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Board 110: Portable Solar-Powered Wireless Display Board

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Portable Solar-Powered Wireless Display Board

Abstract

In this industry-sponsored senior design project, a light-weighted low-consumption portable digital display is designed and developed for outdoor use with the capability to be charged by solar energy. A Raspberry Pi microprocessor controls the data display process and provides the live data tracking functionality through a mobile application. The custom-built display board is designed by arranging LED light strips into a matrix formation that is ultra-light and low consumption, while allowing the user to change the text color, size, and brightness. The display process is wirelessly interfaced with the user through a mobile application. The entire system is powered by a 50 (Ah) LiFePO4 battery storage system that is fed by a 175 (W) solar photovoltaic panel. The structure is made of lightweight materials that make the system portable. This project is sponsored by Vanguard Energy Partners, LLC, Branchburg, New Jersey, and conducted by a group of undergraduate students in the Electrical and Computer Engineering Technology program at New Jersey Institute of Technology.

Introduction

This paper presents the design, development, and programming of a portable solar-powered multi-purpose digital display board. The system includes two LED matrices composed of commercially available SK9822-based LED strips controlled by a Raspberry Pi 4. The Raspberry Pi 4 is used to run Python programs that make use of the General-Purpose Input/Output (GPIO), WiFi, and web server hosting capabilities of the mini-computer to display a local web application interface to a user and send messages to the LED matrices. The web application, which is one of the key features of the design, allows the user to choose between three different modes of functionality. The first mode is “scoreboard”, which allows the display to be used as a dynamically updated scoreboard, adaptable to many outdoor sports. The second mode is “general message display”, which can be configured to display information using static messages. The third mode is “dynamic information display”, which can be used to constantly display updating data, such as time and weather. The required electrical power is provided by a stand-alone Photovoltaic (PV) system that includes one 175 (W) solar panel, a charge controller, four battery cells, and a DC-DC converter. The PV supplies DC power to the charge controller, which then regulates the input power to charge the battery, while preventing overcharging, and supplies DC power to the electronic components. Using the DC-DC converter, the output electricity from the charge controller is converted to 5 (V) and 40 (A) electricity to power the Raspberry Pi and the two LED matrices.

Digital signage is seen as more beneficial in the market, when compared to static signage, due to the ability of the digital signage to be updated frequently, saving on the cost of printing [1]. Digital signage lowers the long-term operating costs of businesses, by eliminating the need for physical advertisement sheets, making it a powerful tool for advertising. Digital signs improve customer engagement and foot traffic in retail stores, leading to several retail industries adopting the technology [2]. Although the main application of digital displays is in advertising, there are many other applications such as billboards, traffic lights, matrix boards, and mobile panels.

Reports show that there is a tremendous attraction towards digital displays in the market, and it is projected to grow every year, as illustrated in Figure 1 below [3].

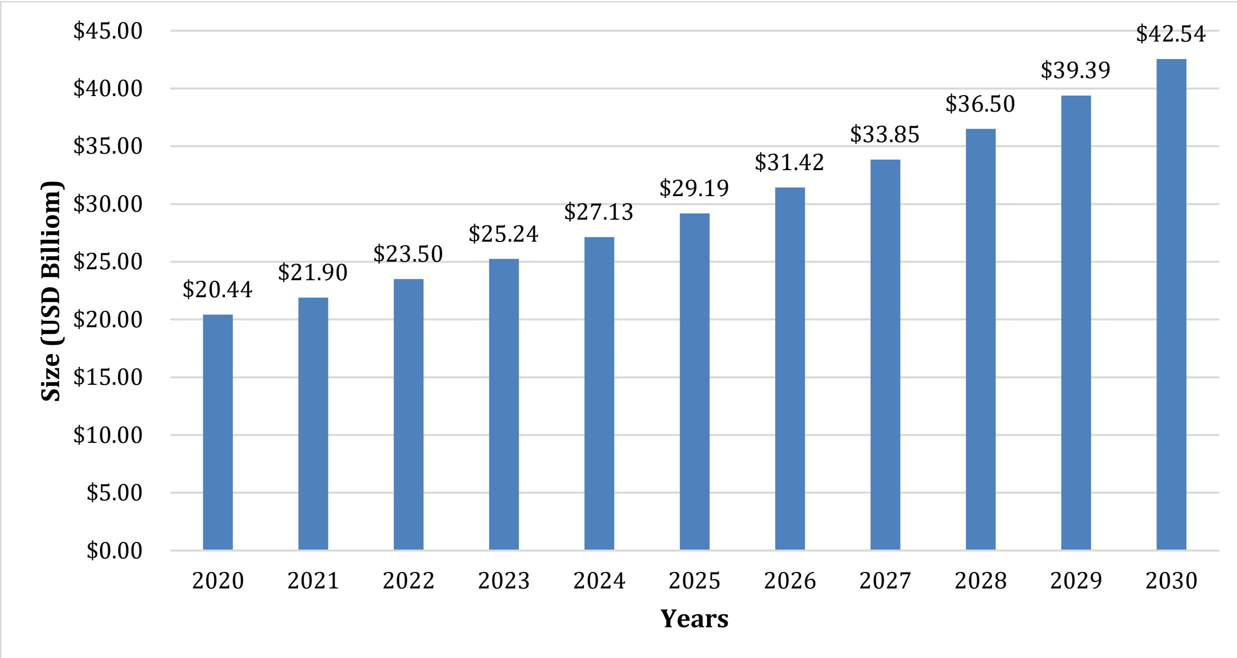


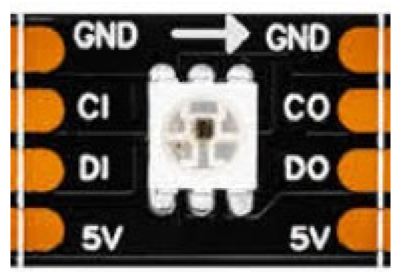
Figure 1. Digital signage market size (forecast) from 2020 to 2030 [3].

