Door Manipulation as a Fundamental Skill Realized on Robots With Differential Drive

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***Abstract*—In the context of assistive mobile service robotics for elderly living in nursing homes, but also for robots realizing autonomous transport in large public buildings in general, a fundamental challenge is to overcome closed doors on their way. We review the state of the art for autonomous door opening by mobile robots and present a modular framework for enabling various robots in this task. The necessary building blocks are introduced, and evaluation results for their application on two different robot platforms are presented. A common property of our platforms, which can be found on many commercial low-cost robots is the use of differential drives. This is limiting the maneuverability and is, therefore, an important constraint for the realization of door manipulation strategies. Furthermore, our method is not dependent on computationally expensive computer vision methods but utilizes the usually available laser-range scanner for localizing and analyzing the door to be manipulated.**

***Index Terms*—door manipulation, handle grasping, laser detection**

I. Introduction

Autonomous mobile service robots nowadays are a good solution in order to take workload from human employees by taking over simple transport tasks. While in industry and hospitals autonomous transport systems are integrated in the infrastructure of the building for many years, in many potential fields of application a non invasive introduction of mobile robot systems is hindered by the fact that there are doors on the way, which can not be automated. If service robots can be enabled to open doors autonomously with their on-board manipulation skills, many new fields of application would open up.

The work presented here is part of our research project RobInCare[1], which aims for developing fundamental skills for mobile service robots enabling them to be used in nursing homes. There are many tasks current mobile robots could be able to accomplish if obstacles like doors could be managed. Such tasks are: transporting objects, access control with accompanying visitors and residents, whether going for a walk or guiding them to a room, even assistance for cognitively impaired persons is considered to be helpful.

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[1]https://www.robincare.de/

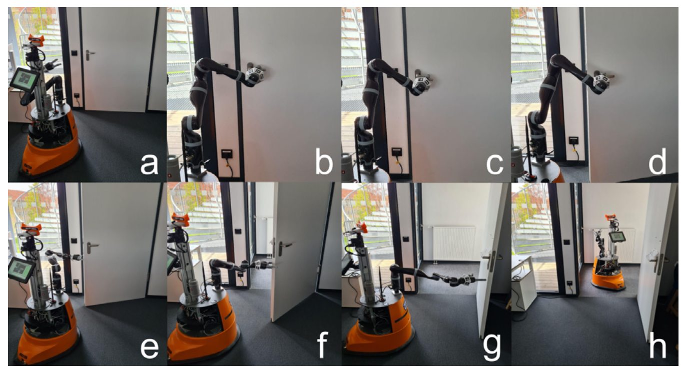

Fig. 1. Zeus robot opening a door from inside.

In order to give the necessary autonomy to a robot, it should be able to open and close doors man-like using only a mobile platform and a suitable manipulator. There are only very few studies on solving the smooth, robust and modular opening of a door leading to another room and thus increasing the robot's range. For accomplishing a door opening motion, the current state of the door must first be determined. While many publications aim for detecting unknown doors and door handles in images, for a practical application it can be assumed that the robot operates in a known environment. Therefore, pure detection of doors is of less importance, while the exact localization of essential parts like handle and hinge with respect to the robot's manipulator can rely on prior information on mapped doors and their properties. We achieve this recognition skills using laser range scan data only, which on today's mobile robot platforms is kind of a standard sensor, since it is essential for localization, navigation and safety.

For real world application the analysis of a doors state in before and during the manipulation is important, since doors are not necessarily completely closed or fully open. There are intermediate opening angles that have to be considered as well. The state may change also by external factors, like people or air draft acting on the door.

In this paper, we propose a modular architecture of the system consisting of independent modules for door analysis and individual manipulation strategies for the various states of the door. Since the manipulation strategies only rely on a standard motion planner for the arm and the 2D navigation of the mobile robot base, our system is easily portable to different robots, which could be shown in our experiments with two completely different differential drive robots. Adaptation to the actual hardware only concerns parameters for the executed movements, while the overall control software stays unchanged.

This paper is organized as followed: In Sec. II a brief review on the current work in the field of door manipulation is given. Then we describe our used robotic platforms and the corresponding manipulators (Sec. III), whereas in Sec. IV the manipulation theory of the proposed algorithm will be explained in its individual steps. The real world scenario with experiments is presented in Sec. V. In Sec. VI a short discussion of the results and problems concludes the paper.

