MANIPULATION FOR MOBILE ROBOTS TO AUTONOMOUSLY USE ELEVATORS AND OPEN DOORS

Christopher Baird[1] and Scott Nokleby[1]
[1] *Mechatronic and Robotic Systems Laboratory, Ontario Tech University, Oshawa, ON, Canada*
Email: christopher.baird@ontariotechu.ca; scott.nokleby@ontariotechu.ca

ABSTRACT

This work presents an approach for a Boston Dynamics Spot robot to autonomously navigate a multi-level indoor environment. This includes algorithms for Spot to autonomously use an elevator to transition between floors and for Spot to autonomously open doors including doors that are locked by key card access. Experimental results demonstrate the successful implementation of the proposed methods. The developed methods can easily be extended for use on other mobile-manipulator robots.

Keywords: manipulation; autonomous; quadrupedal; elevators; doors; Boston Dynamics Spot.

MANIPULATION POUR ROBOTS MOBILES POUR UTILISER LES ASCENSEURS ET OUVRIR LES PORTES DE MANIÈRE AUTONOME

RÉSUMÉ

Ce travail présente une approche permettant à un robot Boston Dynamics Spot de naviguer de manière autonome dans un environnement intérieur à plusieurs niveaux. Cela inclut des algorithmes permettant à Spot d'utiliser de manière autonome un ascenseur pour faire la transition entre les étages et à Spot d'ouvrir de manière autonome des portes, y compris des portes verrouillées par un accès par carte-clé. Les résultats expérimentaux démontrent la mise en œuvre réussie des méthodes proposées. Les méthodes développées peuvent facilement être étendues pour être utilisées sur d'autres robots manipulateurs mobiles.

Mots-clés : manipulation ; autonome ; quadrupède ; ascenseurs ; des portes ; Boston Dynamics Spot.

Fig. 1. The Spot robot used in this work equipped with the Spot Core computer payload and arm.

1. INTRODUCTION

Robots have become more common in everyday lives playing an ever expanding role in how people function at home and at work. Developing robots that work in a world built for humans provides significant challenges, with one of the most fundamental being the ability to navigate in the environment including using doors and elevators. These items present a challenge for most robots that were not necessarily designed to use doors and elevators. These short comings greatly reduce the ability for these robots to traverse most indoor facilities, thus significantly reducing the usefulness of the robots.

The Spot robot from Boston Dynamics is a quadrupedal robot primarily used to perform inspections of industrial assets. The base Spot platform is capable of traversing many different types of terrain including stairs. Spot can then carry different payloads including cameras, sensors, and computational platforms to perform different types of inspections. Spot can also be equipped with a robot arm that allows Spot to perform manipulation tasks like picking up objects, turning valves, or opening doors with the help of an operator. The Boston Dynamics Spot robot used in this work was equipped with a Spot Core computer payload and an arm. Spot can be seen in Figure 1.

This work was done in participation with Ontario Power Generation (OPG) to be used in their nuclear generating stations. These stations are very complex with many different doors and multiple floors that Spot would have to traverse. Normally Spot is confined to performing inspections in a single room at a time until Spot is assisted by an operator to open doors or operating the elevator for Spot. Although the work is being created for Spot to operate in a nuclear plant, the work presented here can also be applied to Spots used in many other industries as autonomously opening doors and riding elevators is a common issue.

The goal of this work was to develop and test a simple and robust method for Spot to both autonomously use an elevator to travel between floors in a building and to autonomously open doors including doors that may be locked by a key card, enabling Spot to inspect a much greater portion of the building autonomously.

The remainder of the paper is as follows. Section 2 covers related works. Section 3 presents the requirements for Spot. Section 4 discusses the proposed methodology. Section 5 presents the testing. Section 6 finishes the paper with conclusions.

2. RELATED WORKS

Many different techniques have been presented to enable robots to use elevators, with most works focusing on a single aspect of the task like button recognition or navigation.

Button localization and recognition have become a large area of focus in the literature. Some of the easier methods for button localization found in [1–3] utilize a location marker on the wall near the buttons or on the ceiling to help with locating the buttons and navigating in and out of the elevator. Visual button recognition techniques have also been presented that attempt to compare the buttons against a previously created button template image to identify the three-dimensional pose of the button using vision techniques such as template matching, Scale-Invariant Feature Transform (SIFT), or Speeded-Up Robust Features (SURF) as found in [4, 5]. Newer techniques have used neural networks to detect the correct buttons [6]. To physically press the elevator buttons a number of robots found in the literature have custom end effectors as seen in [3, 4, 7]. These are usually designed for accuracy as a button is generally a small target. This limits the use case of the manipulator for other tasks including opening doors or manipulation, therefore, the presented work aims to use the general purpose gripper on the Spot arm itself to press the buttons.

A number of robots have a built-in system to communicate directly to the elevator to tell it to go to the correct floor as in [8]. This is not possible for the presented use case as the elevators in the OPG nuclear generating stations are relatively old and cannot be easily retrofitted to communicate with Spot.