There is a growing demand in the market for bright and energy-efficient displays. There is also an effort to move away from traditional billboards that consume more electricity [4]. There are three types of color displays in the market, namely, monochrome, tri-color, and full-color displays. In this project, a tri-color display is used, which has grown at a compound annual growth rate of 15.5% from 2020 to 2023 [5]. In this project, the same brightness as in common roadside digital message boards is produced, with the added benefit of the system being low-consumption and powered by a renewable energy source. This project also has the additional novelty of being lightweight and portable, partnered with the ability to be controlled through a web application for added convenience. The multiple functions provided in this project allows for some nuance in the market, creating an all-in-one multiple-use digital display board. One such example of a foldable electronic display was patented by John Graef, Eric Kline, and Philip Hall. Their foldable electronic display was lightweight and portable and was used for the control of roadway and highway traffic [6]. Similar systems were patented by Brian Nicholson and Adam Nicholson [7], and Michael J. Simmons [8]. Compared to [6], which is controlled by connecting a computer to the display through wires, the contribution of this paper is to control the system through a web application, and also using a solar PV system. Compared to [7], the contribution of this paper is to provide a light weighted system, which is also solar-powered. Compared to [8], the contribution of this paper is that the designed and developed display system is larger-scale, scalable, and solar-powered, and provides multiple modes of functionality. In summary, the novelties of our project include the renewable energy-based source of electrical power, multiple modes of functionality, and the convenience of being light weighted and controlled through a web application.

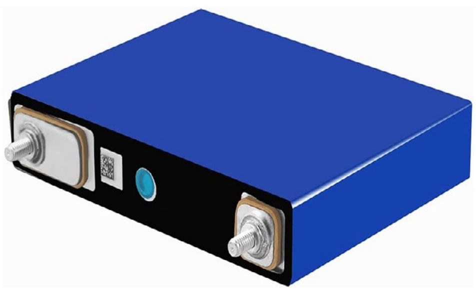
Electrical Components

In this section, the electrical components used in this project are explained in detail, which are demonstrated in Figure 2.

(a) Solar panel



(b) Addressable LEDs



(c) Battery Cells

(d) DC-DC Converter

(e) Battery Management System

(f) Solar Charge Controller

(g) Raspberry Pi 4

Figure 2. Electrical components.

Renogy 175 (W) Flexible Solar Panel (Figure 2-(a)): These solar panels are chosen due to their ideal power-to-size ratio, efficiency, and flexibility. As per the panel's specifications, the dimensions are 59.2" × 26.5" × 0.08" (1504 × 673 × 2 (mm)), with the weight being approximately 6.2 (lb). Compared to conventional rigid solar panels, these flexible solar panels are ideal for minimizing weight. However, this comes at the cost of efficiency, as the flexible materials do not allow as much light to contact the PV cells. The panel includes MC-4 connectors on 12 AWG wire to facilitate connections to other components. MC-4 connectors are the most common for PV installation as they are waterproof. The main electrical specifications of the solar panel are as follows:

- Maximum Power Output: 175 (W)
- Voltage MPP (V_{mp}): 20.3 (V)
- Current MPP (I_{mp}): 8.75 (A)
- Voltage Open Circuit (V_{oc}): 24.9 (V)
- Short Circuit Current (I_{sc}): 9.65 (A)

Addressable SK9822 30 LED/Meter Light Strips (Figure 2-(b)): The SK9822-based LED light strips offer the best specifications that allow the goals of this project to be accomplished, with each LED being addressable. The two considerations of these specific LED strips are brightness and power consumption. Compared to common roadside messenger boards, the LEDs being used produce the same amount of light; however, they spread that light out over double the area. This means that, in exchange for some loss in overall brightness, the display is readable from different angles making the visibility greater in overall. In order to keep power consumption low, while still allowing the display to be legible from a distance, it has been decided to use 30 (LED/m) light strips. At full capacity, each LED strip can consume up to 45 (W). However, this is not realistic, as in practice, all LEDs would not have to be illuminated at the same time. Hence, the practical power each LED strip is expected to consume is calculated to be 23.4 (W). The main electrical specifications of the LEDs are as follows:

- Rated Voltage: 5 (V)
- Rated Current: 50 (A)
- Light output: 6.0-8.5 (lm)
- Dimensions: 5 × 5 (mm)

LiFePo4 3.2 (V) 50 (Ah) Battery Cells (Figure 2-(c)): A custom battery pack is chosen to create a battery with the necessary dimensions to optimize portability. Rectangular Lithium Iron Phosphate (LiFePo4) cells are attached together in a flat configuration in order to minimize height. The cells are designed such that when they are adjacent and parallel to each other, the posts on either end of the cell can be connected with a standard sized bus bar. The main electrical specifications of battery cells are as follows:

- Nominal Voltage: 3.2 (V)
- Rated Capacity: 50 (Ah)
- Dimensions: 5.86" × 4.69" × 1.14"
- Weight: 2.12 (lb)
- Operating Temperature: Discharge: -22°F to 140°F; Charge: 32°F to 131°F

12-to-5 (V) 40 (A) DC-DC Converter (Figure 2-(d)): This converter is used to convert the output voltage of the charge controller (from the solar panels and battery) to the 5 (V) and 40 (A) power source necessary to supply power to the Raspberry Pi and the total of 1200 LEDs. The converter also features over-voltage, over-current, over-temperature, and short-circuit protection.

100 (Ah) 4S 12.8V LiFePo4 Battery Management System (Figure 2-(e)): The Battery Management System (BMS) allows the battery cells to be connected in series to charge safely and optimally. A BMS can actively monitor the voltage of each cell and adjust the current each cell receives, to keep the battery charged to the maximum capacity while ensuring safety. Without a BMS, the individual cells in a battery would rapidly become unbalanced, which creates a dangerous condition by causing cells to be over-charged or discharged. These modules adhere to a standardized design, enabling the printed circuit board (PCB) to be easily reconfigured based on specific requirements through the addition or removal of components. This flexibility allows adaptation for various battery chemistries and series configurations.

Renogy 30 (A) PWM Charge Controller (Figure 2-(f)): This charge controller is compatible with 12 (V) systems which may consist of different battery chemistries, such as LiFePo4 and a variety of Lead Acid based batteries. It has a discharge current of 30 (A). The device is very simple and includes only three status LEDs (solar panel output status, battery status, and battery chemistry) and a single button, which is used to configure the output voltage for charging. The charge controller also includes a three-stage pulse width modulation (PWM) regulation charging mechanism including direct, lifting, and floating charge modes. This allows the charge controller to provide efficient and fast charging, while it effectively prolongs the service life of the battery. It also has built-in over-current, short-circuit, reverse-connection, and open-circuit protections.

