Wireless Charging Table with Automatic Alignment

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Abstract

While the Qi wireless charging protocol is increasingly adopted by the market of mobile devices, the precise alignment required by the Qi protocol between a device to be charged and the base station imposes inconvenience for users of public Qi hotspots. Specifically, in cafeterias and coffee shops that deploy fixed Qi chargers on tables, customers' positions are restricted to those specific locations. To bring a smoother user experience, we design and implement a wireless charging table that allows arbitrary device placement. Devices on the table surface are recognized and located with computer vision. Multiple coils are moved and aligned with the devices by a mechanical grabber with magnetic attachment under the table surface. The system has three charging coils, supporting up to three devices concurrently, with the coils scheduled by a control unit. Both the system and the individual components are tested and verified against design requirements.

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1 Introduction

As an increasing number of manufactures adopt wireless charging into their mobile devices [1], wireless charging hotspots can be found in a larger number of public places such as coffee shops, cafeterias, and airports [2] [3]. However, the commonly adopted standard, the Qi standard, requires the device being charged to be aligned with the Base Stations [4], which limits the positions of the Qi hotspot customers and negatively impacts the user experience.

Our goal is to provide a seamless wireless charging experience at Qi hotspots like cafeterias and coffee shops where customers sit around tables. We intend to design and manufacture a smart table that automatically moves and aligns wireless charging coils with users' devices, allowing the users to place their devices arbitrarily on the table. The table can charge multiple devices simultaneously. The coils are moved with a mechanical structure similar to 3D printers. Devices to be charged are recognized and located with computer vision. A camera is placed at the bottom of the table and inspects the table surface through two layers of glass for our prototype design, while in practical settings, existing surveillance cameras in cafeterias or coffee shops can be used. The control unit communicates with the device to check whether it can be charged wirelessly.

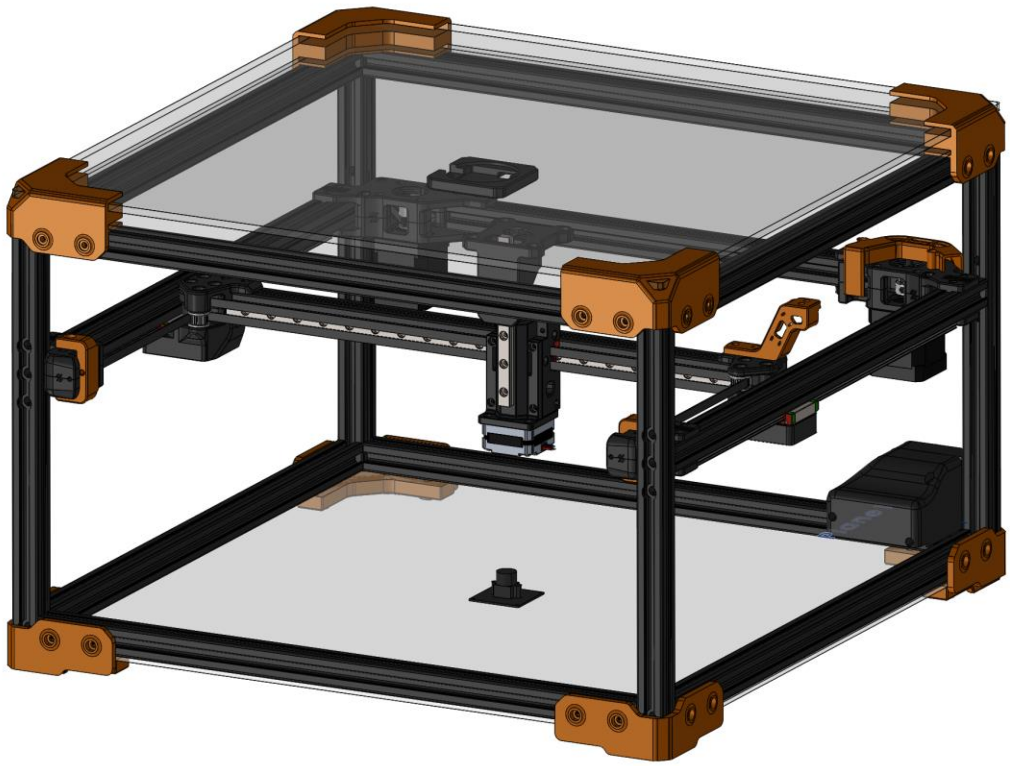

Figure 1. CAD Overview of the Product

1.1 Qi Wireless Charging Standard

Qi is an open standard developed by the Wireless Power Consortium [4]. This protocol has been adopted by major mobile device manufacturers such as Apple, Google, Huawei, and Samsung [1]. A Qi system consists of a power transmitter (the Base Station) and a power receiver (the Mobile Device), which are placed a few centimeters apart during charging [4]. Power is transferred from the transmitter coil to the receiver coil using electromagnetic induction [4]. Magnetic shielding around the coils helps improve the power transmission efficiency. Power regulation is performed by the transmitter control unit, which receives unidirectional communication from the receiver [4].

