Autonomous Door Opening and Traversal

Benjamin Axelrod
iRobot Corporation
Bedford, Massachusetts, USA
baxelrod@irobot.com

Wesley H. Huang
iRobot Corporation
Bedford, Massachusetts, USA
whuang@irobot.com

***Abstract*—In order to access many spaces in human environments, mobile robots need to be adept at using doors: opening the door, traversing (i.e., passing through) the doorway, and possibly closing the door afterwards. The challenges in these problems vary with the type of door (push-/pull-doors, self-closing mechanisms, etc.) and type of door handle (knob, lever, crashbar, etc.) In addition, the capabilities and limitations of the robot can have a strong effect on the techniques and strategies needed for these tasks. We have developed a system that autonomously opens and traverses push- and pull-doors, with or without self-closing mechanisms, with knobs or levers, using an iRobot 510 PackBot® (a nonholonomic mobile base with a 5 degree-of-freedom arm) and a custom gripper with a passive 2 degree-of-freedom wrist. To the best of our knowledge, our system is the first to demonstrate autonomous door opening and traversal on the most challenging combination of a pull-door with a self-closing mechanism. In this paper, we describe the operation of our system and the results of our experimental testing.**

Keywords— door opening, mobile manipulation, grasping, autonomy.

I. Introduction

Many spaces in human environments are behind closed doors, so for autonomous mobile robots to be useful in these environments, they must be able to operate thes doors. Even teleoperated robots would benefit from autonomous door opening and traversal functions that provide the operator a higher level of control.

There are many subtasks for passing through a doorway, and they vary according to door type. The foremost characteristic of a door is its swing, i.e., whether the door must be pushed or pulled. Another important characteristic is whether or not the door is self-closing. Self-closing doors may have a mechanism that exerts forces to close the door, or they may simply have a tendency to close due to the way they are hung. We will consider non-self-closing doors to be doors that will stay in the same position when not acted upon by the robot or that may even swing open on their own. Lastly, the type of door handle (i.e. knob, lever, crashbar, etc.) can also affect the robot's strategy.

Opening a door requires perceiving the door handle, grasping it, unlatching the door if necessary (e.g., by turning a knob or lever), and applying sufficient force to open the door while moving the arm and/or the mobile base in order to comply with the kinematics of the door as it moves.

Simply opening a door is, at best, half of the problem – the robot must also pass through the doorway. Doorway traversal is relatively easy for push-doors, as a mobile robot can just drive through the doorway, using the chassis to push the door open as it drives through. Pull-doors are significantly more difficult because after grasping the door handle, the robot is usually in the way of the opening door.

The most difficult type of door to open and traverse is a pull-door with a self-closing mechanism. This combination requires the robot to get out of the way of the opening door and actively keep it open while traversing the doorway. When people open this type of door, they typically use a dynamic strategy, e.g., fling the door open and quickly walk through the doorway before it closes. A nondynamic strategy typically involves "regrasping" the door, for example, by holding it open with a hand or foot while letting go of the handle and placing that hand on the inside of the door. Since most mobile robots do not have sufficient speed, perception, or stability to utilize a dynamic strategy, a second appendage (or the robot body) must be used for "regrasping" a self-closing pull-door.

A robot's capabilities and limitations can strongly affect the strategies used for door opening and traversal. A primary consideration is how the motion of the base can be combined with the arm motion so that the robot complies with the kinematics of the door as it is opened. An omnidirectional mobile base with an arm that has 7 or more active degrees-of-freedom (DoF) is the easiest robot to use for door opening and traversal, while a nonholonomic mobile base and an arm with fewer than 6 DoF would impose severe constraints. Other considerations include the type of gripper and the sensing available to the robot.

We have developed a system that autonomously opens push- and pull-doors, with knob or lever handles, and with or without self-closing mechanisms using an iRobot 510 PackBot®. The PackBot (Fig. 1) is a teleoperated military-grade unmanned ground vehicle (UGV) typically used for explosive ordnance disposal (EOD) and reconnaissance. It has a tracked mobile base with a 5 DoF three-link arm. While opening and traversing certain kinds of doors with a standard PackBot via teleoperation is possible, it can be a tedious and time-consuming task. It can take an experienced operator multiple tries lasting several minutes or more. In order to enable autonomous door opening for a variety of door types, we have replaced the standard PackBot gripper with a custom gripper and have added sensing to the robot. This work builds upon our previous work [5] which developed the basic gripper

This work was done in collaboration with Honeybee Robotics and supported by the Tank Automotive Research Development and Engineering Center (TARDEC) through TACOM Contract No.W56HZV-12-C-0384. Approved for public release; distribution is unlimited.

