, El-E uses three distinct types of sensors. First, El-E uses a laser pointer interface that consists of an omnidirectional camera with a narrow-band green filter and a pan/tilt stereo camera that is designed to detect a green laser spot and estimate its 3D location [19]. Second, El-E uses a laser range finder attached to the bottom of the aluminum carriage attached to the Zenither. When at its lowest height, the laser range finder scans across the floor. When lifted higher, it can scan across the surfaces of desks, tables and shelves.

Third, El-E uses force sensing fingers that we designed and fabricated for this work.

To enable the manipulator to sense the forces being applied at the end-effector we have replaced the Katana Sensor Fingers that we used in our prior work with our own custom fingers. These are shown in Figure 2. Each finger is a strip of aluminum covered with elastic foam for passive compliance and is connected to the motor via a six-axis force/moment sensor from ATI Industrial Automation. This enables us to measure the resultant forces and moments being applied to each finger independently. The force/moment sensors are ATI Nano25 (with a calibration of SI-125-3).

For any configuration of the manipulator, we transform the forces and moments measured by the fingers into a coordinate frame which is fixed with respect to the mobile base and coincides with the base of the manipulator. Measuring the force vector as opposed to only the magnitude (e.g., by using simple pressure sensors) offers the advantage that we can make estimates about the contact geometry such as the angle of the door handle or the door.

III. The Behaviors

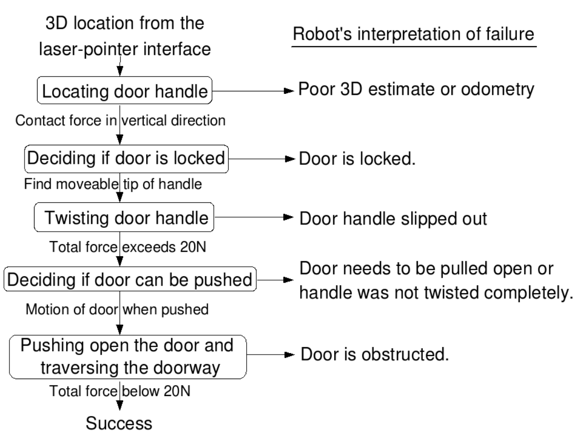

Fig. 4. Block diagram which shows the different behaviors, how the robot transitions between them and the robot's interpretation of failure.

In this section we describe the implementation of the behaviors that form the complete system (Figure 4). It's worth noting that some of these behaviors could be further described in terms of sub-behaviors.

A. Locating the Door Handle

The first step is to orient the mobile base nearly perpendicular to the door and get the manipulator in contact with the door handle. Orienting the mobile base perpendicular to the door is required so that the laser range finder can be used to estimate the extent of the doorway after the robot successfully twists the door handle.

The user shines a laser pointer at the door handle and this gives the robot an estimate of the 3D location. The robot then uses its laser range finder to estimate its orientation relative to the door and moves such that it faces the door handle, is perpendicular to the door and at a distance of 0.7m away. The robot estimates the orientation of the door by splitting the laser scan into two sub-scans (left and right of the robot) from 2° to 20° and -2° to -20°. It then fits a line using least squares to each of these sub-scans and chooses the better fit (line with lower residual error) as the estimate of the orientation of the door.

The Zenither then raises the manipulator to 15cm above the estimated 3D location of the laser point. The mobile base moves forward until the force sensitive end-effector detects contact with the door. To compensate for errors, such as human error, error in the estimation of the 3D location of the laser point, and error in the odometry, the robot haptically searches for the door handle over the surface of the door around the 3D location. It scans the area by moving its end effector horizontally across the door in increments of 5cm. After each horizontal motion, it uses the Zenither to go down by 30cm or until contact is detected. If the fingers detect contact with any part of the door handle (a force in the vertical direction) then the search is terminated. If the door handle is not detected up to 20cm on either side of the initial contact with the door, the robot is unsuccessful in finding the door handle and stops.