The protocol requires the Mobile Device and the Base Station to be aligned. Misalignment or excessive distance between coils lowers the power transfer efficiency [4]. Most commercially available Base Stations for individual users require Guided Positioning [4], where users need to place the Mobile Devices at a specific location. In the Qi hotspot settings, it means that users are required to sit around some fixed positions around the table. In contrast to the guided positioning, Free Positioning allows arbitrary placement of the Mobile Device on the surface of a Base Station. One approach to achieve Free Positioning is deploying multiple overlapping coils, which has been proven to be difficult by the cancellation of Apple AirPower [5]. An alternative approach for Free Positioning is to move coils using mechanical devices. Xiaomi released a wireless charger [6] using this technology, but it is designed for individual users and charges only one device at a time. Our design targets the public Qi hotspot scenarios, allowing table-scale Free Positioning and charging multiple devices concurrently.

1.2 High-Level Requirements

- 3 Qi-compatible devices (possibly with phone cases of at most 2mm) can be charged concurrently with proper power supplies (maximal 15W each).
- Devices placed on allowed locations should be recognized and get charged within 15s after their placement if the table is in the idle state.
- Qi-incompatible devices should be recognized and memorized for 2 hours, given their locations don't change. The system should not try charging those devices repeatedly.
- The table surface should withstand the weight of at least 20kg at the center.

2 Design

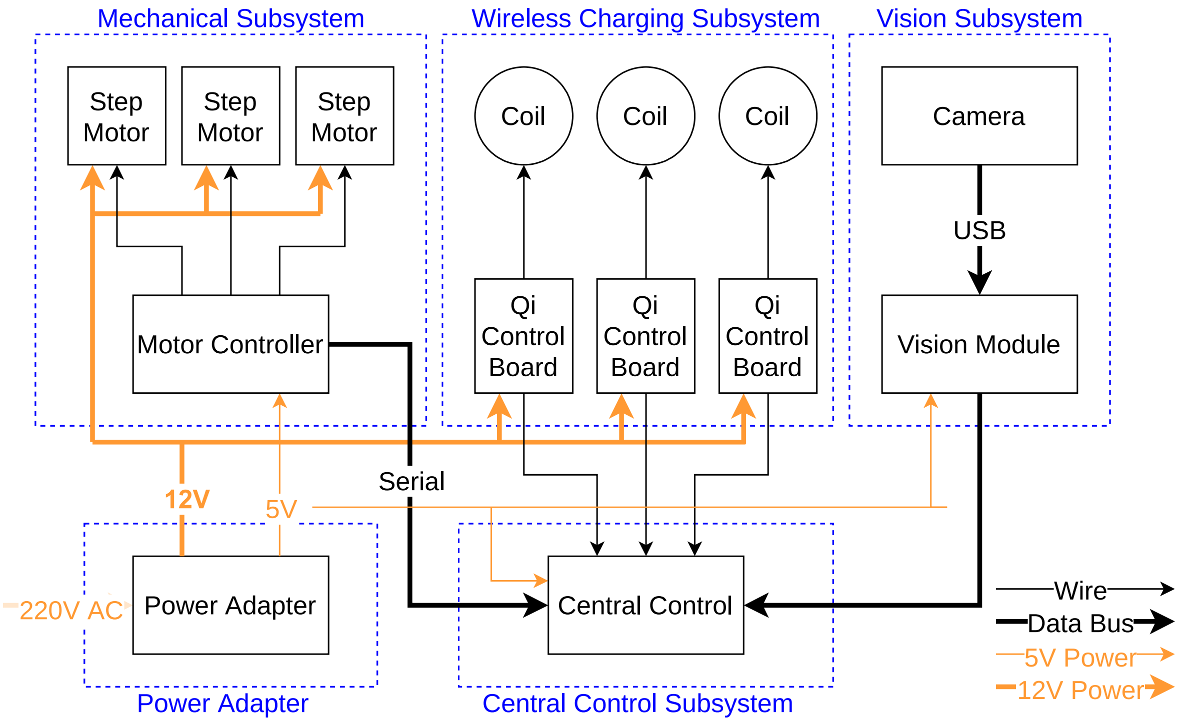

Figure 2. Block Diagram

Our design consists of four subsystems and a power adapter module, as shown in Figure 2. The vision subsystem will process images of the table surface, will identify the locations of the devices, and will send them to the central control unit. The central control unit instructs the mechanical system to move coils to the desired locations. The wireless charging modules then try communicating with the device. Based on the feedback from the charging subsystem, the central control unit decides whether the devices are wirelessly chargeable and moves the coils accordingly. The subsystems are described in detail in the following sections.