978-1-4799-8757-3/15/$31.00 ©2015 IEEE

Fig. 1. A standard PackBot (left) and our door opening PackBot with custom gripper and laser rangefinder (right).

hardware and semi-autonomous behaviors for door opening on a PackBot.

II. Related Work

Door opening with a mobile robot has been studied for over two decades now; the earliest work [12] used a differential drive wheeled mobile base with a 6 DoF arm and parallel jaw gripper with a force/torque sensor. This system opened a non-self-closing push-door with a knob, traversed the doorway, and closed the door behind it! Since then, many other researchers have further developed robotic door opening in conjunction with other developments in robotics such as learning and vision/perception [8, 9, 10]; motion planning [4]; control methods [7, 15]; and so on.

One of our main contributions is demonstrating autonomous door opening and traversal on the most challenging case of pull-doors with self-closing mechanisms. Most prior work addressed only the easiest case of push-doors, with few exceptions (e.g. [4]) and many prior works make no mention of actually driving through the doorway. We are not aware of any previous research in door opening and traversal for self-closing doors.

Prior work has been performed with robots that have a fully actuated 6 or 7 DoF arm [1, 4, 7, 8, 9, 10, 11, 14] or a holonomic mobile base, [4, 7, 9, 10, 14] (or both, which allows the most versatile combination of arm and base motion). Our system can claim some distinction in having, in contrast, both a nonholonomic base and an arm with 5 actuated DoF.

Our system can open doors with knobs or levers, whereas previous work only addresses one type of handle. Only [11] and [14] open doors with knobs, which are still prevalent in residential environments. Although systems with learned visual detectors such as [8] could be trained on knobs just as easily as levers, most robots do not have an end-effector suitable for operating doorknobs. Another differentiator for our system is that, unlike prior work, our robot does not have a force/torque sensor at the wrist; this is impractical for the PackBot as no current sensors have high sensitivity with the required durability for military and law-enforcement missions.

Unlike other door opening robots, the PackBot is primarily a teleoperated robot – our autonomous behaviors provide a specific capability to augment the human operator who points the robot at a door, initiates the behaviors, and takes control again afterwards.

III. Hardware Considerations

The 510 PackBot is not an ideal robot for opening doors, but it is a rugged robot often used in military or civilian law-enforcement situations where an autonomous door opening capability would be useful. We use a slightly customized PackBot that is better suited for autonomous door opening but have tried to stay close to the standard PackBot configuration for fieldability. Our customizations fall into the three areas as described below.

Fig. 2. Custom gripper finger detail (left), and the gripper installed in the PackBot gripper cartridge (right).

A. Compliant gripper

The 5 DoF arm on the PackBot cannot comply with the kinematics of opening a door. It is essentially a 3 link planar arm (with revolute joints) in the vertical plane with a turret joint to rotate that plane about a vertical axis. The wrist can rotate (i.e., roll), but there is no yaw freedom. This lack of a yaw freedom means the arm cannot maintain a fixed grasp on a doorknob while the door swings open. (While there are other strategies such as caging or nonholonomic grasps that might work for certain types of door handles, we chose to maintain a grasp so that both levers and knobs can be operated.) Mobile manipulators can enhance the capabilities of an arm by utilizing motion of the mobile base. However, the PackBot is a tracked skid-steer platform, so the base cannot instantaneously move sideways. Furthermore, the motion of the base cannot be precisely controlled due to the uncertainty of friction when the tracks slip on the ground.

To enable the robot to comply with the motion of the door as it opens, we use a custom gripper (Fig. 2) built by Honeybee Robotics that features a passive compliant 2 DoF wrist. The wrist is normally held straight by a spring and magnetic clutch but will bend when force is applied. In addition, our gripper has two broad fingers for better grasps of knobs and levers instead of the thin L-shaped fingers on a standard PackBot (Fig. 1).

