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Design of a Low-Cost Wireless Charging Station Based on the Robotic Vision System

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***Abstract*—Physical training of autonomous robotic systems are often limited by battery capacity since the intelligent training cycles have to be halted for battery recharge. Many researchers have focused on various solutions of power management for autonomous robots. However, these solutions are usually custom-fitted for the specific applications, and would be difficult to be generalized to other autonomous robotic systems. In this paper, we propose to develop a low-cost wireless charging system based on the on-board vision/camera sensor. This design is capable of autonomous docking for the robot chassis without further external supervision. Specifically, we use the QR codes to label the charging station and establish the robot's camera vision system to recognize the dock. The robot will drive to the station automatically. The low-cost charging station is also designed for wireless charging of the robot. We present the specific designs of charging dock, wireless connection, and battery charging experiments explicitly. This low-cost wireless charging system provides advancements toward a fully autonomous physical training infrastructure for robotic navigation experiments.**

***Index Terms*—Wireless autonomous charging, Turtlebot 3 robot, Robotic QR code recognition, 3D printing, and robotic navigation experiment.**

I. Introduction and Background

Robots equipped with robotic vision, such as the widely adopted TurtleBot 3 robotic systems, are capable of many autonomous tasks, including image-based path planning [1], simultaneous localization and mapping (SLAM) [2], and swarm robotics applications [3]. Current state-of-the-art advancements of these types of robotic vision systems involve autonomous exploration of unknown environments with deep reinforcement learning (DRL) algorithms [4], [5]. However, transitions from computer simulations to real-life trials have been known to be challenging due to a large reality gap. One of the factors that is largely unaccounted for in simulations is the power consumption. During real-life trials, power consumption can vary wildly due to numerous factors including movement action frequency, duration, and intensity. In some cases, a single trial may take up to 20 minutes to finish in an environment even with predictable and perfect artificial layout. Some other path planning cases may take even longer to obtain full coverage of the environment [6]. Because of this reality gap, real-life training tasks usually require a significant amount of time to achieve satisfactory performance. The training process may have also to be paused for a battery recharge, which requires human intervention and attention for power management. This limitation prevents the physical training tasks from becoming fully autonomous and constrains the training process of intelligent algorithms during physical experiments. Solutions such as swapping to a larger battery may offer an extension of single run-time. However, the uncertainty of the aforementioned factors still demands human supervision for uninterrupted operation in long-term applications.

A. Charging Methods

Wireless charging systems were devised to facilitate effective power management, which were expected to increase the real-time training effectiveness and lower the barrier to entry for future experiments. In comparison to traditional metal contact-based interfaces, wireless charging has several advantages, including a wider range of acceptable charging angles and distances [7], more consistent and reliable charging, and cost-effectiveness. These enables numerous robots to adopt the charging station simultaneously.

Therefore, commercially available ready-to-run wireless induction charging systems designed for drones and autonomous robots were initially discussed for our application with the Turtlebot 3 robots. Wibotic had quoted their TR-110/OC-110 system to cost thousands of dollars. With this price, purchasing multiple charging systems for simultaneous robot training would be impractical. Furthermore, the Wibotic wireless charging system is only compatible with the TurtleBot2's Kobuki platform, which the Turtlebot 3 has since replaced [8].

New experimental wireless charging technologies other than magnetic induction also exist. Magnetic Resonance Coupling Charging was recently explored by MIT students and is still under development. Unlike conventional inductive charging technologies today, the charging modules do not have to be aligned perfectly parallel with each other and could eliminate the need for the robot to center itself on the charging station, which could help improve charging consistency. However, the disadvantage is the low power transfer efficiency it possesses. For example, even at close range, a well-designed system might demonstrate an efficiency of 30 percent at 2 cm, dropping to 15 percent at 75 cm coil separation [9]. This would require a large voltage input to overcome the low efficiency value in order to achieve charging of the battery within a reasonable time. Since this experimental method is neither commercially available nor has yet proven suitable for small robots with moderate power demand, this charging technology was not pursued.