2.1 Physical Design

The main idea of the physical design is to develop a reliable 3D motion system that is mounted below two layers of glass. Between the layers, 3D-printed plates with wireless charging coils are fitted inside and magnets at corners are placed. The locations and polarity mappings of the magnets are carefully designed to ensure the pairing unicity with the moving grabber. For the grabber, with 3D motion (X, Y and Z axes) capability, it will have an opposite magnets system that moves up and down to grab and to release the wireless charging coils. For the prototype we implement, the operational area of the X-Y plane is approximately $500 * 500mm$.

Based on the application, we decided to choose $5mm$ ($3/16$”) tempered glass for the table surface. Based on the glass weight load calculation sheet, a $500 * 500mm$ ($20 * 20$”) $5mm$ tempered glass for patio table should be able to hold approximately $140kg$ ($300lbs$) at the center. Usually, for a commercial patio table no larger than 24 inches, the $3/16$” tempered glass is the most common choice.

The distance between the coil and the table surface can be designed to achieve within $1mm$. PCPBT, which is a well self-lubricated material, can be used to print the base for the coils. Thus, the distance between the coil and device can be within $10mm$.

2.2 Wireless Charging Subsystem

For reliability and compatibility, we will use commercial Qi modules from a manufacturer named IC Superman. Each module includes a coil and a control board, driven by a $12V$ power supply. The module can supply up to $15W$ to the device being charged. The maximal wireless charging distance is 10mm by the datasheet, which is verified in the verification section below. The module can detect foreign mental objects.

The module is fitted inside a 3D-printed container. Two wires are used to supply power to the module, and another two wires are connected to the central control unit to transfer status information.

2.3 Mechanical Subsystem

The main moving component of the system is a large-scale moving mechanism under the table surface. The coils are placed in 3D printed base between two layers of glass above the moving mechanism. The 3D printed bases are designed with magnets with certain mapping at the corners. And the moving grabber is designed to have a corresponding magnet mapping to pair with the bases. The moving grabber is capable of moving in X, Y and Z directions to grab and release the coils. The 3D motion system is actuated by stepper motors and controlled by a 3D printer control board.

For the accuracy of the motion system, $1.8°$ NEMA17 stepper motors and TMC2209 stepper drivers are used. Therefore, with a 16 micro step setup, the motion system can advance $0.1125°$ each step. Also, considering 20 tooth 2GT pulleys are used, the radius of the pulley is set as $6.11mm$. Thus, a final theoretical precision of $6.11mm \cdot 2\pi \cdot 0.1125°/360° = 0.012mm$ can be achieved.

For the speed and acceleration of the motion system, the stepper motors can provide a consistent torque of $480mN \cdot m$. Thus, the force provided by the belts is $480mN \cdot m/6.11mm = 78.56N$. The designed weight of the moving component is around 1200g. Therefore, the theoretical maximum acceleration of the system is $78.56N/1.2kg = 65{,}467mm/s^2$. BigTreeTech SKR V1.3 is selected as the control board for the mechanical subsystem for its capability of processing high frequency command.

2.4 Vision Subsystem

The vision subsystem includes two components: a camera along with an embedded GPU that runs the device detection algorithm, and an interface module to pass the information to the central control unit. The camera takes pictures of the table surface and sends them to the embedded GPU through USB. Since we plan to put the camera below the center of the table, we can work on the image directly. The object detection algorithm then identifies smartphones in the image and generates 2D coordinates, which are then sent to the central control unit. The details of the detection algorithms will be covered later. To satisfy the

latency restriction in the high-level requirements, Jetson Nano [7], an edge GPU with hardware acceleration, will be used as the processing unit.
The algorithms will be based on plain computer vision algorithms instead of the neural network solutions as the detection is relatively simple. Also, the simple solution tends to be more robust, lightweight, real-time, and doesn't require the training of the model. OpenCV library is used to process the images and to find the bounding boxes. The overall processing pipeline of the images is as follow:

(1) The colored image fetched from the camera is converted to grayscale.

(2) To ignore the noise in the image, we choose to smooth the image. It essentially takes the average of all the pixels under the kernel area (e.g., 3 by 3) and replaces the central element with the average value.

(3) We then use thresholding to binarize images, which can help us to find the contour. The overall goal is to binarize images such that we keep the brightest or darkest part.

(4) Next, we find contours based on images after thresholding. The OpenCV will find the contour of white objects from the black background and works best on binary images.