B. Gripper sensing

In our previous work [5], we learned that achieving a firm grasp on a door handle is important for efficient door opening: a misaligned grasp may slip off a doorknob, requiring the robot to retarget and regrasp. The PackBot was designed to be teleoperated, so while it does have joint encoders on the arm joints (though not on the passive 2 DoF wrist of our custom gripper), it does not have the sort of sensing typically used for autonomous manipulation such as force/torque sensors. We therefore decided to add sensing to help accurately align the gripper with the door handle. After considering several possible sensors, we settled on tactile sensors in the finger pads.

Our gripper has two fingers, each with 5 tactile sensors from Takktile [16]. Each finger pad has 4 square “nubs” and a similar nub on the fingertip (Fig. 2). Each nub contains a tactile sensor: a MEMS pressure sensor embedded in the

978-1-4799-8757-3/15/$31.00 ©2015 IEEE

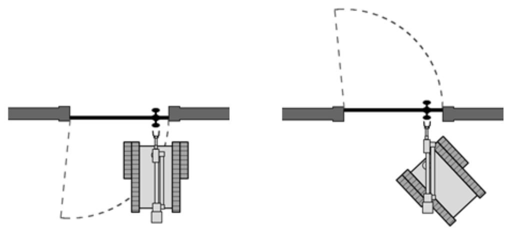

Fig. 3. Initial robot poses for pull-doors (left) and push-doors (right).

rubber below. These tactile sensors are very sensitive to normal forces (1 gram sensitivity), and robust (nearly indestructible), making them ideal for robot end-effectors. Although they do saturate at around 1 kg, this is not an issue because we only use them for light touch maneuvers to center the knob between the fingers.

C. Environment sensing

In order for the robot to traverse a doorway, it must know its pose with respect to the doorway and when the door has been opened enough. Since the PackBot is a tracked skid-steer vehicle, we need an exteroceptive sensor. While visual mapping and localization techniques using the PackBot's monocular cameras may have been possible, we added a 2D laser rangefinder to the base to serve this purpose.

IV. Door Opening and Traversal

We developed a number of behaviors for door opening and traversal. We found that many simple and open loop maneuvers serve perfectly well, so we focused our use of feedback on certain key behaviors. While robustness could be improved by developing more sophisticated behaviors, for example by utilizing motion planners or more complex controllers, our system demonstrates that a collection of simple behaviors can achieve a certain degree of effectiveness for door opening and traversal. We describe the behaviors for each phase of door opening in the following sections.

A. Approach door

The initial pose of the robot with respect to the door and the door handle is important for effective and efficient door opening, particularly for a robot with a nonholonomic base and a nonredundant arm. In the initial pose, the wrist and camera should be perpendicular to the door. Keeping the wrist perpendicular to the door makes it easier to establish a good grasp, and the gripper is much less likely to slip off when turning the handle. Keeping the camera perpendicular to the door provides the best images for targeting the door handle.

The initial robot pose for pull-doors is exactly as one would expect: with the robot right in front of the door handle (Fig. 3). There is no way to keep the PackBot out of the way of the door swing – the robot cannot start to the side and still be able to operate the handle due to the lack of yaw freedom in the wrist, and it cannot start far from the door (despite having a very long arm) because self-closing mechanisms can exert enough torque to tip the robot forwards which causes it to lose traction.

For push-doors, the ideal starting configuration is with the PackBot base angled towards the door center and with the arm perpendicular to the door, directly in front of the handle (Fig. 3). This pose may seem strange, but it keeps the wrist and camera perpendicular to the door while the robot is positioned to start driving through the doorway directly. (If the initial configuration for push-doors was used, the nonholonomic base would need to perform a maneuver to move sideways before traversing the doorway.) The only downside to this angled pose is that it more difficult to put the robot in this starting configuration

We implemented a rudimentary autonomous approach behavior that drives the robot forward, using the laser rangefinder to position the robot at the proper distance from the door. However, this requires an operator (or other autonomy) to position the robot laterally before starting this behavior.

B. Handle targeting

The PackBot has a fixed camera on the gripper cartridge (just above the gripper on link 3) and a pan-tilt camera head at the back end of link 3. Neither of these cameras provide an ideal vantage point for grasping a door handle because part of the door handle and gripper fingers are occluded during grasping. This rules out visual servoing as a viable option.