II. Related Work

An intensive research in the field of mobile robots opening closed doors clarified that there is a wide variety of strategies to manipulate doors. Many strategies try to solve just a smaller part of the opening process [1]–[3] whereas others, in addition to the complete manipulation process, developed a specialized door-detection algorithm [1], [4]–[6]. Only very few approaches state the ability to entirely open doors from both directions often neglecting the two main difficulties in the manipulation: unlatching the door handle and pulling a door from the inside [6]–[8]. Furthermore, low cost robots most often have the disadvantage of having a non-holonomic drive leading to limitations in the motion space of the robot's base. Therefore, it is of high importance to have an in depth look at approaches with different limitations. The following state of the art is organized according to the two main aspects of base motion limitations. The first part lists approaches relying on non-holonomic drives, whereas in the second part holonomic robot platforms are used.

First, we take a look at the non-holonomic approaches starting with [3]. Their robot has two arms enabling it to have a large area of work while being cost intensive. Since the method is not using the second arm or any parallel base movement during manipulation, we count it to one arm, non-holonomic approaches. The approach tries solving an initially inaccurate opening motion by adapting the arm trajectory to the measured force compensating for a linear or circular arm trajectory. In their experiments, only two of the possible six joints were actuated when opening the door. Additionally, the manipulator has been manually positioned at the handle in the beginning due to the lack of respective sensors.

Another approach utilizing a differential drive, one arm, and a laser range scanner detecting the current opening angle of the door is [1]. The robot is positioned in front of the door, which is considered to be already unlatched. Then the paper focuses on dynamically swinging the door to a desired target angle by one initial push, while they are relying on external methods for measuring force and opening angle. According to their experiments, it is possible to learn the necessary force from three trials and demonstrations. However, it is neglecting that the robot can be confronted with a closed door from either of the two sides (only unlatched doors using the push direction are handled).

Another implementation tries to open a door by pushing / pulling the door by turning the robot's base using a force coupled extension rod [2]. It is one of the most cost efficient approaches since it involves no sophisticated robot base nor any form of manipulator. Downside of that solution is that it is starting from an unlatched door. Similar to the methods above, they are using differential drive without the ability to unlatch a door. Additionally, it was never tested in a real-world scenario.

One of the approaches performing a complete door manipulation uses a self-developed detection method to calculate the position and state of the door [6]. They took part in the *Defense Advanced Research Projects Agency (DARPA) - Robotics Challenge* validating their strategy in a real-world scenario. The algorithm moves one of the two manipulators of the two-legged, humanoid robot onto the handle and starts the typical unlatch motion by turning the end-effector around the pivot point of the handle. Afterwards, the door is opened around the door's hinge to an opening angle wide enough to fit in the robot's second arm. Therefore, the door can be fully opened by pushing it with the second arm while turning the robot's torso. Since the robot is walking, the authors were confronted with many new problems, like balancing and compensating noisy force measurements, other than those appearing on wheeled robots with a rigid base. The humanoid robot uses multiple sensors for getting color and depth information. With it's two manipulators it is one of the most cost-intensive approaches for the specific door opening task while being built to accomplish multi-purpose tasks. Some other approaches from the Robotics Challenge were using harsh techniques to forcefully unlatch the handle by simply pushing down and simultaneously pulling/pushing without knowing the exact handle position only utilizing force feedback.

Arduengo et al. [4] detect the door handle with a specialized YOLO-detector (You Only Look Once), drive to the door, move the manipulator onto the calculated handle position, and then start the motion to unlatch the handle. This unlatch motion is a separate strategy determining the correct direction by measuring the appearing force & torque while trying to turn the handle left or right until either is working or both failed. The latter case indicates that the handle does not need to be unlatched (e.g. drawer handles). In the next step, the door opening motion is predicted based on recorded previous openings of this door type. These could either be demonstrated by human, while the handle position is tracked, or tried by the robot itself using the force feedback with compensating motions. With no prior information, the motion initially is assumed to be linear. Then the door type is continuously recalculated based on the real opening motion of the door. This approach uses a holonomic drive able to move in any direction.

Therefore, any arm limitations could be compensated, and the opening motion is done in one smooth sweep, which is impossible for non-holonomic platforms.

Just to complete the overview on approaches using holonomic robots, there are two further methods [9], [10] utilizing learning from human demonstrations or from simulated door openings. Data has been collected by tracking markers on door, handle, human hand and body or by manually simulating the motions during training. Afterwards, the data has been used for training of a machine learning algorithm [9] or by interpolating the trajectories [10]. Both involve robots with no directional restrictions and two arms equipped with manipulators resulting in a minimum of limitations.

In contrast to deterministic approaches with hand-coded manipulation strategies, there are machine learning methods [2], [9], [10] aiming to learn a robust strategy for manipulation based on trial and error. We see that this offers the opportunity to optimize the strategy during operation but at the cost of expensive initial training sessions requiring additional effort for e.g. simulation. Nevertheless, we count on hand-crafted manipulation strategies, where only a few parameters like positions for the robot's base and the arm's end effector are to be defined.