Raspberry Pi 4 (Figure 2-(g)): The Raspberry Pi is chosen in this project due to its ability to handle numerous modules and its built-in GPIO pins that can work with a variety of different components. It has 8 (GB) of LPDDR4-3200 SDRAM for data processing. The main specifications include:

- Broadcom BCM2811, Quad Core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5 (GHz)
- 2.4 (GHz) and 5.0 (GHz) IEEE 802.11ac wireless, Bluetooth 5.0, BLE Gigabit Ethernet
- Standard 40 pin GPIO header
- 2 USB 3.0 ports and 2 USB 2.0 ports
- 2 micro-HDMI ports (up to 4kp60 supported)
- 2-lane Mobile Industry Processor Interface (MIPI) Dual Sequential Ignition (DSI) display port
- 4-pole stereo audio and composite video port
- 2-lane MIPI Camera Serial Interface (CSI) camera port
- 5 (V) DC via USB-C connector (minimum 3 (A))
- Operating ambient temperature: 0 - 50°C

Mechanical and Electrical Design Criteria

The main criteria for designing the mechanical structure were: (i) Portability and foldability, (ii) rigidity and firmness, (iii) size and visibility, and (iv) budget ($2K for the entire project). The main criteria for designing the electrical structure were: (i) Low consumption and maximum contribution from solar energy, (ii) scalability, (iii) visibility, (iv) budget. The mechanical and electrical design processes are presented separately in the following sections.

Mechanical Structure Design Process

The original drawing of the project design is demonstrated in Figure 3-(a). The Fusion 360 software by Autodesk is used to design, lay out, and provide a 3D rendering of the LED matrix, as can be seen in Figure 3-(c). The overall structure's size is 59.5" × 27" × 57.5" when it is fully set up and folds into a stored state of 59.5" × 27" × 4", which is depicted in Figures 3-(b) and (d), respectively.

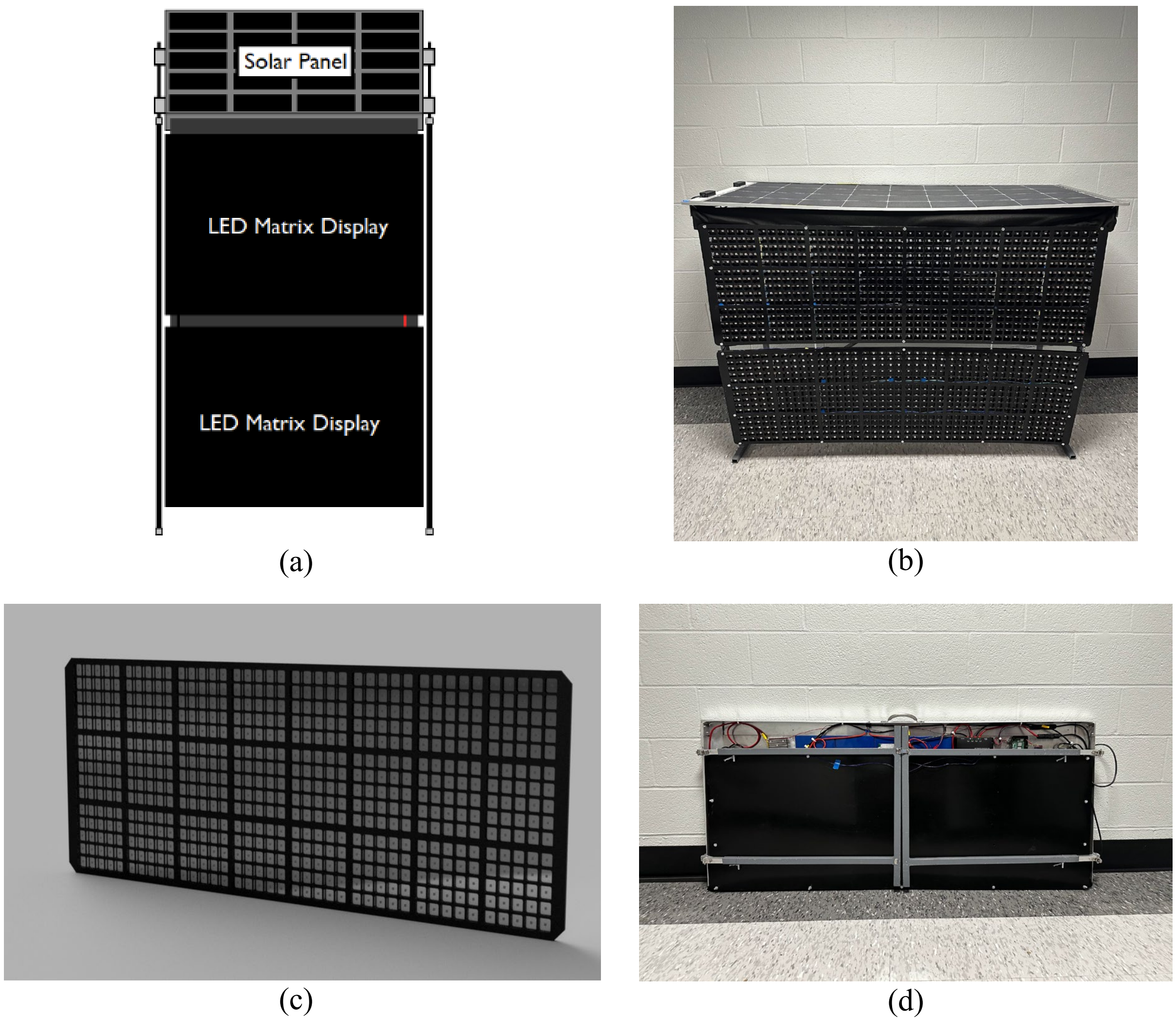


Figure 3. Mechanical structure: (a) Drawing of the overall structure, (b) assembled and integrated with electronics and electrical components, (c) Fusion 360 render of LED matrix, and (d) folded and made portable.

