An Evaluation of *RAD Shopping Carts* with Autonomous and Smart Capabilities for Improved Shopping Efficiency and Satisfaction *(March 2023)*

Rajath R. Author, Anthony F. Author, Divam K. Author, and Prof. Zhiying Wang, Ph.D. (Advisor)

Abstract—**RAD Shopping Cart is an IOT shopping cart, which can follow the user through an aisle, and allow for product lookup through a touchscreen LCD. This project is useful since it simplifies the shopping experience for senior citizens and people with disabilities — both of whom struggle physically pushing around a shopping cart, as well as allowing for an accessible and straightforward item lookup at any point of time. The cart uses a network of three ESP8266 Wi-Fi modules to triangulate a user's location. In addition, the cart uses HC-SRO4 Ultrasonic Sensors in the front, and the sides to allow for lane correction and object avoidance.**

Index Terms—**Autonomous Vehicles, Collision-detection, Finite State Machine (FSM), Firmware, Internet of Things (IOT), Item-lookup, Lane-correction, Liquid Crystal Display (LCD), Mealy Machine, Motor Controls, Received Signal Strength Indicator (RSSI), Ultrasonic Sensors, User-Following**

I. INTRODUCTION

GIVEN the archaic nature of shopping carts throughout the past couple decades, we are motivated to integrate an Internet of Things (IoT) solution for extant shopping carts. These smart features aim to ameliorate a customer's shopping experience. Many senior citizens and those with physical impairments often have trouble pushing their carts around while shopping. Likewise, busy parents managing their energetic children and trying to multitask while shopping often spend a lot longer in the store than necessary.

Previous renditions of smart carts with autonomous shopping carts exist but are not as prevalent as one would assume. Only a handful of companies such as Caper, Robotnik, and Veeve have successfully launched smart cart lines supporting features to automate customers' shopping and save customers' time [1] [2] [3].

The shopping cart will augment performance and convenience for such shoppers. The aim of RAD Shopping Cart will support four main features including user-following, lane-correction, collision-detection, and item-lookup.

For USER-FOLLOWING, the cart follows the shopper around the store by pairing to the user's mobile Wi-Fi hotspot. It will seek to maintain a close (~3 meter) distance from the user.

For LANE-CORRECTION, the cart uses ultrasonic range sensors to automatically detect walls/shelves and the edges of an aisle. It will seek to maintain a pathing closer to the right side of the aisle.

For COLLISION-DETECTION, the cart detects obstructing objects or people that may walk in front of the cart using ultrasonic sensors mounted on the chassis. It will stop moving forward when an obstacle is noticed.

For ITEM-LOOKUP, the built-in LCD touchscreen will support querying the inventory of the store through an online database which makes shopping for products more convenient and speedier. The LCD touchscreen will also support all other user interface requirements.

RAD Shopping Cart primarily uses a distance estimation algorithm using WiFi RSSI for its cost efficiency and better efficacy for the problem statement. A core value of manufacturing was the cost and simplicity of the project.

The LCD touchscreen ties together the FSM of the shopping cart with a straightforward user interface.

R. R. Author is with the University of California – Irvine, Irvine, California, CA 92697 USA. (e-mail: rajathr@uci.edu).

A. F. Author is with the University of California – Irvine, Irvine, California, CA 92697 USA. (e-mail: anthojf2@uci.edu).
D. K. Author is with the University of California – Irvine, Irvine, California, CA 92697 USA. (e-mail: divamk@uci.edu).

To illustrate the key components within the shopping cart, the paper consists of the following sections in key detail: hardware assembly and interface, Wi-Fi tracking, and finite state machine.

II. HARDWARE ASSEMBLY AND INTERFACE

Before being able to assemble anything we had to create a plan for assembly and interface. We created a circuit schematic detailing how each electronic part would be connected. Then a bill of materials was formed to aid with identifying the parts in the schematic. To ensure that everything was connected properly, hardware testing code was made.