The differentiation of approaches according to the motion capabilities of the used hardware clearly shows the advantage of holonomic drives. Nevertheless, insignificantly few low-cost solutions have such. Additionally, the current approaches show, that there are only very few strategies [11], [12] completely opening doors, being able to start in a closed state and having a non-holonomic base.

Our approach tries to overcome the difficulties coming along with a differential drive to accomplish a full opening process beginning with unlatching the handle and driving through the door after the process. In addition to the robot's specific limitations (Sec. III), we take the door's two opening directions into account. Therefore, we developed corresponding pulling and pushing strategies. Further, we enable our robots to open the door from within any sub-state of the door reaching from completely closed to fully opened.

III. Hardware Design

Before our methodology will be explained in the next section, we first want to present the robotic platforms and manipulators used in our evaluation. Both robots are shown in Figure 2 in their current configuration.

TIAGo is build by spanish company Pal Robotics S.L. moving with a differential drive base, having an extensible torso, a pan-tilt-unit (PTU), and a seven degrees of freedom (DOF) arm supporting the five finger hand with three motors opening and closing the fingers. Beneath the hand, a force-torque sensor is mounted allowing for safe manipulation and force feedback during the manipulation steps. The arm by design has strict motion limitations since the joint's rotation ranges beginning from torso to hand are: $\pm 77.5°$ (joint 1), $-91.7°$ and $+63°$ (joint 2), $-200.5°$ and $+91.7°$ (joint 3),

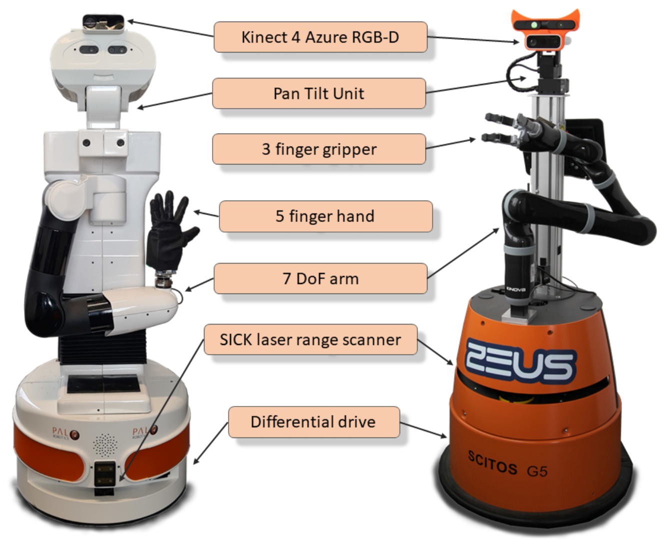

Fig. 2. Robotic platforms TIAGo from Pal Robotics S.L. and *Zeus* as a combination of a SCITOS G5 base by MetraLabs GmbH with an arm by Kinova

$-22.3°$ and $+137.5°$ (joint 4), $\pm 120.3°$ (joint 5), $\pm 80.2°$ (joint 6) and $\pm 120.3°$ (joint 7). This robot is not symmetrical, which makes it necessary to handle left and right opening doors slightly different.

Zeus – our second robot – is a SCITOS G5 robot by the german company MetraLabs GmbH, which also is using differential drive. It has a PTU and a seven DOF arm by Kinova (KINOVA Gen2 7 DOF Spherical) with three finger gripper. The forces at the end effector of the arm are measured by the calibrated current actuating the internal joint motors. This robot has the disadvantage of having a larger drop-like footprint with a diameter of around 65 cm at the front in comparison to the circular shape of TIAGo with a diameter of 54 cm. The main advantage of Zeus is the use of continuous joints of Kinova's arm. Even that every second joint has angular limitations in a range of $\pm 120°$, most motions can be achieved easily.

Both robots are equipped with a SICK laser-range scanner and a RGB-Depth camera on top of their PTU used for 3D modelling the robot's environment and for collision calculation for the arm motion planner [13]. Even if our door manipulation approach does not rely on visual perception, these devices offer the possibility to use alternative door-detection algorithms (see Sec. IV-A) in the future.

IV. Methodology

For a human, the opening process of a door is a continuous motion starting with the hand at the handle, unlatching the lock and pulling or pushing open the door depending on the side of the door. Also dynamic aspects of the door's swing motion are utilized by humans, who can easily predict the necessary power. A robot, which compared to a human is very limited in its maneuverability, in contrast has to rely on statically controlled motions. Due to the restrictions of the operational range of a robotic arm, the robot from pull direction is not able to fully open a door with only one grasp to the handle. Even if the robot base can move, caused by the restrictions of the differential drive, which can not move sideways, for pulling a door to a completely open state, the robot needs to let go the handle at half way and regrasp the other side of the door in order to push it open completely. This two step approach makes it impossible to handle automatically closing doors with only one arm on the robot.