Some robots also try to communicate with a human and get the human to open the door or operate the elevator for it as seen in [9, 10]. As there are a limited number of humans in some of OPG's stations this method would not work for this use case and is not practical for most applications of autonomous robots.

The different techniques stated above to autonomously use elevators have been applied to full mobile robot systems equipped with manipulators capable of traversing multiple floors [1–3, 5, 7]. The ANYmal quadrupedal robot has been presented to have the possibility to use an elevator, but it has only been shown hitting the outside elevator button using the QR tag and moving into the elevator in [11]. It is not apparent if the robot can detect when the elevator's doors are open or if it can use the buttons on the inside of the elevator or traverse different floors.

Opening doors with robotic arms have been done frequently with many different types of robots as seen in [12–14]. The presented application in this work does not look at the mechanics of actually opening a door, but focuses on making the process autonomous and also adding the capability of utilizing a key card to access locked doors. Utilizing a key card to open a normally locked door was not readily found in the literature.

Through this research, it was found that very few robots were capable of both operating an elevator and opening doors with the same hardware. Most of the presented robots that could use an elevator were not nearly strong or dexterous enough to open a door and would rely on an automatic door system. As the arms for the robots using elevators in the literature can produce very little force, none of the papers worry about damaging the elevator's buttons by using too much force.

The novelty of the presented work is: 1) the use of a key card to access a secure door; 2) the first quadrupedal robot to fully autonomously use an elevator to travel between floors; 3) a force sensitive approach to pressing an elevator button so as to not damage the button or the robot; 4) a method to utilize elevator banks with multiple elevators; and 5) an approach to both autonomously open doors and autonomously use elevators with the same robot and a general purpose end-effector.

3. REQUIREMENTS

The goal of this work was to enable Spot to be able to traverse throughout a building autonomously, with the areas of issue being the ability to open closed doors (including locked doors) and ride elevators.

Boston Dynamics has developed a Software Development Kit (SDK) to interface and send commands to

Spot [15]. The SDK obfuscates the lower-level control commands, for instance controlling individual leg joints, while giving the user access to higher-level commands, like controlling the orientation of the entire body. The SDK is used to control Spot throughout this work, therefore, only higher-level control using the SDK is discussed in this paper with any lower-level control being handled by Boston Dynamic's control system.

3.1. Elevators

First, a simple method for Spot to use an elevator to traverse between floors was designed. Some assumptions about the environment were proposed assuming Spot would eventually use this method in a more industrial setting. The assumptions are as follows:

- Spot should be able to utilize the elevator fully autonomously while doing its normal autonomous walks without help or intervention from humans.
- There should be very little change to the elevator or the elevator lobby as they are already built and cannot be retrofitted with new technology. Therefore, a module for the robot to wirelessly activate the elevators is not possible and the timing of the elevator should not be changed. This also applies to the hardware and button configuration inside and outside the elevator, which should already be of a reasonable height and size for Spot, to conform to normal accessibility laws.
- It would be rare for Spot to encounter people while using the elevator. If a person is on the elevator when Spot tries to use it then Spot should not get on the elevator with the person and vice versa, people trying to use the elevator know not to get on the elevator with Spot.
- Spot should be able to use the elevator without the use of an additional payload besides the built-in sensors, the Spot Core computer, and the arm. Spot can then carry whatever other payloads it needs to do its normal inspection duties, e.g., camera, radiation sensor, gas detector, etc. and still use the elevator.
- The algorithm should be able to use elevator banks with multiple elevators to ensure the algorithm is transferable to other buildings.

It should be noted that Spot can already take the stairs to travel to different floors of the building, but this would be less energy efficient for Spot than taking the elevator, especially if Spot has to travel multiple floors at a time to reach its destination.

3.2. Doors

Boston Dynamics has already developed a method for an operator to get Spot to open and traverse through a door. This action still needs a human to help Spot every time, so the presented work automates this process so Spot can autonomously traverse closed doors without a human's help.

The current process for an operator to get Spot to open a door is as follows: 1) the operator drives Spot to an area where Spot is facing the door; 2) the operator then uses a tablet interface and taps on the location of the handle or push-bar of the door; 3) the operator then specifies the type of door mechanism, either a handle or a push-bar based door, then which side of the door the hinges are on, and whether the door should be pushed or pulled to open; and 4) Spot then takes over and will go through the door by itself changing how it opens the door based of the configuration the user provided and the forces acting on the door, including the force of the door closer.

4. METHODOLOGY

To navigate autonomously Spot uses a navigation system called Autowalk. To set up an Autowalk, an operator will drive Spot through a route manually taking inspection measurements at the required locations. After the route is taught, Spot can autonomously repeat the route and take the same inspection measurements over and over again when needed. Autowalks are used in this work to navigate autonomously inside the building.

Opening doors was encoded as an area callback action within an Autowalk. An area callback lets Spot execute the action every time Spot traverses through a certain area, in this case going through a door. This allows Spot to go both ways through the door in case Spot has to deviate from the normal route and needs to travel through the door in the other direction.