A. Wiring Schematic

The wiring schematic acts as a blueprint when it comes time to assemble the parts. The schematic facilitates the task at looking into each component and ensuring compatibility between devices.
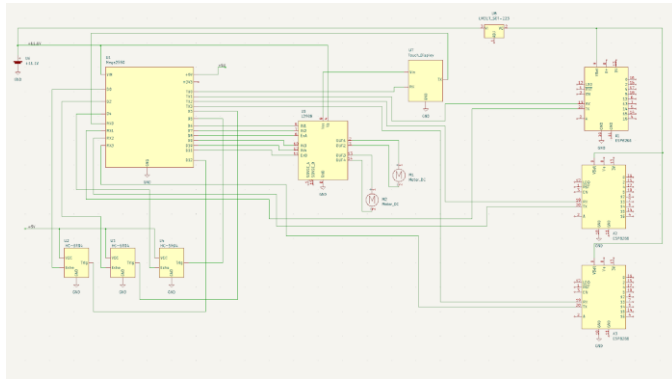

Figure 1. Wiring Schematic of IoT Shopping Cart Circuit Design.

The above schematic (Fig. 1) is built in KiCad, and most of the part symbols are built from scratch. The symbols show relevant device inputs and outputs. The Mega2560 microcontroller and L298N motor controller were provided each with 11.1V which is within each of their operating voltage ranges. It is important that the L298N is supplied with close to 12V to power the 12V motors. 11.1V is still sufficient voltage for the motors to operate and will only result in a slight performance decrease which will not affect functionality. The Mega2560 provides the ultrasonic sensors with 5 volts. Each ultrasonic sensor draws around 15mA of current. This brings the total current load to around 45mA of current which is well within the Mega2560 voltage regulator output current capability. For the ultrasonic sensor to function, it receives a trigger signal from the microcontroller. Once this trigger signal is received, it releases a sonic pulse. The time it takes to receive an echo of this pulse is measured. The amount of time the echo stays in output high is calculated by the microcontroller which in turn is converted into a distance. The resistive touch LCD takes in 5V and is powered by the 5V output of the L298n motor controller. The LCD draws around 145mA which is within the motor controller's current limit. The display has its RX pin connected to the TX pin of the microcontroller to allow for UART serial communication. The microcontroller also sends

out signals to control the motor controller. It can enable the motor with the enable pin. Once it's enabled, it can control the direction of the motor depending on the combination of input it gives to the two input pins for each motor. For the user tracking functionality, three ESP8266 WiFi modules are used to provide signal strength to the microcontroller. Each of the WiFi modules are powered with around 5 volts through a LM7805 linear regulator. The WiFi modules each draw around 170mA which makes the total current load on the regulator 510mA. The regulator is rated for 1.5mA which is well within limits.

B. Bill of Materials

A bill of materials (Fig. 2) is created to help identify the electronic parts used in the schematic. It also helps with overall organization of the project.

Figure 2. Bill of Materials

It includes the number of items, component names, quantity, designated part reference and manufacture. These details make it easy to navigate and know what parts are included in the schematic.

C. Hardware Testing Code

To verify working hardware, test code was created for each part. To test the ultrasonic sensor, we gathered three measurements and different distances away and compared the values to measurements made with a measuring tape. For the L298N motor controller, we tested basic motor movement functionality. The code tested different pulse width modulation (PWM) values to ensure the motor controller is powering the motors sufficiently. The WiFi modules are tested for both hotspot connection and serial communication capability. Having the test code is great as a base for building code from and allows us to go back to it to make sure the hardware is functioning properly.

III. WIFI TRACKING

Since the Arduino Mega2560 does not come with an internal WiFi module, the project uses three ESP8266 modules to set up a triangular network of WiFi modules. This network is responsible for recording and receiving RSSI from the user's paired hotspot. The Arduino Mega2560 processes the information from all peripherals and handles the necessary computations. The ESP8266 modules each wait for notifications from the Arduino Mega2560 for login

configurations and relay RSSI data back to the main controller.

A. WiFi RSSI

Received Signal Strength Indicator (RSSI), as the name says, is a quantitative indication of the connection between the transmitting and receiving Wi-Fi nodes. RSSI values are relative to the device and vary by manufacturer. The RSSI signal strength is a value which generally ranges from 0 to -120. The closer the value is to 0, the more powerful the signal is in the specified range. Collecting RSSI signal strengths at different range intervals is used to determine a range value for the shopping cart [4].
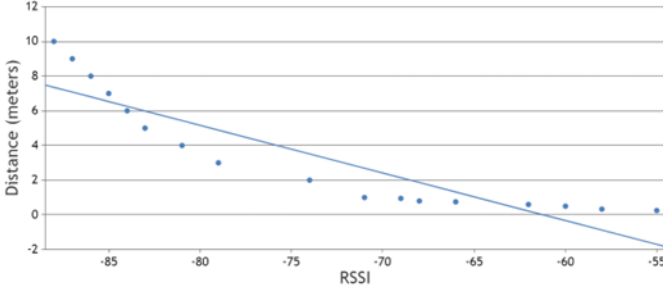