The described strategy has been implemented following our layered application architecture [14]. To that end, we decomposed the process into four stages, which mainly are responsible to bring the door from one state to the next. For that, the door has been defined to be in one of four states: *CLOSED*, *UNLATCHED*, *PARTLY_OPENED* and *FULLY_OPENED*.

Furthermore, the side of the door (inside or outside) together with the state is used by the supervising *Pass door* behavior (see Fig. 3) in order to select the suitable strategy in the sequence. The side and also the opening direction are supposed to be known from a data base given the robot's localization in the map. By means of observing the state of the door also failed attempts of manipulation can be recognized, and the system is able to retry.

The described components directly correspond to modules in our layered application architecture as shown in Figure 3. Here, on top we have the application layer, where the central application logic is implemented responsible for user interaction and task planning. In the next layer, there are so called behaviors, which are small stand alone control loops that are exclusively activated by the application. For example the *pass-door* behavior becomes active, if the robot needs to pass a door, and the way is blocked. The *pass-door* behavior can delegate the control to subordinate behaviors responsible for certain states, which by their own make use of basic functionality of the skills in the next layer. These skills are running in parallel and allow real-time processing. For example, the motion planner for the robotic arm and the mobile base are independent skills, which control the respective hardware components. Also real-time sensor data processing is done in the skill layer comprising the robot localization and the door analysis as well as 3D obstacle mapping.

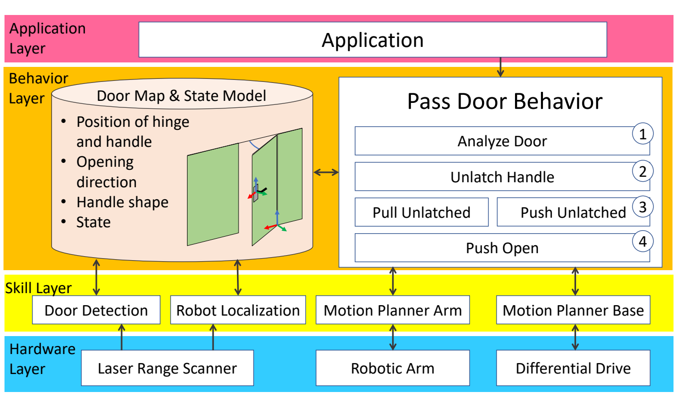

Fig. 3. Overview of the robots software components with corresponding data flow and the decomposition of the door opening process into separate state-dependent stages, which are specialized for the door opening from either inside or outside.

A. Door Analysis and Localization

Since our approach is designed to support various detection algorithms, there are a couple of requirements for such methods.

First, the door needs to be correctly classified within the four valid states (*CLOSED*, *UNLATCHED*, *PARTLY_OPENED* and *FULLY_OPENED*). It is not necessary to detect the precise opening angle of the door as long as it is consistent with the discrete state. The important factors to be considered are:

- Closed doors should be robustly classified as *CLOSED* to trigger the unlatch movements first.
- The transition from *CLOSED* to *UNLATCHED* has to be detected as soon as possible to prevent unnecessary unlatching movements.
- After the door has been pulled open for about 20 cm, it has to be robustly detected to be *PARTLY_OPENED*, which can be realized by means of some hysteresis.
- A door can only be classified as *FULLY_OPENED*, if the robot is able to drive through without touching any part of the door.

Besides the classification of the doors opening state, the exact position of the door's handle and hinge have to be determined with respect to the robot's manipulator.

There are various detection approaches able to identify and localize doors either utilizing a laser scanner [1], relying on RGB data [15], [16], or using additional depth information [4], [11], [17]. Since every detection approach has advantages as well as disadvantages regarding robustness and reliability of the result, every step in our manipulation sequence has its unique fallback mechanism compensating for occasional problems.

The assumption for any retry strategy is the fact that problems should be temporary and can be compensated from a new perspective, and by integrating measurements over an enlarged time span.

Since the focus of this paper lies on the manipulation, our door detection strategy will only be briefly explained. In our detection module, a laser range scanner that can also be found on low cost mobile robots is used to detect the door relying on a RANSAC line fitting algorithm that is further validated by a set of heuristic rules resulting in the four valid states. In order to distinguish doors from walls and other line segments, we use prior information about each door within the robot's working scope. Those information are:

- Base positions: lock and hinge position of the closed door in map coordinates projected onto the ground plane (defining the width of the door panel)
- Door's opening direction stated by the German standard DIN107
- Handle parameter: height above the ground and distance to the edge of the door panel

These parameters are measured once and saved in a local onboard data base of doors. Using these data, the detection module has the coarse position of the door and crops the relevant range-scan points in a rectangle in the target region of the door of interest. This crop is only exact to about 15 cm caused by the robot's localization error in the world. Nevertheless, the longest line segment in this cropped region belongs to the door panel and can be used for further calculations. In all cases except fully closed doors seen from the opening side, the end point of the detected line segment can be used to find the exact position of the handle. By using the fixed handle parameters, this yields the 3D coordinates for the manipulation positions at the handle. These are now in coordinates of the range scan sensor and can, therefore, be converted into the robot's arm coordinates yielding valid poses for manipulation. In case of a closed door, the transition of the door panel to the parallel wall only can be detected by a little gap, which is only visible from within 1.5 m distance depending on the laser scanner's resolution.