The structure of the system is built out of a combination of steel and aluminum, with plastic frames used for the LEDs. A large flat sheet of aluminum placed underneath the solar panel and three sections of aluminum angles are glued to the edges in order to provide a firm and rigid structure to the flexible solar panel, while still maintaining its overall thin structure. In addition to stiffness, it provides an excellent surface to which other components can be attached using rivets, hot glue, and double-sided tape. The long telescoping support legs are made of a combination of ¾” aluminum square tube and 1” mild steel square tube. Aluminum is used in the upper portion of the legs to minimize weight; however, in order to join both legs together and form a sturdy structure, steel square tube is used. In order to lock the structure in the up-right configuration, steel pins are inserted through the holes drilled into the outer steel square tube and the inner aluminum square tube. The overall assembled system integrated with electronics and electrical components is demonstrated in Figure 3-(b).

Electronics and Electrical Design Process

The design makes use of a single solar panel, which can produce a nominal 175 (W) power. The solar panel is wired directly to the input of the charge controller, the output of which is wired to the BMS of the battery pack. Unlike most charge controllers, which contain a load output, the charge controller in this project contains only connections for the solar panel and battery. Instead, the BMS on the battery pack contains independent charging and output connections. Due to the large amount of current required to power all the LEDs, a 40 (A) 5 (V) DC-DC converter is required to power the entire system. This converter is the highest capacity one commonly available given the wiring thickness. The wiring diagram is depicted in Figure 4, in which the power source and supply components are highlighted in red.

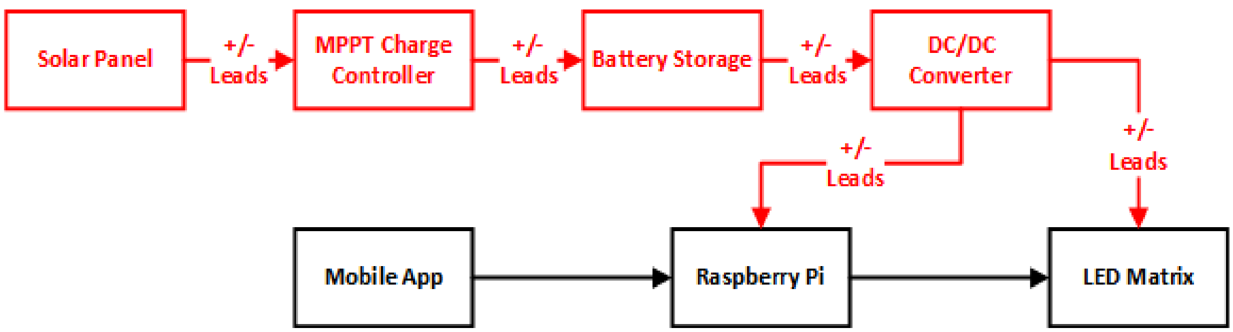
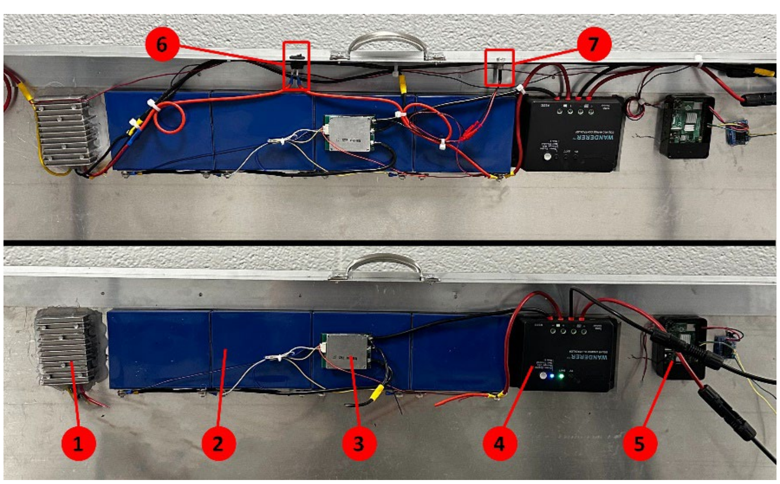


Figure 4. Wiring diagram (power source and supply components are highlighted in red).

The detailed implementation and integration of electronics and electrical components are demonstrated in Figure 5.



1. **DC-DC Converter**
2. **Battery Cells**
3. **Battery Management System**
4. **Solar Charge Controller**
5. **Raspberry Pi**
6. **Power Switch**
7. **External Charging Port**

Figure 5. Implementation and integration of electronics and electrical components.

Calculating the total power requirement is critical for designing the PV system and to maximize battery life. The total power is determined primarily by the power consumption of the LED strips; however, the Raspberry Pi, Solar Charge Controller, and the DC-DC Converter also require electrical power to function. Several factors affect the power consumption of the LED strip matrices, such as brightness, color, and number of LEDs illuminated simultaneously. The design makes use of a total of 1200 LEDs with the assumption that not all of them are illuminated at the same time. Furthermore, a value of 0.3 (W) is used for LED power calculation, which is given in the datasheet [9]; however, through testing, it has been found that the specifications provided include a safety margin of about 10-20%. The maximum total power is calculated as follows:

$$\text{Max Total Power (W)} = \text{Raspberry Pi} + \text{Solar Charge Controller} + 1200 \times \text{SK9822 LEDs}$$
$$= 6.4\ (W) + 0.05\ (W) + 360\ (W) = 366.45\ (W)$$

This power is overestimated, and the maximum power provided by the 5(V) DC-DC converter is only 200 (W) (= 5(V) × 40(A)). Therefore, the total power calculation is modified based on the practical consideration that only a limited number of LEDs is required to be powered at the same time to output text information. To do end, it is necessary to create a font that is legible using 5×5 pixels per letter. The pixel representation of each letter is used to determine the percentage of used and unused pixels required to display the full alphabet and 0-9 digits. The font created for the digital display board is illustrated in Figure 6.

