NORTHERN ARIZONA UNIVERSITY

School of Informatics, Computing, and Cyber Systems

Team Lithium Lumberjacks

Design Document

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Overview: The purpose of this document is to provide details pertaining to our project design.

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Introduction

This project is sponsored by Dataforth Corporation, a company that provides signal conditioning, data acquisition, and data communication hazard protection solutions to the ever-enlarging factory automation markets [1]. The primary objective of this project is to provide Dataforth with a product that is able to utilize and showcase the data acquisition capabilities of the company's MAQ-20 line of products. In seeking to achieve this, a battery management system has been proposed.

The Dataforth Corporation has numerous products that can assist in monitoring the necessary data. This data includes cell voltage levels, cell current levels, and battery cell temperature readings. For this project in particular, the charger must be able to safely and efficiently charge and monitor a 6-cell lithium-ion polymer (LiPo) battery. In addition, the charger must also be able to check and account for fault conditions such as a defective cell or an incorrect connection to one of the battery cells. For the purpose of accessibility, the battery charger will implement an intuitive user interface; one that utilizes both simple controls and an informative display that allows the user to effectively use the device with relative ease. The finished product is expected to be able to outperform similar battery chargers in one or more areas of cost, efficiency, or size. In addition, the project will have a clearly documented path towards applying the concept of this system towards scaled applications such as battery charging for electric vehicles or energy storage systems in homes and other buildings. The battery charger must use the Texas Instruments (TI) MSP430 microcontroller as the primary controlling circuit of the device. The charging, discharging, cell balancing, and fault correction algorithms will all be stored in the MSP430 microcontroller. In addition, the battery charging device must utilize Dataforth products when applicable.

While the premise of this project is well traversed, it provides goals that make it a unique and relevant task for undergraduate students. This is in addition to giving students the opportunity to work with a major player in industrial electronics. Having Dataforth as a client in this project provides access to expertise from numerous experts such as the vice president for product development, John Lehman. The Dataforth Corporation also gives the students involved in this project opportunity to work with state of the art data acquisition equipment, such as the MAQ-20 data acquisition modules. Finally, working with Dataforth in a trade setting will give students experience in presenting a finished product to colleagues and experts in the field, as the team will have to provide all of the periphery needed to supplement the project, including a user manual for proper operation of the battery charger, a presentation outlining the functions of the charger and the associated Dataforth products, and a display suitable for large scale presentations during trade shows.

Previous Work

In order to establish a thorough understanding of the intricacies of designing a battery charger, extensive research must take place. This research comes in the form of a literature review. For this review, members of the team searched for a variety of documents related to battery charging. Some examples include reports on previous projects, sets of standards established by reputable organizations such as the Institute for Electrical and Electronics Engineers (IEEE), and datasheets describing the specifications for batteries, voltage relays, and other components that will be utilized in the project.

The first document for review concerns a project report for a novel universal battery charger. This charger is capable of charging batteries of many different chemistries, including nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion) and LiPo batteries [2]. This charger is able to achieve this through the combined use of a current control loop and a voltage control loop. The current control loop works by utilizing a difference amplifier to drive the gate of a power PMOS transistor, then drives the current through a resistor and then the battery [2]. Meanwhile, the voltage control loop is meant to keep the current flow at the maximum charge rate until the voltage of the battery reaches its maximum, meaning it has been fully charged. The voltage control loop does this by acting as a feedback loop, allowing for high gain to limit the voltage, and a small unity gain bandwidth window to operate in conjunction with the current control loop [2]. Upon a battery cell(s) reaching its nominal value, the current is then reduced exponentially until it reaches a slow trickle charge rate of 5.5 mA. A high precision analog to digital converter (ADC) is used to detect when the cell has reached its nominal voltage. This work is relevant to the present project because there have been discussions about making this Dataforth battery charger system compatible with multiple battery chemistries as well. At minimum, the current and voltage control loop could serve as an adequate model for the battery charger to charge efficiently and safely.

