Custom Data Acquisition System for the Cal Poly Racing Baja Team

A Senior Project Report

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science in Computer Engineering

by

Joe Keenan

June 2025

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1

INTRODUCTION

Baja SAE is an international collegiate competition run by the Society of Automotive Engineers (SAE) where teams design, build, test, and compete with offroad baja-style vehicles. In the United States, there are three competitions each year across the country for teams to compete in. There are three categories of events for which teams are scored: static events, dynamic events, and the endurance event. Static events include different challenges to test a team's ability to effectively communicate design choices and business aspects of making a vehicle. Dynamic events test the abilities of the vehicle to perform in different conditions. These events include an acceleration event, a manueverability event, a suspension event, and a traction event. Finally, the endurance event tests the vehicle's and driver's ability to withstand rough terrain and wheel-to-wheel racing for a full four hours. At the end of the competition, all the event scores are added together to determine who the top three overall teams at the competition are. To win the competition, it is crucial to perform well in all three styles of events.

Cal Poly Racing competes in the Baja SAE series of competitions. Over the last several years, Cal Poly Racing has had moderate success, with several top three trophies in dynamic events. The Baja vehicle runs the series' only dually actuated electronic CVT, an electronically controlled hydraulic clutch for 4WD, and a custom dashboard. Additionally, the car runs with freewheels in the front, an aero package, and Genesis Racing shocks with a custom anti-roll bar.

In order to design a vehicle capable of withstanding all the harsh events in a Baja SAE competition, it is critical to fully understand how every system of the car is behaving. Additionally, understanding the load cases, such as impacts, is essential to making informed design choices and considerations. To understand the the vehicle and load cases, a data collection system is needed to log and process sensor data. Data Acquisition Systems (DAQs) are tools that allow for the logging and processing of data.

Chapter 2

BACKGROUND

2.1 CAN

Controller Area Network (CAN) busses are commonly used in automotive applications to connect different control or instrumentation nodes together developed by Bosch in the 1990s. This allows for any node to communicate with any other node on the bus. CAN utilizes a two wire asynchronous differential twisted pair signal to transmit across the bus. The asynchronous nature of this protocol reduces the number of wires required to transmit data. By utilizing a differential twisted pair, noise and interference are reduced improving reliability and robustness of the network. However, only utilizing a single differential pair means that a node can only transmit or only receive at any given time, reducing throughput.

CAN is an addressed based communication protocol. An address can correspond to a specific node or to a specific message. Since CAN only utilizes a signle differential signal, it must negotiate to determine which node is transmitting and which nodes are receiving. The lowest address trying to be transmitted wins the negotiation, meaning that priority can be assigned to messages by assigning a lower value for an address to the message. This addressing and need to negotiate also adds overhead to the transmission, reducing overall data throughput. Additionally, there are control bits, cyclical redundancy (CRC) bits, and end of frame (EoF) bits that all also contribute to overhead.

2.1.1 CAN 2.0

CAN 2.0 is the most commonly used CAN protocol in the automotive. This version of CAN uses an 11 bit identification or address section with maximum of 8 bytes of data transmitted. The bitrate for this version of CAN can be up to 1 Mega bit per second (Mbps) [7]. With an assumption of 1 byte of data transmission, the overhead can be computed as $\frac{48\text{bits}}{56\text{bits}}$. With the assumption of 8 bytes of data transmission, the overhead can be computed as $\frac{48\text{bits}}{112\text{bits}}$. The more data that is transmitted per frame, the less overhead impacts the total data throughput. An example data frame of CAN 2.0 can be seen in fig. 2.1.

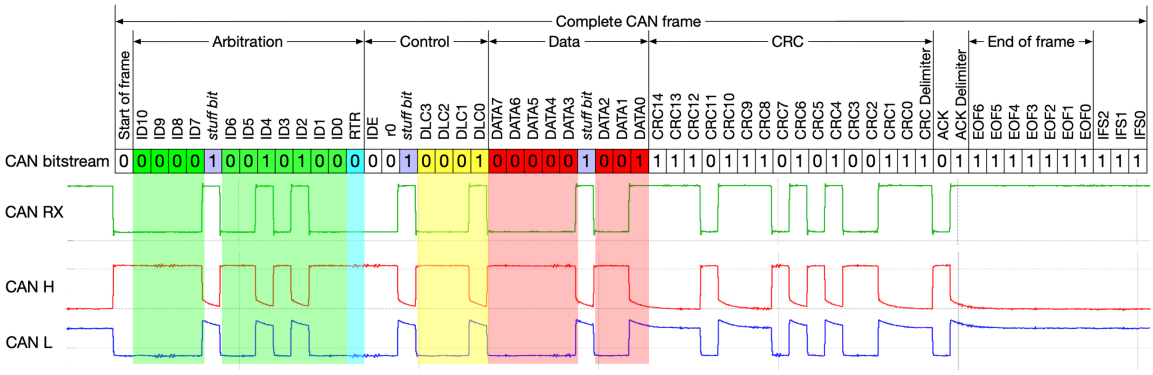


Figure 2.1: *Example CAN 2.0 Frame [4]*

2.1.2 CAN FD

In 2012, Bosch released a new version of CAN with a flexible data rate called CAN FD. This new version of CAN has several improvements including faster data rates and allowing for more data to be transmitted in each frame. The flexible data rate comes from CAN FD's ability to increase the data rate during the data section of the transmission. The protocol supports up to 8 Mbps of throughput during the data section of transmission and up to 1 Mbps of throughput during the beginning and ending parts of the frame [6]. This allows for significantly more

data throughput overall. In addition to the flexible data rate used by CAN FD, the maximum size of the data section was increased from 8 bytes to 64 bytes [6]. This decreases total overhead significantly making the transmission more efficient. These two new characteristics combined provide for a much more efficient transfer of data, particularly when transmitting high amounts of data very frequently.

In order to use CAN FD, it must be supported by the hardware, including both the CAN controller and the CAN transceiver. Additionally, to rely solely on CAN FD, each node on the bus must be using CAN FD. Otherwise, conflicts may occur impacting frames being sent or received. The system would theoretically operate without too many issue, but the control section of the frame would be different sizes to accomondate the additional control bits needed for the CAN FD frame.

2.2 AEM

AEM designs data loggers and dashboards for testing purposed for cars and other vehicles. These dataloggers connect to their different modules that connnect to various can sensors and breakouts for different types of sensors. Some of these modules also come with an inertial measurement units (IMU) and global positioning system (GPS) which are useful for understanding the entire vehicle state.

2.2.1 AEM Loggers

There are several different AEM loggers available for purcahse. The two major loggers available for purchase are the AEM CD-5L and the AEM CD-7L. The CD-5L costs $1,574.95 without the IMU or GPS and the CD-7L costs $2,081.95 without the IMU or GPS [2]. This cost provides access to data logging features as well

as a dashbaord display. These dashboards can be configured to display different information to a driver or engineer to get a snapshot of the current state of the vehicle. A computer can be easily connected to these devices to upload different configurations as well as to download the logged files.

Figure 2.2: *AEM CD5L Dashboard*

The loggers log files in a comma seperated file (csv) format for ease of use with tools such as Matlab or Python for visualizing the data. These files can also be visualized on the dashboard as well to give a quick glimpse at explaining what is happening.

2.2.2 AEM Add-Ons

In order to connect more sensors or instrumentation to the AEM loggers, additional add-ons must be purchased and configured. Some of these add-ons include a CAN module which allows the AEM logger to connect to and interface with a CAN bus and a thermocouple unit for measuring temperature. These expansion units, before the cost of any sensors, are several hundred dollars on their own. In order to hook up any sensors, at least one of these expansion units must be purchased.

Figure 2.3: *AEM thermocouple expansion unit*

AEM also sells some sensors that are simple to integrate into their ecosystem. These sensors include thermocouples, air and water temperature sensors, and several styles of pressure transducers. Each of these sensors is somewhat expensive on their own, costing around $100 per individual sensor. The AEM loggers can also interface with traditional analog or digital sensors so long as the appropriate add-ons are purchased.