We use the camera above the gripper for targeting since it is closer to the door and therefore provides a larger image of the door handle. Since most door handles are installed at a consistent height, we put the arm into a targeting pose with link 3 tilted forward so the gripper camera has a full view of the door handle. Fortunately, the area around doorknobs tends to be free of clutter and other visually confusing elements. Therefore we have been able to use relatively simple image processing techniques for detecting knobs and levers in images.

Our doorknob detector is based on the OpenCV [2] Hough circle detector. The image is first grey-scaled and blurred, then run through a Canny edge detector. Then we look for circles (and arcs) within an appropriate size range. The minimum and maximum circle radii for the detector are calculated after determining the distance to the door with the rangefinder. Then we select the most complete circle/arc found that has pixels on at least one third of its perimeter. We adaptively adjust the Canny edge detector parameters until a suitable circle is found or declare that there is no doorknob detected in the image.

Door levers have a very different shape than round knobs, but we found that our Hough circle-detector approach worked surprisingly well with levers because most levers have a round flange around the stem. However, in order to apply the Hough circle detector to lever handles, we found that we needed looser bounds on the percentage of pixels on the perimeter of the circle which increased the false positive rate. To compensate for this, we added some additional image processing steps to filter out false positives as well as determine which side of the stem the lever is located.

After candidate circles are found and ranked with the above technique, they are filtered by performing an edge detection test. For each candidate, two rectangular regions of interest (ROIs) are constructed on either side of the circle (Fig. 4). We compute horizontal and vertical derivatives with Sobel filters in these ROIs and run a Hough line detector. A strong candidate for a door lever will have significant horizontal lines

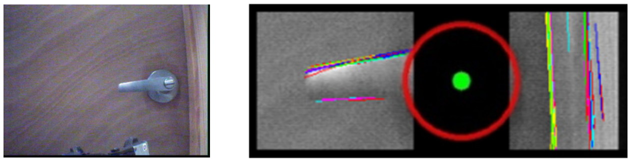

Fig. 4. Handle targeting – initial image (left), masked candidate with horizontal and vertical lines identified (right).

on one side (due to the lever) and vertical lines on the other (due to the door frame), so we calculate the following two quantities:

HV = sum of the lengths of horizontal lines in the left mask and vertical lines in the right mask

VH = sum of the lengths of vertical lines in the left mask and horizontal lines in the right mask

If the larger of *HV* and *VH* is below a threshold, the candidate is discarded. The highest ranked candidate remaining is returned as the detected lever. The larger of *HV* and *VH* determines which side the lever is on, and the centroid of the horizontal lines is used as the grasp location on the lever.

We have also found that this approach improves the robustness of our doorknob detector – a strong doorknob candidate should have vertical lines on one side due to the door frame.

C. Reach to handle

With the pixel coordinates identified for the grasp point on the handle, we compute the ray from the camera origin through this pixel out into the world. We move the gripper onto this ray and then move forward along the ray until the gripper touches the door using the fingertip tactile sensors. This method is robust to depth measurement errors and ensures that the end-effector will travel on a collision-free path to the handle. We put the gripper fingers in a vertical orientation regardless of the handle type in order to keep the fingers safely away from the door frame.

D. Grasp handle

A firm grasp on the door handle is required for the robot to maintain control of the door as the compliant wrist bends and as the robot exerts force to overcome self-closing forces. With doorknobs, in particular, centering the grasp in the fingers is the key to successful door opening. Since there can be errors due to inaccuracies in visual detection, kinematic parameters, actuation, etc., we employ tactile search to achieve an accurate grasp.

Our tactile search operates in two phases. If the reaching motion terminated with one fingertip touching the door handle, we perform a vertical tactile search. The arm kinematics and laser rangefinder readings are used to determine if the gripper has touched the door or the handle. The height of the gripper is adjusted in response to the tactile sensor readings, and the robot repeats the reach for the handle until it touches the door (with the knob or lever between the fingers).

Since levers are not sensitive to horizontal alignment, the robot simply backs the gripper away from the door slightly (to prevent the fingertips from rubbing) and grasps the lever.

For knobs, the robot performs a horizontal tactile search. The robot repeatedly closes the gripper until a tactile sensor exceeds a threshold. The tactile sensors are grouped into six sets of four sensors each: front, back, left, right, top, and bottom. Any group with a tactile sensor reading above a lower threshold is "activated"; the gripper is moved a small distance in the net corrective direction of activated groups. These trial grasps are repeated until there is no corrective action (implying that at least one sensor in each group is above the low threshold.) Note that the vertical position of the gripper may be adjusted during this process, though less than during the vertical tactile search.