The second work involves a proposal for a single-phase onboard battery charger for electric vehicles (EVs). This charger in particular is meant to have three modes and be capable of charging both a high voltage battery system and a low voltage battery system. The first mode is meant to charge the high-voltage battery of the EV when connected to a charging station or to a power grid. The second mode is meant to discharge the high-voltage battery in the event of excess charge being present. Finally, the third mode is meant to charge the low-voltage battery of the EV through transferring power from the high voltage battery [3]. The overall circuit for this onboard battery charger can be broken down into three separate components. The first stage involves a full bridge AC-DC converter. This stage is used to convert the electrical energy into a usable form for both battery systems. The second stage, consisting of a dual active bridge DC-DC converter, which is meant to help filter out any excess noise in the circuit. Finally, a dual functional circuit is added to serve as both the charging circuit for the low-voltage battery as well as an active power decoupler. The active power decoupler portion of the circuit uses two capacitors in series to help alleviate issues such as power ripple [3].

The third work that was reviewed was focused on a fast charging technique for batteries. This paper was looking into lithium ion (Li-Ion) batteries, but the concepts of a fast charging algorithm could assist our team if we decided to allow fast charging in our battery charger. Batteries can be charged in different ways. The standard charging techniques for Li-Ion batteries are trickle charge (TC), constant current (CC), and constant voltage (CV) [4]. These charging methods can also be used on Lipo batteries which helps connect this paper to the project the our team is working on. Each of these charging methods is utilized in different ways when charging a battery. Trickle charging is charging at the same rate as the battery discharging rate allowing for the battery to stay at the charge it was at when trickle charging was started. Constant current and constant voltage charging methods are used at different times when charging a battery and charge at different rates, with constant current being the faster of the two modes [4]. The team from this paper wanted to use the batteries internal resistances and voltages to make the battery believe it needed to be using constant current charging for longer periods of time than it should [4]. This would allow the battery to charge faster by being in the fastest charging mode longer than any other mode. After simulating and testing the team found that “the extension of constant current mode makes the charger charge the battery with faster speed” [4]. Seeing this successful fast charging technique can help our team if we decide to utilize fast charging in our design. This review also helped show how algorithms are thought out and created, useful for our team as we will need to create normal charging algorithms for our battery charger.

Of all the previous documentation the team reviewed, any documents outlining the standards for lithium ion batteries and their charging units were by far the most important. This is because the standards documents provided the team with a set of guidelines that would define a safe and efficient battery charger. One such document provided a detailed description of charging standards for lithium based batteries. In this document, there was a decent amount of terminology that helped the team define how the system architecture would work. Essentially, the standards document described the module that would be responsible for providing power to the battery as a power conversion system (PCS) [5]. This PCS would be responsible for providing DC power to the battery, thus acting as a charger, a rectifier, and an inverter. Additionally, the document went on to describe a battery management system (BMS). The BMS serves two major functions in monitoring the status of the battery, including voltage levels, current levels, and temperature. The system would then be able to take action if it notices a fault in these qualities for any one of the cells. For example, if one of the cells were to lose voltage completely, the BMS would recognize this and deactivate the charging relay of that cell. For this project, the Dataforth Data Acquisition Modules will act in conjunction with the MSP 430 Microcontroller as the BMS.