Another experimental wireless charging technology is Radio Frequency (RF) Energy Harvesting which utilizes ambient radio frequencies and harvests them for use as the name suggests. It has been recorded to be able to charge from a large distance away even without line of sight, up to 40 ft [10]. However, due to its low charging rate, this method will not be enough to power Turtlebot robots directly, but a possible use could be to continuously charge the Turtlebot robots during training cycles, rather than when the battery is depleted. This could be explored in a future project.

B. Other Works

There are also several experimental tests with conventional charging technologies such as electromagnetic induction (using Qi charging standards) and metal contacts. A previous project that focused on autonomous drones implemented a wireless inductive charging system that has proven to be effective [11]. They achieved a charge time of 1 hour using a 12-volt system. This proves the feasibility of inductive wireless charging stations on drone/robotic applications.

Similarly, the commercially available charging system used by iRobot Roomba vacuum robots, similar to the Kobuki platforms, where the robot drives into a dock and charges using metal contact connections, has also proven to be effective and safe [12]. However, as they must maintain good contact in order to charge, it requires more user attention to ensure proper operation. Therefore, any robot that integrates this charging system must have good obstacle avoidance and path-finding to consistently connect and dock. Since the focus of this paper is on ensuring consistent charging performance rather than path-finding and/or obstacle avoidance, the design of the dock avoided reliance on these components. Consequently, metal contact charging was not employed.

There has also been an experimental method utilizing conformable bumper contacts instead of traditional metal contacts, and have shown to be more effective than the latter with the same contact area [13]. While effective, fabrication would be difficult, as that system was designed for large full-scale vehicles.

Harvard's Kilobots are an advancement toward fully autonomous swarm robots in terms of simultaneous mass-charging [14]. Utilizing contact-based charging, no specific attention needs to be paid to individual robots while charging. However, human intervention is still required in order to start the charging process. As such, improvements in charging autonomy is still possible in this platform.

Furthermore, the Wifibots provided by the FIT IoT-LAB were able to achieve autonomous charging using infrared sensors and QR codes with custom docks [15]. The mechanism of QR code recognition and homing is used in this paper to detect the dock because of its robustness and reliability. Notably, the Wifibots' infrared sensors have been replaced with the Turtlebot 3's onboard LiDAR sensor to enhance real-time obstacle avoidance. While the work with the Wifibots emphasized the path-finding aspect of the docking procedure, our paper is focused on the physical aspects of charging process.

In addition, the GRITSbots used in the Robotarium project also have an autonomous charging system that significantly extends the run time of the robots [16]. The work was centered around multi-agent remote swarm robotics research which required numerous robots with long run time for training. The GRITSbots are small in dimension and can recharge in 30 minutes due to its small battery of 150 mAh, but also only have a run time of 30 minutes when under heavy use. They utilize metal strips that run along the edges of the walls of the testbed as a large dock and drive the robots into them until the dedicated pins on the robot contact the strips to recharge. This method eliminates the need for accurate path-finding, as the long strips on the wall accept a large angle of approach and positioning. While effective, this charging system would be difficult to adapt to other robotic training platforms, since most obstacle avoidance and robotic vision testing platforms require independence from environmental factors due to the change of testing locations. Therefore, this charging system would not be suitable for our purposes.

Based on the above studies, both induction wireless and contact-based charging systems have demonstrated reliability and effectiveness. A combination of both types would be ideal for a robotic vision system. Therefore, this paper designs a charging system utilizing wireless electromagnetic induction modules, which accept a wide range of approach angles, as well as a docking system that is based on the physical motion of the robot, similar to those used by the Roomba vacuums, to ensure alignment.

The structure of this paper is organized as follows. In Section II, the design and fabrication processes of the charging interface and dock are discussed in detail. In Section III, we conduct two different tests: The first test focus on the electronic components and charging performance of the system and the second is a preliminary proof-of-concept test that combines the charging system with our separate robotic vision homing project. Section IV concludes this paper.