In addition to wired sensors, AEM is also compatible with some wireless sensors for things such as tire pressure monitoring systems (TPMS) or fuel sensors. In order to communicate with these wireless sensors, a wireless module in needed or a logger with wireless capabilities is needed. AEM utilies a propietary system call X-Wifi to connect to these wireless sensors that is already a part of their CD5 and CD7 loggers. AEM's sensors that can utilize the X-Wifi capabilities of the logger are priced Similarly to their more traditional wired sensors.

2.2.3 DBC Files

In addition to AEM specific sensors, the AEM dataloggers can interface with any custom hardware that is outputting it's data over CAN. In order to configure the AEM to read data from a CAN bus, including its own CAN capable sensors, a configuration file must be made to tell the logger which value corresponds to which bytes of a specific CAN frame. A CAN Database file (.dbc) is a standarized file format for configuring which is able to describe what information is contained within a CAN frame. An example .dbc file can be seen in listing A.1 in the appendix. AEM utilizes this file format for its dataloggers to interface with a CAN network so long as the proper hardware add-ons are purchased.

2.3 AiM

Another company that makes dataloggers to attach to a vehicle is AiM Sports. AiM makes dataloggers that are specifically intended for motorsport applications as well other products such as dashboards, steering wheels, and ECUs. Similarly to AEM, AiM also makes combined dashes and loggers, as well as different accessories and senors for their dashboards and loggers.

2.3.1 AiM Loggers

AiM develops several loggers with similar specs to the AEM loggers with some additional features. The MX series and MXM series loggers are comparable to th CD5 and CD7 logger dashes that are sold by AEM. These loggers also act as dash displays, with the MX series having a nicer display than the MXM series. The MX

series and the MXM series both support many different ECU communication protocols over CAN or RS-232 as well as several different direct sensor inputs.

Figure 2.4: *AIM MXS 1.3 Dashboard*

AiM also develops loggers that do not serve as a dash, only containing the functionality for aggregating and logging data. These loggers offer most of the same features that the dash loggers offer with CAN connectivity, wireless connectivity, and different direct sensor inputs. There are two main products offered in this line, the ECULog and the XLog. The ECULog is the cheaper version with fewer features, only supporting external sensor inputs and communication. The XLog includes all of this and also includes and on board IMU and GPS, making it easier to monitor vehicle position and behaviour during a lap.

2.3.2 AiM Add-Ons

In order to communicate with sensors or other pieces of information, there are a few required accessories needed. These are a datahub that can be used to communicate with different accessories and a channel expansion to provide more ports for connecting different sensors to the CAN network. The channel expansion ports provide power and ground signals, as well as an analog sensor input for reading the sensor data. The data hub just acts as a way to reduce the number of devices directly connected to the logger itself. These devices cannot be purchased directly from AiM and instead must be purchased from a retailer like Summit. On Summit's website, the data hub is $77 and the channel expansions are $288, making them somewhat expenive requirements for using sensors.

Besides these essential add-ons, there are some other useful add-ons. AiM makes a GPS add-on that can be added provide real location data as well as a thermocouple hub that can be used similarly to the thermocouple add-on that AEM makes. They also make a storage expansion option, to increase the total amount of data that can be stored on board. None of these add-ons are required to utilize the system and to log data, but they are useful tools that improve the system and provide some useful functionality.

Figure 2.5: *AiM GPS09C GPS Module*

In addition to all of the hardware accessories to improve the experience and connectivity of AiM data loggers, AiM also sells many different kinds of sensors for automotive applications. These include temperture sensors, pressure sensors, combined temperature and pressure sensors, position sensors, speed sneors, and rpm sensors. Most of these sensors are analog voltage outputs, meaning that in order to communicate with the data logger, these sensors must be conncted to a the logger directly or to a unit that can transmit the data over CAN or other supported communication protoocls. These sensors, similar to the other add-ons and loggers, cannot be purchased directly from AiM and must be purchased from a third party retailer. The pricing on sensors is similar to the pricing of similar sensors sold by AEM.

AiM utilizes a tool that they call CAN builder to setup the logger to properly handle and process CAN inputs. This tool is essentially a graphical interface for configuring the logger to properly read CAN messages. CAN builder is capable of interfacing with AiM's propietary XC1 file types, the standard DBC file types, or building a custom driver for reading CAN messages. The CAN builder tool can only be used on AiM devices that are supported by their Race Studio 3 software.

2.4 MoTeC

A third company that makes datalogging solutions for automotive application is MoTeC. MoTeC is an automotive aftermarket company owned by Bosch that focues on making electronic equipment for race sport uses. They make ECUs, data loggers, dashboards, PDMs, and several other products that can be used to monitor or improve the performance of vehicles. These products are similar in spec to the products made by AEM and AiM.

2.4.1 MoTeC Loggers

Similarly to AEM and AiM, MoTeC offers both independent logger units as well as combined dash and logger units. These loggers have similar specs to the AEM and AiM loggers, with the basic functionailty of CAN channels, RS-232 channels, analog sensor inputs, digital sensor inputs, and the ability to use expansion units to increase the total amount of available connectivity. The dashboard options are very similar to the dashboards available from AEM and AiM.

There are three available options that support the full range of connectivity for a combined dash and logger and three additional options for just the logger. The

cheapest of the dash and logger combined units, the C125, costs approximately $2,200 from third part retailers before any additional add-ons are acquired. The cost of the cheapest logging only option, the L120, costs approximatel $1,800 from third party retailers. These prices are higher than the previously discussed AiM and AEM options.

One of the main differences between this option when compared to the AEM or AiM loggers is that none of the available loggers or combined dash and loggers have telemetry available. In order to add telemetry data, an additional fee or upgrade is required to add the MoTeC T2 Telemetry features.

2.4.2 MoTeC Add-Ons

Like the AEM and AiM, MoTeC also makes different devices and sensors to compliment their data loggers to improve the overall functionality and compatability. MoTeC makes an expander unit, similiar to the CAN expander made by AiM called the SVIM that can collect several different analog or digital sensors and connect to the CAN network for the MoTeC. Additionally, MoTeC makes an expansion unit called the E888 that has similar features the the SVIM, but includes thermocouple specific inputs. This unit additionally is more limited on which loggers it can connect to, only being compatabile with the SDL3 logger and the ACL logger.

In addition to the expansion units, MoTeC also makes various sensors that can be connected to the loggers or expansion units. Similiarly to AEM and AiM, they make thermocouples, various temperature sensors, pressure sensors, and speed sensors. Additionally, they also make linear and rotary potentiometers for applications such as steering angle measurements or suspension travel measurements as well as an

IMU. Just like AiM, these sensors are not sold directly by MoTeC and must instead purchased from a third party retailer. These sensors are somewhat expesnive but comparable in price to the sensors made by AEM and AiM.

Chapter 3

FORMAL PROJECT DEFINITION

The aim of this project is to make a fully functional and simple to use data acquisition system for the Cal Poly Racing Baja SAE team for monitoring controls information and logging sensor data on the CPx25 vehicle and for use in future vehicles. This will include the hardware unit, the software and firmware required to run the system, and tools for interfacing with the system.

3.1 Customer Requirements

The customer for this project is the Cal Poly Racing Baja Team. As the Electrical Technical Director of this team for this year, I can also be considered the customer for this product and as such am reesponsible for defining the customer requirements for this project. These requirements come from a combination of the existing systems on the car, desired data that is wanted to be collected, the ability to expand the desired sensors, the programming and data collection experience of the team, and reusability.

