Abstract

The High Reliability NFC Battery Connection is a Binghamton University ECE Capstone project for 2023-2024 that encompasses the development of a wireless interface to replace four physical signal wires that go between a Raymond electric forklift and its Smart Energy Source (battery pack). The project aims to reduce failures in the battery-to-forklift physical interface from damage to the pin connectors by operators; the small, delicate data connections are removed completely and replaced with a close proximity (less than 10cm) wireless interface. CAN (controller area network) traffic as well as two control signals that previously required four wires are now sent wirelessly using NFC (near field communication). The project will encompass two circuits: one that interfaces with the battery and its already-existing electronics, and the other that is attached to the truck. The truck side of the system must sense the closure of the key that signals a user wishes to power on the truck; it must do this while no external power is available other than the energy it can harvest from the NFC RF field (a feature of NFC technology). Once the key signal is wirelessly sent, the battery side system must electrically pull a line called RTN low, which signals to the already-existing Battery System Manager the command to enable power to the forklift. Once the truck has power, the wireless system must enable CAN (controller area network) traffic that previously traveled along a two-wire interface to flow wirelessly between the battery control systems and forklift control systems.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 System Overview

This report is for the ECD401 High Reliability NFC Battery Connection project of 2023-2024.

The project encompasses the development of two sides of a wireless system that replaces four physical data and control lines that run between an electric forklift and its battery pack. The wireless interface helps to solve issues caused by the physical failure of the hardwired physical connections due to operator misuse or general wear, such as recurring maintenance and repair costs.

Each side of the system is comprised of a circuit based around a microcontroller, with peripherals attached that include a CAN transceiver IC for interfacing the MCU to the physical CAN bus wires of the battery and forklift systems, and an NFC transceiver that takes data from the MCU and converts it into an RF signal. There is also a power management circuit for each side that can step a variety of possible input voltages down to the 3.3V necessary for all parts.

The truck side of the system is responsible for sensing when a user is requesting power-on; to sense the turn of a key, the system must harvest energy from the NFC field generated on the battery-side. It was necessary, then, to choose an NFC chip with inbuilt energy harvesting capabilities that could sense a key on some sort of IO pin, as well. A microcontroller with inbuilt CAN is being used on both the truck and the battery side. A separate NFC transceiver chip meant for high-speed communication is also being used on both the truck and the battery side. Because NFC is a close-proximity (less than 10cm) wireless interface, the two sides will each have a small planar coil antenna embedded in a PCB; all signals that pass between the two sides are transmitted via the coupled RF fields of the antennas.

1.2 Document Overview

This report provides the essential project requirements in Section 3, Requirements, along with some non-essential stretch goals.

In this specification, a requirement is identified by “shall”, a good practice by “should”, permission by “may” or “can”, expected outcome or action by “will”, and descriptive material by “is” or “are” (or another verb form of “to be”).

2 Referenced Documents

The following documents of the exact issue shown form a part of this report as specified herein.

ECD401_Project_Specification_Document.docx

3 Problem Definition

3.1 Problem Scope

Raymond Corporation produces various models of electric forklifts, as well as power sources for them, known as Smart Energy Sources. Both the forklifts and the energy sources contain embedded systems that need to exchange data with each other, containing items such as status and error codes, as well as control signals that, for example, disable and enable power to the forklift. The current interface for these signals is a set of four wires that are part of a connector that also carries two large terminals for the positive and negative battery supply.

Figure 1: Example of Anderson connector with 4 signal pins in the middle

When changing the battery pack or performing other maintenance, this connector is frequently unseated and reseated, eventually causing the small data pins to fail; customers then must seek repair or replacement from Raymond. Frequent pin breakages also disrupt communication, affecting the overall efficiency and dependability of forklift operations.

This project replaces the hardwired arrangement with an NFC (Near Field Communication) interface to address the durability concerns. NFC technology offers a wireless signal path for the data lines we will be replacing, possible through the placement of two coupling antennas within close (less than 10cm) proximity. Data will need to travel from existing truck or battery systems into our system, where it must be converted into NFC signals, sent across the air gap, and be received, reconverted to their original form, and sent along to its destination. This leaves power terminals as the only physical connection between the battery and forklift.

3.2 Technical Review

NFC allows wireless data transmission over short distances using radio waves. This NFC technology is used to communicate between the truck and the smart energy source. The NTAG 5 NFC chip which can power itself, is configured through I2C to sense the key signal and command to the battery via NFC. The power regulator LM5008 has a DC-DC converter capable of converting 6 - 95 Volts to 3.3 Volts. The CAN Transceiver TCAN1042 supports high speed CAN FD and takes data from the microcontroller and drives the CAN lines. The STM32 Microcontroller has an inbuilt CAN bus which can specifically communicate with the transceivers. It also has low power modes which can be used during energy harvesting and supports high speed I2C communication. The STM32 HAL libraries are used for fast software development. The ST25 NFC chip is used for high-speed communication of CAN data wirelessly and can reach up to 848kbps.

3.3 Design Requirements

The following requirements have been identified from the ECD 401 High Reliability NFC Battery Connection project Specification [ECD401_Project_Specification_Document.docx]

a. The device shall communicate over at least a 2-inch gap.
b. The device shall communicate with +/- 1 inch of misalignment.
c. The device shall be able to communicate up to 125KBaud.
d. The Bit Error rate shall be less than 1%.
e. The cost of the board shall be less than $20.
f. The device shall use 13.56 MHz NFC.
g. The device shall be able to communicate with the CANopen bus.
h. The device shall have a bootloader to allow firmware updates of applications.
i. The truck side NFC shall harvest power from the battery side.

4 System Design

4.1 System-Wide Design Decisions

From the project context and requirements, two different circuits would need to be designed: one attached to the smart energy source, and one attached to the forklift. We knew we needed to use NFC to send and receive data at a significant (at least 125 kbps) rate, so our first decision was on the overall implementation of NFC.

Traditionally, NFC operates between either a reader and a tag, or between two readers. The data rate between a reader and tag is much lower than between two readers, but an NFC tag can harvest energy to self-power itself – a key requirement of the project. We ultimately landed on a hybrid NFC design that uses the NFC reader-to-tag model when the forklift is unpowered and the system is waiting for a key to be turned, and uses the NFC reader-to-reader model once the system is powered on and data needs to be transmitted at a high rate. Each side of the system will have its own NFC reader, but the forklift-side will also have an NFC tag IC (NTAG) that will allow it to send a control signal when there is no battery power.

We also knew that we would need to choose a microcontroller platform, as each side of the system would need one to control the various peripherals. The STM32L4 series microcontroller with an integrated CAN peripheral was chosen to allow for effective CAN communication processing, allowing a separate CAN transceiver to manage data and operate the CAN lines. It also possesses multiple I2C peripherals, which is the serial data protocol used to configure and communicate with the NFC parts.