II. Design & Fabrication

1) Charging Interface: The electronic components of this system consist of integrating wireless charging modules onto factory parts with as few modifications as possible to reduce the cost. Due to the limitations imposed by the included LiPo battery, which has four pins on its power cord and prevents direct wireless charging module connection as they only contain two pins, the factory battery charger was also included in the system. This design eliminates the requirement of developing new circuits to utilize the extra two pins, which are used to monitor the battery level during charging, or ditch them altogether, which compromises safety during charging as LiPo batteries may combust if overcharged [17].

Switching to a Lithium Ion (Li-ion) battery type was also considered, which would eliminate any complications with battery level monitoring and allow for the wireless charging modules to be connected between the charger and the battery. However, a separate charger would still be required, which would also need to be assembled and tested separately before it can be integrated, therefore increasing the total amount of modifications and time needed for the project. Thus, the factory LiPo battery was used.

Since a wireless charging module was not able to be connected between the charger and battery, they were instead relocated to between the wall adapter and the battery charger. This effectively replaces the cable that runs between the adapter and the charger and avoids any complications with pin amount differences. The final electronic layout of the charger is displayed in Figure 1. An example of how the receiver and transmitters interact when docked is also shown in Figure 2. All the electronic components of the charging system cost around 35 dollars.

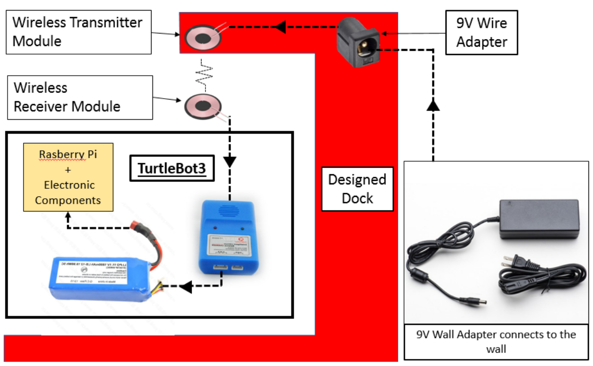

Figure 1. The overall layout of the electronic components of the charging system. The design utilizes as few permanent modifications of the existing parts as possible, thus decreasing the cost and time of installation.

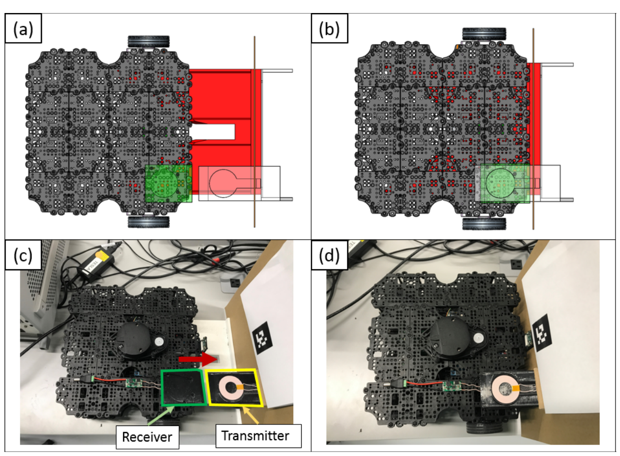

Figure 2. Top view of the wireless charging module docking alignment. Shown in (a) and (b), the docking procedure and the final alignment of the charging modules are modeled in Solidworks. The same procedures are shown in the real-world experimental setup in (c) and (d).

2) Dock Design: A dock was created to house the components of the charger that are not directly on the robot. As seen in Figure 3, the dock was designed with little reliance on the robot's path-finding, image recognition, and obstacle avoidance capabilities by using guiding rails on both the robot and the dock that accept wide incoming angles of docking. A traditional mechanical charging system that relies on the kinetics of the robot and metal contacts, such as the iRobot vacuums, was the inspiration for this design. In Figure 4, the complete layout of the system as well as the docking procedure is shown.