B. Deciding if the Door is Locked

Fig. 5. Finding the tip of the door handle that can be moved down or declaring the handle to be locked. Left image: Rigid tip, Right image: moveable tip.

The robot's model of a door handle is based on its relevant features for manipulation which are its two tips, one of which is rigid and the other which can be moved, if the door is unlocked. If the robot twists the door handle at the tip, it maximizes the moment arm and minimizes the force it must apply to twist the handle. Also, by sensing whether the tips can be moved or not, the robot can determine whether the door is locked. To twist the door handle, the manipulator first uses force sensing to estimate the tips of the door handle – It searches in steps of 1cm along the line parallel to the floor and the surface of the door, until it either overshoots the door handle (no force in the vertical direction) or the end-effector comes in contact with the walls on the side of the door (forces in the horizontal plane).

After finding the tips of the door handle, the robot tries to move the tips down and uses a force threshold to determine whether the tip is moveable or not (Figure 5). If both the tips are rigid, the robot declares the door handle to be locked. If both the tips move down, the robot aborts because the dynamics of the object do not match the robot's model of a door handle. If one tip is moveable and the other is rigid, the manipulator moves above the moveable tip and starts twisting the door handle.

C. Twisting the Door Handle

Fig. 6. Twisting the door handle using force-feedback

Figure 6 shows the robot twisting a door handle in the counter-clockwise direction. The robot assumes neither the twisting direction nor the radius of the door handle. It uses the direction of the contact forces between the finger and the door handle as an estimate of the direction perpendicular to the door handle. It then moves the end-effector along this direction through a distance of 2cm before re-estimating the angle of the door handle. The robot declares success if the force applied by the end-effector exceeds 20N. This is close to the maximum force that the Katana can apply. If the magnitude of the measured force goes below 2N, the end effector is assumed to have lost contact with the door handle.

D. Deciding if the Door can be Pushed

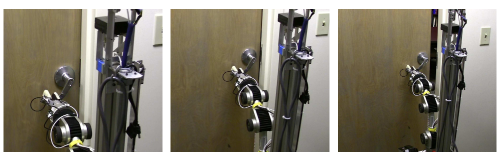

Fig. 7. Left to right: Robot twists the door handle until the end. Robot pushes the door and estimates the doorway. Robot pushes the door so that the handle can be released.

After twisting the door handle, the robot determines whether the door can be pushed open or not and estimates the location of the moveable end of the door (Figure 7). Keeping the door handle twisted, it tries to push the door by 5cm using only its arm. The robot stores a laser scan before and after this push. It takes the difference of these two laser scans to perceive the motion of the door. It performs connected components on the points from the original laser scan that moved more than 3mm. The points within 4cm of each other are considered part of the same component. The robot assumes that the largest connected component is the door. It then estimates the location of the moveable end of the door by looking at which end of this connected component has more motion between the two scans.

If either the number of points in the largest connected component is less than a threshold (i.e. the manipulator did not push open the door) or the manipulator applies a force of greater than 20N in the direction perpendicular to the door (implying that the door is obstructed or must to be pulled open) the robot declares failure in pushing open the door. Otherwise, the robot moves the mobile base to push the door by 15cm so that keeping the door handle twisted is no longer required. The geometry and configuration of the manipulator ensures that 15cm will not result in the base colliding with the wall.

E. Pushing Open the Door and Traversing the Doorway

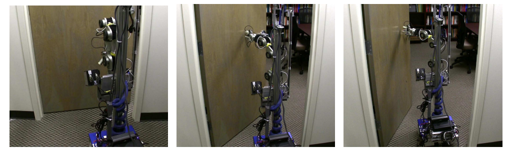

Fig. 8. Left image: Positioning itself to prevent collision with the wall. Right two images: Traversing through the doorway while pushing the door open.