E. Unlatch door

For knobs, unlatching the door is as simple as rotating the gripper. For levers, the arm and gripper follow a circular path centered at the lever stem. The robot simply attempts to turn the handle through a fixed angle, but this step is closely monitored to determine if the unlatching procedure succeeded.

First, the amount of rotation of the wrist is measured; if it is below a threshold, the door is deemed locked. This works well for levers that don't move when the door is locked. It does not work as well for knobs because the wrist motor usually overpowers the friction of the gripper, and the tactile sensors cannot detect slip or shear forces.

For knobs, if the gripper closes further during rotation, we assume the knob has slipped out of the gripper. This may indicate a locked door or that the initial grasp was poor.

Lastly, the door is pushed or pulled open a small amount to determine if it is truly unlatched. While it is possible to use the arm kinematics to determine the amount of travel, this method is error prone because the robot base can slide when the arm exerts large forces on the environment. Therefore, we rely on the 2D laser rangefinder to verify the angle of the door opening.

F. Traverse doorway

Our doorway traversal behaviors are designed to work regardless of whether the door is self-closing or not, making them more robust for doors without self-closing mechanisms.

Push-doors are the easiest type of door to traverse because after the door is unlatched the robot can basically drive directly through the doorway. First, the gripper releases the door handle, and the arm is kept extended to ensure the door remains open. (It is moved below the level of the handle so it doesn't catch on the handle.) The robot then drives through the doorway on a planned quadratic Bézier curve path. For PackBot applications, it is generally acceptable for the robot to drive against the door or push against the door with the gripper. For other applications, more care (different hardware, coordinated base and arm motion, etc.) may be needed to avoid scratching the door.

For pull-doors, the PackBot uses a flipper to hold the door open against possible self-closing forces while the robot releases the door handle and "regrasps" the door by moving the gripper to the inside of the door to hold it open. Images (a)-(h) in Fig. 5 illustrate the sequence of motions. After the door is unlatched (a), an open-loop behavior is executed that pulls the

978-1-4799-8757-3/15/$31.00 ©2015 IEEE

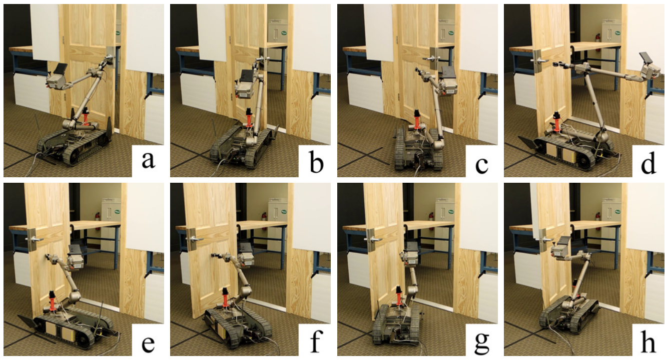

Fig. 5. Pull-door traversal sequence.

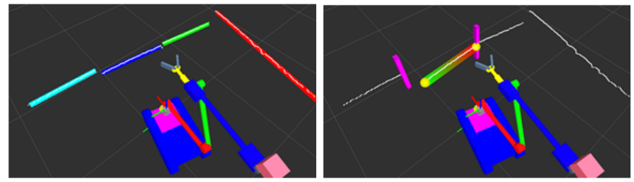

Fig. 6. Laser scan segmentation (left), and tracked door, door edges, and door frame (right).

door open, rotates the base, and extends the flippers (b). Even though this behavior is open loop, it is surprisingly robust.

Next, the gripper releases the handle and is pulled back behind the front of the robot so it will not accidentally catch on the door during subsequent motions. The flippers now essentially cage the door, preventing it from closing (c). The robot then rotates until parallel to the doorway and drives forward slightly, causing the flipper to push the door open further (d).

Finally, the gripper is moved to push against the inside of the door (e). Using coordinated motion, the end-effector holds the door open (and tries to push it slightly more open) while the robot retracts the flippers and rotates the base towards the door (f). When the base has turned enough towards the doorway, the arm moves to a nominal driving position – the robot chassis now prevents the door from closing – and drives a straight-line path through the center of the doorway (g)-(h).

