An Automatic Docking System for Wheeled Mobile Robots

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An automatic docking system for wheeled mobile robots

Alexey M. Romanov and Andrey A. Taratin

***Abstract*—This paper presents an algorithm for wheeled mobile robots with differential kinematics, which increases positioning and orientation accuracy of docking to charge station. Localization of the charging station is carried out by detecting ArUco markers. Unlike other localization methods such ones based on IR sensors and LIDARs, this method is more robust and easy to configure. The software designed based the proposed algorithm and Robot Operating System provides simple integration with robots of different designs. The simulation results, shows that the estimated docking accuracy is within 3cm, and the minimum docking distance is 58cm.**

***Index Terms*—robotic, ros, charging, localization, aruco, docking, path planning, charging**

I. Introduction

In order to achieve autonomy in energy, mobile robots need to independently replenish the battery capacity. For this, there are robot charging stations, with which the robot can dock and start charging. The relevance of the work lies in the fact that the standard algorithms for the navigation of robots such as GPS navigation combined with Inertial Mesurment Units [1], AMCL [2] or beackon based navigation systems [3], [4] do not always provide sufficient positioning accuracy of the robot for automatic docking because a slight offset of the station relative to the map or beacons can greatly affect the docking accuracy. For this purpose, there are special algorithms for locating the charging station and accurately docking to it. [5]

The automatic docking process can be divided into two stages: the first stage of localizing the charging station and the second stage of constructing the trajectory of movement and movement to the station.

Section II provides a short overview of existing automatic docking solutions. Section III provides a description of the automatic docking system I have developed. Experiment results and analysis are given in Section IV. Section V summarizes the main results of the study.

II. Related work

As mentioned above, there are 2 stages in the algorithm for automatic docking to the charging station: localizing the charging station and building a trajectory to it.

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A. Localization of the charging station

There are several methods for localizing the charging station based on the use of different sensors.

Localization using infrared sensors is one of the most common methods in mobile robotics, in particular used in robotic vacuum cleaners [5]. As shown in Figure 1, the method uses IR emitters with different wavelengths located in certain sectors of the charging station, and the IR receivers are located on the robot. By receiving signals from different sectors of the station, the robot can get the position of the station relative to itself [6].

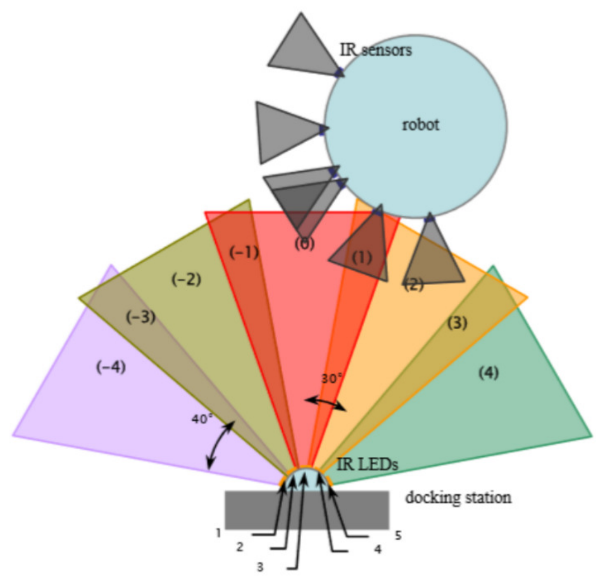

Fig. 1. Charging station localization system based on IR sensors

When using this method, the localization accuracy is ± 7 cm and the angle error is ± 2 degrees. The main disadvantage is the need to install a large number of IR sensors and IR emitters.

Localizing a charging station using a lidar means representing the lidar readings as a cloud of points (a set of points in space) and searching for the station's geometric pattern as shown in Figure 2. To find a geometric pattern, you can use the Iterative Closest Point (ICP) algorithm. This algorithm is used to minimize the difference between two point clouds so that the position of the target object relative to the robot can be calculated [5].