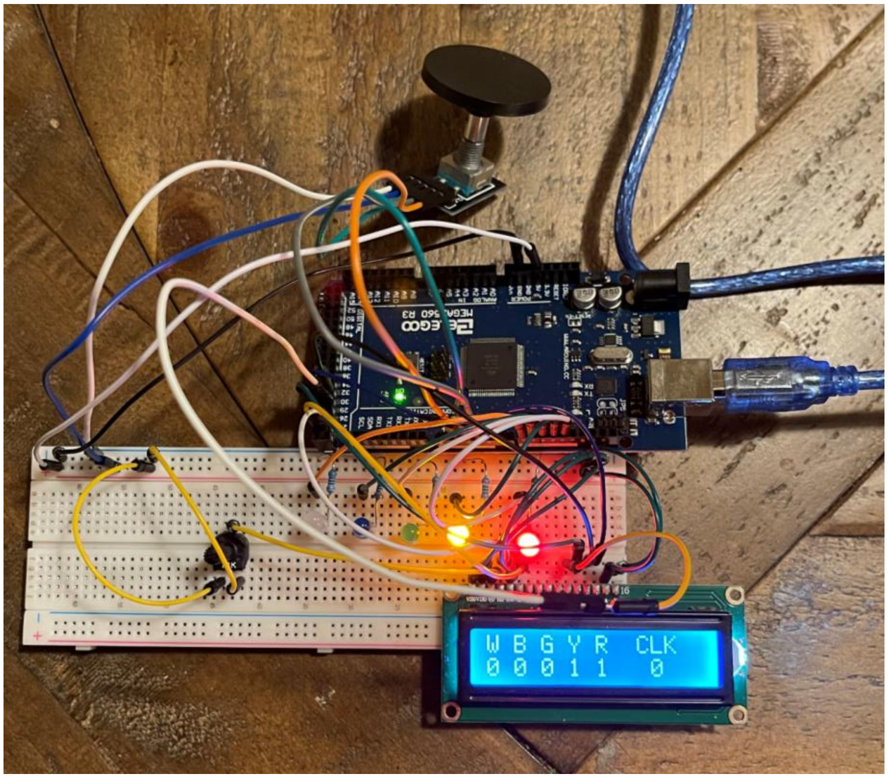
Prototypes

This section will go into detail about the process of prototyping the different subsystems of our team's design. Prototyping is a necessary step in the design process. It allows for products to be tested for any major design flaws without spending as much money or time as would happen during the final design. Prototyping will allow the team to test specific parts of our design that we believe to be the most important to better understand devices we will be working with, and to find any flaws in the overall design at this time. The specific subsystems that were prototyped were chosen based on how important the system was in the design and if we needed to learn more about the system. Each member of the team was assigned a subsystem to prototype and all members of the team learned about the system via the prototyping process. This section will explain each subsystem and how it was prototyped during the prototyping stage of this project.

User Interface

One subsystem that needed to be prototyped was the user interface. This is an integral part of our design since the interface will allow the user to see details about the charging battery, and will be able to provide inputs to change how the battery is charging. A well designed user interface would create ease of use for our users and make the overall project look and feel more professional. The user interface was designed on an arduino using a 16x2 LCD display and a rotary encoder. Figure 1 shows the prototype of this subsystem. The prototype allowed the team to learn more about coding LCD displays and how to function a rotary encoder. This knowledge will be utilized when the final design of the user interface is created. The prototype already allowed the team to see some chances for changes within the design. The LCD screen did not have enough space, nor did it look as professional as the team would like, so for the final design the team plans on using a small OLED screen as shown in Figure 2.

Figure 1: Completed user interface prototype



This prototype was successful. It allowed the team to gain knowledge that will be useful in the further development of the product. The prototype was a chance to test how to code a menu that can be changed and scrolled through using a rotary encoder. While the menu was not as in depth as the final design it still had scrolling features, and allowed the user to press a button to change the menu. These were the results the team was looking to achieve when it was decided that this subsystem would be prototyped. Since the prototyping phase this subsystem has started to be worked on to get closer to the final product wanted by the team. With it being such an important part of the design it was good to see a successful prototype that allows for implementation faster than if the prototype was not successful and required more in depth testing and changes.

Figure 2: OLED screen taking the place of LCD

Cell Balancing and Charging Algorithms

The initial portion of planning out a prototype for the cell balancing submodule was focused on determining how it would be implemented. In other words, the team needed to figure out what kind of hardware or software would need to be created as a relevant cell balancing submodule for the battery charger. The best resource to aid in this question was the Project Sponsor, Mr. John Lehman. He was a key figure in this stage of planning because he knew which hardware components would be required to include in the battery charger. After meeting with Mr. Lehman, he had told us the hardware Dataforth was providing us, the MAQ-20 Data Acquisition System, was able to read voltage, current, and temperature values of the battery cells directly. In addition, the MAQ-20 was able to communicate directly with our central microcontroller for the project, the MSP430, via UART to Serial communication. With that in mind, the prototyping of a cell balancing submodule would be solely focused on software, namely programming the MSP430 to react to the data received from the MAQ-20. The first step in designing a prototype was to create an algorithm for the MSP430 to execute and command other modules to help balance the cells. Thus, the flowchart, as seen in Figure 3, was created to help aid in visualizing this algorithm.