The elevators were originally encoded as an area callback like the doors, but it was found that the Spot software version 3.2 did not work as the environment changed too drastically from when the action starts to when it ends. Instead, to test the elevator system the action was encoded as a normal action that would only be run a single time in an Autowalk, like an action to read a gauge. This means that Spot would not be able to take the elevator if the route changes unexpectedly. This does not change how the elevator action operates. The area callback should be fixed in a future software patch for Spot and the elevators can then be encoded as an area callback.

Both algorithms were designed to run on the Spot Core computer payload that is mounted on Spot's back. This enables the software to run without being connected to an external network.

4.1. Elevators

For development and testing, the elevators in the engineering building at Ontario Tech University were used. The elevators can be seen in Figure 2. These elevators presented some notable design challenges. First, there are two separate elevators working in tandem. Both elevators go to mostly the same floors, but Spot needed to be able to detect which elevator to use depending on which one opened when the up or down buttons are pressed outside the elevator. The button configurations are also different in either elevator. The elevator doors and the inside walls of the elevator are made of shiny metal. This limits the types of sensors that can be used for things like detecting if the doors are open. For example, the point cloud from Spot's onboard depth cameras will return erroneous values due to reflective surfaces. These issues seem to be common with other elevators in industry.

The algorithm for Spot to use an elevator is shown in Figure 3. To allow Spot to locate the elevators and buttons, fiducial markers with different identification numbers were placed on each level of the building Spot would travel to as seen in Figure 2(a). A fiducial maker was also placed inside each elevator as seen in Figure 2(b). Spot uses these fiducials during normal operation to help with autonomous navigation. Spot's built-in software can identify the pose of the fiducial in three dimensions along with the identification number using the cameras on the sides of Spot.

A vision based button recognition algorithm could be used to identify the location of buttons instead of using the fiducials, but that is beyond the scope of this work and just adds to the complexity of the system, which could affect reliability.

Information about the elevators was encoded in a file on the robot according to the fiducial number. This included the floor number, the number of elevators, the position of each elevator door, and the position of each button relative to the fiducial. Using unique fiducial numbers also accommodated having different button configurations in either elevator. A worker then needs to measure all the button and door positions before Spot can use the elevators.

Before Spot can use the elevators, Spot takes a baseline image of the elevator doors in both a closed and an open position from a known location relative to the fiducial on each floor of the building. These images

(a) (b)

Fig. 2. The elevators on the fourth floor of the Ontario Tech University engineering building. (a) Outside the elevators. (b) The buttons inside one elevator.