If the door can be pushed open, the robot moves back and positions itself such that it does not collide with the wall close to the moveable end of the door. The assumption here is that the doorway is wide enough for the robot to pass through and thus it is sufficient to estimate only the moveable end of the door. To traverse through the doorway, the robot holds its arm out in front and moves forward until the end-effector detects contact with the door. It estimates the angle of the door using the component of the contact forces in the horizontal plane and uses the manipulator to push open the door to provide clearance (Figure 8). The contact forces are sufficient to decide in which direction the door needs to be pushed and no assumptions are needed about the location of the hinges of the door relative to the robot. If the force required to push the door out of the way is greater than 20N, the robot stops and declares that the door is obstructed or too heavy for it to push further.

IV. Experiments

Fig. 9. The starting position and orientation of the robot for four trials.

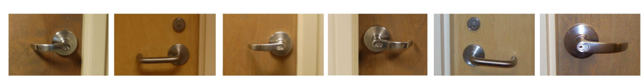

Fig. 10. The door handles from the six doors used in the experiments.

We carried out a total of 30 door opening trials using six different doors, as shown in Figure 9. For each trial, a person illuminated the door handle with a laser pointer and the robot's task was to open the door and pass through the doorway. There were five trials for each door. In one of these five trials the door handle was locked. In the remaining four trials, the door was unlocked and the robot started in two different orientations relative to the door and two different positions with respect to the door handle. The starting position of the robot was approximately 1.5m perpendicular to the door and

TABLE I

RESULTS FROM 30 TOTAL TRIALS WITH 5 TRIALS FOR 6 DIFFERENT DOORS.

Door #	Door state	Locate door handle	Decide if locked	Twist door handle	Decide if door can be pushed	Push and traverse
1	Unlocked Locked	4/4 1/1	4/4 1/1	4/4	4/4	4/4
2	Unlocked Locked	3/4 1/1	3/3 1/1	2/3	3/3	2/2
3	Unlocked Locked	4/4 1/1	4/4 1/1	3/4	4/4	3/3
4	Unlocked Locked	4/4 1/1	4/4 1/1	4/4	4/4	4/4
5	Unlocked Locked	4/4 1/1	4/4 1/1	4/4	4/4	4/4
6	Unlocked Locked	4/4 1/1	4/4 1/1	4/4	4/4	4/4
Overall Success Rate Success Percentage		29/30 96.6%	29/29 100%	21/23 91.3%	23/23 100%	21/21 100%

around 0.75m to the right or left of the door handle in the direction parallel to the door. The angle between the normal to the door and the robot was varied between -60°and 60°, see Figure 9.

Table I shows the performance of the robot for each of the trials. 'Locate door handle' is deemed successful if the robot servos to the door and makes contact with the door handle using its end-effector. 'Decide if locked' requires the robot to correctly report whether the door is locked or not. 'Twist door handle' is successful if the door can be opened once the robot stops twisting the door handle. 'Decide if door can be pushed' reports if the robot correctly determined whether or not the door could be pushed open. Finally, 'Push and traverse' reports whether the robot successfully traversed the doorway while using the manipulator to push the door open.

The only failure with 'Locate door handle' was when the robot made contact with the wall instead of the door and thus could not haptically find the door handle. One of the two failures with 'Twist door handle' occurred because the handle slipped out during twisting. The other failure occurred because the handle required a force greater than 20N to be completely twisted, which resulted in the robot transitioning to door pushing without twisting the handle completely. The current threshold of 20N is governed by the maximum payload of the Katana manipulator. We believe that a manipulator capable of exerting greater forces would be able to overcome this failure, while still being safe for humans and avoiding damage to the environment. In general, we found that some door handles require greater force to twist than others. Likewise, door handles can get partially stuck and require greater force to twist free.

In all three failure cases, the robot detected failure and stopped in a safe manner without requiring human intervention. These three were the only failures in the 30 trials using 6 different doors. In the trials where the door was unlocked, the robot successfully completed all the sub-tasks in 21 out of 24 trials (87.5% success).

V. DISCUSSION

We conclude this paper with a discussion of broader issues related to intelligent manipulation within human environments.