The *UNLATCHED* state can be separated from *CLOSED* by calculating the angular difference between the line segment of the door panel and the connection line of reference points taken from the wall segments on both sides of the closed door. If the difference is larger than a threshold of 1.5°, the door is detected as *UNLATCHED*. The states further opened are defined through the door's opening angle calculated between the line going through the reference points in the data base (map coordinates) and the actual line segment of the door panel (measured in robot coordinate). Note, that the robot's localization is updated once hinge and lock position of a door have been detected. Therefore, the deviation between the coordinate systems is limited, and a hysteresis on the angle is sufficient to stabilize the door's estimated state.

From the outside, the localization is easier since the door frame is showing a U-like shape in the closed state with the corners defining the base positions.

Even that the described approach is pretty simple, it is able to consistently detect every state and the corresponding coordinates of hinge and handle. In [18] details on this method can be found together with a comparison to machine learning based door localization methods.

B. Pass Door Behavior

As already described, the *Pass Door* behavior observes the state changes of the door in the database, and at the beginning an initial observation pose is approached, which ensures that the door can be seen properly (see Fig. 3 *Analyze Door* behavior and Fig. 1 a). As soon as the door state is consistently detected, the associated subordinate behavior is immediately started taking over control.

To describe the whole process, we will discuss every step following an entire opening sequence starting with a closed door. Note, that the process can start at the other states as well. Every sub-behavior solves its individual situation of responsibility and passes the result or error messages to the managing *Pass Door* behavior. Then the next sub-behavior will be started, or a second try can be initiated respectively.

C. Unlatch Handle Behavior

The most important skill is detecting and unlatching a closed door, since every following state can be reached by pulling or pushing open the door further, if it already got unlatched. A triggered *Unlatch Handle* behavior starts by moving the base to a robot specific manipulation position in front of the door. This is a parameter defined with respect to the base points of the door. Subsequently, the robot should grasp the handle of the door. Since we do not rely on vision sensors, we do not have an exact 3D point cloud of the handle and thus can not use the obstacle avoidance capabilities of the motion planner for fiddling the fingers of the robot in the gap behind the handle. Rather, we use the laser range scan points to generate a vertical plane in the collision model which represents the door panel, but without any details like the handle.

The grasp pose at the handle, therefore, is approached on a trajectory which is defined by intermediate points with respect to the handle coordinates. This yields a collision-free movement which additionally is guarded by observing the forces at the end effector.

Once the gripper is closed around the handle (Fig. 1 b), a circular motion with the handle as pivot point is executed in order to unlatch the lock (Fig. 1 c). Again the process is guarded by force and torque limits to avoid damage to the robot and the door. When the max torque is reached, the robot starts a pulling motion to bring the door in the recognizable *UNLATCHED* position. Finally, the handle is put back in neutral position by rotating the hand back.

If the *UNLATCHED* state can not be recognized after the motion sequence ends or expected forces are not reached, the door might be locked or the robot may be slipped of the handle. The sequence then is repeated, while the exact grasp target positions are adapted incrementally either to the left or to the right depending on the actual situation, which hopefully will increase success probability in the next run.

D. Pull/Push Unlatched Behavior

A door in *UNLATCHED* state will trigger the *Pull/Push Unlatched* behavior, which depending on the side of the door needs to perform a coordinated motion of the robot base and the arm either to pull or push the door into the *PARTLY_OPEN* state. If the sequence does not start with the end effector at the handle, the grasp motion is executed first as described in Sec. IV-C.

Depending on the robot platform, the exact movement again is defined by a set of waypoints either on a linear or a arc like trajectory with respect to the door's base coordinates. While the robot base is executing its trajectory, the arm follows a horizontal circular trajectory defined by the door's hinge as pivot point (Fig. 1 d). We do not have a combined motion planner for arm and robot base so far, but the dynamic motion planner for the arm [13] is able to reactively compensate

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for the moving coordinate system of the robot's base while following its trajectory in door coordinates.