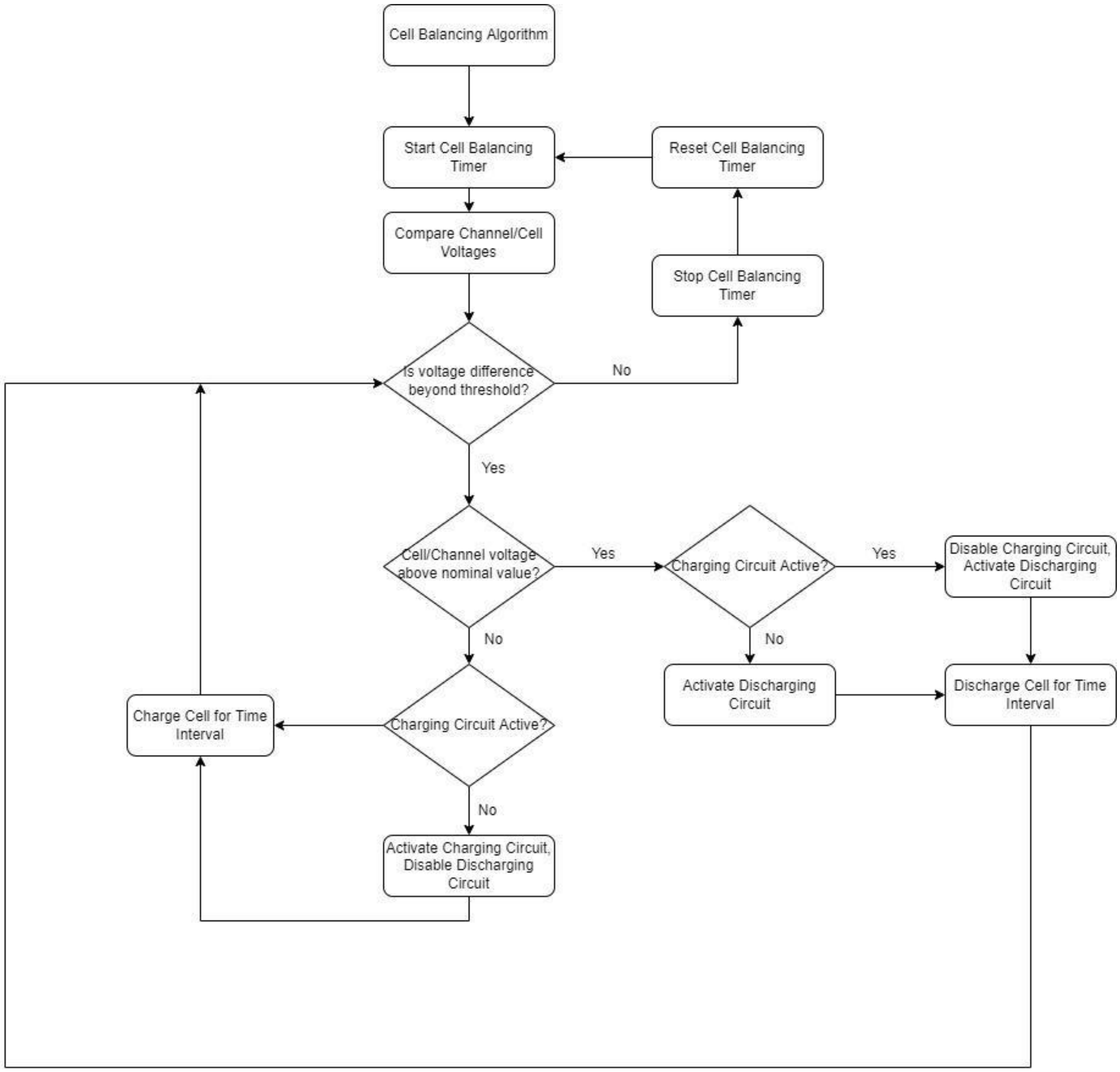


Figure 3: Charging algorithm flowchart

The algorithm is based off of a timer that resets each time before checking the cell voltages. Should the algorithm find that the difference between one cell and the other cells exceeds the threshold (0.1 V is the test value), the algorithm then proceeds to check where the cell voltages are in relation to their nominal value. In this case, the nominal voltage of our 6 cell LiPo battery at full charge is 3.4 volts. Should the cell be below the nominal value, the algorithm then ensures that the charging circuit is active for that cell. If the cell is overcharged, or above the nominal value, the algorithm will then activate the discharging circuit. This charging or discharging will be repeated over a set of time intervals until the cell has matched with the other cells at the nominal voltage rating.