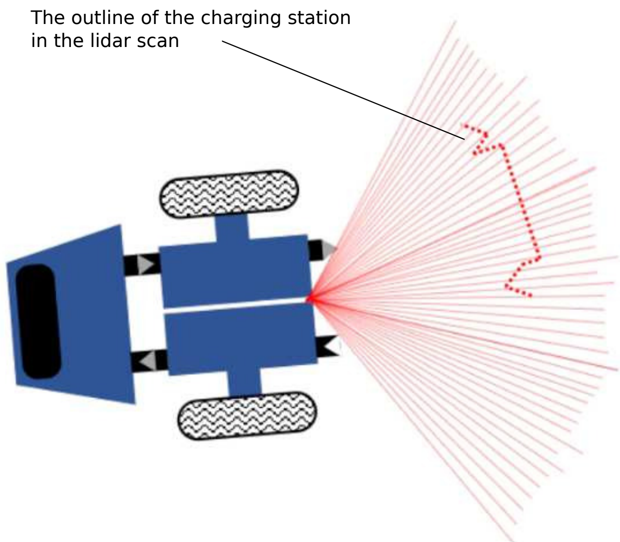

Fig. 2. Charging station localization system based on LIDAR

This method has a sufficiently high accuracy, but the number of false positive detections depends on the uniqueness of the geometric shape of the object in the lidar scanning plane.

The method of visual localization of a station using marks is based on searching for marks of a certain color or shape in the frame received from the camera. By positioning the black rectangular marks as shown in Figure 3, it is possible to determine the angle between the camera and the center axis passing through both marks [7].

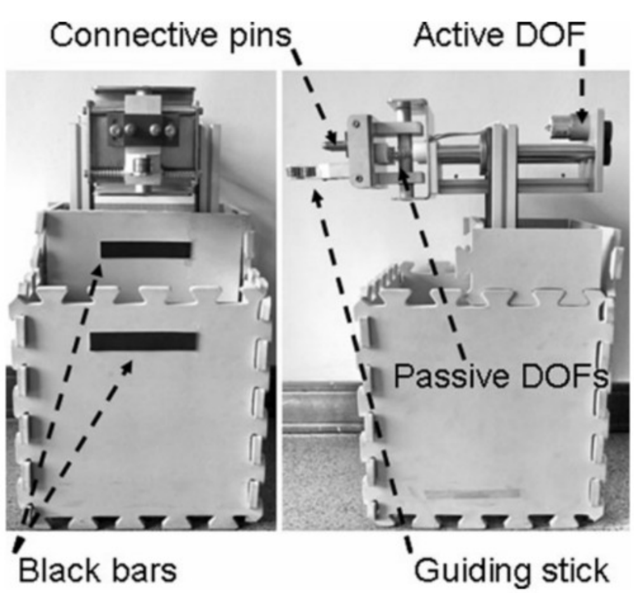

Fig. 3. An example of a charging station with visual label

The disadvantages of this method are the impossibility of accurately determining the distance to the object, as well as the likelihood of false positive determination of marks if they do not have a unique shape.

The method of visual localization using markers is based on extracting patterns from a video stream. ArUco markers can serve as such patterns. Knowing the geometric dimensions of the marker, it is possible to determine its position and orientation relative to the camera coordinate system. As shown in Figure 4, the marker positioning algorithm first detects the corners of the marker, then determines the id from a discrete grid converted to binary code (1 if the cell is black, 0 if it is white).