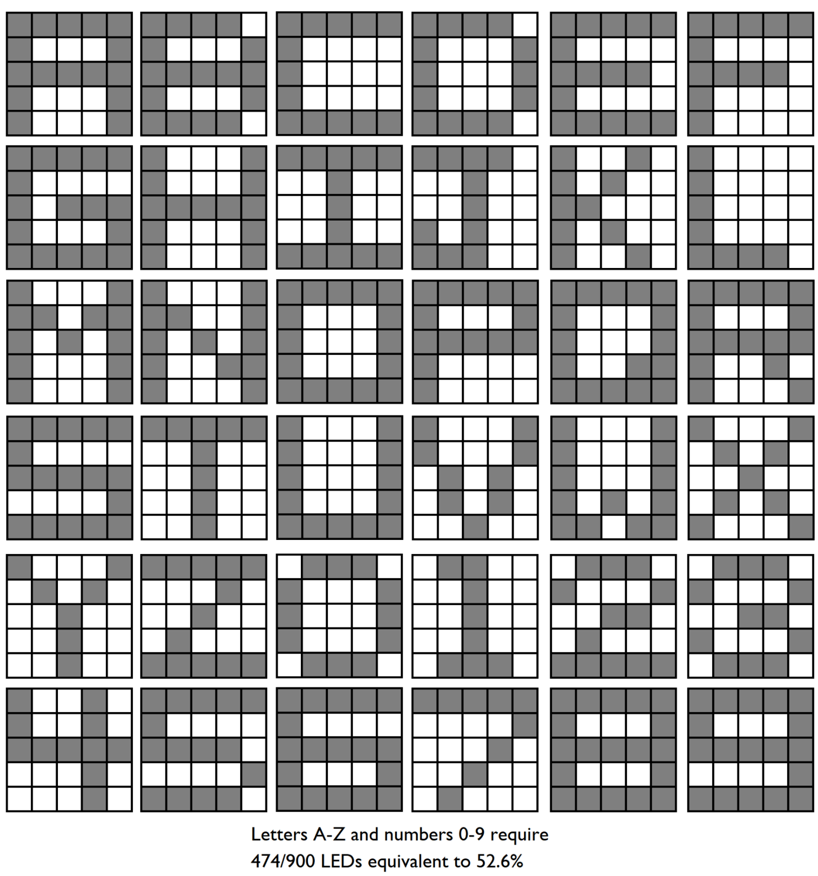


Figure 6. The 5×5-LED font created for the digital display board.

It is now determined that on average, only 52.6% of the LEDs are required to be powered at the same time. Using this information, the practical total power is calculated as follows:

Practical Total Power (W) = Raspberry Pi + Charge Controller + 0.526 × 1200 × SK9822 LEDs
= 6.4 (W) + 0.05 (W) + 189.4 (W)
= 195.85 (W)

The solar panel chosen is not capable of powering the display indefinitely unless steps are taken to minimize power consumption. Using the industry standard of 75% efficiency rating [10], which accounts for factors such as shading, clouds, and average daily sunlight, it is possible to produce about 131.25 (W) (= 175 (W) × 0.75) at peak sunlight hours. This means that given the practical total power above, the system consumes an average power of 64.6 (W) (= 195.85 (W) - 131.25 (W)) from the battery, while the solar panel is exposed to sunlight. New Jersey receives an average of 4.21 peak sunlight hours per day. This number of hours considers various factors such as expected average cloud coverage and solar panel orientation.

The battery is fully charged before the display board is used, and to save battery life, it should not be discharged below 20% of its full capacity. Therefore, it is determined that the display has enough power to last 5.44 (h) on a full charge as per the following calculation:

Total Battery Energy: 50 (Ah) × 12.8 (V) × 80% = 640 (Wh) × 80% = 512 (Wh)

Battery Energy Consumption during Peak Sunlight Hours: 64.6 (W) × 4.21 (h) = 272 (Wh)

Remaining Battery Energy Off Peak Sunlight Hours: 512 (Wh) - 272 (Wh) = 240 (Wh)

Battery Energy Consumption off Peak Sunlight Hours: 240 (Wh) / 195.85(W) = 1.23 (h)

Total Battery Life: 4.21 (h) + 1.23 (h) = 5.44 (h) Total

The exact results of the calculations vary from location to location based on peak sunlight hours. For example, in New Mexico, a more southerly state which receives 6.77 (h) of peak solar output per day, the display could function for as long as 7.15 (h) on a full charge using the above calculation.

The functionality of the display can be extended even further by using an external power adapter. In this project, both a DC 15(V) 4(A) and a DC 15(V) 8(A) adapter, which have identical barrel plug outputs, are used interchangeably at different stages of the project. In indoor testing, which closely mimics the power requirements for night-time operation, either adapter can supply enough power for the display to operate continuously. It indicates that both adapters are well suited to enable the display to have all-day operation as power requirements decrease throughout the day.

Software Development

The data flow diagram is shown in Figure 7, in which the information is transferred from the input, into the processing unit, and then to the output. The developed algorithm is demonstrated in Figure 8.

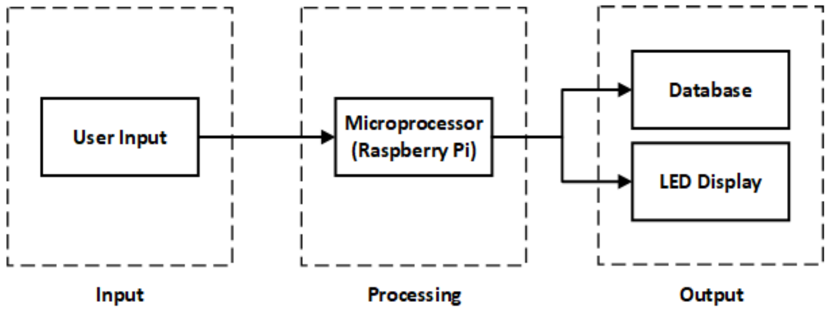


Figure 7. Data flow diagram.