Cell Discharge Hardware

In balancing each cell, discharging current is necessary to level the differing cell chemistries. Conceptually, the best thing to discharge a battery safely is an incandescent light bulb or functional equivalent. This is because the incandescent bulb will vary its resistance as a function of current going through it. As the filament heats up the resistance increases and therefore the voltage drop across the filament can be normalized to a value related to the wattage of the bulb.

While the design includes a varistor, the prototype of our discharging circuit was done via incandescent bulb to an expected outcome. In testing the prototype an ammeter was used to determine the current going through the bulb, which varied as the filament got brighter and warmer. The incandescent bulb prototype was tested to withstand up to three of our LiPo battery cells before the rated wattage was exceeded.

Charging Hardware

Our charging circuit prototype was more conceptual; gathering from research into safety standards for lithium battery charging and battery charging theory. Concepts such as constant current and constant voltage regulation were explored in detail. It was concluded that, in the interest of battery longevity and safety, the entire battery could be charged at a rate of 1C (amp-hours) at the rated voltage of the pack.

This led to the final subsystem design goal of providing a nominal 1.25A at 22.2V to the battery pack terminals. While the prototype of this circuitry was not completed on schedule, the design requirements have brought to light many issues regarding high-performance battery packs. In particular the amount of current every module needs to handle and the control of that current for safety and ease of maintenance [A].

Design

System Architecture Overview

Our system architecture can be split into six functional areas including hardware which handles power, charging of the battery, discharging of each cell, data acquisition, communication, control and processing, and user interface / peripheral devices. The power subsystem provides interfacing between consumer electrical outlets and all devices within the product. The charging subsystem acts as a controllable high amperage power supply for battery charging. The discharge hardware is mostly passive and interfaces only with the primary power supply ground.

The data acquisition subsystem is provided from the Dataforth Corporation product line of MAQ-20 modules. Communication between their acquisition and our control systems is a combination of their dedicated communications module and a serial encoding transceiver independent of our microcontroller. The microcontroller provides minimal processing and acts as a master for all other subsystems. The user interface and peripheral subsystems include modules for both audio and visual interaction as well as system cooling.

Power Subsystem

Shown in the upper left of the system block diagram (Appendix A), the power subsystem starts with an AC to DC converter power module. This module steps down consumer AC power of 100-240VAC to regulated DC power in the 24VDC range. From there the DC voltage is stepped down through use of buck converters in a parallel configuration to give the system a wide range of DC power rail options for the differing voltages each subsystem works at. For the most part, consolidation of these into a 12V power supply and a 5V power supply has reduced cost, necessary thermal conditioning, and size of the final design.

Charging Subsystem

The charging subsystem is the only active area of the design which does not take step down voltage from the smaller buck converters, but instead taps directly into the primary power supply for functionality. This is because, as a stretch goal, our design should be able to charge the battery at a rate of 5C which means providing a nominal 6A at 22.2V to the battery pack. In the interest of achieving this, a separate DC-DC step down converter module which can handle up to 9A is utilized. Relays rated for 8A are used for control of the circuit [5]. An array of smaller buck step down converters are used as constant current / constant voltage modules for delivering power to the battery.

Discharging Subsystem

Being the only passive subsystem, the discharging hardware interfaces between the primary system ground and individual battery cells. With typical noise-reducing capacitors to ground, the discharge hardware consists of varistor(s) which are capable of varying their resistance automatically depending on the throughput current. These varistors are rated at 3.5V to operate, which is perfect for our battery pack [6].

Each cell in the pack has a nominal ideal charge of 3.7V which means even if the control for the discharge circuit fails, the cells will not be discharged to lower than 3.5V. Small value capacitors will be added to ground to smooth transitions between the state of discharge and nominal disconnect.

Dataforth Data Acquisition Subsystem

The Dataforth MAQ-20 data acquisition subsystem consists of five separate components. The first of these is the MAQ-20 COM4, which serves as the primary communication liaison between the MSP430 Microcontroller and the other MAQ-20 components [7]. The MAQ-20 ISOV2 and ISOI1 measure the current and voltage levels of each cell in the battery respectively [8]. The MAQ-20 JTC is a thermocouple unit that can monitor the temperatures of each cell [9]. Finally, the MAQ-20 DORLY20 is a circuit breaking relay that can cancel the charging of the channels in case of a fault [10].