(5) We generate the bounding box for each contour. Then, we filter the bounding box if it is too small, or it does not match a certain aspect ratio range.

(6) Given the bounding box, we will further filter it based on real-world settings, like the width and height of the bounding box.

The overall flow can be expressed in the following chart on the right. Each number on the transition indicates the step mentioned above.

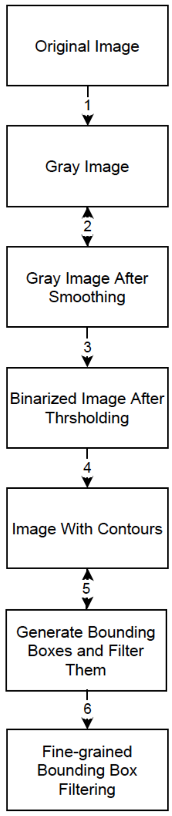

Figure 3. Image Processing Flow Graph

When we get the bounding box, we can calculate real-world location easily. The OpenCV will give the center location for each bounding box in the image. The table width and height are known. The image resolution/width and height are known. Since the camera is right below the table. We can calculate real-world location using a similar triangle. Then we send the location information to the central control unit through GPIO pins.

2.5 Central Control Unit

The central control unit in the block diagram mainly consists of a micro-computer, with its interfaces to other modules and the scheduling algorithm running on it.

For the hardware to use for the central control unit, originally in the design document, we planned to use BeagleBone Black as the hardware for the central controller, which has an AM335x 1GHZ ARM Cortex-A8 processor, 512MB DDR3 RAM, 4GB on-board flash storage, serial ports, etc. BBB is selected mainly because it runs a Linux OS, which gives convenient interfaces for the user to control outer devices. However, the vision subsystem uses NVIDIA Jetson Nano as the hardware to handle the image processing in computer vision, which also has a CPU and runs Linux OS. As a result, using only the Jetson Nano is enough to complete all the works and we decided not to use BeagleBone Black.

2.5.1 Interface with the Mechanical Subsystem

The central control unit instructs the motor controller to control the movement of step motors. Specifically, messages encoding motor indices, directions, and distances to move are sent from the central control unit to the motor controller. Those messages are calculated by the scheduling algorithm based on the recorded positions of the motors, charging status information from the wireless charging subsystem, and the destination positions from the vision subsystem.

The communication between the central control unit and the mechanical subsystem is done via a serial bus. The mechanical part requires this because it is based on a 3D printer model with a controller to accept commands sent by serial port.

2.5.2 Interface with the Wireless Charging Subsystem

The Qi protocol would handle whether it should start charging or not according to the device placed on it. As a result, the central control unit only needs to pull its status and use the information for the mechanical subsystem.

The interface between the wireless charging subsystem is wires. Originally the wireless charging coil only has LEDs that show the charging status. Nevertheless, if wires are connected at the position of the LEDs, the charging status information can be read. As a result, the status message is sent by the voltage level through wires. The voltage information is collected by the GPIO pins of the hardware of the central control.

2.5.3 Interface with the Vision Subsystem

After the central control is deployed on the Jetson Nano, the communication between the vision subsystem and the central control becomes an inter-process connection on the same device. We decided to run the central control and data collections on different threads.

2.5.4 The Scheduling Algorithm for the Central Control Unit

The central control unit operates a state machine with four states: Waiting, Calculating, Moving, and Error, as shown in Figure 4. At the high-level, at the Waiting state, the state machine fetches and analyzes the information from the vision subsystem and the wireless charging subsystem; at the Calculating state, coils are scheduled and assigned to the detected devices; at the Moving state, the central control unit instructs the mechanical subsystem to move the coils according to the scheduling result; the Error state is the fallback for problems that cannot be handled by the control unit. Appendix A shows the detailed operations of each state.

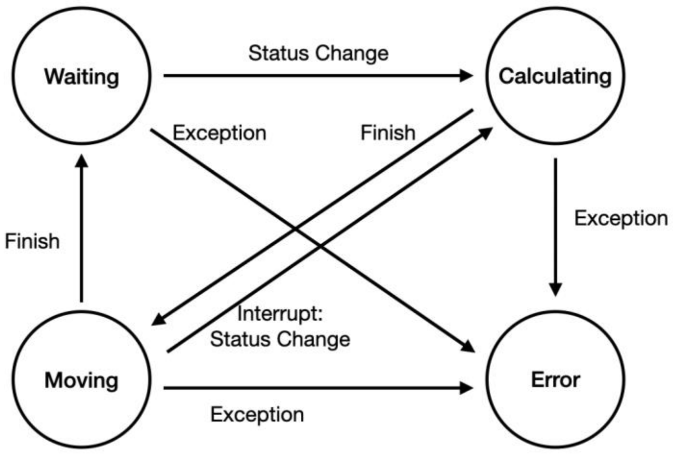

Figure 4. State Machine of the Central Control Unit

2.6 Power Adapter

A power adapter converts 220V AC input to 12V and 5V DC outputs, driving components of the whole system. 12V output drives the Qi modules, the step motors, and the electromagnet. 5V output drives Jetson Nano and microcontrollers. The power adapter has overcurrent and short-circuits protections. The specific model is selected to meet the needs shown in Table 1, with a certain amount of safety margins.