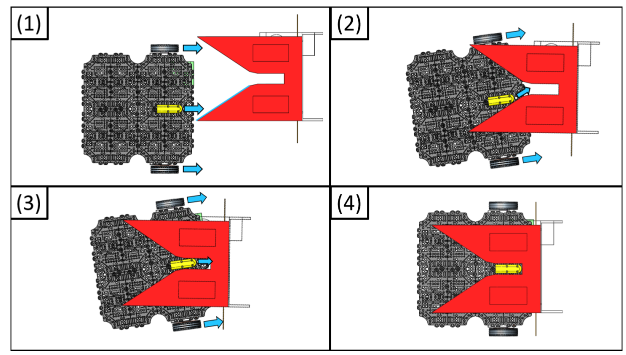

Figure 3. (1) As the robot begins to approach, it will recognize the QR code that is positioned on the dock and partially align itself. It has been observed that the robot tends to be offset a few millimeters from the center if approaching off-centered. The blue arrows indicate the intended direction of motion of the wheels and guide rail. (2) Once the robot makes contact with the slanted edges of the dock (red), the rounded edge of the guiding rail (yellow) will cause the robot to rotate toward a more correct and centered angle. (3) As the guiding rail moves deeper into the dock, the straight cut-out slot will force the robot to be aligned parallel to the dock. (4) Fully docked position of the robot.

3) Fabrication: The complete set-up as seen in Figure 4 was modeled in Solidworks. After numerous iterations of the positioning and design of the parts, the designs were printed using a Fused Deposition Modeling (FDM) 3D printer in Polylactic Acid (PLA) through steps laid out in Figure 5. All the printed parts together cost under 30 dollars to print. The dock and the charging module holders were the parts that required the most iteration, as later testing showed that distance and alignment have significant effects on power output. Parts of the dock were also constructed using corrugated paper boards, which were needed for the image recognition and path-finding component of the project. The electronic components were connected together with solder-less wire adapter connections that can be seen in Figure 1, which allows for quick and easy installation, as well as modifications.

III. Experiments and Results

A. Charging Experiment

The docking procedure was tested using the built-in Bluetooth controller function of the TurtleBot, rather than using the path-finding program. The robot was placed in several locations around the dock, a few inches off center from the dock and then driven into the dock using the controller while keeping the dock centered with respect to the robot.

The charging performances were tested separately from the docking. All batteries were drained with normal robot use until the built-in low-voltage alarm on the robot was activated. At that time, the battery was removed so that all batteries start

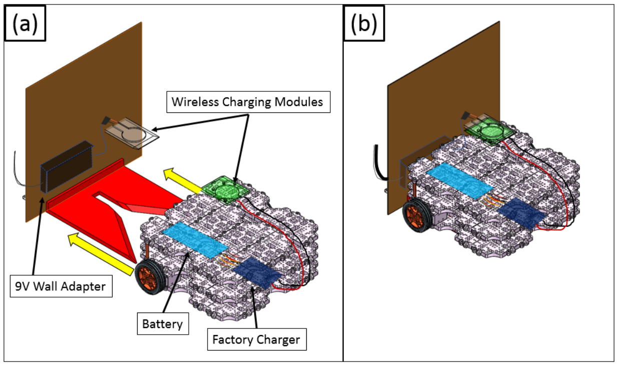

Figure 4. The complete layout and docking procedure of the system. (a) All electrical components were connected solder-free for ease of maintenance and/or modifications. (b) Once fully docked, the wireless charging modules will be concentrically aligned and charging will initiate.