Communication and Data Transmission

The MAQ-20 COM4 is able to send and receive data from the MSP430 via a bidirectional UART to serial module [7]. This module is then connected to the COM4 via RS-485 cable. The MAQ-20 COM4 will be able to send data such as voltage, current, or temperature values to the controller. The controller can then send instructions based on that information, such as cutting off one of the relays in the case of overheating.

MSP430 Microcontroller and Processing

The MSP430 microcontroller is the system that will control communication between the battery charging subsystems and the user interface subsystems. This makes it a focal point in our design. Within our design it takes input from both subsystems and allows them to communicate with one another. The MSP430 will also run all peripherals in the design of the user interface.

Peripheral Modules

The project design contains peripherals for the user interface and for cooling our system. Due to the design of the discharging circuit using a varistor that will create a lot of heat the system needs a cooling system to allow for the heat to dissipate before it can cause problems in the rest of the system, or create a safety hazard.

Display, Menuing, and Physical Interface Devices

The display, menuing, and physical interface devices are a simple design. All three will utilize the MSP430 to communicate with the rest of the design. The MSP430 will also run the code to create the menus to be displayed on the OLED screen. The physical interface will be composed of three physical devices as shown in Figure 4. The OLED screen will be used to display battery data and fault detection data when a fault occurs within the battery. The rotary encoder will allow the user to change through the different menus on the OLED and make selections about different charging modes. The active buzzer fits into the design for providing an audio warning if a fault is detected, which was requested by Dataforth. Figure 4 also shows the voltages and connections of the design. The OLED will utilize an I2C connection. The rotary encoder utilizes a SW, DT, and CLK connection. The active buzzer uses just a DATA connection, and all devices use

5V for VDD and have a GND connection.

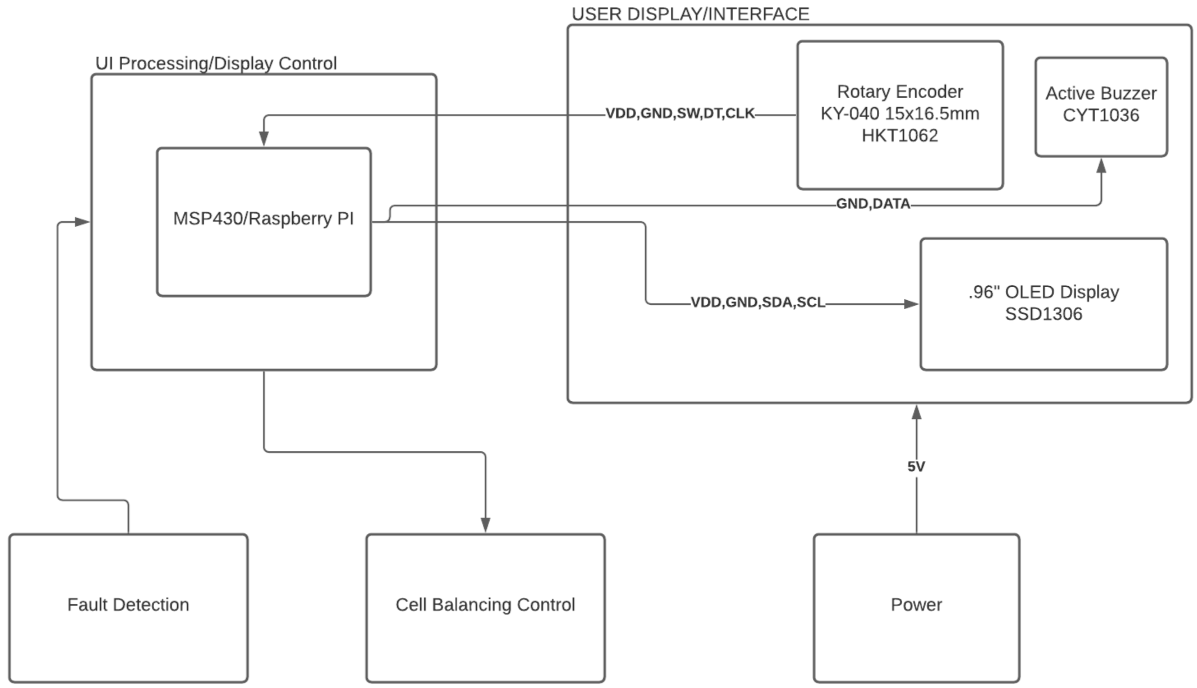


Figure 4: User interface block diagram

The menus that will be displayed will be coded onto the MSP430 using TI C as the programming language. The code will be split into three different functions and the menus will be static with variable input from other functions that are constantly reading the battery information. Figure 5 shows how the display will function. User interaction or lack of user interaction will be the main factor in the design of display function.