A. A 3D Location to Select and Influence Behavior

We have shown that providing a coarse 3D position near the door handle enables the robot to haptically find the door and then search for the handle with respect to the surface of the door, which becomes a 2D search problem over a small area that can be performed robustly and efficiently. This indicates that fully autonomous behavior might be achieved with a high-level attention system that provides 3D locations to lower-level, task-specific behavior systems. From this perspective, in our work the human user plays the role of a high-level attention system that selects a task-relevant 3D location. We have previously shown the usefulness of this approach to select behaviors for object grasping and delivery.

B. Task-relevant Features

The presented behaviors illustrate the value of task-relevant features in enabling the robot to generalize by ignoring irrelevant features unrelated to the task. In contrast to approaches that use explicit models of environments, doors, door handles, and door kinematics [3, 4, 5, 6, 11, 12, 13], our system focuses on task-relevant features, such as the approximate location of the door handle, the orientation of the door, the ends of the door handle, the manipulable end of the door handle, the magnitude and direction of the force vector, and the boundaries of the moving door.

C. Active Perception and Force Sensing

The robot uses force sensing coupled with behaviors that actively move the end-effector in several distinct ways.

1) Detecting Task-Relevant Locations Through Contact: First, the robot uses force sensing to detect contact and in doing so implicitly estimates the position of the end-effector with respect to task-relevant features in the environment, such as the surface of the door, the surface of the handle, and the end of the handle. As we have previously noted, this implicit estimation is used to find task-relevant features instead of fitting a detailed geometric model.

2) Estimating the contact geometry: Second, the high-fidelity 3 DoF force sensing provided by the fingers enables the robot to estimate key aspects of the contact geometry between the end-effector and the door or door handle. In particular, the resultant force vector gives an estimate of the direction in which the end-effector should move and apply force. If the finger is held in place in the middle of twisting the door handle, the spring-loaded door handle will push into the finger generating a resultant force vector that is parallel to the door handle's direction of motion. While pushing the door, the reaction forces enable the robot to estimate whether the door opens to its left or right. The robot can thus move the manipulator in small steps in the appropriate direction while traversing the doorway.

3) Detecting Manipulability, Success, and Failure: Third, the behaviors use force sensing to detect when task-relevant elements of the environment can be manipulated by assessing whether they can be moved by applying a force with a magnitude below a predefined threshold. This is used to decide which, if either, of the two ends of the door handle can be twisted, when the door handle can no longer be twisted, and whether or not the door can be pushed open. In effect, this decision uses the maximum force that can be safely applied by the mobile manipulator to decide if something can be manipulated by the mobile manipulator. This is reasonable for this robot which has a low maximum force. However, for other robots additional criteria would need to be used including safety to the environment and safety to people in the environment.

In turn, the robot uses the manipulability of task-relevant components of the environment to detect progress, termination conditions, success, and failure. For example, when the handle can no longer be twisted, the robot transitions to door pushing. By pushing on the door and detecting whether it moves or not, the robot determines whether door handle twisting was successful or not. Similarly, if the end-effector slips off of the handle, the magnitude of the force would drop below a threshold, indicating a loss of contact, and failure.

D. Scaling Systems to Handle More Tasks of Greater Complexity (Scaling Systems Through Failure Detection)

By decomposing the overall task into subtasks with associated behaviors that robustly estimate transitions, one can readily add more behaviors in a coherent way. For example, failure conditions could lead to additional behaviors, such as behaviors for pulling open the door if pushing fails, trying to turn the handle again if it slips out, or gracefully disengaging from an unexpected situation. Moreover, we have shown that a substantial part of door opening and doorway traversal naturally decomposes into a serial chain of behaviors with branches for failure. When considered in conjunction with our previous work on object fetching, placement, and delivery [18], this work indicates that many manipulation tasks in human environments may be amenable to serial chains of behaviors, and that the composition of modular behaviors may enable robots to handle a variety of tasks of greater complexity.

VI. Acknowledgment

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