The customer requirements are as follows:

- A data storage rate of at least 400 Hz
- Enough storage to be able to store at least 5 hours worth of data
- The ability to download files
- A long range wireless radio to monitor data periodically

- The ability to add or remove different sensor or data modules
- An IMU and GPS to monitor vehicle dynamics
- The ability to directly wire some sensors to the DAQ unit
- The data must be in a format that can be easily viewed
- Low enough powere draw to not impact the battery life of the vehcile

The storage rate comes from the controls loop rate of the fasted controller on the vechicle. Since there are no current plans to increase the controller frequencies or add any sensors that require a faster sampling rate, this can be the minimum achievable collection rate for a while. The endurance event at a baja event lasts for four hours. Accomondating for time spent waiting for race to start and any final checks just before the event, five hours should accomondate a full endurance days worth of data. In order to quickly diagnose issues on the vehicle, knowing what is happening before the car arrives back in the pits is useful. Downloading files directly off the DAQ has been an issue for several years and significantly delays the processing of data. Additionally, it often was the case that the user would forget to add the storage device back onto the system, and no data would be collected until the system was reopened to analyze data again. The ability for the system to be modular and add other sensors is also important. It is often the case that there is a sensor that is wanted for a single test but would not want to be left on the vehicle permanantly. For a similar reason, being able to directly wire a sensor to the DAQ is useful. Having an onboard GPS and IMU are critical sensors for monitoring vehicle dynamics and they are always wanted. Finally, since the majority of the team are mechanical engineers, it is important that all data is easily accessible and that everyone is able to view the data.

3.2 Engineering Requirements

From the customer requirements, engineering requirements can be derived. These requirements reflect the technical specifications that the rest of the system will be designed to.

Table 3.1: *Engineering Requirements Table*

Spec. Number	**Metric**	**Requirement**	**Tolerance**	**Risk**	**Compliance**
1	Data Storage Rate	400 Hz	Min	M	A, T
2	Storage Capacity	4 GB	Min	H	I
3	IMU Sampling Rate	200 Hz	Min	M	T, S
4	GPS Sampling Rate	10 Hz	Min	M	T, S
5	Radio Distance	2 miles	Min	L	T
6	Power Draw	5 W	Max	H	A, T
7	CAN Busses	2	Min	L	I
8	ADC Resolution	10 bits	Min	L	I

These engineering requirements are mostly tied to the customer requirements regarding the data storage rate and the desire to understand the behaviour of the car's dynamics. Additionally, the length of an endurance event was used to derive several engineering requirements as well. The rest of the customer requirements come down to design choices and less down to numbers.

3.3 Use Cases

There are three main use cases for this system:

(1) To collect vehcile and subsystem data to validate design models

(2) To monitor vehicle health during drives at testing and competition

(3) To diagnose unexpected failures of a system

In the first case, an engineer is attempting to validate a braking model for the car. The model is a 9 degree of freedom model and uses brake pressure, shock heights, vehcile acceleration, and other paramaters to determine when the wheels will "lock", or break traction. In order to validate the model for our design for information for the next design cycle as well as the design event part of competition, these sensor's data is needed. This is the case for several different vehicle dynamics models used to design the baja car.

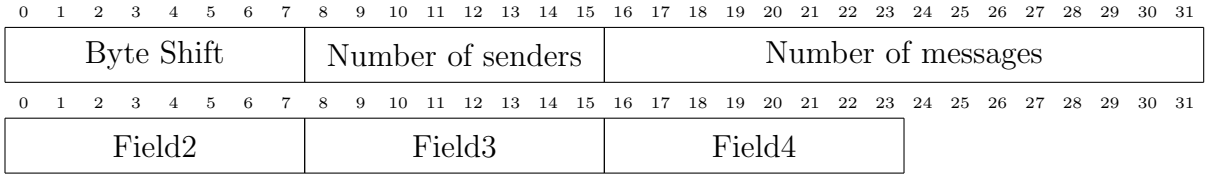
In the second case, the car is driving in the endurance event of a competition. During an endurance event, the car will be driving continuously for several hours without the ability to regularly inspect parts or systems for failure. To maintain an understanding of the vehicles health and criticial systems during this event, we can view wirelessly transmitted data. This helps the pit crew know if or when to expect the vehcile coming back to the pits for a repair.

In the third case, we are at testing or at competition, and something breaks or starts performing worse unexpectedly. To properly diagnose the root cause of an issue, knowing what was happening immediately preceding a failure can be useful or

even critical. In many instances, the car or the component may not have been visible to the tester and the driver may not be able to diagnose the issue on their own. In this case, having access to sensor data that can be used to extrapolate what the vehicle was doing prior to a failure can help an engineer fix or improve upon their design to reduce risk of failure in the future.

Chapter 4

SYSTEM DESIGN AND IMPLEMENTATION



4.1 System Level Design

In order to accomplish all of the tasks necessary for this DAQ, there were several design choices that were made at the system level. These include decisions about what microcontroller was being used, the type of data that is being stored, the media device that data is being stored on, how other sensor or control nodes will communicate with the DAQ, what on-board sensors are on the DAQ, how or if the DAQ is able to communicate wirelessly, how a user can interface with the DAQ, and how firmware updates can be applied.

The first thing considered was how nodes are able to communicate with the DAQ. The previous solution used CAN communicating at 1 Mbps to collect data from all nodes on the car. This became a throughput bottleneck as lower priority CAN ids would occasionally be blocked by the high throughput, higher prioirty data. The robustness of the CAN bus was very nice and allowed for reliable communication between all nodes on the car. To keep the robustness of CAN and to improve issues

related to throughput, CAN FD with an arbitration rate of 1 Mbps and a data rate of 5 Mbps was selected.

The next consideration was how data is stored on the DAQ. The previous DAQ solution utilized the on-board micro SD card reader on the Teensy 3.5 and Teensy 4.1 microcontrollers and stored data in a CSV format. The mirco SD card worked well with the small form factor, wide amount of resources available, common communication support with SPI or SDIO, and a sufficient amount of storage for 10 hours of data collection. An alternative option would be to use an SSD. This would allow for larger storage volumes at the cost of implementation complexity, increased mass, increased physical volume, and increased power consumption. As a result, a micro SD card was selected as the storage media.

With an SD card as the storage media, the maximum amount of data stored is the largest constraint. In a CSV file, each digit of a number is represented as a character, meaning that in order to represent the number 100, three bytes are required in addition to the comma deliniator. This same number can be represented with just a single byte if the data is stored in a binary format. Knowing that the total amount of data stored is ADD CALC RESULT HERE at 400 Hz, and the worst case values for 1 byte values being three characters, 2 byte values being 5 characters, and 4 byte numbers being ten characters, the amount of data stored over a 10 hour period would be X. As a result, the data is stored in a binary format described in INSERT FIGURE.

To be able to parse this data, the data contained in the file is outlined at the beginning of the file, including information about data group ids, the number of variables per id, the size of each variable, and the name of the data associated with

each variable as described in INSERT FIGURE. This header is generated dynamically at runtime, so that if new data is added to the list of logged values, DAQ firmware does not need to be modified to accomondate new data. Each data group is defined by the CAN message that will transmit the data. Due to this, each data group is a maximum of 64 bytes in size.

The selected microcontroller was the STM32H750VBT6. This microcontroller was selected for several reasons, including a vehicle wide platform switch to STM32 microcontrollers, internal CAN FD controllers, SDIO connectivity, and a 480 MHz core frequency. The platform switch is driven by three main criteria:

- The ability to layout the chip on a PCB
- Having access to the debug pins for programming and debugging
- Large amounts of community support and open-source libraries

Teensy development boards utilize NXP chips that have most of the same features as STM32 chips, but it has slightly less community support. Additionally, STM32 microcontrollers are used in EE 329 and CPE 316, providing experience on the platform for students who have taken those courses.

Something that all off the shelf data loggers do is provide the ability to directly connect some analog or digital sensors directly to the logger. This functionality is desireable as it allows for a sensor to be added without external electronics, so long as sensor output is supported by the logger. To include similar functionality, 4 analog sensor channels are available to be directly plugged into the DAQ. This includes a 5V source for each and a GND for each. Additionally, there is an on-board IMU and

GPS to be used for the common measurements of acceleration and velocity. These sensors are on the PCB itself and require no additional wiring by a user.