Figure 3. Scatterplot for RSSI vs. Distance (m)

B. Serial Communications

Each of the ESP8266 modules communicate with the Arduino Mega2560 through Serial communication. Serial communication requires the receiving and transmitting sides of the two modules to be inverted which allows bitstream data to be sent from different circuits.
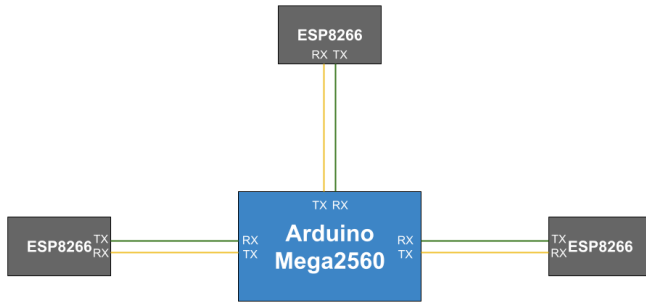

Figure 4. Serial Communication Schematic for MEGA/ESP

The above diagram (Fig. 4) depicts the communication wiring schematic between each of the ESP8266 modules and the Mega2560. The ESP8266 modules behave as slaves for the master Mega2560 and wait for login information to be sent through the RX [1-3] channels and attempt connection. Once the connection is successful (user is paired), the ESP slaves intermittently transmit RSSI back to the master through the TX [1-3] channels. The Mega2560 accepts the data and parses the bitstream as a string of RSSI information and calculations take place.

C. Tracking the User

The RSSI values transmitted from each of the ESP8266 modules were highly sensitive, due to environmental factors such as noise interference and physical obstructions. This resulted in fluctuating data which made it difficult to ascertain the proper RSSI at a given moment.
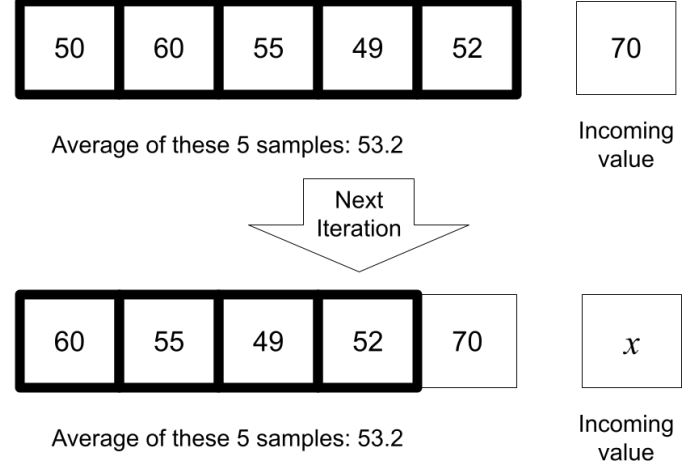

Figure 5. ESP WiFi Reading Queue Structure

To circumvent this problem, a queue data structure (Fig. 5) is used for each ESP module. The structure 5 RSSI values sampled at 0.2 second time intervals. The queue allows for new samples to be pushed in while popping the old values out making it ideal for normalizing the instantaneous WiFi RSSI values. Before a new RSSI reading is pushed into the respective queue, the average of the current samples in the specified queue is yielded as the normalized RSSI signal. Each ESP module has a queue which serves as a container for 5 instantaneous RSSI values with 0.2 second time intervals, ultimately resulting in a normalized RSSI value for every 1 second.
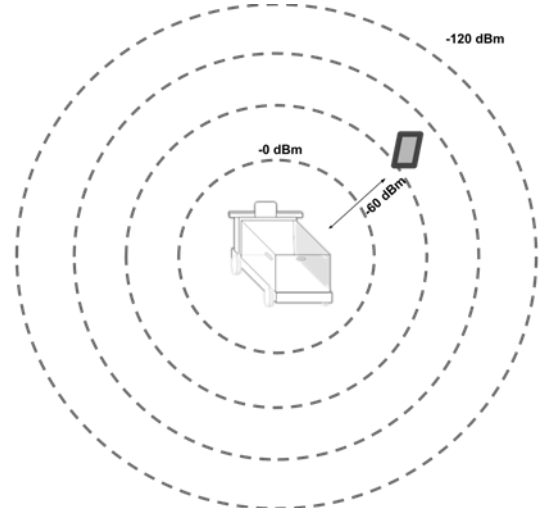