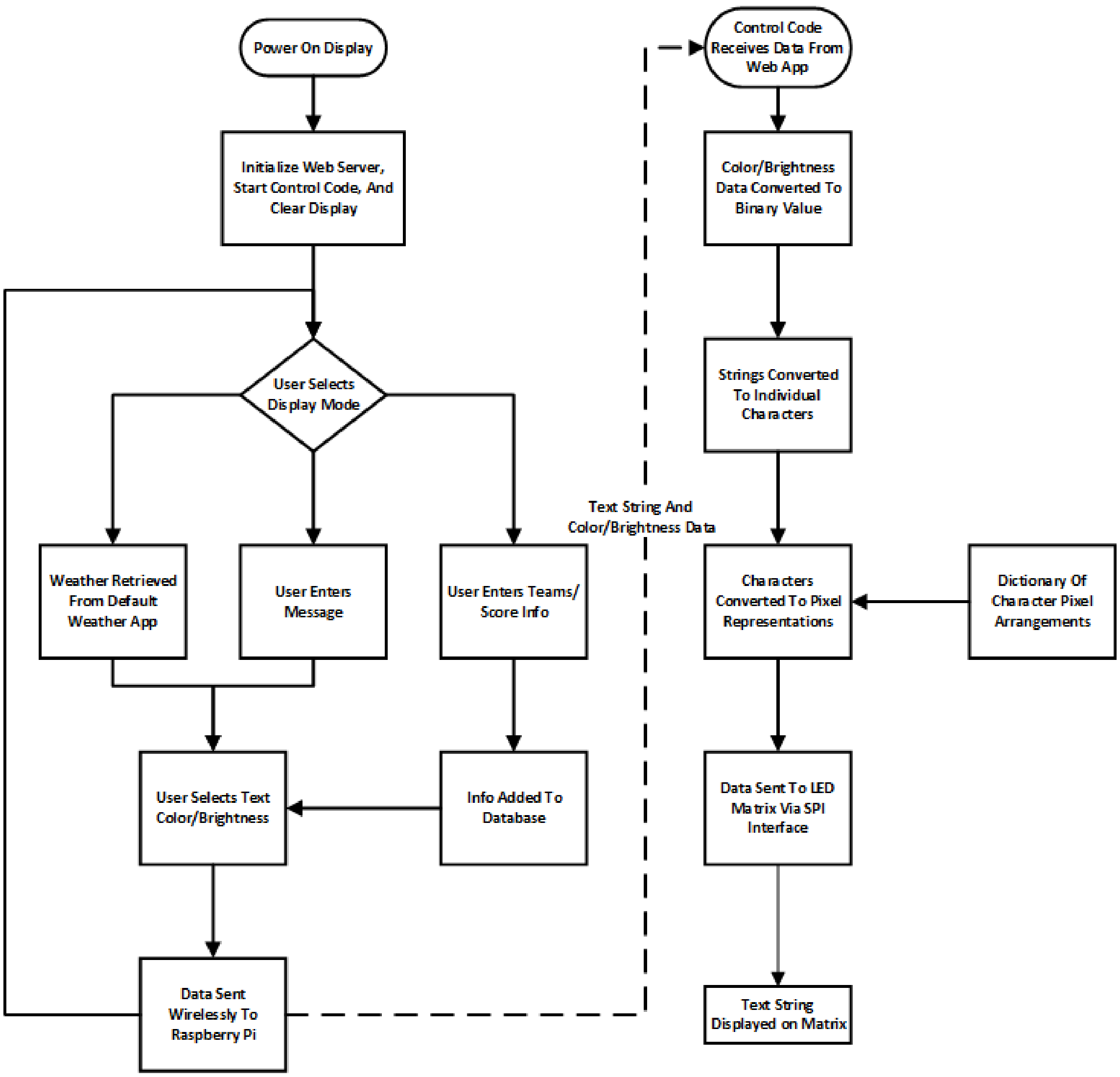


Figure 8. Developed algorithm.

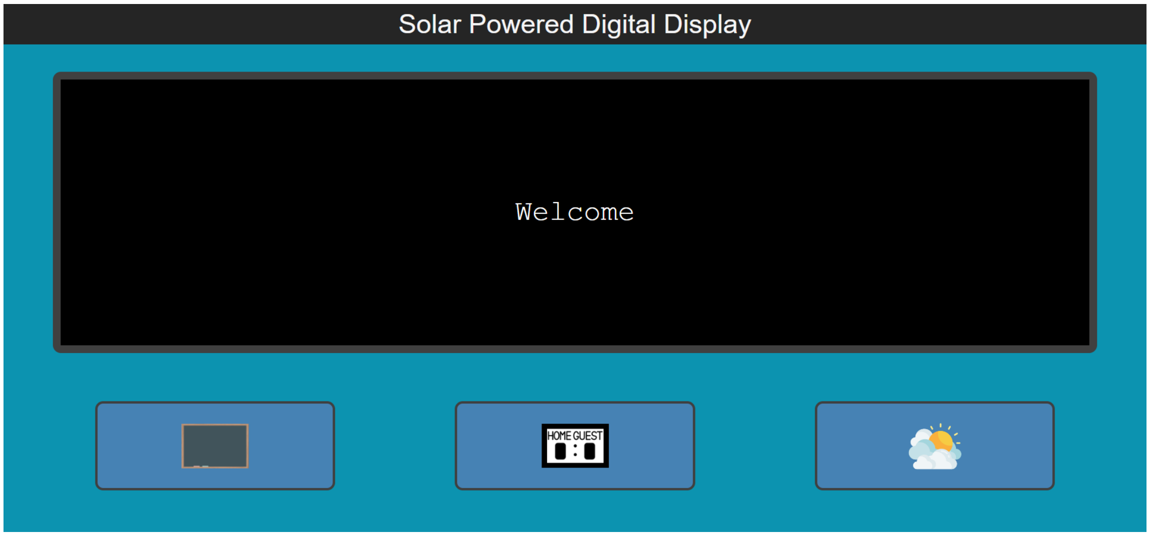


Figure 9. The home menu of the web application.

For the web application development, HTML, CSS, and Javascript are used as the front end, and Python is used as the backend programming language. The backend, Python, handles the user input and updates the text displayed, while the HTML, CSS, and Javascript are mainly used to allow the web application to be interactive and responsive for users. Javascript is used to send the information input by the user back to Python to ultimately display the information onto the display board. Flask, a web application framework written in Python, is used for the development of the application, mainly to be employed for efficient routing and data handling.