The final major piece of functionality provided by the DAQ is the ability to wirelessly transmit data acorss a range of up to 2 miles. This is to provide live diagnostics during testing or competition to the crew it the pits to help diagnose issues and reduce time debugging if issues occur. To do this, a radio module was added. In order to comply with FCC and competition regulations, the main options for frequency ranges were 900 MHz, 2.4 GHz, and 5 GHz. Since competition and testing sites are often hilly and full of trees, higher frequency nodes struggle to transmit over long distances reliably. This drove the desire to utilize a 900 MHz radio module. The XBee 3 Pro was selected due to its wide community support and ease of integration. Figure 4.1 describes the basic way in which these components all interface together.

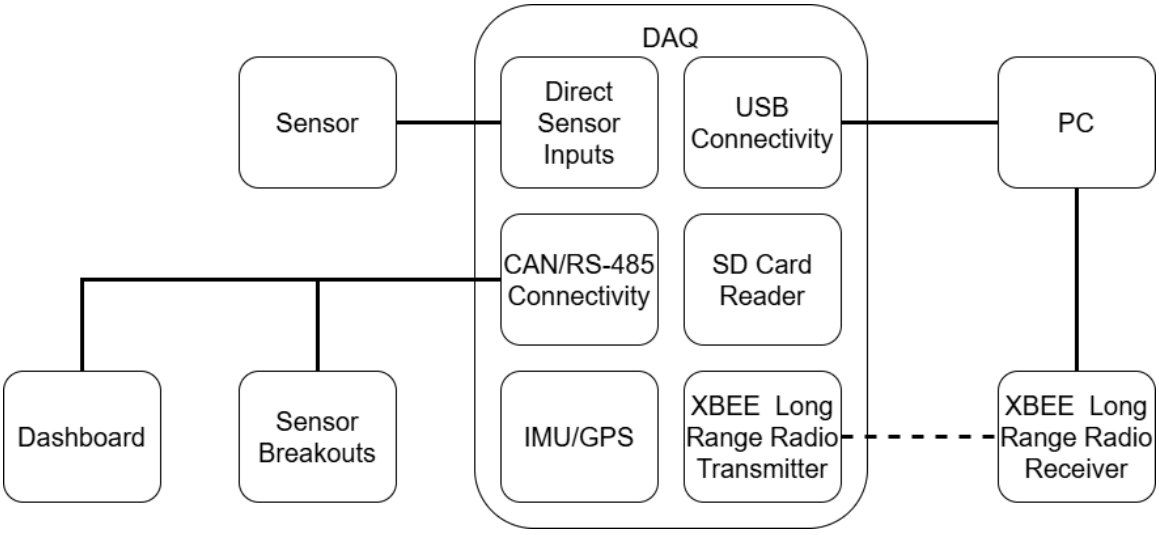


Figure 4.1: *System Level Block Diagram*

4.2 Hardware Design

The hardware design, with the exception of component selection, was largely outside the scope of this project and was completed by other members of the competition team. As the most senior member of the electronics team and the Electrical Technical Director, though, part of my responibilities to the project included design reviews and feedback on schematic design, layout, and routing.

As with any embedded systems project, the code for the project does depend on the hardware design

4.3 Software Design

The majority of the scope of this project was related to the software and firmware design and implementation. This section details the design of the software, it's implementation, as well as issues encountered and the ways in which they were addressed or what needs to happen to address the issue.

4.3.1 High-Level Design and Implementation

The software for this DAQ is designed and implemented to be run in a pseudo-parallel manner. This means that there are several different tasks that are running sequentially, with each task running small chunks or sub-tasks during each cycle. Each task is then designed as a state machine to segment itself into these smaller sub-tasks. In order for each of these tasks to communicate with each other, there is one group of data that each task can reference. Since this is a sequential action

still, conflicts will not occur and ther does not need to be any extra protections for accessing the same data or variable at the same time.

The DAQ runs four main tasks that are continuously cycled through:

(1) Storage

(2) Communication

(3) Radio Communication

(4) Sensors

(5) Health Monitoring

The storage task is responsible for the actual logging of data. The communication task is the task responsible for reading data off the CAN bus. The radio communication task is responsible for medium-long range telemetry. The sensors task is responsible for the reading of all on-board sensors. The health monitoring task is responsible for updating any LED indicators for the health of the system. Together, these five main tasks handle the running of all parts of the system. As can be seen in fig. 4.2, these tasks all run sequentially before looping back to the start.

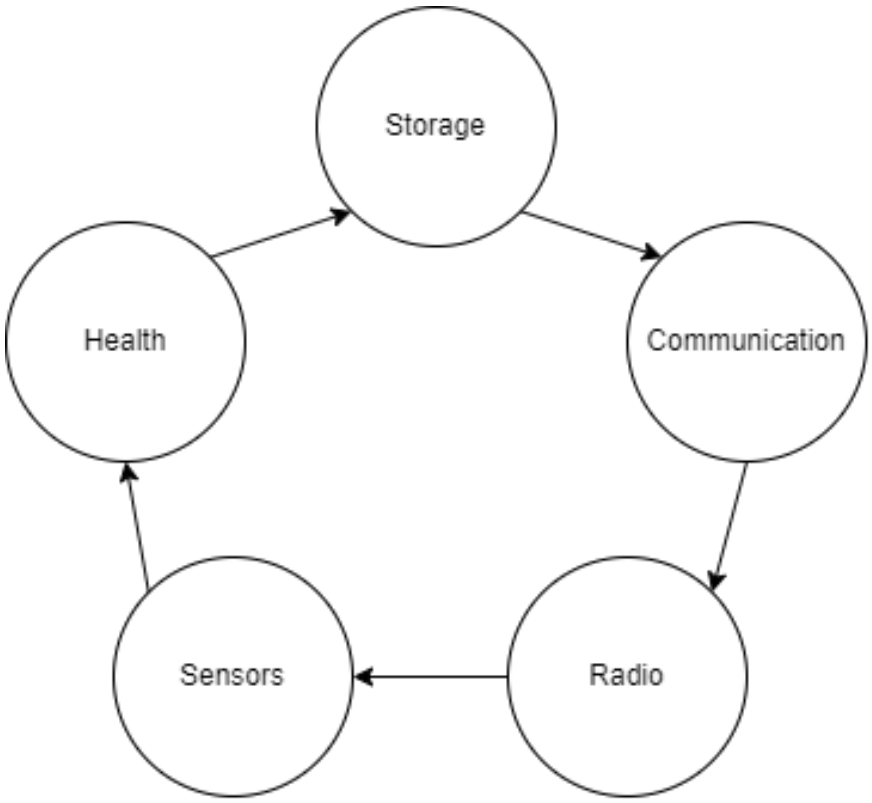


Figure 4.2: *Software tasks loop diagram*

Object-oriented programming (OOP) is utilized significantly for this design. Every task and sensor is a class that have individiual constructors depending on the needs of the task. Additionally, each task gets its own enum classes to define the various states for each state machine. There are two parent classes that are utilized by everything. For different tasks, there is an abstract task class that forces an implementation for a function that runs the task and requires the intercommunication data to be passed in. For sensors, there is an abstract sensor class that forces an implementation for two functions, an initialization function and an update function. Additionally, this class implements a read function that returns the current sensor value.

Since this project is based on the Arduino platform, several of the basic tasks for interacting with the hardware are handled by the platform. This includes things such

as setting the mode of a pin, reading and writing from data registers, configuring UART, SPI, and SDIO interfaces, and configuring the interrupt vector table. Even with the configuration of these periphreals being handled by Arduino, they still need to be configured with the proper settings to be used. Despite all falling under the Arduino umbrella, each platform is maintained independently of each other. The people maintaining the Arduino platform for Teensy and the people maintaining the Arduino platform for STM do not communicate with each other, and as a result there are some implementation differences that exist between different hardware platforms using Arduino.