Figure 6. Visual Graphic of RSSI to Distance

To determine the user's direction, a simple approach was used using the normalized values for the front, back-left, and back-right ESP8266 modules. The normalized values returned from each of the front, back-left, and back-right RSSI queues is systematically and conditionally checked to get the two-dimensional direction of the user. If the RSSI for the front is less than the back-left and back-right RSSI values, it means that the user is closer to the front, indicating that the shopping cart should move forward, and vice versa. If the front and back

RSSI values are below the threshold 40 dB, this indicates that the cart is already at a very close proximity to the user which does not require any motor movement.

IV. FINITE STATE MACHINE

The main procedure dictating the state of the automated system of the RAD Shopping Cart can be displayed as a Finite State Machine (FSM). In essence, this control structure serves to facilitate and handle possible scenarios and cases revolving around the user of the cart. The aggregate of multiple peripherals embedded to the shopping cart help arrive at a next action and eventually, a final state.

A. Mealy Machine

The program's overall control-loop from the main module dictates the different possible environment conditions and user-cases. These scenarios are mapped out in software to facilitate the shopping cart's movement, features, etc. Specifically, this FSM is a Mealy machine, which means that the states switch not only when based on the changes that occur within the state, but also by user input [5]. The key feature that makes this a Mealy machine is the item-lookup feature which requires that the user input an item into the search bar in the LCD user interface to find items. The Mealy Machine involves the user input which is granted through the embedded touchscreen LCD.
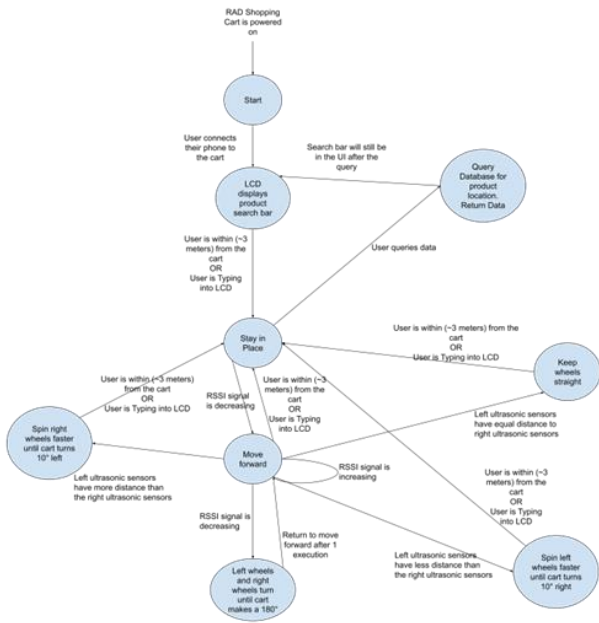

Figure 7. The Finite State Machine of RAD Shopping Cart

RAD Shopping Cart's mealy machine uses a rudimentary finite state machine for a general-purpose autonomous vehicle as a reference for the potential states that are needed for an autonomous vehicle [6]. The design is more simplified and adapts to all the potential use cases and states that our shopping cart would possibly need.

B. User Interface

The mealy machine described above revolves around the Nextion TFT LCD which prompts user input and also toggles

the movement capabilities of RAD Shopping Cart. The LCD starts The LCD allows for powering the shopping cart on, pairing the user's phone, following and tracking the user's RSSI values in real-time.