Table 1. Current Requirements of the System

Module	5V Current Requirement	12V Current Requirement
Qi Modules * 3		1.5A * 3
Jetson Nano	3A	
Mechanical motors		10A
Other Microcontrollers	2A	
Total	5A	14.5A
Selected Power Adapter	20A	20A

3 Design Verification

3.1 Wireless Charging Subsystem

The verification on the wireless charging subsystem focuses on two aspects: the ability to charge devices wirelessly and the correctness of charging statuses reported to the central control unit. A few tests have been performed to verify that the Qi modules meet our requirements.

The major concern about the wireless charging ability is the maximal charging distance of the Qi modules. The module datasheet claims the maximal charging distance is $10mm$, which is verified by our unit test following the Requirement and Verification Table 6. The coil is placed below a piece of glass with approximately $1mm$ margin, allowing free movement of the coil. One or two layers of 3mm glass are used to simulate a table surface of $3mm$ or $6mm$. An iPhone Xs and an AirPods Pro are used as testing devices. They are placed on the glass with or without a phone case of approximately 2mm thickness in between. The test results are shown in Table 2. The results for both devices are the same for all the settings and therefore combined as one.

Table 2. Test Result of the Maximal Charging Distance

Glass Thickness	Phone Case	Result
3mm	No	OK
3mm	Yes	OK
6mm	No	OK
6mm	Yes	Require strict alignment

For the prototype we implement, we use $5mm$ (less than the one in the test setting, 6mm) glass for the table surface. In addition, with precisely designed coil containers, the distance between the coil and the glass (approximately $1mm$ in the trials) can be further reduced. Therefore, the maximal charging distance of the module meets our needs. However, the test shows that accurate alignment is still preferable to ensure successful communication between the module and the device to be charged. To accommodate possible errors in the coordinates calculated by the vision subsystem, the central control unit should move the coil around the target location a little to thoroughly search the coils of the devices.

The charging statuses are reported to the central control unit through voltage variations of the status pins. On the Qi control board, there are two LEDs (red and green) that indicate the status of the module. Their electrodes are exported as four metal contacts (LR+, LR-, LG+, and LG-) at the edge of the control board, which can be used as the status output sent to the central control unit. To reduce the processing complexity, we select the one that is most easy to interpret as the status output. Partial measurements on the four contacts corresponding to the two LEDs are shown in Table 3.

Table 3. Test Results of LED Pin Output Voltages

Status	Behavior	LR+	LR-	LG+	LG-
Idle	Red on Green off	0V	1.8V	-	3.3V
Charging	Red off Green breathes	3.3V	3.3V	-	Alternating between 0 and 3.3V
Foreign Object Detected	Red blinks Green off	Alternating between 0 and 3.3V	-	-	3.3V

As Jetson Nano GPIO (General Purpose Input and Output) pins use the 3.3V voltage level, the 3.3V output will be recognized as high (1) and 0V will be recognized as low (0). Based on the result above, LR+ and LG- are suitable as the status indicators, summarized in Table 4.

Table 4. Mapping from Qi Module Statuses to LED Outputs

To Status	Input
Idle	LR+ high to low
Charging	LG- high to low

3.2 Mechanical Subsystem

The design verification of the mechanical subsystem involves system rigidity test, motion system test and stall detection test. For the rigidity test, heavy object and the significant impact was placed on the glass sheet on the top of the table to mimic real-life situations.

For the motion system test and stall detection test, the tests were performed with the PronterFace software. The software is designed for 3D printer testing with user interface and g-code communication capability.

During the test, the stepper motors powering the X and Y movements were operating with $1A$ of current ($1.6A$ max) and the Z motor was operating with $0.3A$ ($0.5A$ max). The system was able to achieve 600 mm/s moving speed with a $5{,}000mm/s^2$ acceleration configuration. Thus, the system would be able to move between any two points in its working area within 0.6 second and be quick enough for this application.

The stall detection function is already used during the system homing phase to detect whether the system reaches its mechanical limits. And tests of manually place foreign objects in the way of the motion system were also performed. The motion system is able to stop without exserting any significant force on the foreign object.