Additionally, not every family of microcontrollers from STM receives the same support or even the sample supported functions from the Arduino framework. One specific issue that arose was a versioning issue for STM32duino. In versions 18.0.0 onwards, the memory sizes of the H7 family of STM microcontrollers was updated incorrectly, causing code to not run and the debugger to be unusable. This issue was resolved by reverting the version of STM32duino back to 17.6.0. The PlatformIO team have been notified of this issue and have responded that they are working on a fix. Other issues that arose that were not issus on the Teensy platform were the signedness of pins on the STM32, multiple timers on the same timer channels, timer registers having different sizes, and the same interrupt being tied to multiple pins. One of the largest benefits of this change was having access to the debugger. Without access to a deebugger, many of these issues would not have been solved or would have taken weeks or longer to debug.

The last main component that impacts each part of this system is a shared data segment. This shared data segment is what allows for all of the tasks to communicate with each other. Specifically, this includes variables for storing all of the data that

needs to be logged, flags for indicating when data has been updated, and fault flags to indicate when a task is encountering problems. Since this code runs sequentially, there are no issus of different tasks attempting to read from or write to the same chunk of the shared data section at the same time. As a result, there are no added protections for this scenario.

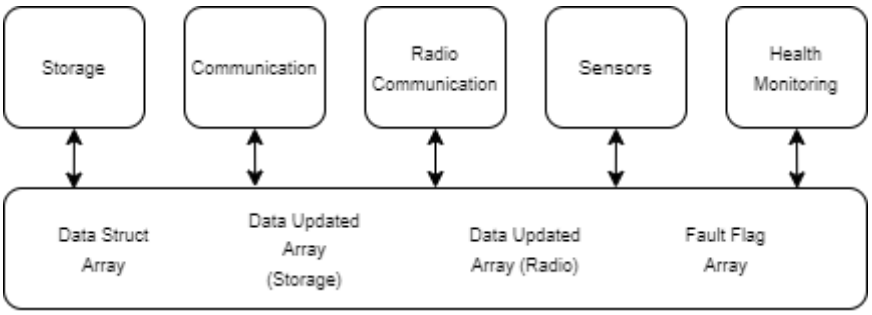


Figure 4.3: *Shared Data Section Diagram*

4.3.2 Storage Task

The first and foremost task that the DAQ runs is the storage task. This task is responsible for managing the SD interface as well as managing the filesystem. This includes things like initializing the communication interface with the SD card, setting up the filesystem, and writing data to the SD card.

As with all tasks, this was implemented via a state machine. A diagram for this state machine can be seen in fig. 4.4. This machine consists of seven states, with each state handling a single part of the task. These state are:

- Initialize
- Wait to Open
- Open

- Wait to Write
- Write
- Close
- Error

In this state machine, there are two types of states. These are action states and waiting states. The action states are all capable of entering the error state if their action fails unexpectandtly. The waiting states are incapable of entering the error state, since their sole purpose is to wait for certain conditions needed for their corresponding action state.

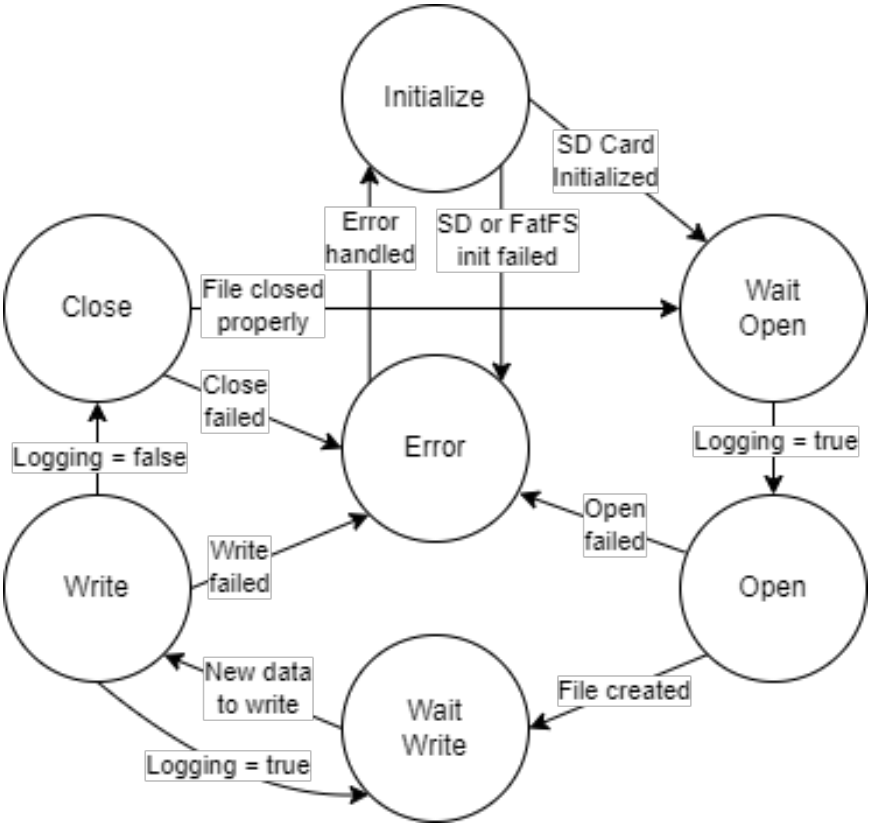


Figure 4.4: *Storage State Diagram*

The Initialize state is responsible for creating the SD instance. This includes configuring the SDIO communication interface that physically connects the SD card to the microcontroller as well as mounting the FatFS filesystem that is used by the SD card. The creation of the SD and File objects relies on STM32SD library [11]. This library provides the functions for initializing the SD interface and for mounting the filesystem. One major issue is present in this library that needed to be fixed. The library expects the FatFS implementation to have a function f_unmount, which can be used to unmount the filesystem. This function is not present in the FatFS implementation provided by STM32duino. To resolve this issue, the function call can be replaced with a f_mount function call with the approriate arguments, or a wrapper function f_unmount can be created that calls f_mount with the approriate arguments. The former was used in this project. If the returns of both the SD initialization and the FatFS initialization are success codes, the next state is Wait to Open. If any other codes are returned, the next state is the Error state. This is outlined in the decision tree in INSERT FIGURE.

The wait to Open state is a waiting state that holds the storage task until the logging flag is high. If the logging flag goes high, the next state is Open. The task can be held in this state indefinately if the logging flag stays low. This can occur if the logging switch on the dashboard is disabled or removed.

The Open state is responsible for the creation of files. Once the task enters this state, it searches for the next available file name and attempts to create the file. The file is created and opened properly if the return of the open function, which is a wrapper around the FatFS f_open function, returns a non-null value. This state will attempt to open a file three times before deciding it is unable to. This is outlined in

INSERT FIGURE. If the file is opened properly, the next state is the Wait to Write state. If the state is unable to open a file, the next state is the Error state.

The Wait to Write state is another waiting state that holds the storage task until new data is received. Once a new piece of data is received from the CAN bus or from reading the onboard sensors, this state transitions to the Write state. If there are no nodes on the CAN network or a CAN error and all the onboard sensors are disabled, the storage task can be held indefinately in this state. It is determined that a piece of data is new by checking a boolean value for each data segment. These booleans are set to true in the communication task or the sensors task.

The Write state is responsible for actually writing the most recent data to the SD card. Once the task enters this state, it iterates through all possible pieces of data to see if they have been updated. If a piece of data has been updated, a data packet is created with the data id, the data, and then a checksum to improve resiliency. This packet is then written to the SD write buffer. Once all updated messages are written to the SD write buffer, the buffer is then flushed to the SD card. This is done on each iteration as opposed to waiting for the buffer to fill up to reduce the blocking when writing to the disk to reduce the potential risk of missing data updates. This is outlined in INSERT FIGURE. If the writes and flush are completed sucessfully and logging is true, the next state is Wait to Write. If the writes an flush are completed suggessfully and logging is false, the next state is Close. If the writes or flush fail, the next state is Error. Once the writes are complete, the booleans that are true for a data segment are reset to false.

The final normal state is the Close state. This state is responsible for safely closing the current open file. If the file fails to close properly, the next state is the Error state. If the file closes properly, the next state is the Wait to Open state.