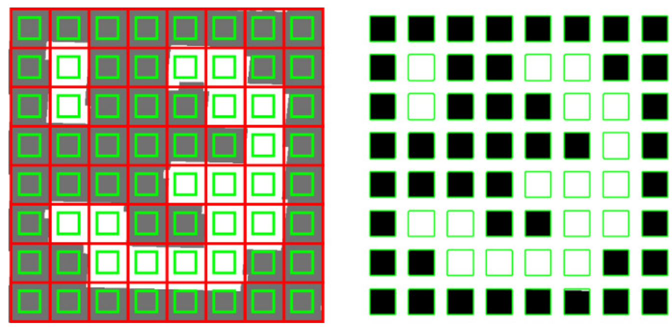

Fig. 4. ArUco marker detection

The pose estimate of the ArUco marker is calculated using matrix products. These matrices are determined by the camera parameters and the four corners of the marker. Thus, the accuracy of determining the marker pose depends on the accuracy of determining the marker angles. The accuracy of the marker angles depends on the resolution and angle of view of the camera and on the marker size.

The advantages of this method are the absence of false positive detections, a sufficiently high localization accuracy. The disadvantage of this method is the dependence of the localization accuracy on the marker size and camera resolution.

B. Constructing a docking path

The docking path depends on the design of the robot and the charging station. Charging stations often have a fixed charging contact, so the trajectory must be straight with minimal deviations for accurate docking as shown in Figure 5.

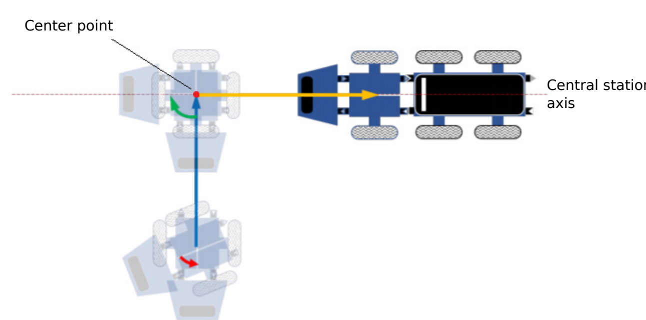

Fig. 5. An example of a straight docking path

In this case, the trajectory can be approximated by two segments. The first segment from the initial position of the robot to the centering point; the second segment from the centering point to the station. The overall accuracy of joining depends on the accuracy of the centering point calculation. Figure 6 shows the charging station with a special tapered contact guide that allows for a smooth path for docking [8].

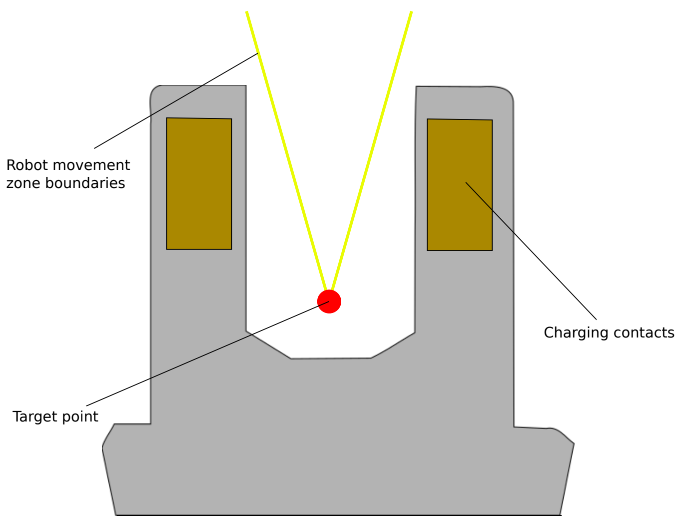

Fig. 6. Example of charging station contact with a cone-shaped guide

Straight docking trajectory is more versatile and allows you to achieve higher docking accuracy compared to a smoothed one.

There are no publicly available software solutions that include localization of the charging station using ArUco markers, building a straight-line trajectory and providing protection against collisions when moving using data from a laser lidar, as well as presented in the form of a ROS package with convenient integration.