Figure 8. LCD Pages and Touch Events

In the following images above (Fig. 8), the Nextion LCD serves as the event handler for the Mega2560, the ESP8266, and the motor controller all through touch events from buttons and pages. Upon startup, the cart starts with its power set to OFF which is enabled to ON when the user starts the cart from the Power page. Subsequently on the User page, the user has the option to pair their cellular phone with RAD Shopping Cart by typing in their user SSID and password. The submit request from that page, induces the serial communication between the Nextion LCD → Arduino Mega 2560 → ESP8266 modules. The Store page allows the user to view and search for specific products and their respective locations in the store which is reflected on the LCD's user interface. Finally, the Drive page is responsible for motor movements and viewing the RSSI readings in real time. The button "Follow" enables the cart to follow the user using the the WiFi tracking algorithm while the button "Track" enlists detailed information about RAD Shopping Cart's RSSI readings and sensor readings which can be seen in the Fig. 9.
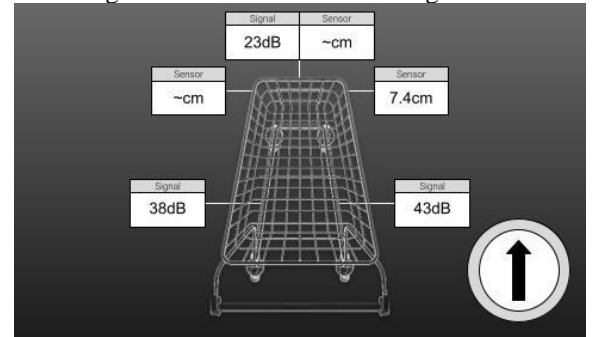

Figure 9. Real-time RSSI Tracking on LCD

C. Ultrasonic Range Sensors

A baseline algorithm for collision avoidance can be developed by configuring the ultrasonic sensors. The ultrasonic sensors use a pulse of 4 ultrasonic waves within 100ms to determine distance by measuring the time between the creation of the pulse and the time when the pulse is

reflected. The HC-SR04 ultrasonic range sensor that we are using accurately returns the time it takes for the ultrasonic sound wave to return to the receiver [7]. This time value can be converted into distance using the following formula:

$$Speed\ of\ Sound:$$
$$v = 340\ m/s$$
$$v = 0.034\ cm/\mu s$$

$$Time = Distance\ /\ Speed:$$
$$t = s/v = 10/0.034 = 294\ \mu s$$

$$Distance:$$
$$s\ (cm) = t \cdot 0.034\ /2 = t \cdot 0.017$$

Figure 10. Ultrasonic Sensor to Distance Conversion Formula

The collision detection feature is implemented using ultrasonic sensors because it will communicate information to the FSM which instructs the cart to "move" or "rest" if within ~3 meters of the user. This ensures the safety of our users and others while preventing any sort of potential collisions. The ultrasonic sensor also is responsible for lane correction which utilizes the sensor on the right side of the cart which calculates the distance from the aisle's shelf. This distance value is used to keep the cart calibrated to the right side of the aisle and prevent it from veering in certain directions. Along with the motor controller's actions, the cart stays in a straight path and corrects its trajectory.

D. Motor Controllers

The movement for the RAD Shopping Cart involves functional motor controls such as moving forward, moving backward, making 180° turns, and 90° turns. The motor controller is a crucial component responsible for facilitating the motor speeds and the motor direction for the shopping cart. In addition, with the right ultrasonic sensor's readings, the motor controller consistently commands the left motor to spin at a higher speed and tunes the right motor's speed to correct its lane trajectory which is how forward movement is made possible.

E. Store Database

Store inventory and products can be found through the built-in LED on the cart which reads information from one primary ESP8266 on the cart. The front ESP8266 on the cart has a priority to read from the database and transmit the content as a bitstream of a JSON object to the Mega2560 which parses and prints the content on the store page of the LCD.
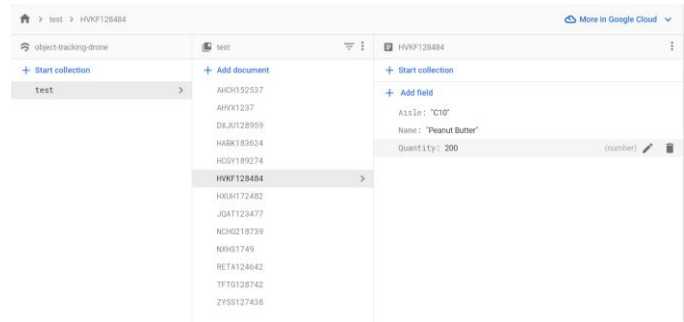

Figure 11. Google Firebase for Store Inventory / Item Lookup

The database is made through Google Cloud's Firebase (Fig. 11) which allows for initializing a generic grocery store item list. For instance, items such as peanut butter, milk, etc. can be searched and discovered with the corresponding attributes such as aisle number and availability. A Flask RESTful server acts as an intermediate host API to handle HTTP Post/Get requests. This was done through Python and was hosted on a versatile, personal computer.