Last, we knew that we would need a way to power the system, and that the only power source is the smart energy source output. The issue is that, depending on its configuration, the output voltage varies from 20V-84V. We decided to find a power management IC that would be capable of producing the 3.3V needed by all parts of our system from a wide variety of input voltages. The DC-DC converter we chose was a Texas Instruments part, the LM5008A, which has a 6V-95V input range, and a programmable output capable of 3.3V at over 90% efficiency.

Last, one major factor in all component decisions was the availability of evaluation boards or development kits. Since manufacturing the PCBs for a completed system is not a project requirement, we needed to be sure we could still assemble a working prototype and not be run aground trying to hand-solder extremely small components. Most of the parts we ended up going with take the form of Arduino shield-style boards, and allow easy interconnect with jumper wires.

Figure 2: Example of development board for NTAG 5 Link with Arduino-style header pins

4.2 System Components and Interfaces

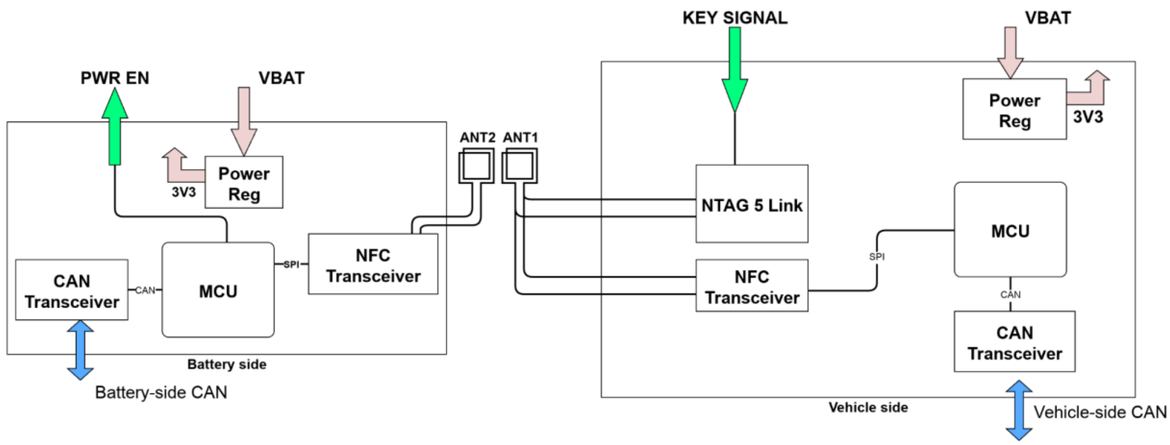

Figure 3: Block diagram of project

The overall block diagram with component choices can be seen in Figure 3. Attached to the two antennas ANT1 and ANT2 are NFC transceivers, the STM25R3916B. This part is responsible for generating the RF field on the antennas, modulating the field to transmit data, and then sending that data back to the microcontroller over an I2C serial bus.

Figure 4: Image of ST25R evaluation board

The NTAG 5 Link is also an NFC part, though it is only on the truck side of the system. Its sole purpose is to watch the KEY signal (the physical key a user must turn to power on a forklift) go from high to low, and pass that information from ANT1 to ANT2. It can harvest energy from the RF field of ANT2 to self-power, which is a project requirement because the key signal must be sensed when there is no power to the forklift, a feature that the ST25 part lacks. It has a low data rate, however (around 42 kbps), which made it necessary to pair it with the ST25.

The central processing unit of the system is the STM32L4 microcontroller, which has an integrated CAN receiver. It interconnects with NFC parts through the SPI protocol, ensuring a standardized and efficient data exchange between the two components. The NTAG 5 chip is configured through SPI, providing a straightforward means of programming and customizing the authentication parameters.

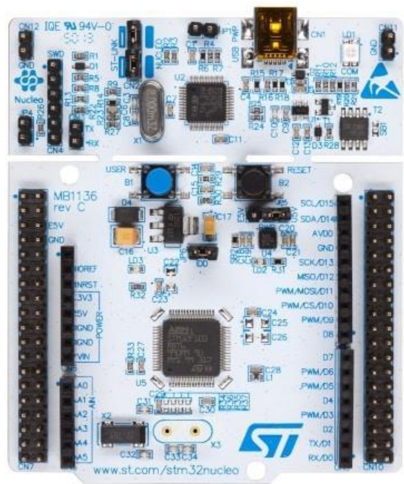

Figure 5: STM32L476RG development board

A Texas Instruments part (TCAN1042) was chosen as the CAN transceiver – it is the interface between the microcontroller and the physical CAN data lines. While it came as a bare chip, it was easy to solder to a SMD to DIP adapter to allow it to fit on a breadboard for prototyping.

Last, as mentioned earlier, the LM5008 takes the varying battery voltage and converts it into the 3.3V suitable for all of our components (ST25, TCAN1042, STM32). Its output voltage is configurable by setting two resistors and does not need to be reconfigured for different input voltages.

4.3 Concept of Execution

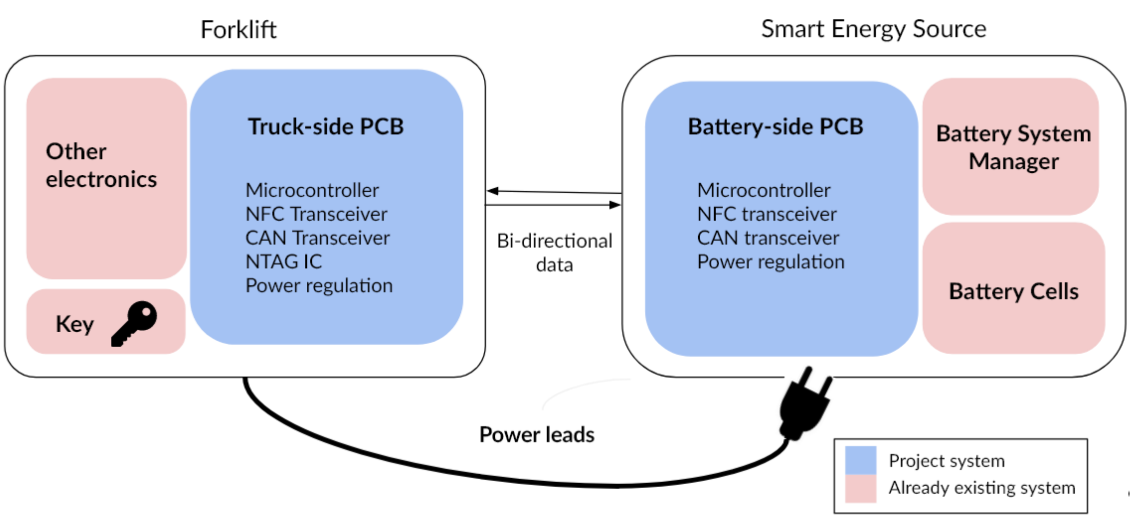

Figure 6: Operational context of the system

Figure 6 is the block diagram of the project in its operational context. It outlines the two main circuits: the truck-side (which interfaces with the forklift electronics) and the battery-side (which controls the smart energy source). Both sides are almost identical in terms of the project system, the only difference is the addition of the NTAG IC on the truck side. The basic use case is as follows:

1. Starting the forklift: When the forklift is powered off, the user initiates the starting process by turning the key. This action is primary user input.
2. Key signal transmission via NFC: Turning the key triggers a signal, which is then transmitted wirelessly to the battery side using Near Field Communication (NFC) technology. This replaces traditional wired signaling methods, increasing the system's resilience to physical connection failures.
3. Start power supply: After receiving the key signal through NFC, the battery system responds to start the forklift power supply. This activation is a critical step as it transitions the forklift from an unpowered state to a powered state.
4. CAN Bus Data Flow Active: With the truck now powered, the Controller Area Network (CAN) bus becomes active, allowing data flow within the vehicle network. This data includes operating parameters, diagnostic information and other important information about the forklift's operation.
5. Turn off the forklift: To stop the forklift, the user turns the key again. This action sends a signal (via NFC, similar to the boot process) to the battery system indicating that power should be disabled.
6. Return to initial state: After the system receives and processes the power-off signal, it returns the forklift to the initial, unpowered state to prepare for the next cycle of operation.

This NFC-based system increases the reliability and ease of operation of forklifts, especially in industrial environments where efficient energy management and strong communication systems are crucial.

4.4 Hardware Design

4.4.1 Power Management Chip - LM5008A

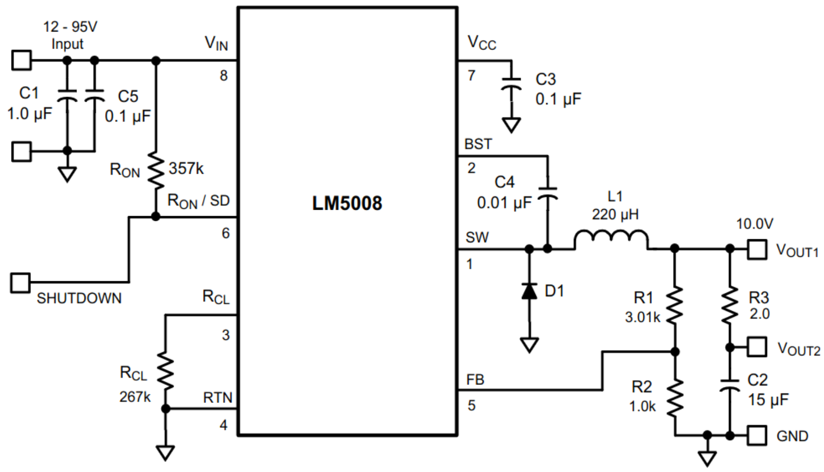

Figure 7: Typical application circuit for LM5008

The circuit in Figure 7 is used to power the project electronics by efficiently converting higher DC voltages to lower DC voltages. The output voltage VOUT2 can be set with resistors R1 and R2 according to the formula

$$Vout = 2.5 \times (R1 + R2)/R2$$

By setting R1 = R2 = 1k, we get an output of 5V that can be converted from any input voltage from 6V to 95V. An evaluation board for the LM5008A is available and will be used during testing. This allows us to power our system prototype from a high voltage to simulate its use in the battery-forklift context

4.4.2 CAN Transceiver - TCAN1042

The physical CAN bus consists of 2 wires: CAN_H and CAN_L. The MCU can not directly interact with these 2 wires. A CAN transceiver is necessary to provide the platform for the MCU to communicate with the CAN bus. The schematic is shown in Figure 8. The MCU connects with the CAN transceiver through CAN_Tx and CAN_Rx.

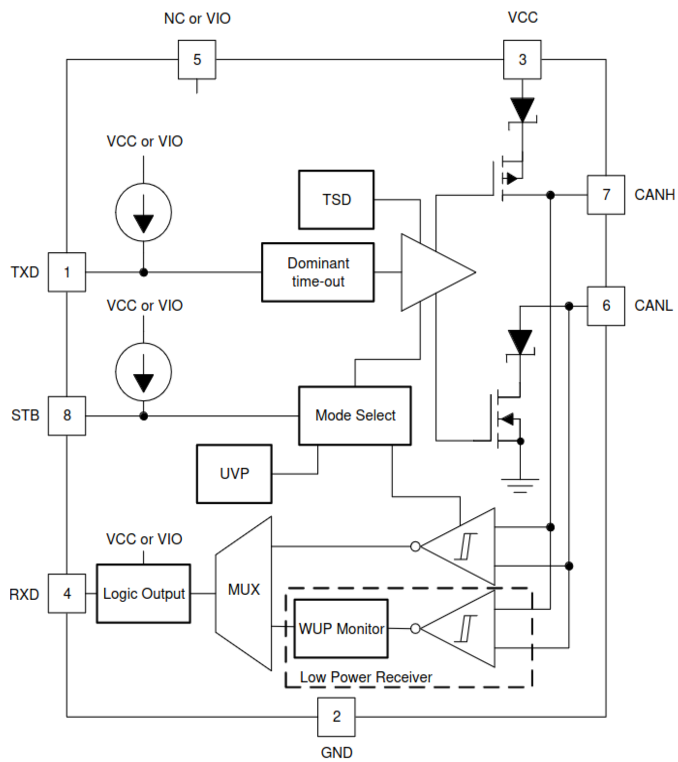

Figure 8: Block diagram of TCAN 1042

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4.4.3 Microcontroller Unit - STM32L476RG

STM32L4 series is a suitable MCU for this task. It has two I2C ports, supporting fast mode up to 1Mbps. It also has a built-in CAN interface which allows the software to easily transmit and receive data from CAN bus. The NUCLEO board is selected as the evaluation board to assist the development.

Using the SPI interface on the STM32 requires using the STM32 HAL (Hardware Abstraction Layer) libraries, which will allow us to easily read and write to registers in SPI devices (used to communicate with the NFC transceivers) without having to write our own drivers.

4.4.4 NTAG 5 Link with Energy Harvesting – NTP5332

The heart of the energy harvesting and sensing mechanism, the NTP5332 chip serves as a reliable and power-efficient component for sensing the key signal. Energy harvesting capabilities enable it to operate by harnessing RF energy from an NFC device, allowing it to operate without being connected to power. GPIOs (General Purpose Input/Output) on the chip facilitate seamless sensing of the key. We configure it by writing to configuration registers over NFC from the battery-side microcontroller. On power-on, the battery-side programs the device to operate in GPIO mode, and can poll the device to determine if the GPIO line has been pulled low by the switch closing.