III. A NOVEL ALGORITHM FOR AUTOMATIC DOCKING

The automatic docking system is used on a robot with differential kinematics and a video camera, optionally a 2D lidar and a bumper to detect obstacles. The charging station has an ArUco marker for station localization. The station also has contact pads with a contact patch of 5 cm in diameter. The station has guides that allow the robot to move only in a straight line in a given corridor as shown in Figure 6. The robot is able to approach the charging station using the built-in navigation system; navigation accuracy of 0.25 meters does not allow docking. The maximum distance for detecting a station is 1 m. After that, an automatic docking system is used to accurately approach the station. Docking accuracy must be + -5 cm for successful contact and starting the charging process.

The automatic docking system software is developed using ROS (Robotic operating system), for more convenient integration into the robot and testing the system in the simulator.

The algorithm of the automatic docking system operation includes 4 stages.

A. *Find a charging station*

The search for a station is carried out by turning the robot around its axis at a certain angle and detecting the ArUco marker. If the marker was not found within 60 seconds, it is necessary to stop the operation of the algorithm and display a message stating that the markers were not found. If the marker is found, then go to the next step.

B. *Turn towards the station*

It is calculated between the center axis of the camera and the position of the marker. Then the rotation is performed by the calculated angle. After the robot has turned with an error of at most, go to the next stage. As shown in Figure 7, the marker system (ar_marker) is detected relative to the camera coordinate system $(camera\_link)$. The angle θ_m is calculated using the following formula 1.

$$\theta_m = \arctan \frac{marker_x}{marker_y}, \tag{1}$$

C. *Centering point calculation*

The centering point is the point closest to the robot located on a straight line passing through the center of the marker and perpendicular to its plane. In order for the robot to arrive at the centering point, it needs to turn in its direction and travel the required distance to it. In Figure 7, the centering point is marked in red.

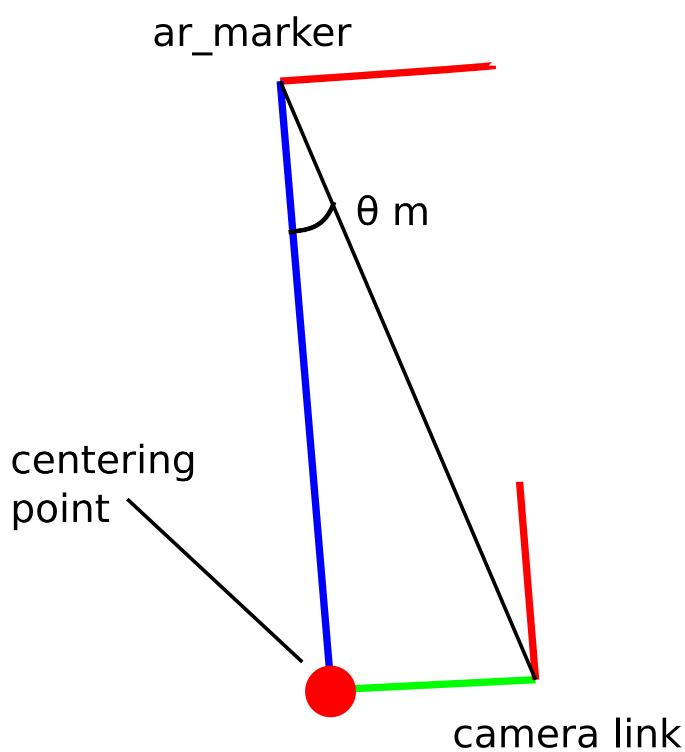

Fig. 7. Camera and Marker Coordinate Systems

The angle of rotation to the centering point θ_c is calculated using the following formula 2.

$$\theta_c = -(\frac{\pi}{2} + \theta_m - (\alpha_t - \alpha_0)), \quad (2)$$

where α_t - current orientation of the robot, α_0 - init orientation of the robot.