Again, the whole process is safe guarded by observing the forces and torques occurring at the robot's end effector. In case of human intervention or slip off, this can be recognized and the process starts over with the correct sub behavior responsible for the current state of the door. If the door reaches the *PARTLY_OPEN* state, the control is given to the next sub-behavior in the chain.

E. Push Open Behavior

A partly opened door from inside can not be pulled any further with the end effector at the handle. This is caused by the limitation regarding the maneuverability of the differential drive robot platform. Thus, for the remaining opening process, the robot has to bring its arm to the outside of the door. Therefore, it has to let go the handle, and the door for this moment is not longer under control of the robot. External forces or automatic closing mechanisms would disturb the process at this position. There may be options to use extensions to the robot platform or a second arm to lock the door in place for the time of repositioning the arm, but we do not have such available at our platforms. In consequence, our experiments could only be done with doors without automatic closing. Further, the opening motion from the outside can be done analogous to the inside described below, without the need to reposition the arm at another position.

In order to execute the push motion, depending on the current position / side of the robot, a series of way points and synchronous arm trajectories have been defined, which consider the characteristics of the individual robots. The TIAGo robot for example is pushing with the closed fist put in the gap of the partly open door, while the Zeus robot gently touches the door with its finger tips (Fig. 1 e & f).

For the push motion, the contact to the door has been defined in the area beneath the handle and a bit more central to the panel to avoid slip off. Also from the outside, the robot pushes the door in front of it while slowly progressing forward.

Depending on the current door angle, the robot might not be at a suitable start position for the movement. To compensate for that, before the push motion can begin, the start point along the trajectory is interpolated depending on the actual door angle, and the robot is going there with its arm retreated. By means of that, a smooth contact to the door can be made also if the robot does not come from the *Pull/Push Unlatched* behavior.

If the *FULLY_OPEN* state of the door is reached without any violation of force thresholds, the door is ready to pass through, after the robot arm has been retreated. The control then is given back to the *Pass Door* behavior, which finally can set the desired navigation goal.

V. Experimental Results

We tested the proposed manipulation approach on different doors (same base specifications like width and handles) in our office building. The robot completed a consecutive test of 72 door opening tasks (Zeus) given different start conditions. The results of this validation cycle can be seen in Table I. The robot faced 36 doors from the outside, which were pushed open, and 36 doors from the inside using a pulling strategy. There were variable starting conditions for these tasks due to different positions of the robot with respect to the door and variation of the door's initial opening angle.

TABLE I
Evaluation of the door manipulation using the robotic platforms *Zeus* (Z) and *TIAGo* (T)

Trials	Success	Side	State	Duration	R
72	93,06%	both	all	1:36	Z
17	88,89%	both	all	2:30	T
36	94,44%	inside	all	1:45	Z
36	91,67%	outside	all	1:25	Z
51	92,5%	both	closed	1:42	Z
6	100,0%	both	unlatched	1:52	Z
15	86,67%	both	partly	1:04	Z

In this experiment, our approach reached a success rate of above 90% in average of both robots. Table I shows the specific sample number and corresponding success rate of the different start opening states. The states unlatched and partly opened, are slightly underrepresented in the test cycle. There are two main reasons for neglecting those states originating from our use case.

Since most of the time all doors in care facilities, leading to a resident, are shut, the robot is more often confronted with the closed state than the others. Second, a closed door is, regarding detection and manipulation strategy, the most challenging state. Thus, validation and testing of this state is more important. The variation on the trial's duration for opening a closed door either from the inside and outside is shown in Fig. 4. The average duration for this type of manipulation is 102 seconds. According to the histogram, most of the outside manipulations were quicker, while the slower cases are dominated by inside manipulations. This shows that the door can be pushed open faster than it can be pulled open because for pushing from outside there is no need for an additional repositioning of the arm.

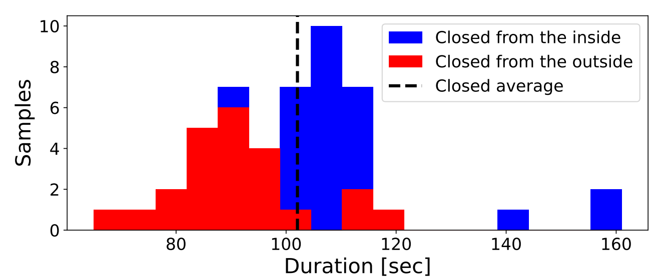

Fig. 4. Variations in the duration of the opening procedure starting with a closed door using *Zeus*

Note that both sides show two significant outliers that correspond to cases were an automatic retry was necessary to compensate errors that occurred during motion or detection.