4.3.3 Communication Task

The next task is the communication task. This task is responsible for configuring and managing communication on the CAN bus. In order to do this, the ACANFD_STM32 library [1] was modified to support the operations needed to configure the CAN controller into CANFD mode and to read and write from the bus. One requirement of this library is that the CAN IRQ handler functions need to be defined by the user. These functions are defined in the main file and must be named properly to use the proper CAN controller, such as adding a 1 or 2 to distinguish between CAN1 and CAN2 hardware.

The state machine for the communication task contains four states. These states are:

- Initialize
- Wait for Message
- Process Message
- Error

As can be seen in fig. 4.5, the two main states that will be looped between are the Wait for Message and Process Message states that handle reading and processing messages.

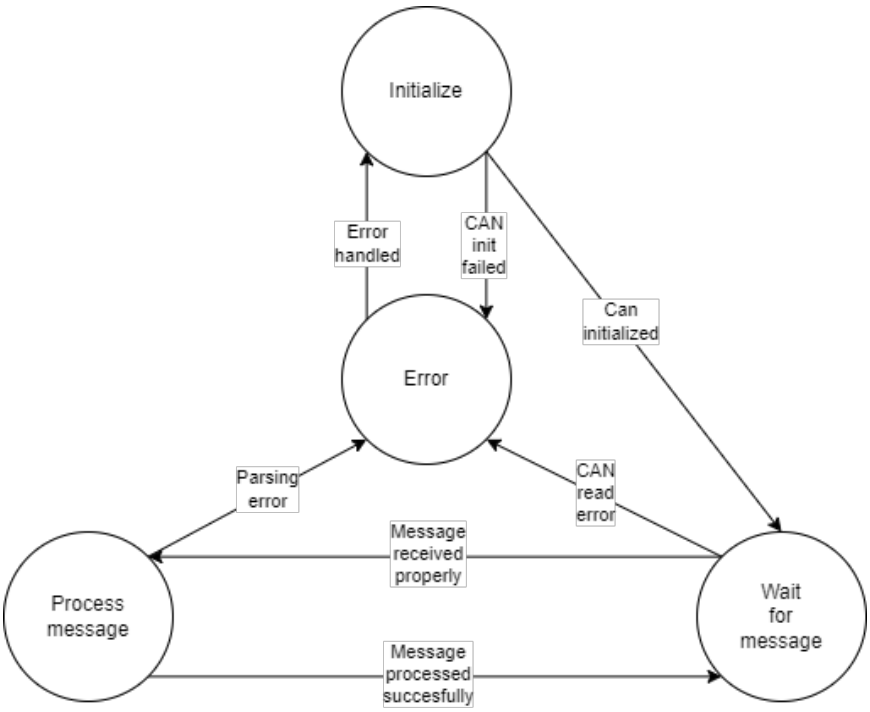


Figure 4.5: *Communication State Diagram*

The Initialize state is responsible for configuring the settings and initializing the CAN controller into CAN FD mode. In order to configure the hardware into CAN FD mode, the pins that connect from the internal CAN controller to the external CAN transceiver need to be set to their alternate functions and the bits in the configuration register need to be set to Normal FD mode. Additionally, the desired arbitration clock rate and data clock rate need to be set as well so that the bus is transmitting at the desired speed. If there are no issues when configuring the CAN controller, the next state is set to Wait for Message. If there are any issues, the next state is set to Error.

The Wait for Message state is the state that is directly responsible for reading data off of the CAN bus. As is described in INSERT FIGURE, if the CAN bus has a message available to be read, it reads the contents into a message variable. If no messages are ever received, it is possible to become stuck in this state indefinately.

If there is a message received, the next state is set to Process Message. If there are errors reading the message, the next state is set to Error. Only one message will be read in this state, so if there are multiple messages ready to be read, the system will need to enter this state multiple times.

The Process Message state is responsible for taking the data from a received CAN message and moving it into the section of data shared by all tasks. Additionally, in order to indicate to the storage task that a piece of data is new, an array of booleans that is equal in size to the number of data blocks exists. When a message is received, the boolean that corresponds to the same integer value as the index of the received data block is updated to true. This boolean will be reset to false in the storage task. As is detailed in INSERT FIGURE, this state first checks if the CAN ID of a message is valid, something expected or able to be handled. It then copies the contents of the CAN message into the corresponding data segment in the shared data. Since it is expected that the CAN messages will fully correspond to the data segment and that the data segment will be byte aligned with no gaps, a simple memcpy operation can be done to move the data from the received message into the shared data. If this processing is completed without error, the next state is set back to Wait for Message. If there are any issues with the CAN message or the copying of the data, the next state is set to Error.

The final state of the communication task is the Error state. This state is responsible for handling any errors that occur as a result of initialization, reading CAN messages, or processing the CAN messages. The most common errors that can occur are the bus failing to initialize properly and an invalid or unhandled CAN message IDs are received. The most likely cause of the CAN hardware not initializing properly are improper wiring on the PCB or invalid configuration options or settings. In either

of these scenarios, recovery is not possible and the task must be held in the Error state. In the event of an invalid CAN ID received, the system can continue to operate sucessfully, and the task can be recovered by returning to the Wait for Message state. In the shared data, a flag is set high indicating a fault in the communication task.

4.3.4 Radio Communication Task

The radio communication task handles the communication with the radio module and the transmission of from the vehicle to the pit area. The Xbee module handles the over-the-air transmission of data. The Xbee module is configured seperately, before being installed into the DAQ, accepting a UART communication line and relaying that data over the error. The module is not configured to handle lost packets, invalid packets, or any issues related to the data transmission as dropping packets is not a catastrophic failure.

The radio communication task has five states:

- Initialize
- Wait
- Build
- Send
- Error

The state machine describing how to transition between these states can be seen in fig. 4.6. Similarly to the storage task, there is a wait state whose only function is to

hold the task until a certain condition is met. This is the only state that cannot enter the Error state.

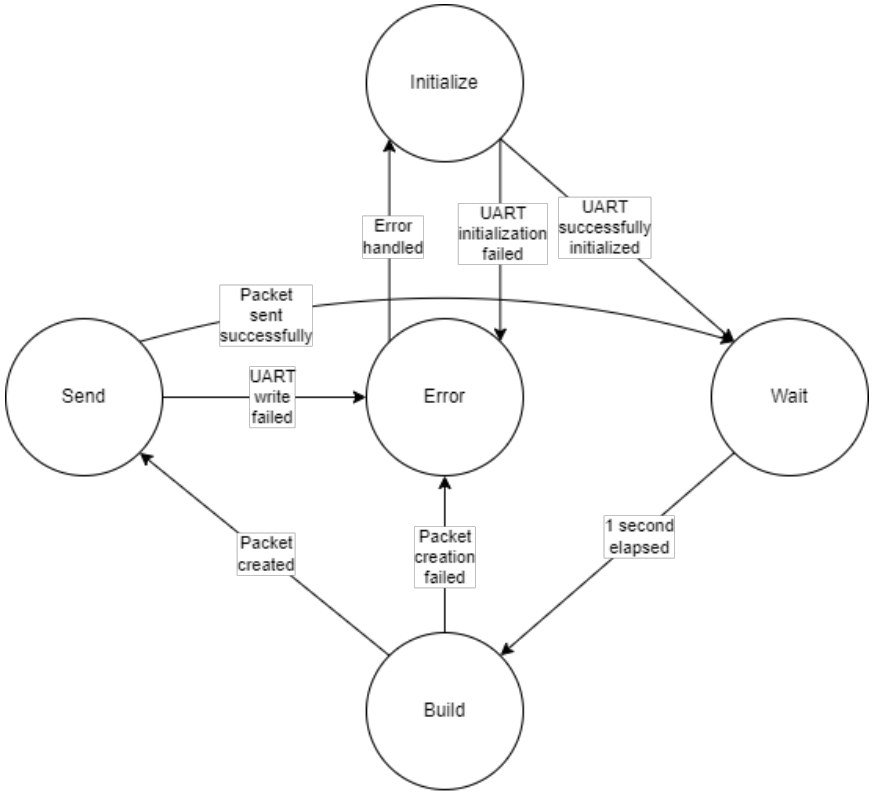


Figure 4.6: *Radio Communication State Diagram*

The Initialize state is responsible for configuring the UART communication interface with the Xbee radio. The Arduino HardwareSerial library handles configuring the registers to their alternate functions, so long as the proper tx and rx pins are set. The baud rate is configured to by 57600 to comply with the Xbee's configuration. If the UART initializes sucessfully, the next state is the Wait state. If the UART communication is not initialized successfully, the next state is the Error state.

