Autonomous Electric Vehicle Charging System

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Abstract - **Electric vehicle (EV) adoption has surpassed the growth of charging infrastructure. As the demand for charging stations surpass the supply, expanding charging infrastructure for consumers is crucial to improving the experience of owning and maintaining an EV. One solution is to simply provide more charging stations; however, this requires significant upfront hardware and space cost. In addition, parking spots allocated for EVs should only be used by EVs, forcing manufacturers to make a decision on the number of EV and non-EV parking spots. Current charging stations also have their own problems. When an EV is finished charging, any additional time it spends in the charging location is time that another EV could be using to charge itself. Innovative new products are necessary to create an adequate charging network. In this work, a mobile autonomous robot which charges parked EVs at any location with its own battery is presented. We created a proof-of-concept autonomous charging robot to demonstrate feasibility and motivate future work. The goal is to provide three main decoupled functionalities: parking lot navigation, EV plug guidance, and robot battery swapping. The current iteration meets these functionalities using a TurtleBot to navigate a mock parking lot, new designs and prototypes for swapping batteries, and a robotic arm paired with a computer vision algorithm to guide a 3D printed plug. Ongoing challenges for future iterations involve integrating the main functionalities and dealing with a wider range of less common use cases.**

Index Terms – Electric vehicle, autonomous navigation, battery swapping, computer vision

INTRODUCTION

The transportation industry made up 28.5% of U.S. greenhouse gas emissions in 2018 [1]. Although EVs are seen as one of the most promising solutions to reduce greenhouse gas emissions, the charging infrastructure available today limits widespread electric vehicle adoption. Many studies point to inadequate charging networks as a key deterrent in purchasing an EV [2] [3] [4] [5]. Consumers who have purchased EVs are experiencing the frustration of inadequate charging networks firsthand. It is projected that between 14 million and 30 million public charges will be required globally by 2030, to sustain a 30% market share of EVs. Today there are only 632,000 public charging outlets. The lack of standardization of these outlets are also a major inconvenience to users. EV plugs by different car manufactures may be different, and require owners to carry around adaptors to service their car. For example, Tesla owns charging stations that are not compatible with other EV models [8]. In addition, people may misuse the existing stations by parking an internal combustion engine (ICE) car in a designated EV spot (referred to as ICE-ing), or keeping a fully-charged EV parked in the spot [9]. Ultimately, this worries EV about how far their EV can take them, called “range anxiety.” EV Battery Range anxiety motivates daily scheduling of charging times and frustration when no charging spots are available.

The current system angers both EV drivers, who struggle to find charging locations, and ICE drivers, who feel EV charging spots minimize their parking choices. However, since EVs still only account for about 1% of vehicle sales in the United States, installing additional charging stations may appear costly and unnecessary [10]. Therefore, limited charging infrastructure and low adoption rates influence each other, making it difficult to break the cycle of cause and effect [8].

Modern infrastructure that takes advantage of current technology can be utilized to disturb this cycle. This project introduces an autonomous robot electric vehicle charger. These robots can be stationed in a parking lot or garage, drive to a parked EV, and charge the car while the driver is away. The autonomous robot would charge the EVs with an on-board battery. To maximize efficiency, while the robot is charging a parked EV, a designated charging station will charge backup batteries. When the robot depletes its battery, it can swap its battery with a charged battery from the charging station.

This solution eases the burden on EV owners, who can park in any spot and have their vehicle charged. In addition, the robot precludes the necessity of installing more dedicated EV charging infrastructure in new parking spots. As more electric vehicles come on the road, the solution can easily scale without taking up more room by adding more robots. This project introduces a less intrusive, scalable, and likely cheaper option for widespread EV charging infrastructure. The autonomous charging robot would minimize range anxiety for current owners and encourage wider adoption of EVs.

PROJECT OBJECTIVES

The goal of this project is to develop a prototype that demonstrates the functionality and feasibility of an autonomous charging robot. The proof-of-concept project focuses on three challenges: (1) EV plug guidance, (2) parking lot navorigation, and (3) robot battery swapping. The

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final prototype will be evaluated based upon the functionality of these three subsystems individually. The system will be improved on and eventually integrated by future capstone teams.