The distance to the centering point D_c is calculated using the following formula 3.

$$D_c = marker_x \times \cos(\frac{\pi}{2} - \theta_m), \quad (3)$$

D. Moving to the station

The robot begins to move to the charging station, adjusting the angle of rotation to it by the angular velocity. The line speed decreases in proportion to the distance to the station. The movement stops when the robot has approached closer to the specified distance $(15cm)$ to the station. In parallel with the main branch of the algorithm, a check is performed for the presence of obstacles using a 2D LIDAR in the sector behind the robot, as well as a check for pressing the bumper. If an obstacle is detected, the robot stops. The block diagram of the algorithm is shown in the Figure 8.

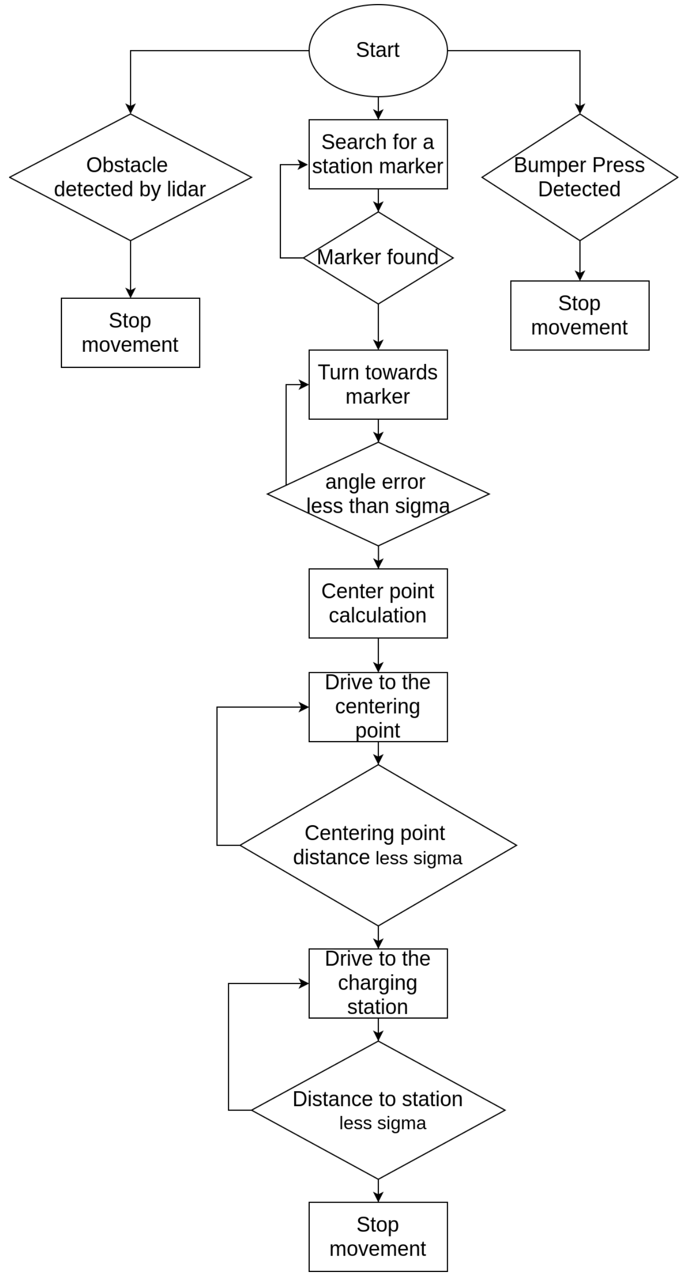

Fig. 8. The block diagram of the novel algorithm for automatic docking

IV. Experimental results

To test the software of the automatic docking system, experiments were carried out in the Gazebo simulator, which is the main stimulator of robotic systems in the Robotic Operating System.

The main criterion for the successful docking of the robot to the station is the exact calculation of the centering point. Therefore, it is necessary to conduct an experiment on the dependence of the calculation of the centering point on the position of the robot relative to the station in the radius accurate to the error of the global navigation of the robot. An experiment was carried out on 10,000 tests with a change in the position of the robot within the navigation error.