V. Implementation and Results

A. *Door state estimation and tracking*

Our door opening and traversal behaviors depend upon knowledge of the door configuration (angle) and the robot's pose with respect to the doorway. We developed a module that passively observes the environment using the laser rangefinder and maintains estimates of these quantities regardless of the robot's motion or occlusions in the laser rangefinder data (Fig. 6). The problem of estimating the door state is not trivial because both the door and robot move in the world and can create significant occlusions of important features.

Our door state estimator makes some minimal assumptions:

- The bearing to a point on the door is provided for initialization since the door is typically closed when it is first observed.
- The door width is within a standard range.
- There is some amount of wall on both sides of the door.

Although ideally the laser rangefinder would be mounted on the robot chassis, we have mounted the laser rangefinder on the base of the arm. This location is convenient because it does not interfere with arm motion, but since it rotates with the arm turret joint, the range scan must be transformed into the robot frame. The sensor is raised enough so that the robot's flippers cannot intersect the sensing plane.

The tracker first partitions each range scan into connected components by identifying large discontinuities in the Cartesian position of successive points. Then, line segments are fit to each component and further subdivided based on angular discontinuities.

If a line segment at the initial bearing to the door has an acceptable length, the tracker is initialized. Push-doors are typically recessed, so initialization happens immediately, but pull-doors can be flush with the surrounding walls, so initialization may be delayed until the door is opened enough to detect a distinct door line segment. The door frame endpoints are initialized to the first point on either side of the door line. As the robot moves, the door frame endpoints and door line segment are tracked, even if some parts of the environment are occluded. From this state, the angle of the door and the pose of the robot with respect to the doorway are computed.

B. *Computing and operator interface*

For ease of development, our autonomous door opening and traversal behaviors were implemented on a laptop tethered to the PackBot. This laptop was connected to the tactile sensor microcontroller and the laser rangefinder via USB and to the PackBot via Ethernet. This laptop also served as the operator interface to the door opening and traversal behaviors. There is no reason in principle that our system could not be implemented on the PackBot's computer and the operator interface integrated into the standard PackBot OCU (operator control unit).

To utilize the autonomous door opening and traversal behavior, the operator drives to an initial position and indicates the type of door (push or pull) and handle (knob or lever). The handedness of the door is detected automatically, and our behaviors work with or without self-closing mechanisms. The operator then presses the "go" button, and the PackBot approaches the door and targets the handle. The operator confirms the target, and the PackBot continues the door opening and traversal sequence autonomously.

C. *Results*

Our system successfully demonstrated autonomous door opening and traversal on a variety of door and handle types. Under our limited funding for this work, we were not able to conduct statistically significant testing; our focus was on achieving threshold task completion times for the four cases listed in Table 1. These times are our best completion times, but the typical time does not vary much for successful runs. For all our tests, the robot starts 1m away from the door. Time starts at the first movement of the robot and stops when the back of the robot has passed through the doorway.

TABLE I. TASK COMPLETION TIMES

Door and handle type	***Time***
Push-door, round knob	63 seconds
Pull-door, round knob	128 seconds
Push-door, lever, with self-closing mechanism	83 seconds
Pull-door, lever, with self-closing mechanism	118 seconds

These times could be easily improved by increasing the speed of the PackBot movements and tighter integration with the PackBot software. We limited the PackBot speed in order to obtain cleaner tactile sensor readings and due to the control latency of our off-board PackBot interface. Our success rate is approximately 60%, though this could also be easily improved by better error handling mechanisms. Currently, if any of the phases in our door opening and traversal behaviors fail, the run fails.

VI. CONCLUSIONS

We have developed and demonstrated autonomous door opening and traversal behaviors on an iRobot 510 PackBot, a nonholonomic base with a 5 DoF arm. Our system handles push- and pull-doors, with knob and lever handles, and with and without self-closing mechanisms. In particular, we believe our system to be the first to demonstrate door opening and traversal for the most challenging combination of a pull-door with self-closing mechanism – for this case, the PackBot uses a flipper to hold the door open while "regrasping" it with the arm before traversing the doorway.