3.3 Vision Subsystem

3.3.1 Verification for the Detection Algorithm

To verify the detection algorithm, the testing of the vision subsystem includes static image recognition with a complex setting and a unit test of the real-time recognition for phones requiring speed and accuracy.

For static images, all objects are detected successfully. Although the static images have complex settings with various objects and some other objects with similar aspect ratio and color to the phones, only phones are detected. For real-time detection, the speed can achieve at least 10 frames per second. People will not feel any latency in the detection task. In terms of accuracy, all phones are detected successfully. These two versions of tests show that the system can meet almost all the requirements in the requirement and verification table in the appendix. The only exception is that phones with white covers are hard to detect in the white background (ceiling). The overall accuracy and speed for dark phones are good.

3.3.2 Verification for the Interface Module

To verify the interface module correctness, we print out relevant information including the position and property of the bounding box when the program is running. As such, we can check whether the location updates the information correctly. For example, we unit test the interface when we insert a phone or remove a phone to see whether the system responds correctly.

3.4 Central Control Unit

The interfaces that connect the central control units are tested individually. This includes reading status messages from other submodules and print out the results to the terminal and see whether the values are under expectation.

The core scheduling algorithm also has a unit test. In the unit test, the status messages are entered from standard-in (keyboard) to the program instead of reading from other submodules, and the moving commands and the message are printed out to the terminal instead of sending to other submodules. Since formal verification is hard and seems unnecessary for our design, we manually design some test cases to simulate the real-world situation and check whether the responses are under expectation.

4 Costs

4.1 Cost Analysis for Labor

The labor cost for our four group members can be calculated as follow: we have 4 group members. The project will be done in the rest of the semester, which is 10 weeks. We assume we need 12 hours for every group member because it is a four credits course. Also, we assume the virtual salary is ¥100 per hour, which is the approximate salary for an undergraduate in computer engineering who graduated from Zhejiang University.

$$4\ people \times \frac{¥100}{hr} \times \frac{12hr}{week} \times 10weeks = ¥48000$$

4.2 Cost Analysis of Components

Table 5. Cost Table of Components

Component	Quantity	Cost
NVIDIA Jetson Nano	1	769
Camera	1	445
Qi Module	3	84
Power Adapter	1	97.2
MGN9 Linear Rail Set	3	147
2020 Aluminum Extrusion	6m	84
2020 Extrusion T Nuts	60	20
F695 Bearings	24	36
NEMA17 26mm Stepper Motor	1	57.5
NEMA17 40mm Stepper Motor	2	78
End Stops	2	8
2GT 6mm Driving Pulley	2	6
2GT 6mm Passive Pulley	2	11.8
2GT 6mm Belt	2m*2	13.6
Power Switch	1	4
M5 Self-locking Nuts	20	2.2
M5*10*1.0 Washers	50	2.7
M5*10 BHCS Screws	20	3.23
M5*16 BHCS Screws	20	4.23
M5*30 BHCS Screws	10	3.28
M3*40 SHCS Screws	5	1.49
M3*30 SHCS Screws	30	5.63
M3*20 SHCS Screws	40	5.08
M3*10 SHCS Screws	60	5.08
M6*25 SHCS Screws	12	5.08
M5*40 SHCS Screws	10	4.34
3mm Glass Panel	1	50
5mm Glass Panel	1	70
Total		2023.44

5 Conclusion

5.1 Accomplishment

We design, implement, and test a smart wireless charging table that allows devices to be placed arbitrarily on the table surface. The table is especially applicable for the cafeterias and coffee shops that intend to deploy Qi wireless charging hotspots. With the automatic alignment, customers are no longer required to stay close to the fixed charging locations. Both the whole system and the components work as expected. The vision subsystem accurately recognizes and locates the devices placed on the table surface. The central control unit properly schedules the coil movement. The mechanical subsystem moves and aligns the coils smoothly and reliably. The wireless charging subsystem well accommodates typical wirelessly chargeable devices with possibly phone cases.

5.2 Uncertainties

Our system works well in the lab environment. However, when generalizing to the application settings, several uncertainties may arise. One major uncertainty lies in the accuracy of the vision detection. During our experiments, there used to be cases that the vision subsystem fails to recognize the devices placed on the table surface, depending on the light conditions and the surroundings. In real-world settings, the light condition and the environment can be even more complicated, imposing more challenges to the vision detection algorithm. The parameters of the vision algorithm may need to be tuned based on the specific environment.

Another uncertainty is the thickness of the phone cases that customers use. Although our tests show that the system well accommodates phone cases with typical thickness, it’s still possible that our product can encounter much thicker phone cases in practical settings. If the wireless charging module fails to communicate with the device due to such an obstacle in between, the device will be marked as incompatible by the central control unit and won’t be charged, even though it’s actually Qi-compatible.