To conclude the evaluation of our approach, we need to discuss the differences between the two used robots. *TIAGo* has the same degrees of freedom as *Zeus* but lacks the ability to rotate individual joints infinitely as Zeus can in four of the seven joints. This enables Zeus to reach the specific targets much faster than TIAGo. Additionally, the robotic platform of *TIAGo* sometimes slips on the carpet in our office rooms causing loss of localization. Then the robot needs a longer time span for movements until the localization catches position again. Those are the reasons for *TIAGo* to have a slightly worse success rate but a much higher duration.

In Table II a comparison of different approaches from literature is given in order to rank our method. Since most of the approaches correspond to the *DARPA Robotics Challenge* in 2015 where robots often are two legged, the driving / walking time will be excluded in our comparison, as long as it was declared. Our approach dominates the field with respect to pure manipulation time and also the overall time is best for inside openings while for openings from outside it comes close to the best.

[9] proposes another approach that uses machine learning techniques to drive to, detect and manipulate a door. They need several hours of manual training using a human controlled robot, which is pre-teaching the opening and driving motions. Further, the robot is using a holonomic drive to overcome all restrictions for the base movements. After the teaching cycle their robot is able to open the door within 30 to 60 seconds. Thus, our approach is one of the fastest methods while relying on differential drive as well as using a laser scanner for the door detection and localization.

TABLE II

COMPARISON OF THE DURATION FOR PULLING AND PUSHING DOORS IN [MIN : SEC]. FOR OUR APPROACH, THE TEST RESULTS OF THE ROBOT *Zeus* ARE USED. FOR A BETTER COMPARISON, THE DURATION OF [6] IS SPECIFIED WITHOUT MOTION CALCULATION TIME.

Approach	Op.	Driving	**Manipulation**	Total
[6] in real world [19]	both	4:45	2:50	7:35
[6] in simulation	pull	2:45	1:51	4:36
	push	2:30	1:57	4:27
[7]	both	-	-	4:20
[8]	pull	-	-	1:48
	push	-	-	**1:02**
Our approach	pull	0:26	**1:19**	**1:45**
	push	0:27	**0:58**	1:25

VI. Conclusion and Discussion

In this work, our goal was to overcome the challenges of detecting and manipulating doors to an open state, such that a mobile robot can pass through. We achieved a robust and fast manipulation strategy opening doors beginning from different opening states. The restrictions of a differential drive are compensated by simultaneous base and arm trajectory calculations as well as cutting the opening motion into several smaller steps. Another objective was to achieve a manipulation strategy that can be used by different types of robotic platforms and manipulators, while acknowledging the problems coming with the specific robots. Furthermore, our approach still has a few problems regarding generalization and fully automating the process, that need to be solved in future methods and are explained below.

One of the main problems is related to the generalization of our detection method. The manipulation approach relies on robust and stable detection results regarding the localization of necessary door features. Currently, a heuristic approach only able to consistently detect the office doors is used. Thus a machine learning method will be implemented and validated against the heuristic algorithm, most likely leading to an increase in the generalization towards more variable door types.

Another issue is the manual definition of motion parameters during an installation procedure. A future plan seeks to optimize and robustly adapt a Reinforcement Learning agent to various doors, while reducing the duration and manual parameters needed. Therefore, another validation cycle in other buildings will be conducted to make the approach able to adapt to changes in the appearance of doors.

In around 10% of our test trials the robot would not have been able to open the door since any error stopped the algorithm (e.g. collisions related to the motion planner and lack in perception of 3D environment). In our approach, several retry strategies are implemented solving errors that occur more frequently, like loosing the handle in an opening or unlatching motion, detection errors, reaching force boundaries, and solving wrong assumptions about the door's current state.

Finally, the operating space in front of the door required to open it, currently is rather big while being already smaller than many of the approaches discussed above. Currently, the robot operates slightly off center of the door to get a better start position. This position is needed to slide the door in front of the robot, because the differential drive is not able to compensate all arm motions while holding on to the door. Thus, the robot stands up to 30 cm outside the door's frame if the door is opened from the inside. On the outside all positions are already chosen to be between the door's left and right frame. In the future we are planning to update the manipulation strategy for inside doors to a synchronous opening motion including backwards driving motion and simultaneous arm movements, which could reduce the necessary time even more.

References

[1] F. Endres, J. Trinkle, and W. Burgard, "Learning the dynamics of doors for robotic manipulation," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013, pp. 3543–3549.

[2] Y. Sun, L. Zhang, and O. Ma, "Force-vision sensor fusion improves learning-based approach for self-closing door pulling," *IEEE Access*, vol. 9, pp. 137 188–137 197, 2021.