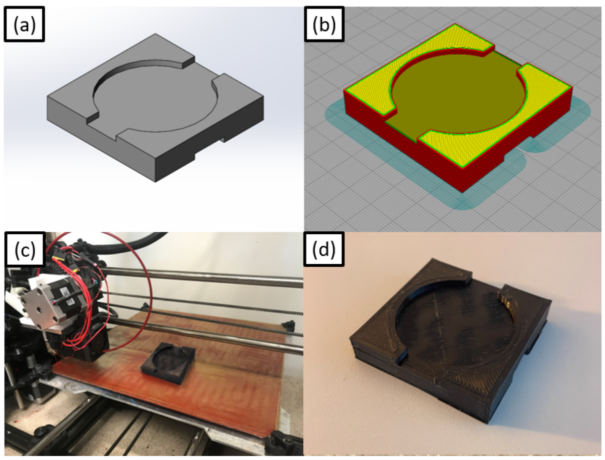

Figure 5. General 3D printing procedure. (a) For testing charging 5mm separators, they were first modeled in Solidworks. (b) Then the models are exported as an STL file and imported into a slicer software such as Ultimaker Cura as shown. (c) The Gcode file generated from the slicer is then executed by the 3D printer to initiate printing. (d) The resulting final part.

at similar voltage levels. The control test involved modeling and printing a holder that concentrically aligns the charging modules and separates them 5mm in parallel. This removes any other factors and focuses on the lowest possible charging time possible with the wireless charging system without the robot involved. A GoPro camera was used to record the charger during testing with the time-lapse function. The time-lapse was recorded with one frame taken every 60 seconds. The charging time was calculated by counting the amount of frames it took for the battery to finish charging. The amount of frames was then divided by 60 to convert to hours. Next, a separate test was conducted where the final charger was mounted onto the robot and then manually hand-docked to simulate optimal alignment. The battery was not connected to the robot and was only connected to the charger. This would test the dock's alignment and separation efficacy and find the lowest charging time possible under optimum docking conditions. The testing results are summarized in Figure 6. After the control tests were finished, another experiment was conducted where the battery was connected to both the charger mounted on the robot as well as the onboard electronics of the robot. The robot was not powered on during the testing. Finally, the factory charging set-up was also tested to compare. Each method was repeated three times for validation.

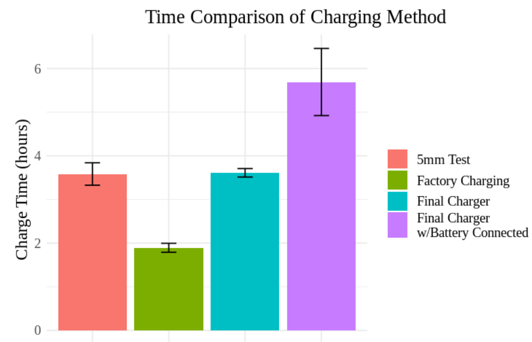

Figure 6. Comparison of four different charging methods.

As seen in the results summarized in Figure 6, the average time taken to fully charge the battery for the 5mm separation control test, final charger control test, final charger with battery connected test, and factory charging test were 3.58 hours, 3.61 hours, 5.69 hours, and 1.89 hours, respectively, all with ± 1 minute uncertainty to account our data collection method. Comparing the 5mm Test with the Final Charger test shows that they are relatively similar, which shows that the alignment of the robot was sufficient to allow for optimal charging. Some tests were also run for concentric misalignment and separation offsets of greater than 5mm. Both cases were small deviations from the control tests, but both yielded charging times of greater than 8 hours. The tests were stopped after 8 hours due to time constraints and the results are not included in Figure 6. The trials with the battery connected yielded semi-inconsistent results but gave an average charging time of 5.69. This was considerably longer than the previous tests. The only possible reason for this would be due to the additional battery connection to the robot's electronics, as the previous "Final Charger" testing was identical in all aspects except the battery connection. The charging time varied between the trials, but they were all consistently longer than the "Final Charger" tests, and thus the additional battery connection must be part of, if not the principle factor. The final average of the factory charger was 1.89 hours, considerably lower than any of the previous tests. This could be due to various factors, some of which include the amperage restriction of 1 amp across the wireless charging modules and the 9V wire adapters as seen in Figure 1 used throughout the system for ease of testing and modification.