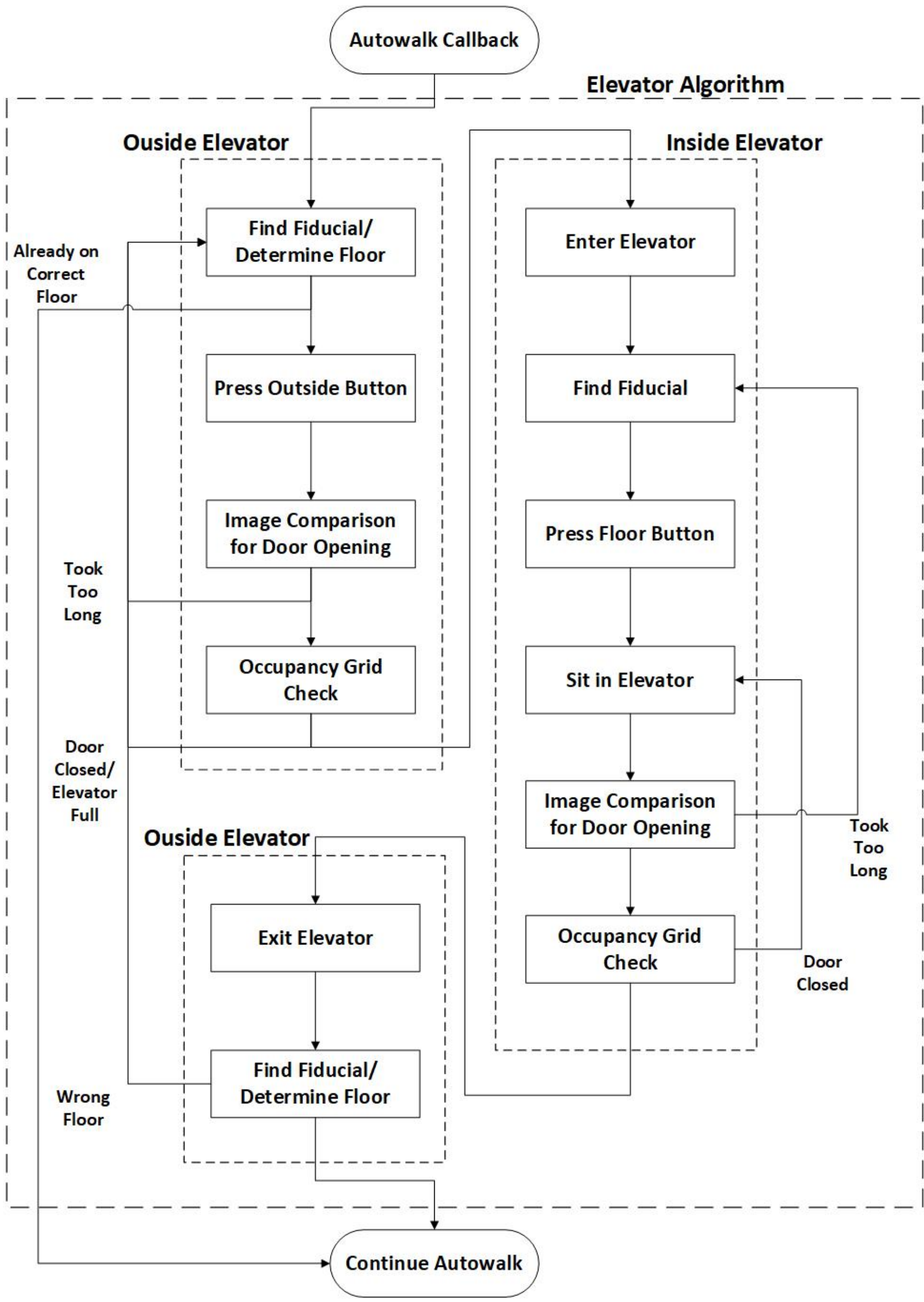

Fig. 3. Overview of how Spot uses an elevator.

act as templates to detect if the doors of the elevator are open or closed which will be explained later in the paper.

As Spot walks around the building autonomously, it would then approach the elevators as close to the fiducial as possible and then execute the elevator action. Spot would then identify the fiducial and get the current floor the robot was on from the fiducial data. The Autowalk data that should appear after the elevator portion was then inspected to determine what fiducial should be seen after the elevator ride and, therefore, what floor Spot should end up on when finished. The current floor and the desired floor were then compared to determine if the up or down button should be pressed. If for some reason the current and desired floor were the same then the elevator ride is skipped and Spot would proceed with its Autowalk inspections.

Spot normally emits an infrared grid from its stereo cameras to help identify flat surfaces like walls. The elevators used in this work have an infrared sensor that stops the door from closing if something is standing in the doorway. Coincidentally Spot's infrared grid interferes with the doors, causing the doors not to close when Spot was close to them. Therefore, Spot's infrared grid was turned off at the elevators and all of Spot's movements are done in a degraded perception mode. However, since the depth sensors are not used in this work due to the elevator's reflectivity, this does not affect Spot's ability to use the elevators. Note that in this mode, the indicator LEDs on the front of Spot that are nominally green change to orange to indicate the degraded perception mode.

Spot then moved and extended its arm to a position a couple of centimetres away from the desired button. To do this a set of transforms $\mathbf{T}$ were calculated as follows:

$$ {}^{O}_{E}\mathbf{T} = {}^{O}_{B}\mathbf{T}{}^{B}_{R}\mathbf{T}{}^{R}_{F}\mathbf{T}{}^{F}_{D}\mathbf{T}{}^{D}_{G}\mathbf{T}{}^{G}_{E}\mathbf{T} \tag{1} $$

where O is a frame offset a couple of centimetres away from the desired button, B is a frame on the button, R is a rotated fiducial frame that makes it easier for a human to measure the position of the buttons, F is the true frame of the fiducial, D is the odometry frame of Spot, G is the gripper frame and, E is a frame at the tip of the bottom jaw of the gripper as the bottom jaw extends farther then the top jaw and would touch the button first.

If Spot was to press the button with full force it could potentially cause damage to the buttons or Spot itself. Instead, Spot was set to hit the button with a force of 15 N which was the best estimate as enough force to actuate the button without causing any physical damage. The gripper starts a couple of centimetres from the button and the arm was then set to a velocity control mode with a gripper velocity of 0.05 m/s in the direction of the button. The forces on the gripper are polled frequently until a force greater than 5 N was exerted in the direction of movement, which means Spot touched the button. The button needs to be actuated for approximately a quarter of a second before it registers, so just hitting the button would not work. Instead, a force-position hybrid mode accessible through the SDK was then used which exerts the required 15 N of force in the direction normal to the face of the button and then moves to the position of the button in all other axes. This keeps the gripper stationary while exerting the required force for the required amount of time.

The force-position hybrid mode was not used at the start of the movement as it was found to cause the position of the gripper to oscillate when not in physical contact with the button. As the diameter of the button was approximately 2.5 cm and the area at the end of the gripper to push a button has an approximate area of 5 cm^2, the positioning of the gripper was very important.