In order to effectively charge parked EVs, the robot must guide its charging plug into the EV's port. This solution is designed to work on various EV make and models, which have various locations of charging ports. Therefore, this system will locate the port location on the car through computer vision algorithms. This vision must guide the plug into the EV's port, dynamically making adjustments as the plug approaches the port.

To further align itself with the parked EV, the robot must seamlessly navigate parking lots to position itself to charge these vehicles. Typically, multiple parked EVs require charging, thus the robot must move to multiple parking spots and vehicles without losing track of its position. In addition, its positional data allows the robot to easily return to its charging station to swap its own battery. Since the robot will be deployed in an active parking lot, this navigation will also incorporate obstacle detection in order to avoid collisions with entering/exiting cars or people in the parking lot.

The autonomous robot must charge multiple EVs with its own power supply, which would inevitably run out of charge. Thus, to minimize downtime and continue charging cars, the charging battery on-board the robot must be replaced or recharged to continue operation. A charging station must be designed to charge depleted batteries, store charged batteries, and interface with the robot to exchange batteries.

The charging station should be preferable to current charging infrastructure, and should take up minimal space. Thus, storing multiple batteries is essential for the charging station to make it scalable and minimize the footprint within the parking garage. In addition, to minimize complexity of the robot, the charging station must be responsible for removing batteries from and supplying batteries to the robot. This proof-of-concept project focuses on mechanical functions of swapping the battery while not directly considering the electrical specifications for charging a battery.

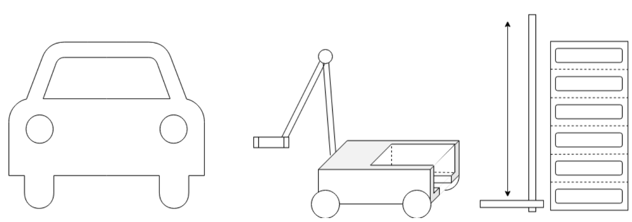

FIGURE I
END VISION OF AN INTEGRATED ELECTRIC VEHICLE CHARGING SYSTEM.

RELATED WORKS

Within the last five years, prototypes from well-known manufacturing companies have emerged in the autonomous charging sector. In 2015, Tesla posted a video showing a charging plug autonomously navigate into a Model S port via a metal arm. The system is mainly composed of a "solid metal snake" as Elon Musk called it, which bends into position to charge the vehicle. Since the release of the video years ago, Tesla has not commented on how the prototype has advanced. However, Tesla's initial exploration into autonomous charging indicates the potential role this technology could play in the future [11].

Recently, the Samsung C-Lab released their take on autonomous charging for parking lots. The proof of concept is run through an app, which calls a charging robot called EVAR (Electric Vehicle Autonomous Recharging Robot) to a specific parking spot. The robot uses LiDAR (Light Detection and Ranging), touch, and ultrasonic sensors that handle obstacle detections on all sides. Once the robot has reached the car, it plugs into an adaptor connected to the car's charging port. The main functionality of the Samsung prototype is comparable to the core requirements ofh this project. Similarities include the ability to navigate a parking lot and plug a charger into a port. However, Samsung's product does not demonstrate battery swapping capability, which is necessary for continuously maintaining the operation of the charging system [12]

METHODS

I. EV Plug Guidance

The design for the plug guidance system uses an off-the-shelf robotic arm and camera in addition to a 3D printed EV plug/port designed to resemble the types currently used in industry. The robotic arm used to guide the EV plug is the Dobot Magician, capable of moving in 3-axis space while keeping its appendage parallel to the floor. This is crucial in that the charge plug attached as the arm's appendage must remain parallel with the floor and therefor perpendicular with the EV charge port (Figure II).