The Wait state holds the radio communication task until it is time to send a packet over-the-air. If a one second timer has triggered, the next state is the Build state.

The Build state is responsible for creating a single packet that will then be transmitted over-the-air. Similarly to the storage task, this state checks which data segments have been updated and adds each segment that has been updated to the packet. The data id and the length of data are added before each data segment and a checksum is computed and added to the end of the data segment. Differently from the storage task, each updated data segment is added to one single packet. If the packet is created successfully, the next state is the Send state. If there are issues creating the packet, the next state is the Error state.

The Send state writes the created packet over UART to the Xbee module. In order to reduce issues related to filling up the hardware buffer, the UART writes just a single byte at a time. Additionally, there is a check to ensure that the hardware buffer is not full and can accept the byte. The reason for this is that the write function that puts a byte or array of bytes onto the hardware buffer does not check if the buffer is full, and it will hold the program until the byte or bytes in the array are written to the buffer. This makes it very likely to cause interruptions in the code, harming the running of the other tasks. Once all bytes are written to the buffer, the next state is set back to the Wait state. If there are any issues with writing a byte, the next state is the Error state.

The last state in the radio communication task is the Error state. Similalry to the communication state, if there are any issues setting up the UART communication line, it is likely a result of faulty wiring or invalid paramaters. In this event, the error is typically not recoverable. If the error occurs withing the Build or Send state, the error can be recovered.

4.3.5 Sensors Task

The sensors taks is responsible for reading the DAQ's onboard sensors. These sensors include the onboard IMU and GPS, as well as a few analog sensor inputs. The IMU and GPS both communicate over I2C and the analog sensors utilize the internal ADC of the STM32. These sensor readings are then added to the shared data section so that they can be written to the SD card.

This task has five states:

- Initialize
- Wait
- Read
- Send
- Error

The state machine describing the transitions can be seen in fig. 4.7. Similarly to the radio tasks, there is a time based waiting task and four additional tasks for functionality. Differently from the radio communication task is that there will be two states that cannot enter the error state, the Wait state and the Send state.

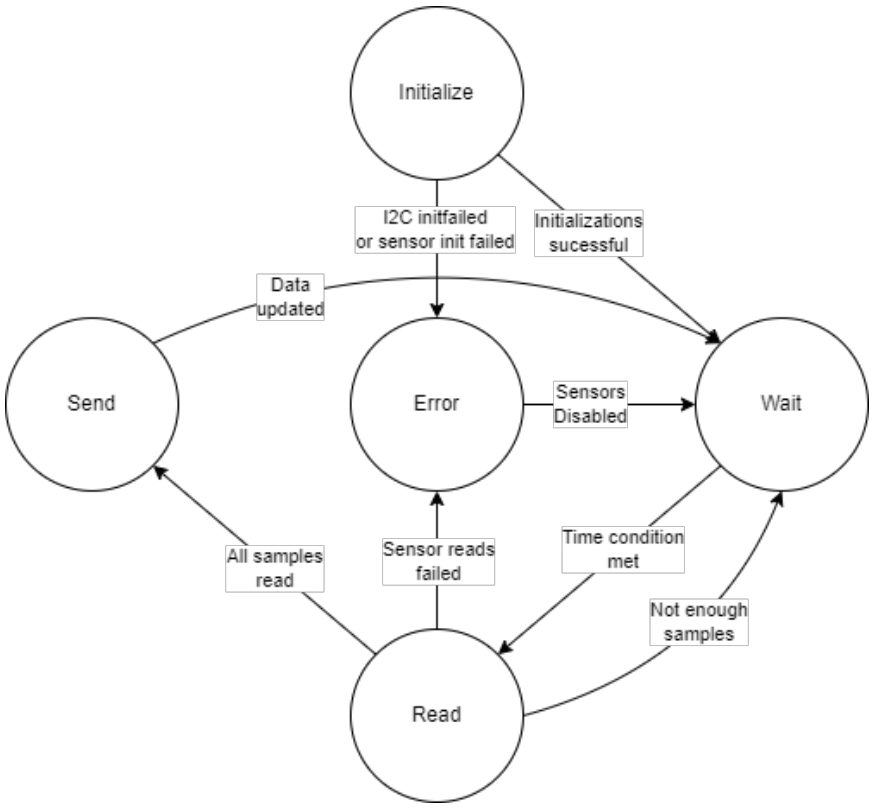


Figure 4.7: *Sensors State Diagram*

The Initialize state is repsonsible for configuring the periphreals needed to communicate with sensors and for configuring any sensors when it is applicable. Since both the IMU and GPS communicate over I2C, two I2C busses need to be configured. Additionally, each of these sensors need to be configured, including items such as setting up the sampling rate, any on board filtering, or changing the sensor range. For the basic analog sensors, the pins need to be configured to use their ADC alternate function. The arduino pinMode function takes care of this. Additionally, the bit resolution also needs to be configured. In order to comply with the requirements of this project, this must be at least 10 bits. If everything is configured properly, the next state is the Wait state. If there are any issues, the next state is the Error state.

The Wait state holds the task for a specified amount of time. The purpose of this is to ensure that sensors are sampled at fixed intervals for the purpose of adding filters. As a result, the amount of time the task is held in this state is determined by the desired sampling rate of the sensors that pre-processing filtering is done on. Since the only thing this state does is wait for a time condition to be met, it is impossile to fault and as such cannot enter the Error state. Once the time condition is met, the next state is the Read state. In the event that no pre-processing of the data is done, the time held in this state is 0 and the next state is immediately set to be the Read state.

The Read state is responsible for reading the data from sensors. To do this, the analog channels need to be sampled and samples need to be requested from the sensors communicating over I2C. Each sensor is only sampled if there were no issus with the configuration of the sensor. If any pre-processing is desired, it will occur in this state directly after reading a sensor's sample. At this point in time, there is no pre-processing, so there are no filter implementations directly on-board the DAQ. If all sensors are sampled without issue and the number of samples taken is equal to the number of samples needed for a filter, the next state is set to the Send state. If the sensors are all sampled without issue, but the number of samples taken is fewer than the number of samples needed for a filter, the next state is the Wait state. If there were any issues sampling the sensors, the next state is set to be the Error state. Issues can arise if there is no response from a request from an I2C sensor, or if an analog sensor returns a value outside of it's expected range. In the event that there is no pre-processing of data, each time the sensors are sampled, the next state will become the Send state.

The Send state is a simple state that updates the data in the shared data section and sets the flag that this data is new to true for the storage task and radio communication task. Since the code is sequential, there are no risks of conflicts arising from different tasks reading or writing at the same time. As a result, it is not possible for this state to fault, and as a result cannot enter the Error state. Once the shared data section is updated and the flags indicating that the data is new is set to be true, the next state is set to the Wait state.

The Error state handles any issues that arise from configuring the communication with sensors,the configuration of the sensors themselves, or sampling of the sensors. In the event that the communication interface fails to initialize properly, it is unlikely to be resolved. A flag is set in the shared data section to inidicate this. However, if any of the communication interfaces initialize properly, the task as a whole is recoverable and receiving some of the data is better than receiving none of the data. The same is true of the sensors themselves. If any of the sensors fail to initialize, a flag is set in the shared data section to indicate this, but the task can continue without this sensor. Reading the sensors behaves in a similar way. If a sensor fails to read properly, a flag is set in the shared data section and the sensor is disabled in the Read state. The state machine then recovers into the Wait state.

4.3.6 Health Monitoring Task

The health monitoring task detects and reports issues with the system. This is done by toggling on-board LEDs to act as visual indicators in the event of issues. These issues include things such as CAN failures, SD failures, and a heartbeat.