Our system uses a custom gripper jointly developed with Honeybee Robotics that provides a passive compliant wrist. Tactile sensing in the two fingers enables the robot to adjust its grip so that a reliable grasp is established on the door handle. A 2D laser rangefinder was added to the skid-steered PackBot to track the pose of the door and the robot with respect to the door frame.

Our system autonomously detects a doorknob or lever in a PackBot camera image, reaches out to the doorknob, grasps and turns the doorknob, pulls or pushes the door open, and drives the robot through the doorway. The operator only needs to specify the type of door and handle and to confirm the detection.

While we have made advances in door opening and traversal, there are many aspects of the general door opening problem that our system does not handle such as sliding doors, locks, crashbars, door pulls, double doors, and so on. For robots to be able to autonomously access space in human environments, they will need to become more adept at operating the great variety of doors that exist.

ACKNOWLEDGEMENTS

We would like to thank Rob Karlsen for his support of this project.

REFERENCES

[1] A.H. Adiwahono, C. Yuanwei, k.P. Tee, L. Bingbing, "Automated door opening scheme for non-holonomic mobile manipulator," Control, Automation and Systems (ICCAS), 2013 13th International Conference on , vol., no., pp.839,844, 20-23 Oct. 2013

[2] G. Bradski, "OpenCV library", Dr. Dobb's Journal of Software Tools, 2000. http://opencv.org/

[3] A. Censi, "An ICP variant using a point-to-line metric," Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on , vol., no., pp.19,25, 19-23 May 2008

[4] S. Chitta, B. Cohen, M. Likhachev, "Planning for autonomous door opening with a mobile manipulator," Robotics and Automation (ICRA), 2010 IEEE International Conference on , vol., no., pp.1799,1806, 3-7 May 2010

[5] J. Craft, J. Wilson, W. H. Huang, M. R. Claffee, E. A. Phillips, "Aladdin: a semi-autonomous door opening system for EOD-class robots", Proc. SPIE 8045, Unmanned Systems Technology XIII, 804509 (May 23, 2011)

[6] R. Diankov, "Automated Construction of Robotic Manipulation Programs", Carnegie Mellon University, Robotics Institute, 2010.

[7] A. Jain, C.C. Kemp, "Pulling open doors and drawers: Coordinating an omni-directional base and a compliant arm with Equilibrium Point control," Robotics and Automation (ICRA), 2010 IEEE International Conference on , vol., no., pp.1807,1814, 3-7 May 2010

[8] E. Klingbeil, A. Saxena, A.Y. Ng, "Learning to open new doors," Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on , vol., no., pp.2751,2757, 18-22 Oct. 2010

[9] D. Kragic, L. Petersson, H.I. Christensen, "Visually guided manipulation tasks", Robotics and Autonomous Systems 40 (2002) 193–203

[10] W. Meeussen, et al, "Autonomous door opening and plugging in with a personal robot," Robotics and Automation (ICRA), 2010 IEEE International Conference on , vol., no., pp.729,736, 3-7 May 2010

[11] K. Nagatani, S. Yuta, "An experiment on opening-door-behavior by an autonomous mobile robot with a manipulator," Intelligent Robots and Systems 95. 'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on , vol.2, no., pp.45,50 vol.2, 5-9 Aug 1995

[12] K. Nagatani, S. Yuta, "Designing a behavior to open a door and to pass through a door-way using a mobile robot equipped with a manipulator," Intelligent Robots and Systems '94. 'Advanced Robotic Systems and the Real World', IROS '94. Proceedings of the IEEE/RSJ/GI International Conference on , vol.2, no., pp.847,853 vol.2, 12-16 Sep 1994

[13] M. Quigley, et al, "ROS: an open-source Robot Operating System", ICRA Workshop on Open Source Software, 2009

[14] C. Rhee, W. Chung, M. Kim, Y. Shim, H. Lee, "Door opening control using the multi-fingered robotic hand for the indoor service robot," Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on , vol.4, no., pp.4011,4016 Vol.4, April 26-May 1, 2004

[15] A.J. Schmid, N. Gorges, D. Göger, H. Wörn, "Opening a door with a humanoid robot using multi-sensory tactile feedback," Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on , vol., no., pp.285,291, 19-23 May 2008

[16] Y. Tenzer, L. P. Jentoft, R. D. Howe, "Inexpensive and Easily Customized Tactile Array Sensors using MEMS Barometers Chips", IEEE Robotics and Automation Magazine, 2014.