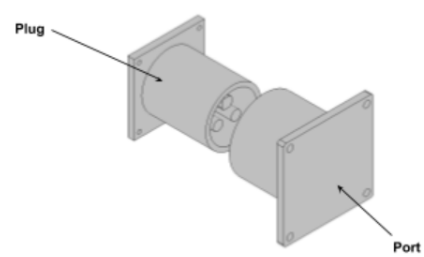

FIGURE II
3D PRINTED EV PORT AND PLUG

To guide the plug into an EV charging port, the arm must detect a port, correct for alignment, and then plug in. A camera is mounted to the arm in order to detect the positioning of the port and perform these actions. For the mock-up in this work, we use a circular plug/port due to the commonality of circular charge ports in the EV industry. Captured images from the camera are analyzed using a Hough Transform and Template Matching algorithm which finds the edges in an image and looks for groupings in the shape of the port (Figure III). It then calculates which grouping most resembles the port and returns the coordinates as well as the size.

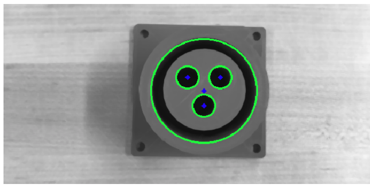

FIGURE III
HOUGH TRANSFORM ALGORITHM DETECTING 3D PRINTED CHARGE PORT.

The arm begins by panning vertically, sampling for the appearance of an EV port. Upon successful detection, the arm will notify the TurtleBot to make any horizontal adjustments. Following, the arm/camera will begin a feedback algorithm which iteratively analyzes the plug location and makes vertical adjustments until the camera is aligned with the port. At this moment, a vertical offset movement equal to the distance between the mounted camera and plug is performed. This is done to align the plug with the port. Then, the plug moves forward to dock into EV port. Upon charge completion the arm will retract from the EV.

II. Parking Lot Navigation

To simulate the requirements of the final system, the project will utilize a TurtleBot 3 WafflePi. The TurtleBot is a wheeled vehicle which receives and executes directional commands. Additionally, it can map its surroundings and detect nearby objects with its LiDAR sensor. These inherent functionalities will be utilized to mimic the final robot's movement around a large-scale parking lot.

A mock parking lot outlined with tape serves as a test location, with RC cars mimicking parked EVs (Figure IV). The robot's charging station is represented by an arbitrary location in the grid, which will be stored by the robot so it can navigate there to perform battery swapping. The mock parking lot has different colors of tape that makes up the parking lot boundary and the parking spot lines, which can be distinguished by the TurtleBot's camera.

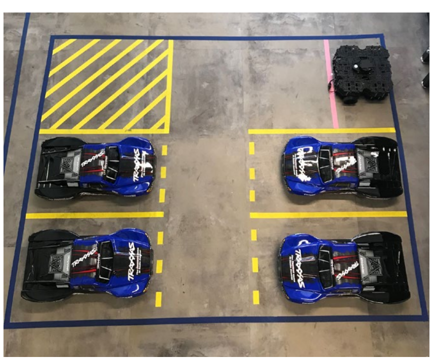

FIGURE IV
MOCK PARKING LOT OUTLINED WITH TAPE ON FLOOR

The TurtleBot runs on Robot Operating System (ROS), which incorporates many prebuilt libraries supporting a wide range of functionalities, including autonomous driving. In addition, it allows the user to edit these libraries and run customized scripts. Finding the relevant libraries, adjusting them to work for our system, and editing their functionality where applicable are essential to meeting the requirements of the system.

The TurtleBot includes a mounted, continuously operating LiDAR sensor that captures information about the TurtleBot's environment, such as the location and distance of obstacles in relation to the TurtleBot. This allows the TurtleBot to detect obstacles like pedestrians or poles, identify vacant or full parking spots, and detect other changes in its environment. The simultaneous localization and mapping (SLAM) algorithm takes LiDAR data and creates a 2D map of the surrounding area. SLAM algorithms are tailored to robotic mapping and are used to construct and update a map of an unknown environment while also monitoring the robot's location on the map. Creating and saving a map of the mock parking lot is crucial for the robot's repeated navigation of the parking lot. The map allows the robot to navigate to specific locations on the grid, such as cars or the charging station. Since the LiDAR is constantly running and updating the TurtleBot's internal map, it is also able to spot approaching vehicles, people, or other moving obstacles. The LiDAR is supplemented by a Raspberry Pi Camera Module v2.1, permitting lane detection and object recognition. While this camera is not suitable for scanning an EV's port and guiding the charging plug, which is handled by a secondary camera mounted above the charging plug, it's scanning capabilities are important for parking lot navigation.