This task is the simplest state machine with just two states and no Error state. These are the initialization state and the update state. The diagram for this state machine can be seen in fig. 4.8.

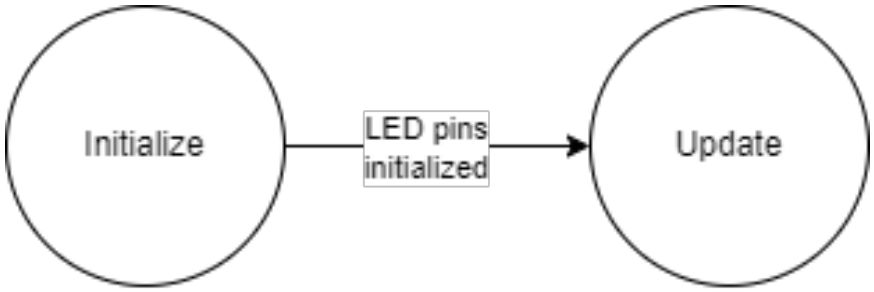


Figure 4.8: *Health Monitoring State Diagram*

The initialization state is responsible for configuring the pins for LEDs. Since all GPIO pins on an STM32 can be configured to be outputs, it is not possible to fail to initialize. As a result, the next state is always set to be the Update state.

The update state checks the status of the other tasks and toggles LEDs as needed. Additionally, the heartbeat is updated in this state. Similarly to the initialization state, since this state is only performing digital writes, or updating the output data register, it is not able to cause a fault. The heartbeat LED is toggled once every half second, for a total frequncy of 1 Hz. The indicator LEDs directly use booleans from the shared data section to write a value to the LED. This means that the output of those LEDs is determined by the other tasks. The health monitoring task remains in the update state for the entire time the system is running.

Chapter 5

SYSTEM TESTING AND ANALYSIS

Chapter 6

CONCLUSION

6.1 FutureWorks

To improve upon this project for the future, there are a few additional features and a few design choices that could be imporved upon. From a hardware design perspective, the storage device could be improved upon to use a file system that supports larger file formats. This would allow for more files to be stored on the DAQ without the need to clear its storage as frequently. Additionally, two additional design choices could be made to improve the users ability to connect to and interface with the DAQ. These would be to replace the UART serial to USB interface with an ethernet connection and to add a short range wireless connection option. The wireless option would allow for an easier way to connect to the DAQ for more people. This would require the addition of some sort of wireless wifi or bluetooth transceiver or to use a microcontroller that supports a wireless interface. By replacing the USB interface with an ethernet based interface, faster file downloads can be achieved. Since the download speed via USB is limited by the stablity of the baud rates for UART, a more stable interface would allow for much faster transfers to occur, removing one of the larger bottlenecks in the system.

Chapter 7

REFLECTIONS

REFERENCES

[1] *ACANFD STM32 Library Github Repository*. 2025. URL: https://github.com/pierremolinaro/acanfd-stm32.

[2] *AEM Electronics Official Website*. 2025. URL: https://www.aemelectronics.com/.

[3] *AiM Sportline Official Website*. 2025. URL: https://www.aim-sportline.com/.

[4] *CAN bus — Wikipedia, The Free Encyclopedia*. 2025. URL: https://en.wikipedia.org/wiki/CAN_bus.

[5] *Digi XBee 3 Zigbee 3 RF Module*. 2025. URL: https://www.digi.com/products/embedded-systems/digi-xbee/rf-modules/2-4-ghz-rf-modules/xbee3-zigbee-3#specifications.

[6] R. B. GmbH. *CAN FD Specification*. Tech. rep. Robert Bosch GmbH, 2012. URL: https:/https://web.archive.org/web/20151211125301/http://www.bosch-semiconductors.de/media/ubk_semiconductors/pdf_1/canliteratur/can_fd_spec.pdf.

[7] R. B. GmbH. *CAN Specification Version 2.0*. Tech. rep. Robert Bosch GmbH, 1991. URL: https://web.archive.org/web/20221010170747/http://esd.cs.ucr.edu/webres/can20.pdf.

[8] *MoTeC Official Website*. 2025. URL: https://www.motec.com.au/.

[9] *PlatformIO Homepage*. 2025. URL: https://platformio.org/.

[10] *STM32 Arduino Core Github Repository*. 2025. URL: https://github.com/stm32duino/Arduino_Core_STM32.

[11] *STM32SD Library Github Repository*. 2025. URL: https://github.com/stm32duino/STM32SD.

Appendix A

CODE IMPLEMENTATIONS

Code Listing A.1: *Example .dbc file for an IMU*

```
VERSION ""


NS_ :
        NS_DESC_
        CM_
        BA_DEF_
        BA_
        VAL_
        CAT_DEF_
        CAT_
        FILTER
        BA_DEF_DEF_
        EV_DATA_
        ENVVAR_DATA_
        SGTYPE_
        SGTYPE_VAL_
        BA_DEF_SGTYPE_
        BA_SGTYPE_
        SIG_TYPE_REF_
        VAL_TABLE_
        SIG_GROUP_
        SIG_VALTYPE_
        SIGTYPE_VALTYPE_
        BO_TX_BU_
        BA_DEF_REL_
        BA_REL_
        BA_DEF_DEF_REL_
        BU_SG_REL_
        BU_EV_REL_
        BU_BO_REL_
        SG_MUL_VAL_

BS_:

BU_: IMU_DBC
```

```
BO_ 1304 MESSAGE_4: 8 Vector__XXX
 SG_ IMU_TEMP : 48|16@1- (0.01,0) [-20|80] "C"  IMU_DBC
 SG_ EULER_Z : 32|16@1- (0.01,0) [-180|180] "deg/s"
    IMU_DBC
 SG_ EULER_Y : 16|16@1- (0.01,0) [-90|90] "deg/s"
    IMU_DBC
 SG_ EULER_X : 0|16@1- (0.01,0) [-180|180] "deg/s"
    IMU_DBC

BO_ 1303 MESSAGE_3: 8 Vector__XXX
 SG_ Raw_GyroII_Z : 48|16@1- (0.1,0) [-1000|1000] "deg/
    s"  IMU_DBC
 SG_ Raw_GyroII_Y : 32|16@1- (0.1,0) [-1000|1000] "deg/
    s"  IMU_DBC
 SG_ Raw_GyroII_X : 16|16@1- (0.1,0) [-1000|1000] "deg/
    s"  IMU_DBC
 SG_ ACC_RAW_Z : 0|16@1- (0.001,0) [-4|4] "g"  IMU_DBC

BO_ 1302 MESSAGE_2: 8 Vector__XXX
 SG_ ACC_RAW_Y : 48|16@1- (0.001,0) [-4|4] "g"  IMU_DBC
 SG_ ACC_RAW_X : 32|16@1- (0.001,0) [-4|4] "g"  IMU_DBC
 SG_ ANGULAR_VEL_Z : 16|16@1- (0.01,0) [-125|125] "deg/
    s"  IMU_DBC
 SG_ ANGULAR_VEL_Y : 0|16@1- (0.01,0) [-327.68|327.67]
    "deg/s"  IMU_DBC

BO_ 1301 MESSAGE_1: 8 Vector__XXX
 SG_ LIN_ACC_Z : 32|16@1- (0.001,0) [-4|4] "g"  IMU_DBC
 SG_ LIN_ACC_Y : 16|16@1- (0.001,0) [-4|4] "g"  IMU_DBC
 SG_ LIN_ACC_X : 0|16@1- (0.001,0) [-4|4] "g"  IMU_DBC
 SG_ ANGULAR_VEL_X : 48|16@1- (0.01,0) [-125|125] "deg/
    s"  IMU_DBC



BA_DEF_  "MultiplexExtEnabled" ENUM  "No","Yes";
BA_DEF_  "BusType" STRING ;
BA_DEF_DEF_  "MultiplexExtEnabled" "No";
BA_DEF_DEF_  "BusType" "CAN";
```