5.3 Ethics Consideration

One major safety hazard is the potential damage caused by wireless charging. The Base Station coils transfer power through an alternating magnetic field [4]. If not controlled properly, the users’ devices can get irreversible damage. Also, if a foreign metal object is placed in the magnetic field, it can be heated up [4], which imposes a risk to the user and the system. Neither can we control the users’ actions, such as overlapping two smartphones on the table. To address these potential safety issues, we will use certified wireless charging modules that follow the Qi standard and have protections against overvoltage, overcurrent, overheat, short-circuit, and foreign objects. In any of these cases, the charging will be terminated, and the central control unit will be notified. Handshakes are performed before the start of power transfer to make sure the Mobile Device accepts wireless charging. Qi-incompatible devices are recognized and recorded by the central control unit. These considerations follow the IEEE Code of Ethics: “to avoid injuring others, their property” [8] and the Qi standard [4].

Another safety risk lies in the power supply chain. As the system is connected to high-voltage AC power directly, the protection of the circuit from any potential dangers is critical.

For example, the people may be tripped over by wires, leading to injury of people and failure of the system. Also, the circuit system should be waterproof to avoid any potential spillover of the drink. These considerations comply with the campus safety requirements [9] and the IEEE Code of Ethics: “to hold paramount the safety, health, and welfare of the public” [8].

As the system includes mechanical devices, we also need to make sure it won’t cause physical damage to the users and their property. The overall structure should be strong enough against any potential damage caused by the motors. The control units should be able to handle unexpected behavior of the motors and cut off the power in time.

The major ethical issue is about the privacy concern of the camera that is used to identify and locate the devices to be charged. To address this concern, we will isolate the vision subsystem from unauthorized access outside. All images will be processed locally in the vision processing unit. Only the positions of the devices to be charged will be extracted from the images. This process won’t be associated with the users. The system will not store the images that have been processed. Through the isolation, we can make sure that the only information flow out of the subsystem is the 2D coordinates of the devices, and any other information will not be leaked out. The users will be notified about the usage of the camera and the information being collected. Such privacy protection follows the IEEE Code of Ethics: “to protect the privacy of others” [8]. We hope our design can provide convenience to its users without intruding on their privacy.

5.4 Future Work

The system we design and implement serves as a prototype that verifies the feasibility of achieving Qi Free Positioning [4] with computer vision and mechanism. To generalize our system for practical usage, the table needs to be made larger. As such, it requires modifications in the physical design, the mechanical system, the placement of the camera, and so on. Also, as an alternative to vision detection, recognizing and locating the device to be charged through sensors (such as NFC) may provide more robust and accurate detection, which may be explored by future work.

Appendix A Requirement and Verification Tables

Table 6. R & V Table for the Wireless Charging Subsystem

Requirements	Verifications
Recognizes Qi-compatible devices and supplies proper power (up to 15W) at the distance of approximately 10mm and possibly phone case (up to about 2mm) in between.	1. Place a Qi module under a piece of 6mm glass with proper support that ensures the free movement of the coil. 2. Place a test phone on the glass. Check whether the device is charging. Measure the output power using a multimeter and compare it with the max wireless charging power specified by the specs 3. Repeat the previous step with a few other typical Qi-compatible devices, 3mm glass, and a 2mm phone case.
Detect foreign objects and stop output within 2s after their placement.	1. Setup the Qi module as above. Place a foreign metal object (such as a wrench) on it. Check the LED status and measure the voltage output using a multimeter. 2. Repeat the previous step by using different foreign objects or by starting with a phone and replacing it with a foreign object.
Correctly indicates charging status through the status pin.	Measure the voltage output of status pins using a multimeter during the tests above.

Table 7. R & V Table for the Mechanical Subsystem

Requirements	Verifications
The accuracy of the motion system should be within 0.1mm on each axis.	The precision test will be performed on the motion system by moving the tool head repeatedly among several points and analyze the final position.
The system should be stable for 24-7 operations.	Endurance tests will be performed on the system by moving the charging coil continuously for a considerable long time.
Speed target: 300mm/s, acceleration target: 5000mm/s^2.	Speed and acceleration are set in the firmware. The stability and actual outputting speed and acceleration of the system will be accessed during the above tests.
Stall detection and emergency stop function for safety.	Safety tests will be performed by simulating obstacles and collisions on the motion system.
All moving components should be within the volume of the aluminum structure for safety.	Verified in the CAD model.