Experiment parameters: the ideal position of the robot relative to the station 0.7 meters; camera resolution 1920x1080; camera viewing angle 60 degrees; marker size 9x9 cm.

Figure 9 shows the results of the experiment. Black circle - robot positioning error in global navigation. The green line is the central axis of the charging station. The black lines are the corridor in which the robot can dock to the station. The dots indicate the position of the robot, the color of the dots - the error in the marker definition angle. (green - less than 1 degree, blue - less than 7 degrees, red - more than 7 degrees). The marker determination error at such a distance from the station is random and rarely exceeds 7 degrees.

Figure 11 A shows that all centering points are in the corridor, which proves that the automatic docking algorithm works. At the same time, if you move the centering points towards the charging station along the X-axis to the intersection with the black lines of the corridor as shown in Figure 11 B, then you can find the minimum distance to the station at which the robot can dock with it. This distance is 0.58 meters.

Tests of the complete docking operation were performed to confirm the accuracy. A total of 3 tests were carried out with different initial positions of the robot (2 unfavorable positions when the robot stands on the edge of the navigation system error circle, 1 favorable position when the robot stands close to the center of the circle). Figure 10 shows the test results. The red circle marks the area where the robot must arrive in order to achieve the stated docking accuracy of + -5cm. The dots indicate the initial positions of the robot. The curves represent the trajectories of the robot.

The accuracy of the matching algorithm based on the recognition of 3 visual markers is + - 17 cm [6], the accuracy of the algorithm based on the recognition of the color volumetric visual marker is + -7 cm [7], they are inferior in accuracy to

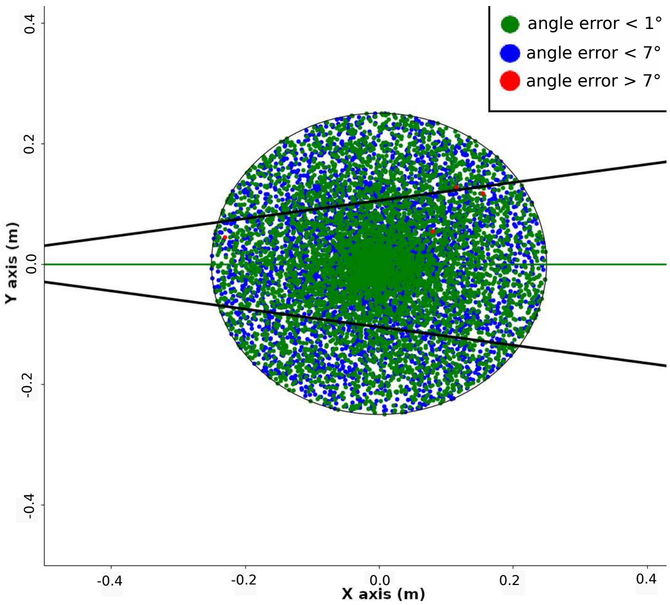

Fig. 9. Experiment Results. Dependence of determining the marker angle on the position of the robot