B. Physical Experiment

Physical experiments were also conducted using the dock and the on-board robotic vision system in Figure 7 placed inside an approximately 213 cm by 213 cm area constructed of custom low-cost cardboard walls as shown in Figures 8 and 9. Three docks were used and QR codes were attached to the

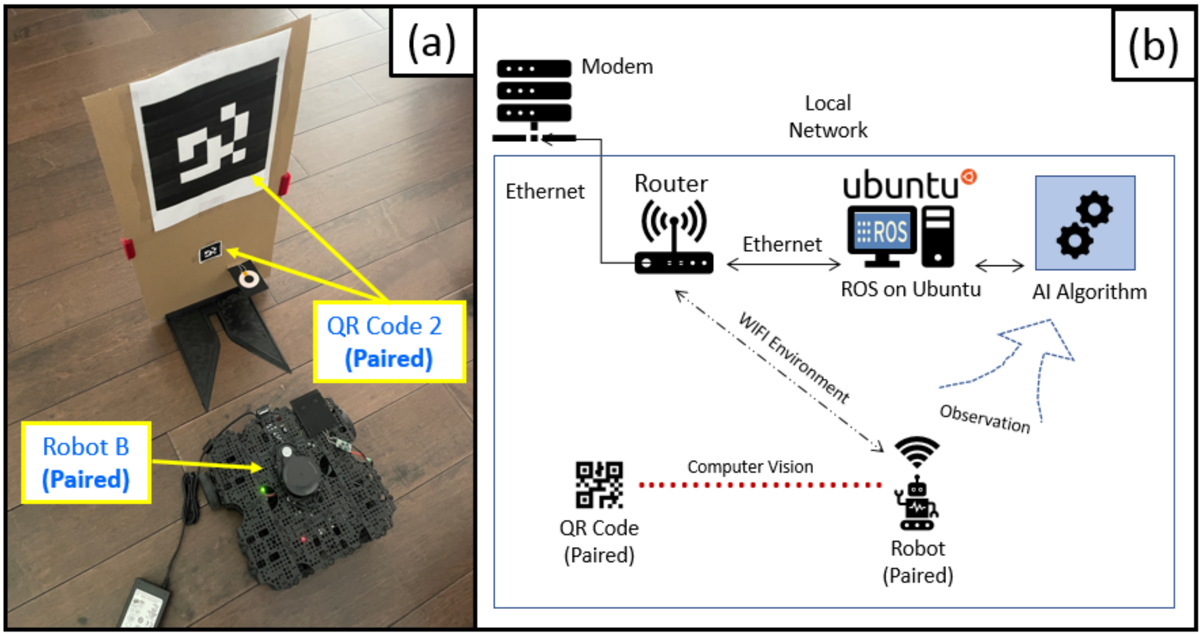

Figure 7. The complete set-up environment of the charger, robot, and dock. The real-world environment is shown in (a), while (b) shows the virtual environment and all the connections in between the members. The QR codes on top of each dock corresponds to each robot available, this will allow the robot to have their own designated docks. Furthermore, a future possibility includes using the QR codes as "available" or "unavailable" signs for the robots to recognize using computer vision.

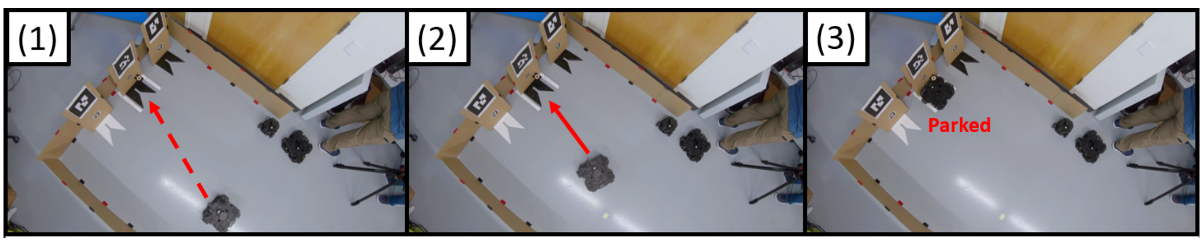

Figure 8. Snapshots from our experiment. (1) Starting position of the robot. (2) The robot scans the environment, locates the designated QR code for the dock, and begins to home in on the location. (3) The robot is fully docked.