Table 8. R & V Table for the Vision Subsystem

Requirements	Verification
Detect all phones on the table at the frame rate of at least 10 FPS.	Deploy the algorithm to Jetson Nano and put the camera above a table. The screen will show the real-time processed image with bounding boxes for those phones and air pods. The FPS should be at least 10.
Generate the location for devices correctly at least 10 FPS and send to the central control unit.	1. After we run the algorithm, the central location of devices will be printed into the terminal shell in (x, y) format. The FPS should be at least 10 FPS. 2. The program will also send the location information through inter-thread communication to the receiver. Ideally, the receiver should receive at the same rate, but we can loosen our requirement to receive locations at 5 FPS.

Table 9. R & V Table for the Central Control Unit

Requirements	Verification
The interface with the mechanical subsystem is functional.	Write a unit test on the interface (without running the whole scheduling algorithm). Send a sequence of simple commands to the mechanical subsystem, and the mechanical part should move accordingly.
The interface with the wireless charging subsystem is functional.	Check the signal received when the wireless charging subsystem is in idle, charging, and error mode.
The interface with the vision subsystem is functional.	Write a unit test on the interface (without running the whole scheduling algorithm). Check whether the correct position can be received when a device is placed.
The scheduling algorithm is functional.	Since this is the central part of our project, it is verified when the overall design works.

Appendix B States and Operations of the Central Control Unit

Table 10. States and Operations of the Central Control Unit

State	Description	To the Mechanical Subsystem	To the Wireless Charging Subsystem	To the Vision Subsystem
Waiting	Wait for changes.	Nothing	Pull charging status. If a device ends its charging, mark the coil as idle and assign a candidate target position to rest the coil. Transfer to Calculating.	Pull position status. If a new device is placed or removed, reschedule the position of all the coils. Transfer to Calculating.
Calculating	Calculate the movement of the coils.	Calculate the movements of the coils to the target positions and send instructions to the mechanical system. Transfer to Moving.	Nothing	Nothing
Moving	Wait for the mechanical system to move and handle any interrupts.	Pull for moving status. If done, set the next state to be Waiting. If changes happen, interrupt the movement.	Pull status as in Waiting. If interrupt happens, do the similar thing as the Waiting state and set the next state to be Calculating. If done, set the next state to be waiting.	Pull status as in Waiting. If interrupt happens, do the similar thing as the waiting state and set the next state to be Calculating. If done, set the next state to be waiting.
Error	Targeted by any exceptions in other states. Manual checking if needed.	Nothing	Nothing	Nothing

References

[1] "All Phones With Wireless Charging – Qi Enabled Phones & Compatible Devices 2021," Qi-Wireless-Charging.net, 16 February 2021. [Online]. Available: https://qi-wireless-charging.net/qi-enabled-phones/. [Accessed 3 March 2021].

[2] J. Perzow, "Aircharge-Qi App Guides You to More Than 3,000 Qi Wireless Charging Locations," 2 March 2015. [Online]. Available: https://www.wirelesspowerconsortium.com/blog/101/aircharge-qi-app-guides-you-to-more-than-3000-qi-wireless-charging-locations. [Accessed 3 March 2021].

[3] J. Rigg, "Starbucks adding wireless charging points to UK stores, starting with London," 20 January 2015. [Online]. Available: https://www.engadget.com/2015-01-20-starbucks-uk-wireless-charging.html. [Accessed 4 March 2021].

[4] W. P. Consortium, "Qi Specifications V1.2.3," February 2017. [Online]. Available: https://www.wirelesspowerconsortium.com/data/downloadables/2/2/0/5/qi-wireless-power-specification-non-confidential.zip. [Accessed 3 March 2021].

[5] M. Panzarino, "Apple cancels AirPower product, citing inability to meet its high standards for hardware," 30 March 2019. [Online]. Available: https://techcrunch.com/2019/03/29/apple-cancels-airpower-product-citing-inability-to-meet-its-high-standards-for-hardware/. [Accessed 4 March 2021].

[6] R.-T. Shaw, "Xiaomi's moving-coil wireless charger: Genuinely useful or just a party trick?," 13 September 2020. [Online]. Available: https://www.androidauthority.com/xiaomi-20w-smart-wireless-charger-review-1156157/. [Accessed 4 March 2021].

[7] "Jetson Nano Developer Kit," Nvidia, 27 January 2021. [Online]. Available: https://developer.nvidia.com/embedded/jetson-nano-developer-kit. [Accessed 4 March 2021].

[8] IEEE, "IEEE Code of Ethics," June 2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed 4 March 2021].

[9] "The Principle of Laboratory Safety Management," 24 August 2016. [Online]. Available: https://coc.intl.zju.edu.cn/en/content/zju-have-announced-principle-laboratory-safety-management. [Accessed 4 March 2021].