The TurtleBot is built with a Raspberry Pi 3 that handles computation, networking, and storage along with an OpenCR1.0 (Open-source Control Module for ROS) embedded board that handles communication between the different devices on the robot. In addition to the prebuilt ROS libraries, the Raspberry Pi 3 is also able to run user-written Python code that grants greater control over the TurtleBot's functionality. The ROS libraries are suitable for implementing SLAM algorithms and elementary autonomous navigation, but the Python code is necessary to customize decision-making algorithms, such as determining whether or not to charge a parked vehicle, as well develop more advanced navigation techniques.

III. Robot Battery Swapping

The design for the battery swapping subsystem is original and was created through ideation and iteration. Thus, no off-the-shelf product contributes to the core functionality. The orientation of the charging station structure underlies the entire battery swapping subsystem. It determines the interactions between the robot, battery, and charging station, and helps to define the robot's navigation through a parking lot.

A vertical charging station, with compartments one on top of another, minimizes the required ground space for the charging station. In addition, multiple compartments charging multiple batteries allow the charging station to service multiple robots and minimize downtime of each robot. This design, however, requires the charging station to have moving parts which take the battery from the robot to the compartment height. The charging station must also transfer the battery into a specified charging compartment above the battery's initial height. While more mechanically complex, the reduced space is a significant improvement over the current system, and the scalability and ability to provide for multiple robots may decrease overall cost.

Therefore, the battery swapping design is comprised of two main components: the removing/replacing mechanism that interfaces with the robot and the battery charging station. An elevator design with a platform is responsible for removing and replacing the robot's battery. The charging station is composed of a stack of compartments and primary function is to store and charge multiple batteries at a time. Figure V shows the interaction of the robot with the charging station. Steps 1-4 illustrate the procedure behind removing, storing, and replacing the robot's battery.

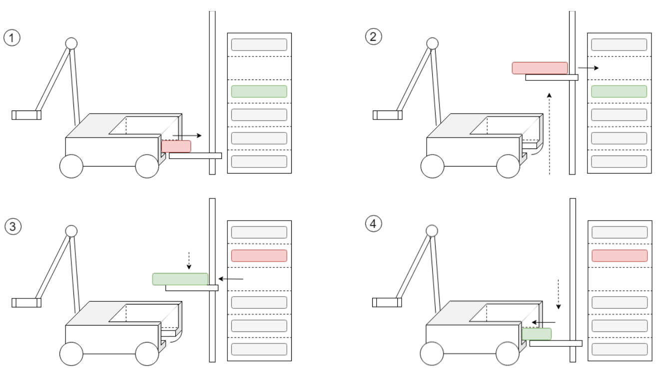

FIGURE V
PROCESS OF REMOVING, STORING, AND REPLACING THE ROBOT'S BATTERY

Elevator / Platforms

With no moving parts on the robot's battery tray, a compatible transfer mechanism between the robot and charging station is necessary. An "elevator" design meets requirements by raising the battery from its starting location on the robot. At no point should the battery be dropped or thrown onto the robot. This necessitates that the platform on the charging station passes through the platform on the robot. Thus, compatible U-shaped and T-shaped platforms shown in Figure VI were designed. The U represents the robot's stationary platform and the T represents the charging station's moving, elevator platform. The charging station platform can lift a depleted battery out of the U-shaped dock or lower a charged battery back on. Both platforms are capable of stably holding a battery.