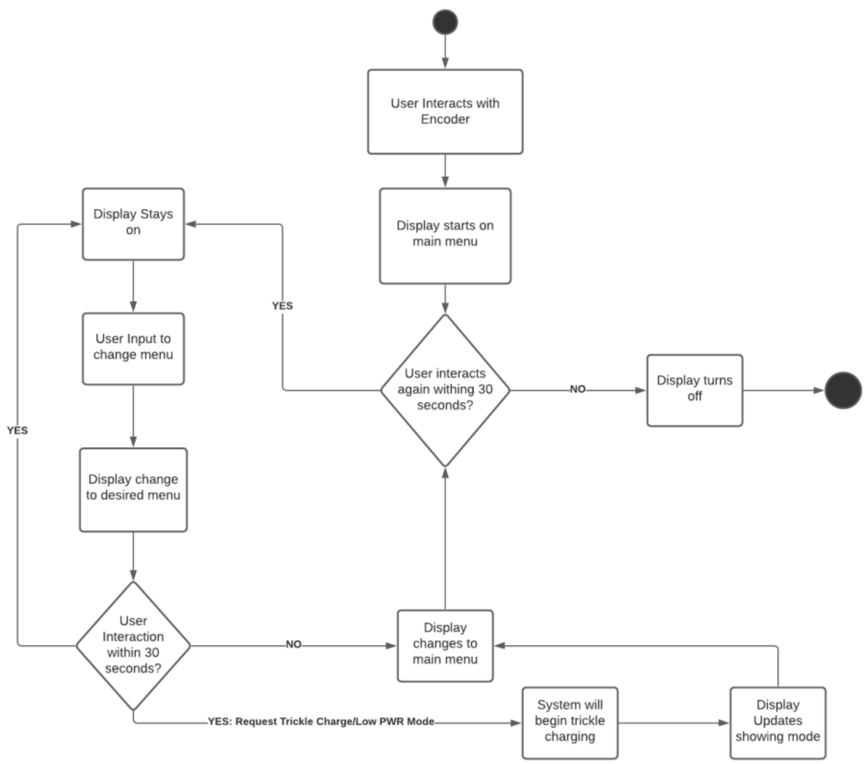


Figure 5: Display menu flowchart

System Cooling

Thermal conditioning is provided in particular to the power circuitry and charging hardware through use of 12VDC brushless motor fans. Positioning and chassis design will be implemented to counteract thermal issues which may arise from high power consumption.

Future Planning

System Integration

System integration is scheduled to begin January 2022. When all necessary parts and processes are collected, the process of integration can begin in earnest with wiring up and testing each individual module. Once an initial fine tuning of each adjustable module is completed, testing of the subsystems can begin.

Testing

The subsystems will go through relevant testing for their application, but in general testing will be done in three phases. Phase 1 of testing will include overview tests of system components such as continuity tests and passive component measurements. Tolerance testing may also be applicable in phase 1. Phase 2 will consist of testing subsystems in their respective general functions. The goal of phase 2 will be to ensure basic functionality is solid and after phase 2 is complete the system as a whole will be functional. Phase 3 is testing the finer details of each subsystem and refining each function to handle different ambient conditions as well as intersystem faults.