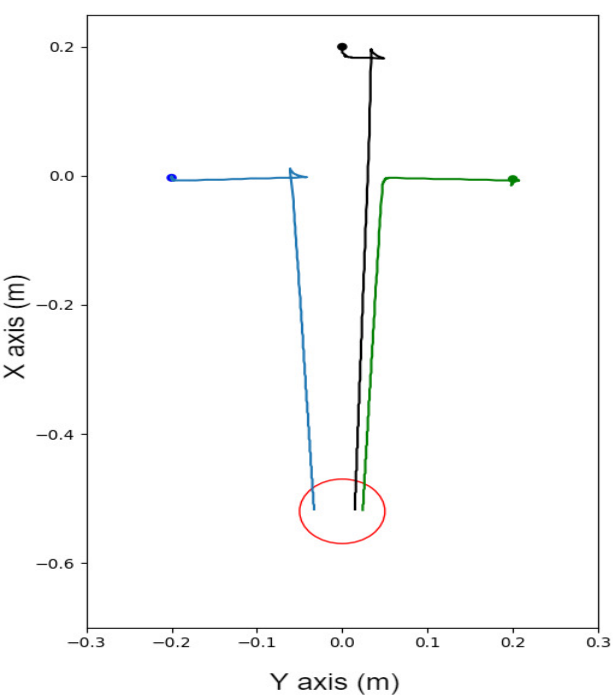

Fig. 10. Test results of the automatic docking system

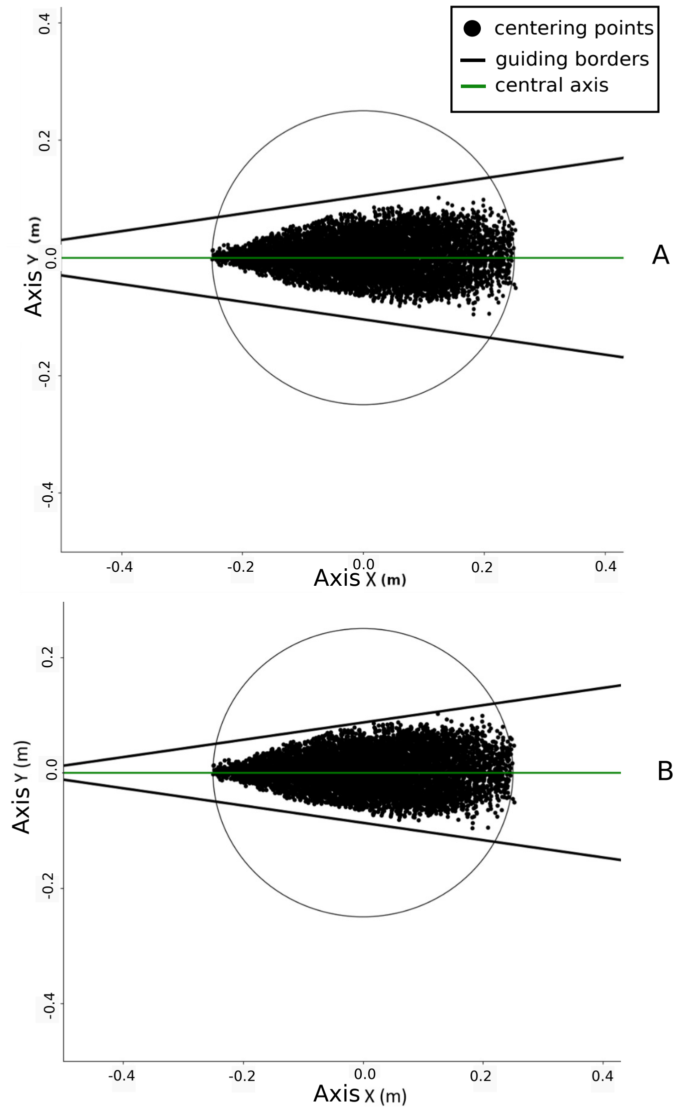

Fig. 11. Experiment Results. A) Centering points at a robot position of 0.7 m. B) Centering points at a minimum position of the robot 0.58 m.

the algorithm presented in this paper.

V. Conclusion

This paper presents an algorithm for wheeled mobile robots with differential kinematics, which increases positioning and orientation accuracy of docking to charge station. This algorithm is based on the robust method of station detection using the ArUco marker and provides accurate docking due to a straight line trajectory. The software implementation of this algorithm is presented in the form of a ROS package, which greatly simplifies integration into an autonomous robot. During the experiment, the accuracy of the algorithm was determined, which is + -5 cm and the minimum distance for the start of docking, which is 58 cm, which allows parking in rather narrow corridors. Comparison with other jointing algorithms shows that the algorithm presented in this article is more accurate.

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