4.4.5 High-Speed NFC Chip - ST25R3916B

The ST25R series NFC transceiver supports high-speed transmission up to 848 kbps and can wirelessly transmit CAN data. It comes in an Arduino shield style for convenient testing and development. Data is sent to and received from it over the I2C bus to the STM32 microcontroller.

4.5 Software Design

4.5.1 Communication protocol configuration

One focus on the software required is in implementing CAN transceiving on the MCU. The parameters regarding CAN timing are shown in Table 1. Note that because the higher layer of the system is CANopen, this design is only compatible with standard ID (CAN2.0A)

Parameter	Value	Comment
Pre-scaler	5	
Number of Time Quanta	16	
Seg 1	13	
Seg 2	2	
SJW	1	Preferred for CANopen
Sample Point	87.5	Preferred for CANopen
Resulting Bit Rate	1000kbps	Expected speed using the above setting

Table 1: CAN timing calculation

NFC mode is set to active peer-to-peer(AP2P) mode and the data rate is set to 424 kbps. NFC board communicates with the MCU using SPI protocol.

4.5.2 CAN frame transform

Each CAN frame contains a header and a data section. Both parts need to be forwarded to NFC which receives data in byte. The header will be compressed into 3 byte as indicated in Table
Transformed array (SPI) CAN frame section

ID (11 or 29bits)	RTR	IDE	DLC (4bits)	Data (1-8 bytes)

Figure 9: Informational field of a CAN frame, functional fields such as CRC are excluded

Transformed Array (SPI form)	CAN field
byte 0	bit 6-7: SOF bit 5: IDE bit 4: RTR bit 0-3: DLC
byte 1	ID [8:10]
byte 2	ID [0:7]

byte 3-10	Data

4.5.3 Data Structure

The system uses a double-layer ring buffer to store CAN messages received.
The inner layer contains sectors that are 11 bytes long each. Each sector stores one transformed CAN frame. The outer layer is divided into sectors that are 256 bytes long each. Each packet contains a maximum number of 23 frames while 3 bytes need to be wasted due to internal fragmentation. However, in the speed achieved, the occupation is less than 50%.
The benefit of using a ring buffer is that both CAN and NFC can directly access the data, avoiding making copies which wastes CPU cycles.

The software performs bi-directional transform between CAN protocol and NFC protocol. Each time a CAN frame is received (either by interrupt or polling), process 4 is executed.

Main Loop:

Process 1: Look for NTAG
This process is only present in the Battery side.
This process keeps looking for a NTAG. Other processes will not be executed. Once the program receives the request from the NTAG, this process is disabled and other processes are enabled.

Process 2: NFC transceive
This is the major process in the loop. This process transmits and receives NFC packets during the data exchange. interrupt is disabled during this process. If the ring is not empty, this process will transmit a 256 packet starting at ring_packet_head. The actual buffer of this packet will be protected during the entire process.
Inside this process, polling for CAN messages occurred in rfalWorker() and Analogconfig().

Process 3: Forward CAN messages.
If the received NFC packet is not empty, this process will execute a loop to transmit all CAN messages in the packet in one setting.

Process 4: Push Rx CAN message
This process pushes the Rx CAN messages to the ring buffer. The byte level head is determined by both of the frame_head and packet_head using head = packet_head*256 + frame_head*11.

4.6 Safety Considerations

All design decisions are considered with safety in mind. This design mainly takes existing parts on the markets which have been well tested for safety and reliability. The only potential risk is that the power management chip, LM5008, may take high voltage which can cause overheating issues. Relevant tests will be performed in the spring. The project system does not interact with any critical forklift systems that would impact user safety.

4.7 Environmental Impact

The project makes use of pre-made development boards to implement a prototype design, which will make no use of hazardous materials.

5 Project Development

5.1 Risk Abatement

Several decisions have been made to mitigate potential risks in this project. The challenge of selecting the right communication protocols to meet project requirements was first. To mitigate this risk, it is crucial to ensure the MCU's compatibility with chosen protocols, consider scalability, and ensure that the I2C bus is capable of Fast Mode to allow the minimum required data rates.

Another risk involves a scarcity of example code for NFC chips, which can be addressed by actively engaging with the developer community, establishing direct communication with chip manufacturers, and exploring alternatives with better community support.

Additionally, there's a concern about translating SPI to CAN and back fast enough. To mitigate this, thorough performance testing, optimization of software, and consideration of hardware accelerators or dedicated peripherals are essential. Documentation, prototyping, testing, staying informed on the latest developments, and having a contingency plan contribute to an overall risk-mitigation strategy for the project.

5.2 Project Schedule

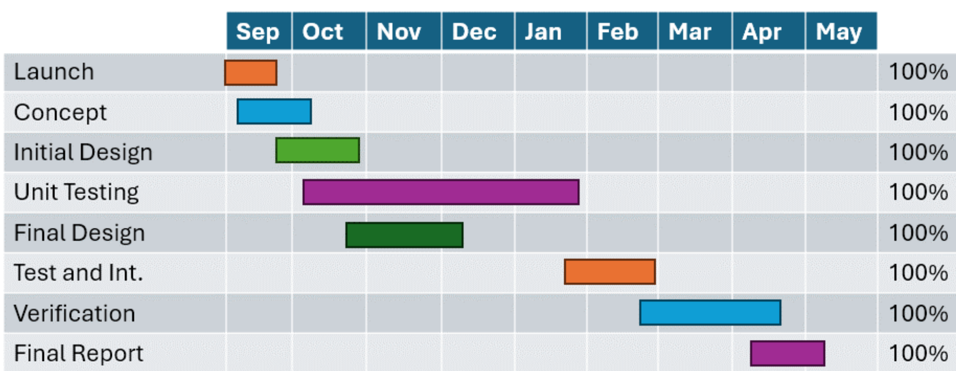

Figure 10: Project timeline

The suggested timeline for completing this project separates the two semesters first into Design, and then Integration and Testing phases. Figure 10 depicts a timetable for the fall and spring semesters. Fall semester's focus was on developing the original system concept and design, as well as deciding which parts to use for each functionality. By prioritizing the development of the original system concept and design in the first semester, the team lays the groundwork for the subsequent integration and testing phase, resulting in a smoother overall project advancement.

Agile methodology is used to allow team members to work on the various subsystems in parallel, with an eye for beginning to integrate them at the start of spring semester.

The Spring semester focused on implementation and testing. Test and Verification ended up progressing past the original goal of end of February and into mid-March due to difficulty in solving various software issues. Primarily, the NFC driver layer provided by ST needed to be tweaked to allow more frequent polling of the CAN receive buffer on each device as it was causing dropped frames and an overall low data throughput (around 50 kbps). By modifying some of the driver files, we were able to get around the blocking nature of the NFC data transceiving routine and not miss CAN frames up to around 210 kbps.