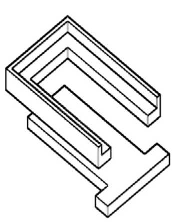

FIGURE VI
COMPATIBLE U- AND T-SHAPED PLATFORMS

Conveyor / Compartments

After the elevator raises the battery from the robot to the desired height, it must move the battery into a compartment within the charging station. This necessitates horizontal motion of the battery. One solution is to put wheels or a low friction surface on the elevator platform, and place the battery atop this surface. Tilting the entire surface upwards would let the battery fall into a specified compartment, but would add an additional degree of freedom and complexity to the motion of the platform. Conversely, adding a conveyor belt on top of the platform would provide a simple method of bidirectional motion to move the battery onto and off of the compartment. Although the conveyor belt and associated motor must attach to the platform, it allows the elevator platform to solely move up and down. The conveyor belt system maintains simple control of the platform and ensures that the battery is stable atop the platform. Additionally, the compartment must return the battery to the T-shaped platform on the elevator, and will contain its own conveyor belt. Implementation of a conveyor belt on the T platform and on each compartment allows for efficient battery exchange.

RESULTS

I. EV Plug Guidance

The guidance system (Figure VII) achieves its goal of detecting and docking a modeled plug into a modeled EV charge port. Given the joint-based design of the arm, it's libraries operated using a radial coordinate system. Thus, an abstraction to the core-library was used such that the arm could be operated with a linear coordinate system. For the detection of a port, images are analyzed using the Hough Transform and Template Matching algorithms, which returns a set of possible ports. A filter is applied to remove extraneous detections and return the most probable location of the port. The algorithm proves to be an appropriate choice by its ability to identify common EV port designs. To prevent optical distortion of the circular shape of the port, the camera is mounted to be perpendicular to the port, despite resulting in the plug being out of camera-view.

FIGURE VII
DOBOT MAGICIAN WITH MOUNTED CAMERA WITH PLUG

After integrating the arm manipulation library and computer vision algorithm, a controller was designed to govern the plug guidance process. Upon arriving to a parking spot, the arm scans for a charging port by panning vertically, taking and analyzing images. Once the computer vision algorithm has identified the port, it calculates the need for horizontal adjustment which is performed by the TurtleBot. The guidance system then uses a PID feedback algorithm to vertically align the camera to the port. At this moment the camera is now in full alignment. The arm then performs a vertical maneuver equal to the distance between the camera and the plug. This results in the plug's alignment with the EV port. The arm then moves the plug forward until fully docked into the port. The arm's plug will retract upon completion of task.

II. Parking Lot Navigation

As previously stated, the TurtleBot's primary objectives are parking lot navigation, object detection, and recognition of parked EVs. The current procedure utilizes TurtleBot's patrolling algorithms in a fixed grid that represents a parking lot. This patrolling algorithm dictates a pattern for the robot to continuously follow, in this case a rectangle tracing the parking spots within the grid. The parking spots and grid boundaries are identified and registered by the TurtleBot's Raspberry Pi camera.

Once the TurtleBot was able to correctly navigate the parking lot, the next step was implementing obstacle detection in order to avoid collision with parked vehicles or walls. SLAM algorithms, which are made possible by the robot's LiDAR sensor, are able to repeatedly map the TurtleBot's environment including any newly introduced obstacles, such as driving vehicles. Identification of an obstruction will cause the TurtleBot to halt and slowly reverse until the obstruction moves or it is able to navigate around the obstacle.

The TurtleBot's LiDAR will also detect parked vehicles and identify them as obstacles, thus the Raspberry Pi camera is necessary to distinguish between a parked vehicle within a designated parking lot or an unexpected obstruction. This camera is able to perform lane detection and distinguish colors, thus it is important that the grid's boundaries are colored differently than lanes outlining parking spots. Additionally, the camera has functionality that permits it to scan and analyze signs or other surfaces, indicating that a parking spot sign rather than uniquely colored lines would also be a feasible approach.

III. Battery Swapping

The battery swapping design was realized through the outsourcing of parts. An elevator, platform, conveyor belt, and storage system are all well-developed technology. However, the integration of these components leads to a unique function. Components were ordered from ServoCity and RobotShop to streamline the building process and more feasibly reach design goals. These companies supply motors, actuators, structural components, and electronics. The size of this prototype is approximately 24'' tall, 9'' wide and 9'' in depth. The size of battery meant for this system is a 7" x 4" x 1" power bank. Once the concept behind the design is verified, the scale of the prototype will increase.