After the button was pressed, the arm was stowed and Spot moved to the location the template images were taken from. To identify when an elevator door opened, Spot repeatedly took images of both elevator doors and compared them to the templates. Spot's cameras at the time of this work only shot greyscale images and as both the walls and door of the elevators are made of reflective material, it was difficult to determine if the door was open or closed. This can be seen in Figures 4(a) and 4(b). To improve the ability to identify the changes in images, the images are cropped to just the floor and doorway of the elevator as that was the only noticeable change in the images and should be a defining feature for most elevators. An example of these cropped images can be seen in Figures 4(c) and 4(d).

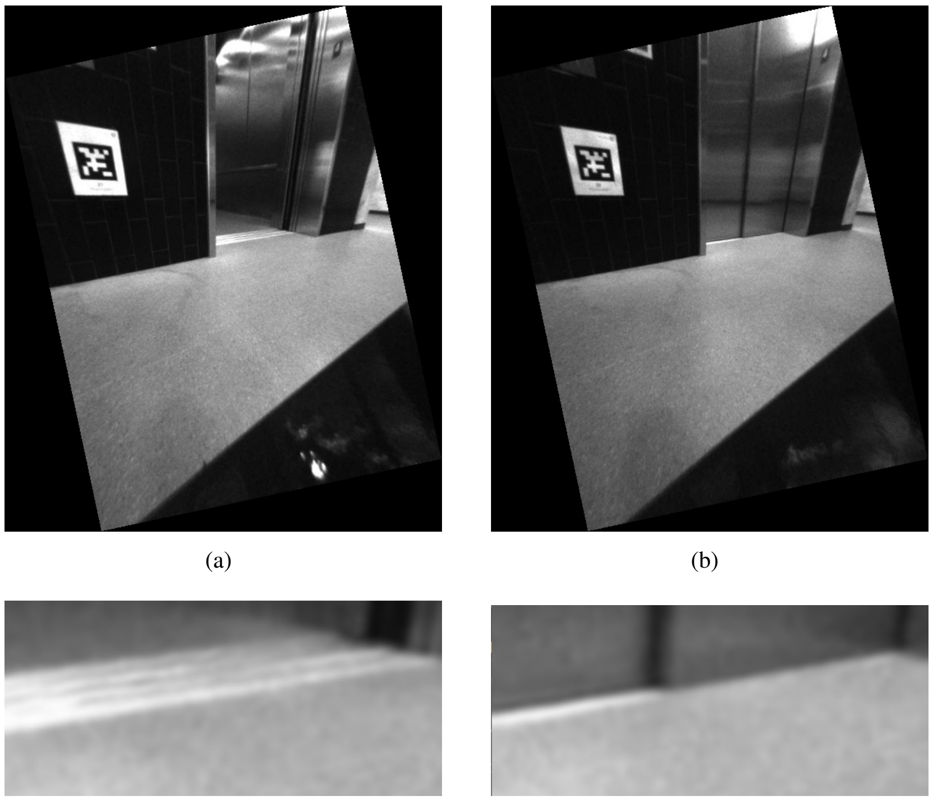

Fig. 4. Images of the elevator doors: (a) open; (b) closed; (c) cropped version of the open door and (d) cropped version of the closed door.

Template images had to be taken before using the elevators instead of taking the template images right after Spot pressed the button as the door may already be open when Spot arrives so the state of the door cannot be known when the button was pressed.

To determine if the door is open or closed, the percent difference between the current image and the template of both the open and closed doors are compared. To calculate the percent difference P between the new image I and the template image H, both with standard pixel values ranging between 0 and 255, the following equation was used:

$$P = \frac{100\,mean(|I-H|)}{255} \tag{2}$$

When the percent difference of the open door template becomes greater than that of the closed door template, that door was determined to be open. Spot then moved and rotated so the rear of Spot was facing the open elevator door. This was done as the buttons inside the elevator were on the same side as the door.

The local occupancy grid was then checked to ensure the door was actually open and to ensure there was nobody inside the elevator. The local grid is normally used by Spot for its internal path planning system and is automatically generated by Spot's software. The occupancy grid was then converted to a binary image.

Lines were then drawn on the image originating from the centre of Spot and radiating out by half the width of the image at angles of 0, ± 0.1, and ± 0.2 radians with a reference straight from the rear of Spot pointing into the elevator. The image was then inspected to see if the lines intersected more than five occupied pixels, to ensure the object was not just noise, in the obstacle grid. If the lines intersected more than five pixels, then either the door was still closed or there was a person inside the elevator. Spot would then move back to the starting position by the fiducial and the algorithm would reset. An example of the occupancy grid with the inspection lines overlayed for both cases, the elevator door closed and the elevator door open, can be seen in Figure 5.

(a) (b)

Fig. 5. The local grid and inspection lines that were used to determine the state of the elevator door. (a) With the elevator door closed. (b) With the elevator door open.

Note that the local grid cannot be used instead of the imaging system as it does not extend far enough to check both doors at the same time and was found to be erroneous when the doors are closed due to the door's reflectivity. The issues with the local grid and the reflectivity of the doors can be seen in Figure 5(a) with only parts of the elevator door appearing in the occupancy grid.