V. SUMMARY

RAD Shopping Cart is a project consisting of research and development for an IoT shopping cart which includes four primary features: (1) user-following (2) collision-detection (3) lane-correction (4) item-lookup. This project is useful since it simplifies the shopping experience for senior citizens and people with disabilities who struggle physically pushing around a shopping cart, and allows for an accessible, straightforward item lookup. The hardware assembly laid out the foundation for the user-tracking, as well as allowed for each of the critical components for the FSM, which dictates the functionality of the entire project.

VI. CONCLUSION

Smart, autonomous shopping carts are the future. They provide a valuable utility not only for ordinary shoppers, but also to senior citizens and people with disabilities by providing a less-physically intensive way to shop, as well as a more streamlined, efficient shopping experience. In addition, smart shopping carts provide utility to shop owners as well since they can gather data from item-lookups about which items are in demand, which items are in stock, etc. This project is a simple application of the capabilities of autonomous shopping carts since it just implements the four key features described in the introduction, however, by expanding on this project to include self-parking, self-charging, advanced user-following, easier pairing with the shopping cart via Bluetooth, data analysis from item-lookup data, to even having games within the LCD tablet to keep children occupied, the applications of smart shopping carts are seemingly endless. Overall, smart shopping carts are still not the norm, thus, more research should be done to implement more features to provide more value to shop owners and consumers alike, and to bring the manufacturing costs down to make smart shopping carts practical.

REFERENCES

[1] Russell Redman 1 | Oct 19, "Instacart acquires Smart Cart Maker Caper," Supermarket News, 19-Oct-2021. https://www.supermarketnews.com/technology/instacart-acquires-smart-cart-maker-caper. [Accessed: 29-Nov-2022].

[2] Anna, "E-mart introduces Eli Autonomous Shopping Cart," Robotics & Automation News, 04-May-2018. https://roboticsandautomationnews.com/2018/05/04/e-mart-introduces-eli-autonomous-shopping-cart/17113/. [Accessed: 29-Nov-2022].

[3] Annierpalmer, "Ex-amazon engineers roll out their smart shopping carts in Albertsons Stores," CNBC, 19-May-2022. https://www.cnbc.com/2022/05/19/albertsons-deploys-smart-grocery-carts-from-veeve-ex-amazon-engineers.html. [Accessed: 29-Nov-2022].

[4] Yu, M.; Yao, S.; Wu, X.; Chen, L. Research on a Wi-Fi RSSI Calibration Algorithm Based on WOA-BPNN for Indoor Positioning. Appl. Sci. 2022, 12, 7151. https://doi.org/10.3390/app12147151

[5] Chiuchisan, Luliana, Alin Dan Potorac, and Adrian Graur. "Finite state machine design and VHDL coding techniques." Development and Application Systems (2010): 75. [Accessed: 1-Dec-2022].

[6] Hejase, Mohammad, et al. "Identification of risk significant automotive scenarios under hardware failures." arXiv preprint arXiv:1804.04348 (2018).

[7] HC-SR04 ultrasonic distance sensor module. [Online]. Available: https://www.bananarobotics.com/shop/HC-SR04-Ultrasonic-Distance-Sensor. [Accessed: 8-Nov-2022].

Rajath R. Author is a 4th year expected to graduate with the B.S. degree in Computer Science & Engineering at the University of California – Irvine in 2023. He is interested in pursuing the M.S. Computer Science degree in the concentration of Machine Learning and Computer Vision. From June 2021 till present, he is a Software Engineering Intern at Intel Corporation. His research interests include image classification methods, computerized perceptron of human experience, and computer vision applications for autonomous system.

Anthony F. Author is a 4th year majoring in electrical engineering in the Department of Electrical Engineering and Computer Science at the University of California - Irvine. He is specializing in digital signal design. His interests lie in the field of semiconductors and embedded systems.

Divam K. Author is a 4th year majoring in computer science and engineering as part of the school of engineering and the school of computer science at the University of California Irvine. He is interested in all aspects of computer science and software development, and is currently pursuing his interests in blockchain technology, embedded systems, and software engineering.