To access the web application, the user must connect to http://192.168.50.10:5000/ using an internet browser. After connecting to the Raspberry Pi, the user is then welcomed by the home menu, as can be seen in Figure 9. The web application starts by importing the files and declaring variables. Once loaded in, the user has the option to choose between three different modes of functionality, namely, general message display, scoreboard, and dynamic information display.

In the general message display mode, the user is allowed to input a message to be displayed on the display board. It also works interactively with the homepage of the web application. After submitting a message for display, the user is redirected to the homepage. On the top of the page, they find their message prominently showcased in a textbox. Simultaneously, the message appears on the display board. The general message display homepage also allows for other user inputs, such as the color and brightness of the text being displayed. The general message display mode screen is depicted in Figure 10.

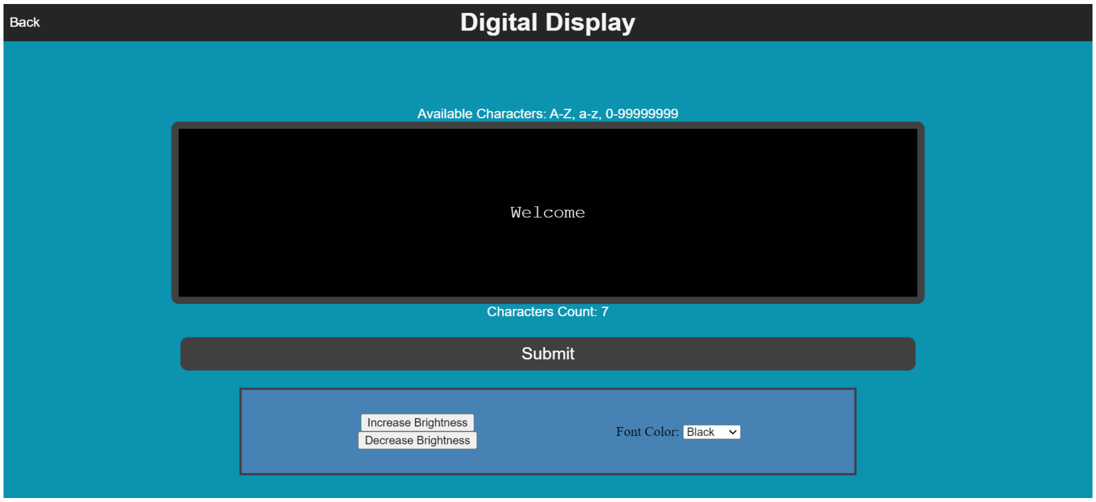


Figure 10. General message display mode screen.

In the scoreboard mode, the display board automatically displays "Home" and "Away", which indicate two different teams, and each has the numbers "00" displayed next to them. On the web application, the "Home" and "Away" teams have their own set of buttons that allow for the increment, decrement, and reset of scores using the "+1", "-1", and "0" buttons, respectively. This mode also includes a timer. Once in the scoreboard page, the user is able to click on a stopwatch icon. This starts the countdown of the timer. There is also a button with a "play" icon that can be used to pause or resume the timer. The scoreboard screen is shown in Figure 11.

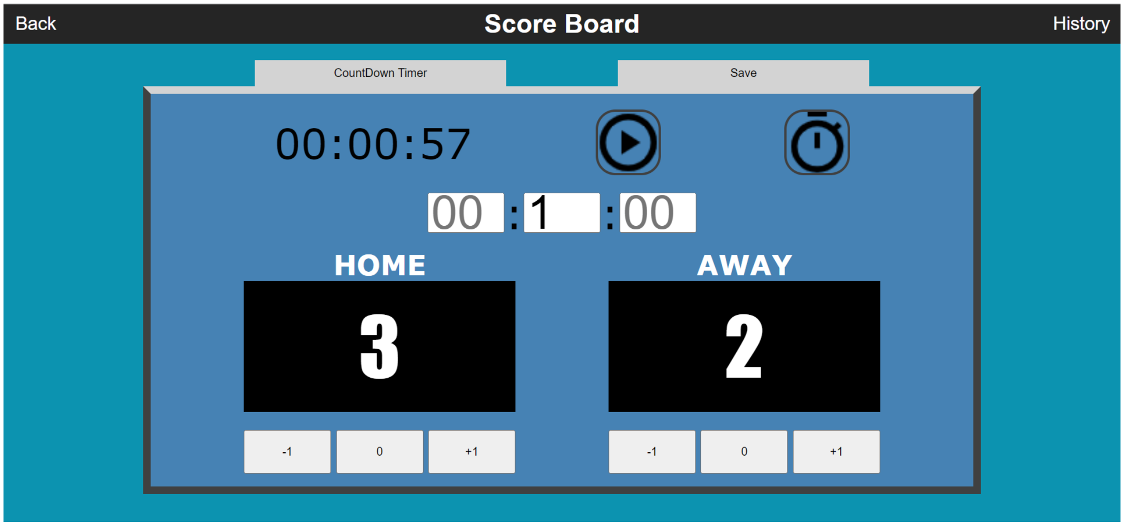


Figure 11. Scoreboard mode screen.

There is also a "save" tab at the top of the timer display. Clicking on this tab switches from the timer to a textbox that allows the user input for the title of the game, and a save button to save the information of the game including the scores. Once a title is inputted, the user can save the information, which is then sent to a Raspberry Pi database to be stored.

The window (menu) indicating that the "save" functionality works successfully is depicted in Figure 12. The scoreboard page has a "history" setting on the top right corner that, when clicked, retrieves and displays the saved data from the Raspberry Pi. It also allows the user to delete any saved data. The database history screen, with prior information saved onto it, is shown in Figure 13. If a game is saved with the same title as a game already saved onto the database, it will ask the user if they would like to overwrite the saved data with the same title. The database system used in the web application uses a text file to log (store and retrieve), which is handled by Python.