Maintenance and Upgrades

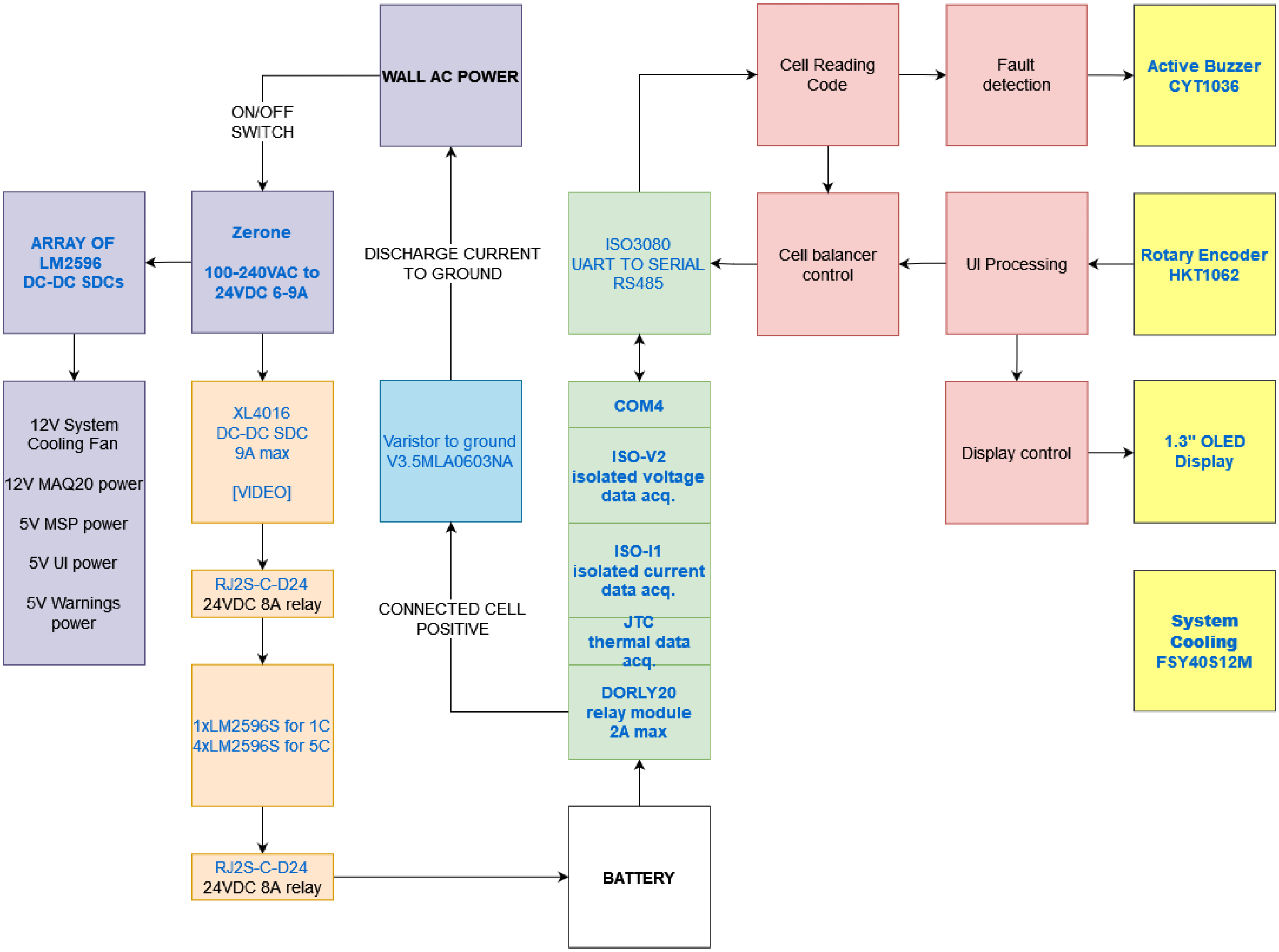
Maintenance instructions will be documented and sent along with the system as well as being available online through the project website. Upgrades may be necessary in the future to continue adequate functionality. Scalability will be discussed with that in short.

Conclusion

The Dataforth Corporation has tasked the team with creating a battery charger that can be utilized to show Dataforth products in use at trade shows. Dataforth asked that the team use at least one of their products in the final design of the battery charger. The battery management system in development follows industry standards and meets all requirements set by the Dataforth Corporation and the team.

Throughout the course of this project the team has followed a ten-step design process provided as guidelines to electrical and computer engineers to work through and create a successful system. Starting at the beginning of the process the team identified the problem through the project proposal submitted by Dataforth. This document shows the team also worked through the research portion of the design process wherein each team member researched literature and standards that relate to the project. This has allowed the team to make informed decisions about the design of the battery charger and follow industry standards along the way. This document also covers the team's work through the planning and creation stages of engineering design by providing details about the prototypes created by the team. These prototypes helped expand the knowledge of the team about the different subsystems in the battery charger design. The team has ended this semester, the half-way point in the timeline, in the system integration stage of the process, but plans to move onto the testing and product delivery stages in the coming months.

Appendix A: Hardware Block Diagram



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