ISBN: 978-3-8007-6140-1

[3] Y. Karayiannidis, C. Smith, F. E. Viña, P. Ogren, and D. Kragic, "“open sesame!” adaptive force/velocity control for opening unknown doors," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 4040–4047.
[4] M. Arduengo, C. Torras, and L. Sentis, "Robust and adaptive door operation with a mobile robot," *Intelligent Service Robotics*, 2021, http://dx.doi.org/10.1007/s11370-021-00366-7. doi: 10.1007/s11370-021-00366-7.
[5] W. Meeussen, M. Wise, S. Glaser, S. Chitta, C. McGann, P. Mihelich, E. Marder-Eppstein, M. Muja, V. Eruhimov, T. Foote, J. Hsu, R. B. Rusu, B. Marthi, G. Bradski, K. Konolige, B. Gerkey, and E. Berger, "Autonomous door opening and plugging in with a personal robot," in *2010 IEEE International Conference on Robotics and Automation*, 2010, pp. 729–736.
[6] N. Banerjee, X. Long, R. Du, F. Polido, S. Feng, C. G. Atkeson, M. Gennert, and T. Padir, "Human-supervised control of the atlas humanoid robot for traversing doors," in *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*, 2015, pp. 722–729.
[7] S. Karumanchi, K. Edelberg, I. Baldwin, J. Nash, J. Reid, C. Bergh, J. Leichty, K. Carpenter, M. Shekels, M. Gildner, D. Newill-Smith, J. Carlton, J. Koehler, T. Dobreva, M. Frost, P. Hebert, J. Borders, J. Ma, B. Douillard, P. Backes, B. Kennedy, B. Satzinger, C. Lau, K. Byl, K. Shankar, and J. Burdick, "Team robosimian: Semi-autonomous mobile manipulation at the 2015 darpa robotics challenge finals," *Journal of Field Robotics*, vol. 34, no. 2, pp. 305–332, 2017. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21676
[8] J. Lim, I. Lee, I. Shim, H. Jung, H. M. Joe, H. Bae, O. Sim, J. Oh, T. Jung, S. Shin, K. Joo, M. Kim, K. Lee, Y. Bok, D.-G. Choi, B. Cho, S. Kim, J. Heo, I. Kim, J. Lee, I. S. Kwon, and J.-H. Oh, "Robot system of drc-hubo+ and control strategy of team kaist in darpa robotics challenge finals," *Journal of Field Robotics*, vol. 34, no. 4, pp. 802–829, 2017. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21673
[9] H. Ito, K. Yamamoto, H. Mori, and T. Ogata, "Efficient multitask learning with an embodied predictive model for door opening and entry with whole-body control," *Science Robotics*, vol. 7, no. 65, p. eaax8177, 2022. [Online]. Available: https://www.science.org/doi/abs/10.1126/scirobotics.aax8177
[10] T. Welschehold, C. Dornhege, and W. Burgard, "Learning mobile manipulation actions from human demonstrations," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 3196–3201.
[11] Z. Li, Z. Xia, G. Chen, Y. Gan, Y. Hu, and J. Zhang, "Kinect-based robotic manipulation for door opening," in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2013, pp. 656–660.
[12] H.-R. Su and K.-Y. Chen, "Design and implementation of a mobile robot with autonomous door opening ability," in *2017 International Conference on Fuzzy Theory and Its Applications (iFUZZY)*, 2017, pp. 1–6.
[13] S. Müller, B. Stephan, and H.-M. Gross, "Mdp-based motion planning for grasping in dynamic scenarios," in *2021 European Conference on Mobile Robots (ECMR)*, 2021, pp. 1–8.
[14] H.-M. Gross, Ch. Schroeter, St. Mueller, M. Volkhardt, E. Einhorn, A. Bley, Ch. Martin, T. Langner, and M. Merten, "Progress in developing a socially assistive mobile home robot companion for the elderly with mild cognitive impairment," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*. IEEE, 2011, pp. 2430–2437.
[15] M. M. Shalaby, M. A.-M. Salem, A. Khamis, and F. Melgani, "Geometric model for vision-based door detection," in *2014 9th International Conference on Computer Engineering Systems (ICCES)*, 2014, pp. 41–46.
[16] W. Chen, T. Qu, Y. Zhou, K. Weng, G. Wang, and G. Fu, "Door recognition and deep learning algorithm for visual based robot navigation," in *2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014)*, 2014, pp. 1793–1798.
[17] S. Prieto, A. Adan, A. Vazquez, and B. Quintana Galera, "Passing through open/closed doors: A solution for 3d scanning robots," *Sensors*, vol. 19, pp. 4740–4762, 2019.
[18] S. Müller, T. Müller, A. Ahmed, and H.-M. Gross, "Laser-based door localization for autonomous mobile service robots," *Sensors*, vol. 23, no. 11, p. 5247, 2023.
[19] N. Banerjee, "Human supervised semi-autonomous approach for the darpa robotics challenge door task," 2015.

ISBN: 978-3-8007-6140-1