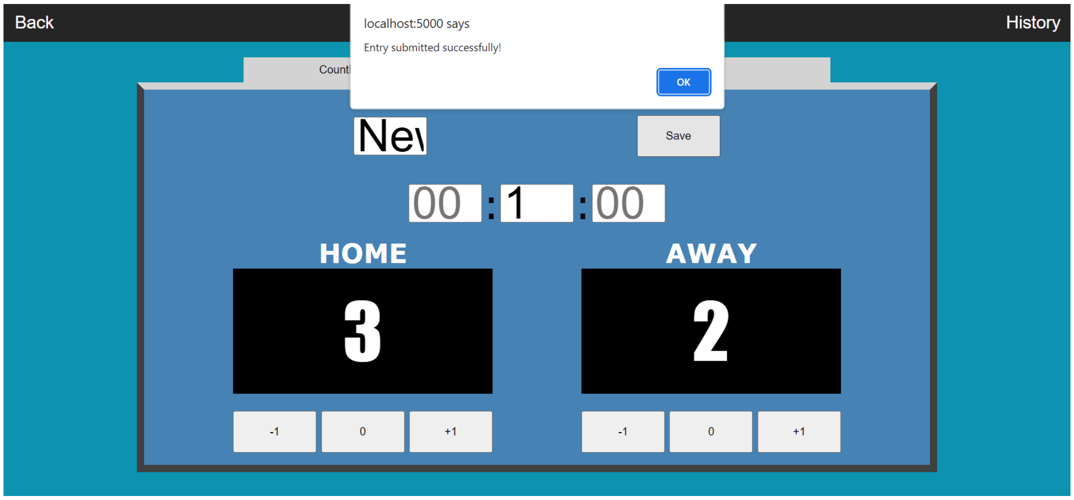


Figure 12. "Save" button in scoreboard mode.

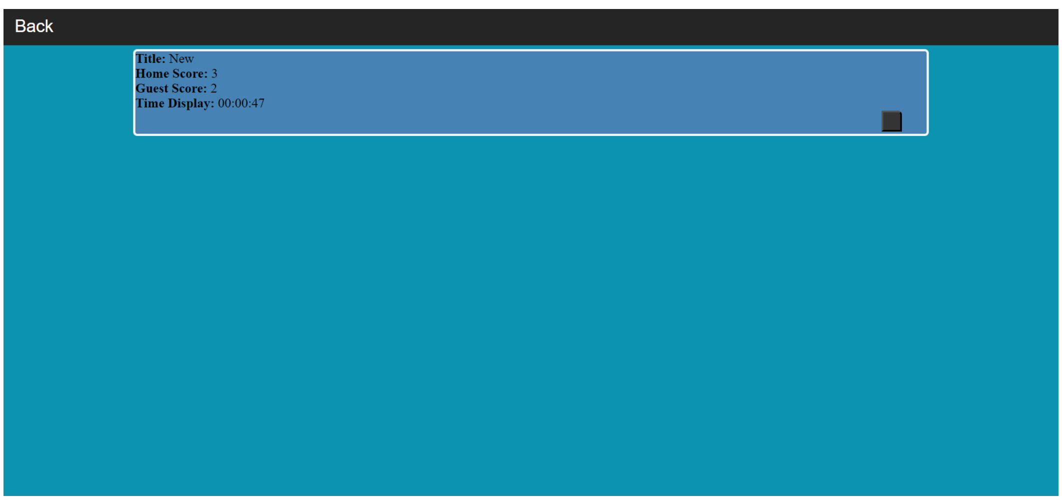


Figure 13. Database history screen in scoreboard mode.

In the dynamic information display mode, the user is allowed to input a town and country to receive the weather of the area. The weather page uses an Application Programming Interface (API) to retrieve the weather information. The website hosting the weather API is named OpenWeather. APIs are used for communication between two applications, allowing the web application to receive weather information. Javascript and Python work together in parallel to keep the information in order and display the user input onto the digital display board. Javascript sends a request to the weather API and processes the received data. It then proceeds to send the information to the backend, Python. The weather API fetches and displays up-to-date weather information from the searched location. The information displayed includes the current weather condition, description, temperature in Fahrenheit and Celsius, humidity, and wind speed. The weather mode screen displaying the weather information for Newark, New Jersey, is shown in Figure 14.

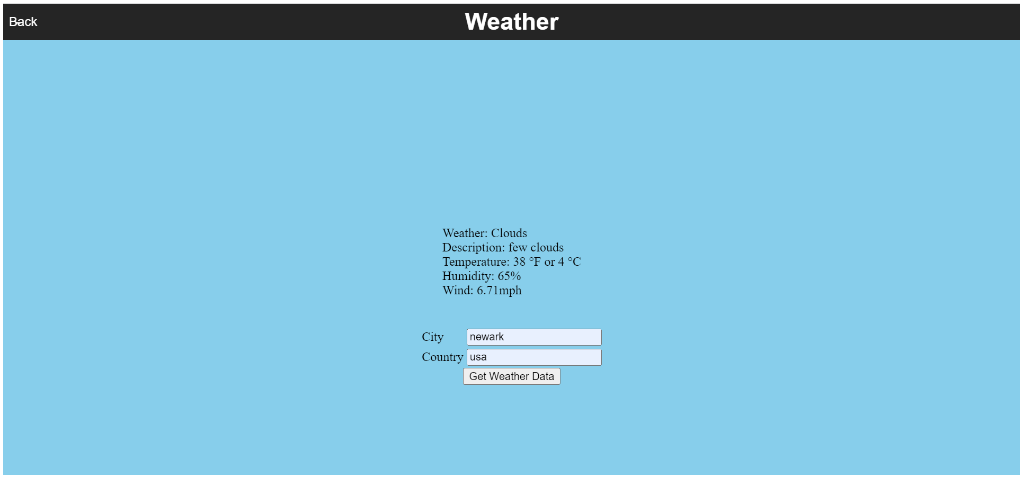


Figure 14. Dynamic information display mode screen.

Conclusion

In this project, a low-consumption portable wireless digital display board is designed and developed. The display includes three modes of functionality, namely, scoreboard, general message display, and dynamic information display. The display functionality of the device is designed and developed using a Raspberry Pi and by arranging LED light strips in a matrix formation. The display is controlled through a web application, which allows the user to change the mode of operation and interact accordingly with the system in each mode. The digital display board is powered by a battery storage system that is fed through a solar PV. The solar panel has a nominal conversion rate of 175 (W) and provides power to run the display using 50 (Ah) LiFePo4 battery cells. The highlighted features of this project include the renewable energy-based source of electrical power, multiple modes of functionality, and the convenience of being light weighted and controlled through a web application.

Acknowledgement

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