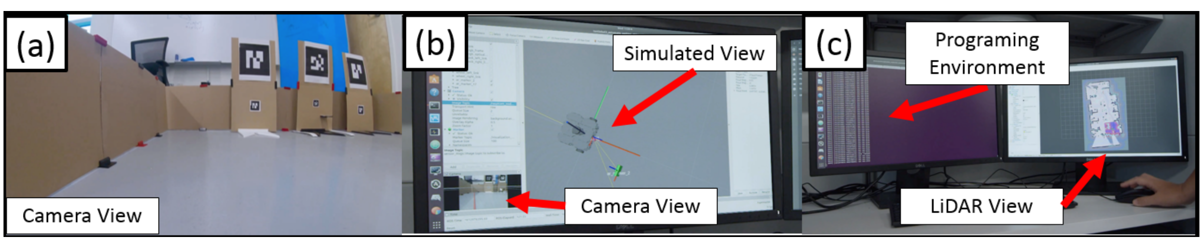

Figure 9. Snapshots from our experiment. (a) POV of the robot on its approach. (b) The feedback displays from the robot. The bottom left corner contains the camera view, as seen in (a). The rest of the display shows the computer-generated simulated view based on data collected from all the sensors on the robot. (c) The LiDAR view of the robot's LiDAR sensor. This figure displays a scan of the room where the experiment took place.

dock to allow for the system to recognize dock availability and other important information. However, in this experiment, these QR codes are used only for homing. The robot is programmed to recognize only the QR code of the middle dock to simulate an "occupied" status of the other docks. The Turtlebot was placed to the left of the dock to test its path-finding ability, then a docking algorithm was executed on the programming environment. After execution, the robot was fully docked. Thus, QR code recognition, docking, and wireless charging module alignment were all proven to be successful. A top-down view of the experiment is shown in figure 8, and it shows the general procedure of dock homing. In figure 9, different views are shown, including the camera view, and two computer UI views. As this paper does not focus on dock homing, this experiment was performed as a proof of concept instead of a detailed multi-trial test. Testing of the autonomous docking was also performed and recorded [18].

IV. Conclusion & Discussion

Through several iterations and tests, the fabricated wireless charging system yielded charging times that were functional for autonomous real-life robotic vision tasks. While the wireless charging times were longer than the factory charging times, numerous other variables helped it become a better option for power management. From the factory, the robot must be powered off and the battery needs to be manually removed each time when the battery needs charging, which not only halts the robot's task but also requires user presence and intervention. The wireless charging system does not require the robot to be powered off or for the battery to be removed. This opens a new possibility for the training to be paused if the battery is low and resume once charged, which increases the length of tasks possible in an amount of time. Due to the robot being continuously powered on with the wireless charging method, the robot could continuously operate until stopped by the user. Thus, the convenience of autonomy is much more valuable compared to the factory charger. Furthermore, this charging system is also affordable, costing less than 70 dollars to fabricate. Therefore, this method of power management would be superior to the factory chargers as well as other forms of existing chargers, not only in training efficiency but also in cost and ease of implementation.

While the robotic navigation methods have been shown to be increasingly effective in simulations, transitions to physical experiments would require a power management system to satisfy the power demands of the robot agent that were previously disregarded in simulations. Moreover, the reality gap between simulation and physical trials poses many unknown variables and imperfections that may cause problems and delays in practice, further increasing potential power demand. Thus, the implementation of this charging system would greatly benefit any projects exploring experimental robot navigation methods, as it would ease the transition from simulation to real-life testing, and allow for advancements towards fully autonomous physical training.

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