5.3 Project Finances

OrderNum	OrderDate	TotalOrderCost	ProjectBudget	AvailableFunds
1	29-Sep-2023	$ 131.30	$ 1,500.00	$ 1,368.70
2	13-Oct-2023	$ 128.24	$ 1,368.70	$ 1,240.46
3	9-Dec-2023	$ 135.57	$ 1,240.46	$ 1,104.89
4	19-Feb-2024	$ 197.09	$ 1,104.89	$ 907.80
5	12-Mar-2024	$ 111.83	$ 907.80	$ 795.97
6	2-Apr-2024	$ 159.83	$ 795.97	$ 636.14

Table 2: Total financial expenditure

The total financial plan for the specific components required for the ECD 401 project, with a comprehensive budget set at $1,500 is listed in Table 2. The list includes all major purchases of development modules required to test and begin assembling as a prototype. After accounting for the total cost of these components ($863.86), the remaining budget for the project is $636.14. A list of purchased items can be found in Appendix B.

6 System Implementation

The final system is implemented as a two-node CAN bus with the truck and battery sides of the system connected to laptops over a USB-to-CAN adapter.

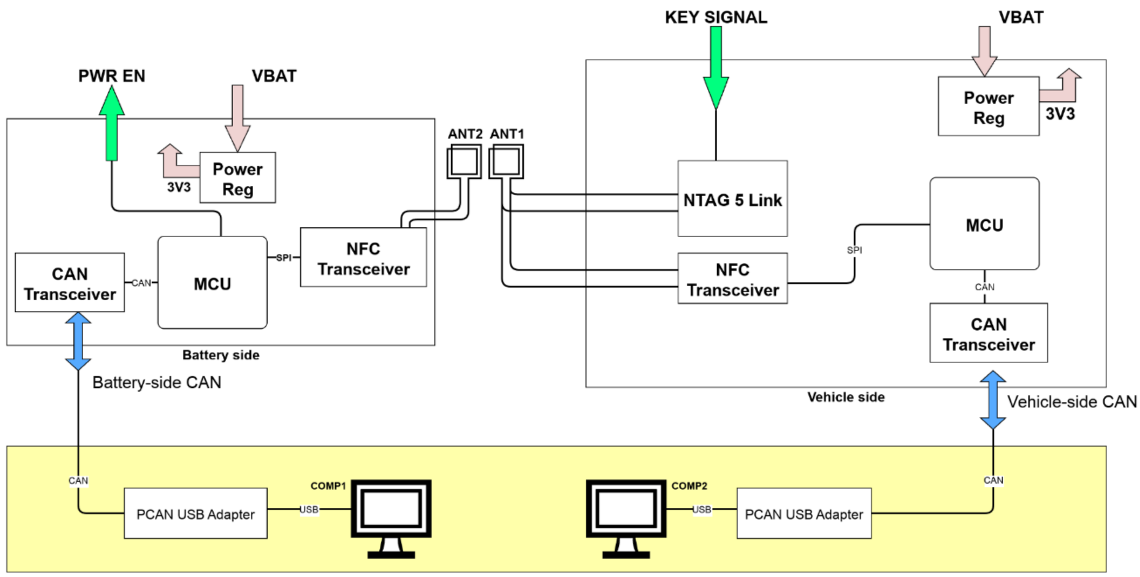

Figure 11: System implementation diagram

The software for the project is written in C in an STM32CubeIDE project, based on the X-CUBE-NFC6 application middleware provided by ST. Looking at the file structure of the project, the relevant application code is located in the `Core/Src` and `X-CUBE-NFC6/Target` folders. The main application is in `demo_polling.c`, and `main.c` and `ring_buffer.c` provide configuration and global objects. Configuration of the NFC subsystems is done in `rfal_defConfig.h` and `rfal_platform.h`.

The laptops are used to send CAN frames through the system and then look at the received frames on the opposite side, and can work bidirectionally. They are also used in testing, as the timing and contents of the CAN frames can be adjusted. The physical implementation looks very much like the diagram, with discrete enclosures containing the two sides of the system.

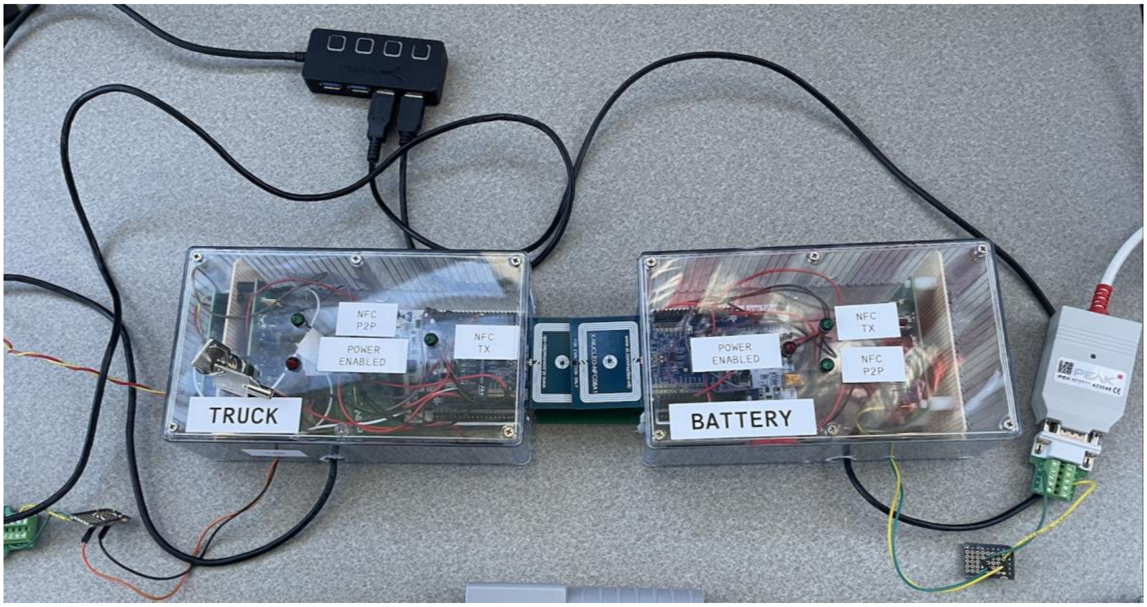

Figure 12: Actual prototype implementation

The NFC antennas can then be positioned at various distances and alignments to test the effect on the signal. The software used to send and read CAN frames is PCAN-View and is shown below.