If the elevator was found to be empty, Spot then backed into the elevator and moved over toward the buttons. Spot then detects the new fiducial inside the elevator, gets the data about the elevator from the fiducial, and then determines which button to press to get to the desired floor.

Spot extends the arm to the button staging position and presses the button using the same method as the button outside the elevator. When the button was pressed Spot stowed the arm and moved over in front of the elevator doors and then sat down. Spot must sit while in a moving elevator as the unexpected acceleration of the elevator affects Spot's control system making Spot slightly unstable.

Spot had to move very quickly from the time the button on the outside of the elevator door was pressed to getting into the elevator so the elevator doors did not prematurely shut on Spot. Spot also had to move quickly from the time the button was pressed on the inside of the elevator to when Spot sat down as the elevator starts moving very quickly after the button was pressed.

With Spot sitting and the elevator doors closed, Spot takes a template image of the closed door and then takes images to compare them in the same way as the outside doors to detect when the doors reopened. Spot then stood and checked the local occupancy grid to ensure the doors were open. If the occupancy grid check failed Spot would sit back down. If Spot sat for an unreasonable amount of time, Spot would stand and press the floor button again.

When the door was determined to be open, Spot would exit the elevator. Spot then detects the new fiducial outside the elevator and determines what floor Spot was now on. If Spot was on the desired floor, Spot would continue the Autowalk inspection mission. If Spot was on the wrong floor, Spot would restart the entire elevator process over again until it reached the correct floor.

4.2. Doors

As Spot can already open doors with the help of an operator, the goal of this part of the work was to automate that process. To do this, a fiducial is placed on both sides of the door. In a similar fashion to the elevators, the information about the door is stored in a file based on the fiducial number. This data included the handle type, what side of the door the hinges were on, the direction the door swings, and the position of the handle relative to the fiducial. Through this information, Spot can automatically choose how it approaches the door opening using the SDK. Different fiducials can then be put on either side of the door to provide different configuration information allowing Spot to autonomously traverse through either side of the door. An example door with fiducial can be seen in Figure 6.

Fig. 6. The door to the Mechatronic and Robotic Systems Laboratory in the Ontario Tech University engineering building.

To open a normal door, Spot first approaches the door autonomously during an Autowalk. Spot then identifies the position and identification number of the fiducial on the door. Spot then extends its arm and using a trajectory command moves the arm to a staging position just before reaching the handle and opens the gripper at the same time. Spot then moves the arm to the handle position and then closes the gripper on the handle. A similar transform-set to Equation (1) was used to position the arm, but with the handle as the end point instead of the elevator button. Spot can then use a warm start door command, passing the parameters of the door, and then Spot will open the door using Boston Dynamics' built-in technique. When Spot is through the door, it closes the gripper and stows the arm and then can continue on its Autowalk.

If the door has a push bar, instead of Spot gripping a handle, Spot will immediately move from the staging position to opening the door.

The developed algorithm was also designed to open doors that require an access card to unlock the door. The access card pad can be seen in Figure 6 to the left of the door. To do this, Spot was given its own access card which was mounted to the bottom of the gripper. Spot's access card can be seen in Figure 7.

The access panel's position was also included in the fiducial file. If the door requires the access card Spot

Fig. 7. Spot's access card attached to the underside of Spot's gripper.

will add an extra movement to the arm trajectory command to place the underside of the gripper near the access card pad. The length of time the door stays unlocked could cause issues with some doors. It was found through testing that Spot needs approximately seven seconds to start opening the door from the time of unlocking the door. Some doors may lock faster than this, which would cause issues with Spot.

The developed algorithm also identifies if the door is already open when Spot reaches it. To do this, Spot calculates the angle of Spot's body relative to the fiducial on the door. When the door is fully closed this angle should be approximately ninety degrees. If the angle is less than thirty degrees the door is determined to be already open, so Spot would just walk through and not attempt to open the door. Also, if the angle is between ten degrees and thirty degrees, the door would then be determined to be propped open but not wide enough for Spot to walk through. In this case, Spot will not use its access card and will just open the door and then walk through.

Through this algorithm, Spot can autonomously open almost any type of door found in an industrial or commercial building.

5. TESTING

To test the autonomous elevator riding, Spot was tested riding the elevator multiple times from the fourth to the third floor to ensure Spot can perform the necessary actions in time. Ensuring Spot could perform the necessary movements to use the elevator without the doors closing on Spot while maintaining accurate enough positioning to reliably hit the elevator buttons was the biggest challenge, but a good balance was reached without having to alter the timing of the elevators. The sequence of Spot using the elevator can be seen in Figure 8. The testing showed that the developed algorithm allowed Spot to autonomously move from floor to floor in a building by using the elevator instead of stairs.

Spot was also tested entering and exiting the Mechatronic and Robotic Systems Laboratory multiple times. Spot entering the lab including using its key card can be seen in Figure 9. The test results showed the effectiveness of Spot being able to open and close doors.