A linear motion kit with a servo motor was used to drive vertical movement of the elevator platform. The platform was attached to the kit on one side, which provided actuation, and an X-Rail on the other, which provided stability. The T-shaped platform extended perpendicularly from the kit and rail. The built elevator and platform system are detailed in Figure VIII.

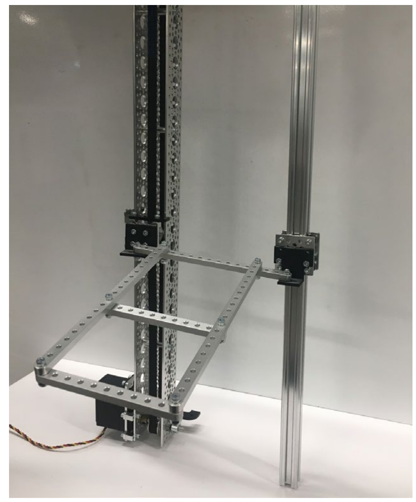

FIGURE VIII
ELEVATOR SYSTEM USED FOR BATTERY SWAPPING

The charging station structure was created with X-rails. Four 24'' X-Rails provide the frame for the height, and are connected by three perpendicular 9'' X-rails. A 3'' Lynxmotion track, 6 tooth sprockets, and passive idler hub were order to make the conveyor belt. Although this assembly will go in each charging station compartment, for the first proof of concept just one compartment and the T-shaped platform contain the conveyor belt.

The construction and integration of each component of the battery swapping subsystem is in progress. In the near term, the assembly of this initial prototype will be completed and tested. Since this is the first stage of the small-scale battery swapping design, many more complex considerations must be taken into account. However, understanding the methodology behind the mechanical system will prove invaluable to future iterations.

FUTURE WORK

I. EV Plug Guidance

The current design succeeds in the autonomous detection and docking into a modeled charge port. However, there are areas in which the prototype is limited. The joint-segmented arm results in a spherical range of motion of the arm. Due to this factor, the arm's horizontal reach is not constant but varying depending on the vertical height of the arm. While constraining movement to a smaller rectangle space inscribed within the spherical space is a feasible solution, using a robot with a rectangular range of motion eliminates this problem.

Additionally, the guidance system bases its adjustments off of the pixels from the camera's image. For this reason, using a camera with a higher resolution will allow for more accurate alignment; however, this is computationally more expensive.

II. Parking Lot Navigation

The current navigation of the parking lot, while functional, is not robust enough to handle all of the edge cases and the time spent by the TurtleBot charging vehicles. Moving forward, a more sophisticated algorithm will need to be implemented that allows the TurtleBot to navigate to specific parking spots and to return to its charging station when necessary. This will eliminate wasted power spent patrolling the parking lot and will allow the TurtleBot to seamlessly pause or resume charging a specific EV.

Furthermore, the TurtleBot will eventually require a different, safer way of responding to obstacles detected within their path. Instead of halting and reversing, a new algorithm will need to ensure that the robot correctly navigates around the obstruction without losing track of its position or hitting another obstacle. The current implementation raises concerns involving reversing into another approaching vehicle and is also apt to incorrectly alter the robot's patrol pattern.

III. Battery Swapping

With the mechanical prototype underway, the next focus should be to implement charging functionality. The electrical specifications for the charging mechanism must be considered in future iterations. Neither the connections of the battery to the robot nor in the charging station were tested. Additionally, the power required to charge an EV and the speed of discharge must be considered to choose an appropriate battery.

Additionally, autonomous control of the motors should be implemented. This control is necessary for any real-world implementation of the design so it is not reliant on human operation. The robot also requires a method to keep track of which compartments are full and how charged each battery is.

CONCLUSION

In this work, three subsystems for an autonomous electric vehicle charging robot are presented. These include a robot that maps and navigates a parking lot while avoiding obstacles, a battery swapping device that replaces the robot's depleted battery with a charged one, and a robotic arm that guides an EV plug into a port. These components indicate a promising path to an integrated system for EV charging. This first attempt at this large design problem confirms the feasibility of its goals. Once the components are acting together, they may offer a promising solution to the limited charging infrastructure for electric vehicles.

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