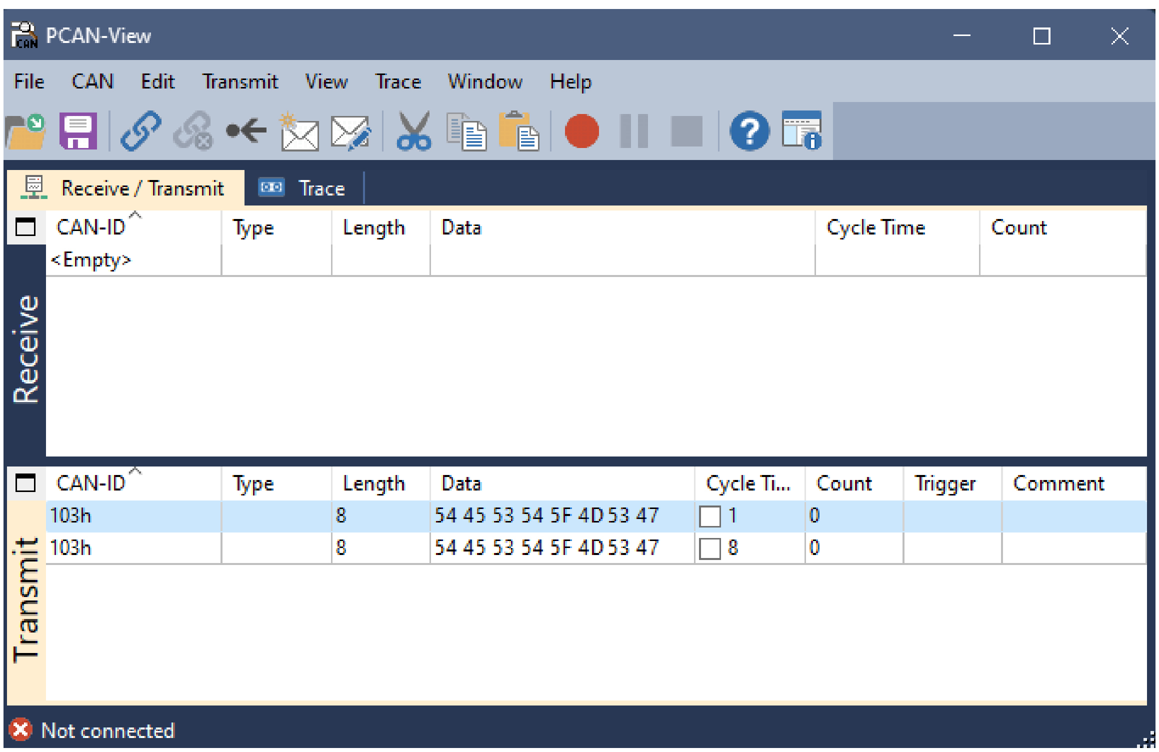

Figure 13: PCAN View software used for sending and receiving CAN data

The top portion of the window shows and received CAN frames and their contents, and the bottom portion shows frames that can be sent, their contents, and the cycle time (how many milliseconds per frame).

7 Project Evaluation

7.1 Overview

The full list of project requirements is provided in Appendix A. A list of tests to be performed is presented in Appendix C, and the procedure for each test is provided in Appendix E. Results were recorded according to the schedule in Appendix D, and reported in the Final System Verification Report, provided in Appendix F.

7.2 Testing and Results

To test the NFC communication, the team connected all the boards and the PCAN USB adaptors as shown in the implementation diagram. The key on the truck side turns on the Peer-to-peer communication between both the systems. Once the link is established, CAN data can be sent using PCAN-View from one side to the other. The highest communication data rate we could achieve was 210Kbps with a Bit error rate of 0.073%.Both devices communicate with each other with up to 2 inches distance between antennas with 1 inch misalignment.

7.3 Assessment

Our team was able to fulfill all our derived requirements and successfully achieve our goal of sending CAN data over NFC. The NTAG board senses the key turn without any power and signals the system to turn on P2P communication. Once the NFC devices start communicating, CAN data can be sent over. We couldn't achieve our stretch goals due to time constraints and problems that arose during this project. Some of the problems encountered included achieving the desired data rate as we would need a faster microcontroller and upgrade our NFC dev boards as the ones we are using have a limitation of 424 Kbps.

7.4 Future Potential

Project stretch goals were *not* met – there is clearly potential to increase the total data throughput, as well as the robustness of the connection with varying distance and misalignment. Significant software optimization would need to be done to increase the data rate, and some configuration of the analog parameters of the ST25R3916B would need to be done to increase transmitter power and antenna performance. Redesigning the antenna could also provide a way to help meet these extended goals.

8 Notes

8.1 Acronyms and Abbreviations

ECD	ECE Capstone Design
ECE	Electrical and Computer Engineering
NFC	Near-Field Communication
CAN	Controller Area Network
I2C	Inter-Integrated Circuit
EH	Energy Harvesting
MCU	Microcontroller Unit
RF	Radio Frequency

8.2 Bibliography

NXP Semiconductors. (2020, January 9). *AN11203 NTAG 5 - Use of PWM, GPIO and event detection.* Retrieved from NXP Semiconductors: https://www.nxp.com/docs/en/application-note/AN11203.pdf

NXP Semiconductors. (2020, May 18). *AN12365 NTAG 5 - How to use energy harvesting.* Retrieved from NXP Semiconductors: https://www.nxp.com/docs/en/application-note/AN12365.pdf

NXP Semiconductors. (2020, July 3). *NTP53x2 NTAG 5 link - NFC Forum-compliant I2C bridge.* Retrieved from NXP Semiconductors: https://www.nxp.com/docs/en/data-sheet/NTP53x2.pdf

STmicroelectronics. (2019, September). *STM32F072RB Mainstream Arm Cortex-M0 USB line MCU with 128 Kbytes of Flash memory, 48 MHz CPU, USB, CAN and CEC functions* . Retrieved from STmicroelectronics: https://www.st.com/resource/en/datasheet/stm32f072rb.pdf

STmicroelectronics. (2023, May). *ST25R3916 High performance NFC universal device and EMVCo reader.* Retrieved from STmicroelectronics: https://www.st.com/resource/en/datasheet/st25r3916.pdf

Texas Instruments. (2016, February). *TCAN1042-Q1 Automotive fault-protected CAN transceiver with flexible data-rate.* Retrieved from Texas Instruments: https://www.ti.com/lit/gpn/tcan1042-q1

Texas Instruments. (2018, October). *LM5008 95-V, 350-mA, Constant On-Time DC/DC Buck Switching Regulator.* Retrieved from Texas Instruments: https://www.ti.com/lit/gpn/lm5008

8.3 References

9 Appendices

Appendix A - Project Specifications Document

The following Qualification Method (QM) is to be used:

- Demonstration (D): The operation of the system, or a part of the system, that relies on observable functional operation not requiring the use of instrumentation, special test equipment, or subsequent analysis.
- Test (T): The operation of the system, or a part of the system, that uses instrumentation or other special test equipment to collect data for analysis.

- Analysis (A): The processing of data obtained from another qualification method. For example, reduction, interpolation, or extrapolation of test results.
- Inspection (I): The visual examination of system components, documentation, etc.