With both the developed autonomous elevator riding and autonomous door opening algorithms, Spot is able to traverse a wide range of industrial and commercial settings.

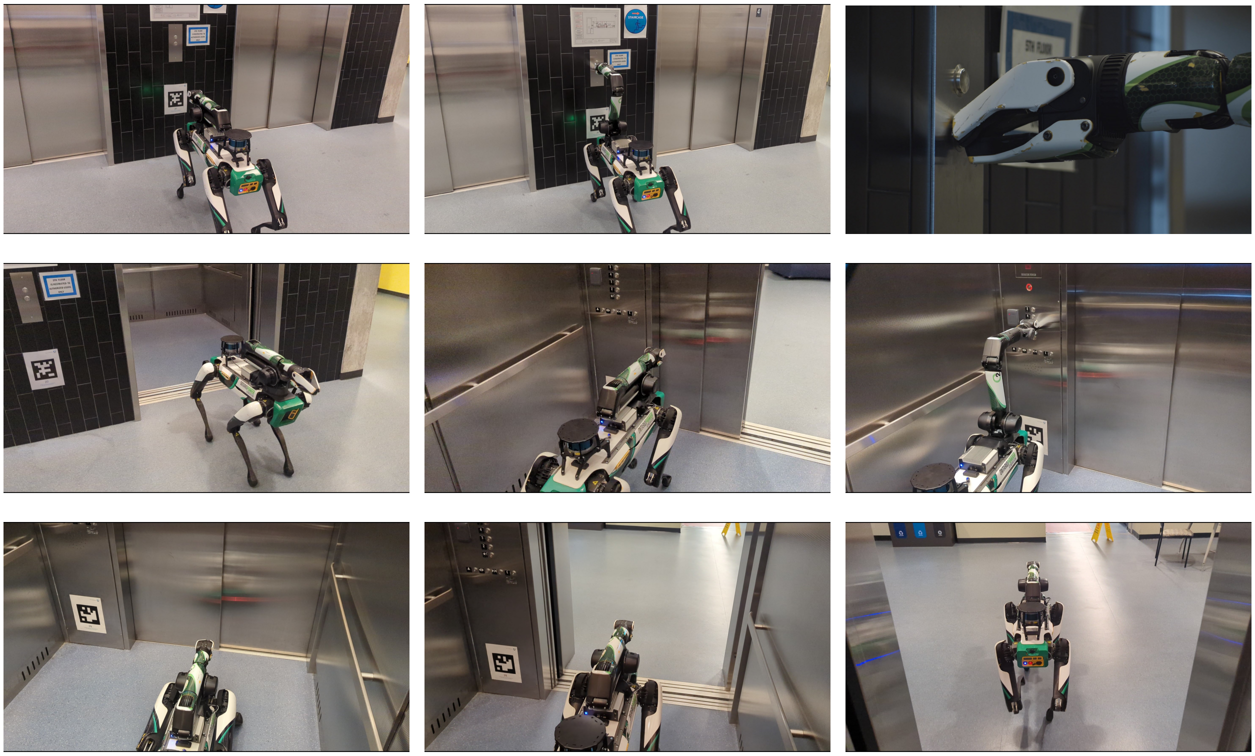

Fig. 8. Spot using the elevator.

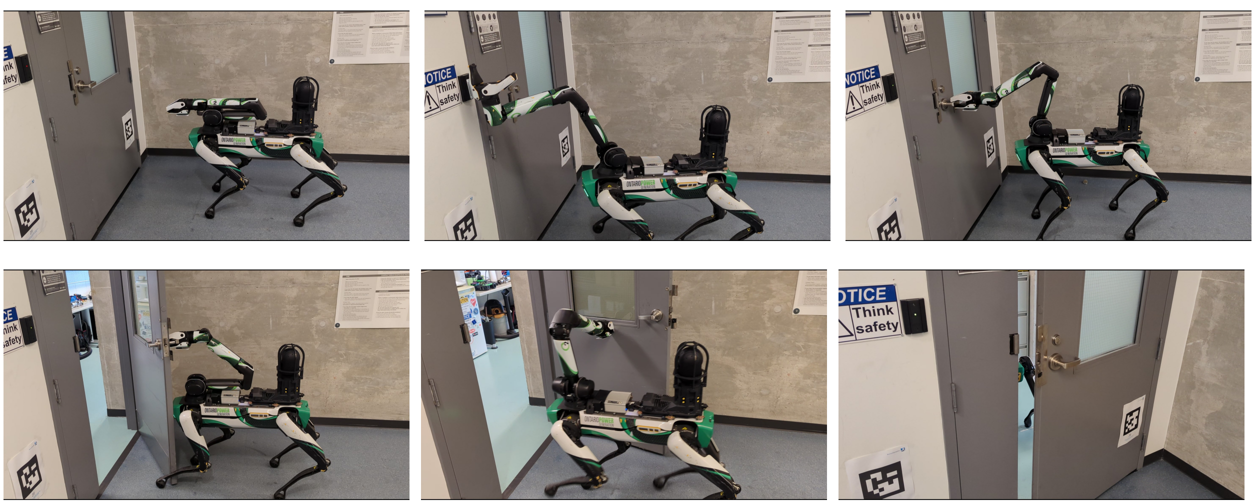

Fig. 9. Spot opening the lab door.