The following Requirement Categories (RC) are to be used:

- System Capability Requirements (SC): Requirements pertaining to the functionality and behavior of the system.
- System External Interface Requirements (EI): Requirements based on the external interfaces of the system. Interfaces with input power, user input, or any other outside source
- Project Business Requirements (PB): Requirements pertaining to business objectives set by a sponsor such as installation requirements, requirements pertaining to specific lab access or lab equipment needs etc.
- Other Requirements (O): Safety, Security and Privacy, System Environment concerns etc.

ID	QM	RC	Derived Requirement
ECD401-R-001	T	SC	The device shall communicate over at least 2 inch gap.
ECD401-R-002	T	SC	The device shall communicate with +/-1 inch of mis-alignment.
ECD401-R-003	T	SC	The device shall be able to communicate up to 125KBaud.
ECD401-R-004	T	SC	The Bit Error Rate shall be less than 1%.
ECD401-R-005	A	PB	The cost of the board shall be less than $20.
ECD401-R-006	I	SC	The device shall use 13.56MHz NFC.
ECD401-R-007	D	EI	The device shall be able to communicate with CANopen bus.
ECD401-R-008	D	O	The device shall have bootloader to allow firmware updates of applications.
ECD401-R-009	T	SC	The Truck side NFC shall harvest power from the battery side

Derived Stretch Goals

ID	QM	RC	Derived Requirement
ECD401-G-001	T	SC	The device should communicate over at least 4-inch gap.
ECD401-G-002	T	SC	The device should communicate with +/- 2-inch of mis-alignment.
ECD401-G-003	T	SC	The device should be able to communicate up to 500KBaud
ECD401-G-004	T	SC	The Bit Error Rate should be less than 0.1%.
ECD401-G-005	A	PB	The cost of the board should be less than $10.

ECD401-G-006	D	EI	The device should mount to the Anderson Connector.
ECD401-G-007	D	EI	The device should be able to communicate through Anderson Connector.
ECD401-G-008	D	EI	The device should be sealed and mechanically sound for use with Battery connector.

Appendix B - Financial Status Table

S No	Item	Qty	Price
1	STM32 NUCLEO-F072RB boards	4	$67.27
2	OM2NTP5332 NTAG 5 NFC Evaluation Board	2	$64.55
3	ST25 NUCLEO-NFC08A1	4	$147.20
4	STM32 NUCLEO-L476RG	4	$66.57
5	ADP5092 Energy Harvesting Power Management Evaluation Board	1	$63.54
6	1/1 Transceiver CANbus 8-SOIC	2	$3.74
7	SMT ADAP 6 PACK 8SOIC/MSOP/TSSOP	1	$2.95
8	120 Ohms ±1% 0.25W, 1/4W Through Hole Resistor Axial Metal Film	10	$0.76
9	TCAN1042D Interface Evaluation Board	4	$235.20

10	LM5008A - DC/DC, Step Down 1, Non-Isolated Outputs Evaluation Board	2	$124.59
11	Enclosures, Boxes, & Cases Polycarbonate 7.5x4.3x2.2" Clear	2	$49.01
12	Keylock Switches 1A 125VAC .5A 250VAC Key Pull Pos. 1,2	2	$7.84
13	LED Panel Mount Indicators 5mm 6" Leads Green	10	$5.50
14	LED Panel Mount Indicators 5mm 6" Leads Red	10	$7.90
15	Adafruit Accessories DE-9 (DB-9) Female Socket Connector to Terminal Block	4	$11.80
16	USB 2.0 Cable A Male to Mini B Male 3.28' (1.00m) Shielded	2	$4.68
17	1 kOhms ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric) Automotive AEC-Q200 Thick Film	50	$0.76
Total Expenditure			$863.86
Total Budget			$1,500.00

Appendix C - Tests Coverage

Test ID	Test Name	QM	RC	Requirements Addressed	System Requirement
ECD401-T-001	NFC Range and Alignment Test	T	SC	ECD401-R-001 ECD401-R-002	Shall communicate over a 2 inch gap with +/- 1 inch mis-alignment
ECD401-T-002	Bit Error Rate Test	T	SC	ECD401-R-004	Shall be less than 1%
ECD401-T-003	Communication Rate Test	T	SC	ECD401-R-003	Shall be able to communicate up to 125 KBaud
ECD401-T-004	Cost Assessment	A	PB	ECD401-R-005	Shall be less

	Test				than $20
ECD401-T-005	NFC Frequency Test	I	SC	ECD401-R-006	Shall use 13.56MHz
ECD401-T-006	Bootloader Test	D	O	ECD401-R-008	Shall have a bootloader to allow firmware updates of applications
ECD401-T-007	Energy Harvesting Test	T	SC	ECD401-R-009	The truck side NFC shall harvest energy from the battery side

Appendix D - Testing Schedule

Test To be performed	*Start Date*	*Test Completion Date*
NFC Range and Alignment Test	*03/11/24*	*03/11/24*
Bit Error Rate Test	*03/16/24*	*03/21/24*
Communication Rate Test	*03/16/24*	*03/21/24*
Cost Assessment Test	*02/26/24*	*02/28/24*
NFC Frequency and Energy Harvesting Test	*02/28/24*	*02/29/24*
Bootloader Test	*03/22/24*	*03/22/24*

Appendix E - Testing Procedures

ECD401-T-001 NFC Range and Alignment test

Objective : To determine the maximum distance/range between the truck and the battery system before they stop communicating with each other.

Requirements Addressed :

ECD401-R-001 and ECD401-G-001
ECD401-R-002 and ECD401-G-002

Step-by-Step Operations	Expected Results
Connect the NFC boards to their respective MCU's. Connect USB cables from each board to their respective laptop.	Boards are connected
Upload test firmware to each board. Observe serial terminal output to ensure it is running.	Indication in serial terminal that firmware is running on each board
Align antennas so that they are centered on each other and separate until spaced 2 inches apart. Send a test data from the initiator to the target device	Should see the data sent on the terminal of both the devices, fulfilling requirement ECD401-R-001
Keeping antennas aligned, move the boards 4 inches apart	Should continue to see the data on the terminal of both the devices, fulfilling requirement ECD401-G-001
Reposition boards center aligned to 2 inches apart. Adjust alignment to the left 1 inch from center and observe serial terminal output. Re-center and adjust alignment 1 inch to the right and observe serial terminal output.	Should see the data sent on the terminal of both the devices when positioned to the left and right of center alignment, fulfilling requirement ECD401-R-002

Repeat the above process, but using a left and right alignment of 2 inches.	Should see the data sent on the terminal of both the devices when positioned to the left and right of center alignment, fulfilling requirement ECD401-G-002

ECD401-T-002 Bit Error Rate test

Objective : To assess the reliability of the NFC communication system. It is done by comparing the transmitted and received CAN data on both sides of the system during a set period of time. It must be below 1%.

Requirements Addressed :

ECD401-R-004 and *ECD401-G-004*
ECD401-R-007

Step-by-Step Operations	**Expected Results**
Connect the NFC boards, MCU and CAN as shown in the block diagram. Connect boards to USB of the laptops.	Boards should populate in device manager and power LEDs lit
Build test firmware and upload to boards	Should run without errors
Send a predefined data stream over a time period from the truck-side	Data should be transmitted
Check the terminal on the battery side for received data, and observe any errors	Same data should be seen on the battery terminal, fulfilling requirement ECD401-R-007
If any errors, calculate the number of errors over the number of bits sent during the time frame, to get the Bit error rate. Proceed to test ECD401-T-003.	Should be less than 1% for requirement ECD401-R-004 and less than 0.1% for ECD401-G-004

ECD401-T-003 Communication Rate test

Objective : Determine if system can communicate at required baud rate

Requirements Addressed :

ECD401-R-003 and ECD401-G-003

Step-by-Step Operations	Expected Results
Using PCANview software, test computer A starts 2 transmissions to the battery-sideboard, which forwards the messages to the vehicle sideboard. The cycle time of the 2 transmission is configured to 1ms/7ms, which sends 1000/142 full frames each second. One full CAN frame occupies 111 bits. Therefore 1142 frames/s is equivalent to 125.3 kbps.	
The test computer B connects to the vehicle-side board which forward the received frames from the NFC interface.	The PCANview on computer B should see the same speed of receiving as the transmitting on computer A.

ECD401-T-004 Cost Assessment Test

Objective : To calculate the overall cost of the board and prove that it's below $20.

Requirements Addressed :

ECD401-R-005 and ECD401-G-005

Step-by-Step Operations	Expected Results
Make a list of all BOM items except for common passive components (capacitor, resistors, etc)	
Determine the cost of all non-trivial BOM items using highest quantity break point from a major	

supplier (Digikey, eg)	
Calculate the total cost	Should be less than $20 to fulfill ECD401-R-005 and less than $10 for ECD401-G-005

ECD401-T-005 NFC Frequency and Energy HarvestingTest

Objective : To demonstrate that the system runs on 13.56 Mhz and utilizes energy harvesting

Requirements Addressed :

ECD401-R-006
ECD401-R-009

Step-by-Step Operations	Expected Results
Ensure the system is assembled and the NTAG board and NFC reader are positioned at required distances of at least 2 inches apart and 1 inch misalignment to the left or right, with no external power to the NTAG board. Upload test firmware to the board.	Serial terminal output indicates firmware is flashed and running
Press the push button connected to the NTAG board.	Message on serial terminal indicates button is pushed, fulfilling requirement ECD401-R-009
Reference datasheets of NTP5332 and ST25R3916B and observe frequency of NFC communications specified	Frequency of operation is 13.56 MHz, fulfilling requirement ECD401-R-006

ECD401-T-006 Bootloader Test

Objective : Able to update the MCU code/setup through an outer source

Requirements Addressed :

ECD401-R-007

Step-by-Step Operations	**Expected Results**
Test computer A connects to the battery-side board through CAN transceiver	
Test computer B connects to the vehicle-side board through CAN transceiver.	
Test Computer A sends a message with unmatched ID	No message received on computer B
Computer A updates the program of the vehicle-sideboard that contain the correct ID setup	
Test Computer A resends the message with the same ID	Computer B should receive the same message

Appendix F - Test Results with Details

Test ID	Test Name	QM	RC	Requirements Addressed (Requirements ID	Test Completion Date	Pass/ Fail	Test Results (Details)
ECD401-T-001	NFC Range and Alignment Test	T	SC	ECD401-R-001, ECD401-R-002	3/11/2024	Pass	Communication range between two systems is more than 2 inches and has up to 1 inch of misalignment. Overall test successful, all dependent requirements met.
ECD401-T-002	Bit Error Rate Test	T	SC	ECD401-R-004	4/10/2024	Pass	Bit Error rate is 0.073% at 210.9 kbps and 0 at 160kbps

ECD401-T-003	Communication Rate Test	T	SC	ECD401-R-003	4/10/2024	Pass	Communication rate is 210.9 Kbps
ECD401-T-004	Cost Assessment test	A	PB	ECD401-R-005	3/15/2024	Pass	The total cost of the board is $12.83
ECD401-T-005	NFC Frequency and Energy Harvesting test	I,T	SC	ECD401-R-006, ECD401-R-009	2/29/2024	Pass	The NTAG board senses the key without any power and the system runs on 13.56Mhz
ECD401-T-006	Bootloader Test	D	O	ECD401-R-008	3/22/2024	Pass	Can update the MCU code

Appendix G - Project Standards

Adhering to industry standards is crucial in both software and hardware projects. Coding standards ensure uniformity in structure, enhance readability and make it easier for developers to understand and maintain the coding style. By following these standards, developers can ensure that code remains compatible with various platforms and operating systems.

The specifications provided below gives a clear overview of the standards and the communication protocols we used in our project.

Software Engineering Standard

1. ISO/IEC 12207 (Software Life Cycle Processes)

Hardware Engineering Standard

1. W Model

Standard in C Programming Language

1. GNU Coding Standards
2. MISRA
    a. STmicroelectronics HAL (Hardware Abstraction Layer) and RFAL (RF Abstraction Layer) driver is MISRA C: 2012 compliant[1]

Communication Protocols

1. Controller Area Network
    a. CAN2.0A (sample point: 87.5%, data rate: 125kbps)

2. Near-Field Communication
    a. ISO-15693 Identification cards – contactless integrated circuit cards – vicinity cards
        i. Also referred to as NFC Forum NFC Type-V standard
    b. ISO-18092 Near Field Communication Interface and Protocol (NFCIP-1)
        i. Peer-to-peer communication also specified by NFC Forum NFC-DEP

3. Serial Peripheral Interface

Appendix H – Bill of Materials

Part	Manufacturer	Description	Quantity	Notes
NUCLEO-L476RG	ST	STM32L476 Nucleo-64 STM32L4 ARM® Cortex®-M4 MCU 32-Bit Embedded Evaluation Board	2	
NUCLEO-NFC08A1	ST	ST25R3916B Near Field Communication (NFC) RF Nucleo Platform Evaluation Expansion Board	2	
TCAN1042DEVM	TI	TCAN1042D Interface Evaluation Board	2	
OM2NTP5332	NXP	NTAG5 Near Field Communication (NFC) RF Arduino Platform Evaluation Expansion Board	1	Energy-harvesting NFC GPIO board
RB85P12C24C	Serpac	Box Plastic, Polycarbonate Clear Cover Included X 3.540" (89.92mm)	2	
KO103C701	E-switch	Keylock Switch 2 Position SPDT 1A (AC) 125 VAC DC Panel Mount	1	
ST-DB9-F-R-MIN	SchmalzTech	DB9 Female Mini Breakout Board	2	
SSI-LXH600ID-150	Lumex	LED Panel Indicator Red Diffused 60° 2V 30mA Wire Leads - 6" (152.40mm)	1	