6. CONCLUSIONS

Algorithms to allow the Boston Dynamics Spot robot to autonomously utilize elevators and doors, including using a key card, were developed. Both methods were repeatedly tested in a real-world setting. The test results showed the effectiveness of the developed methods. The ability to autonomously use elevators and open doors significantly increases the usefulness of Spot to perform autonomous inspections of a wide range of industrial and commercial facilities allowing Spot to access spaces autonomously that it was previously restricted from.

ACKNOWLEDGEMENTS

The authors would like to thank Ontario Power Generation and Rocky Mountain Unmanned Systems (RMUS) Canada for their financial support of this work.

REFERENCES

1. Abdulla, A.A., Liu, H., Stoll, N. and Thurow, K. "A New Robust Method for Mobile Robot Multifloor Navigation in Distributed Life Science Laboratories." *Journal of Control Science and Engineering*, Vol. 2016, 2016.
2. Ali, A.A., Ali, M.M., Stoll, N. and Thurow, K. "Integration of Navigation, Vision, and Arm Manipulation Towards Elevator Operation for Laboratory Transportation System Using Mobile Robots." *Journal of Automation, Mobile Robotics and Intelligent Systems*, pp. 34–50, 2017.
3. Kim, E.H., Bae, S.H. and Kuc, T.Y. "Mobile Service Robot Multi-Floor Navigation Using Visual Detection and Recognition of Elevator Features." In "2020 20th International Conference on Control, Automation and Systems (ICCAS)," pp. 982–985. IEEE, 2020.
4. Wang, W.J., Huang, C.H., Lai, I.H. and Chen, H.C. "A Robot Arm for Pushing Elevator Buttons." In "Proceedings of SICE Annual Conference 2010," pp. 1844–1848. IEEE, 2010.
5. Troniak, D., Sattar, J., Gupta, A., Little, J.J., Chan, W., Calisgan, E., Croft, E. and Van der Loos, M. "Charlie Rides the Elevator–Integrating Vision, Navigation and Manipulation Towards Multi-floor Robot Locomotion." In "2013 international conference on computer and robot vision," pp. 1–8. IEEE, 2013.
6. Yang, P.Y., Chang, T.H., Chang, Y.H. and Wu, B.F. "Intelligent Mobile Robot Controller Design for Hotel Room Service with Deep Learning Arm-Based Elevator Manipulator." In "2018 International Conference on System Science and Engineering (ICSSE)," pp. 1–6. IEEE, 2018.
7. Nguyen, T.V., Jeong, J.H. and Jo, J. "An Efficient Approach for the Elevator Button Manipulation using the Visual-Based Self-Driving Mobile Manipulator." *Industrial Robot: the international journal of robotics research and application*, Vol. 50, No. 1, pp. 84–93, 2023.
8. López, J., Pérez, D., Zalama, E. and Gómez-García-Bermejo, J. "Bellbot - A Hotel Assistant System Using Mobile Robots." *International Journal of Advanced Robotic Systems*, Vol. 10, No. 1, p. 40, 2013.
9. Ilyevsky, T.V., Johansen, J.S. and Siskind, J.M. "Talk the Talk and Walk the Walk: Dialogue-Driven Navigation in Unknown Indoor Environments." In "2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)," pp. 4903–4910. IEEE, 2021.
10. Liebner, J., Scheidig, A. and Gross, H.M. "Now I Need Help! Passing Doors and Using Elevators as an Assistance Requiring Robot." In "Social Robotics: 11th International Conference, ICSR 2019, Madrid, Spain, November 26–29, 2019, Proceedings," pp. 527–537. Springer, 2019.
11. Péter, F., Marko, B. and Marco, H. "ANYmal Using an Elevator." `https://www.youtube.com/watch?v=gM1z60aeunU`, October 2017.
12. Meeussen, W., Wise, M., Glaser, S., Chitta, S., McGann, C., Mihelich, P., Marder-Eppstein, E., Muja, M., Eruhimov, V., Foote, T. et al.. "Autonomous Door Opening and Plugging in with a Personal Robot." In "2010 IEEE International Conference on Robotics and Automation," pp. 729–736. IEEE, 2010.
13. Nagatani, K. and Yuta, S. "An Experiment on Opening-Door-Behavior by an Autonomous Mobile Robot with a Manipulator." In "Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots," Vol. 2, pp. 45–50. IEEE, 1995.
14. Prieto, S.A., Adán, A., Vázquez, A.S. and Quintana, B. "Passing Through Open/Closed Doors: A Solution for 3D Scanning Robots." *Sensors*, Vol. 19, No. 21, p. 4740, 2019.
15. "Spot sdk."
URL `https://dev.bostondynamics.com/`