WIRELESS TRAIN SIGNALIZATION

EEE493 Industrial Design Project I Committee Meeting 4 Report

Electrical and Electronics Engineering Department

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Savronik

Savronik, founded in 1986 to serve the Turkish Defense Industry, has been working since its establishment to meet the product and system requirements of our defense industry, using domestic resources to the maximum extent possible, while addressing the current needs of the user authority with original solutions.

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ABSTRACT

The escalating global and local demand for railway services has accelerated the development of railway networks, necessitating control systems for enhanced efficiency and safety. This project aims to address these issues without the need for costly infrastructure changes over the tracks by introducing a wireless railway signalization system utilizing RF-based wireless technologies and passive RFID antenna balises. Each balise, embedded with a unique checkpoint ID that aligns with specific coordinate data, is strategically positioned along the railway tracks. Potentially compliant with ETCS Level 3 standards, our system ensures continuous train integrity monitoring and real-time positioning with an onboard RF antenna which reads the RFID tags and GPS data to gather critical information such as current timestamp, train ID, expedition ID, and the train's precise geographical position including latitude, longitude, and speed. The project aims to optimize track capacity and safety by a continuous communication pipeline of data between the trains and cloud-based database (Google's Firebase) via a WiFi module, allowing for dynamic, real-time management of train movements for collision and speed detection. The system's interface is managed through a Graphical User Interface (GUI) that visualizes the train movements and statuses on the railway network. The system's functionality was simulated and tested on a series of simulated track runs in a controlled, traffic-free environment where the balises were arranged linearly. The simulation results were validated and cross-checked by external checkpoints with known coordinates; which yielded a data stream with at most 3 second latency and absolute coordinate error of 4 meters. Hence, a promising wireless signalization system including onboard devices, RFID tags, and a GUI was shown to be viable as a proof of concept.

1. MOTIVATION AND NOVELTY

1.1 Problem at Hand

Rising traffic demand, security of energy supply, increasing population, and climate change are some of the major issues of today's world. Tackling these problems requires the railway sector to take on a larger share of the global transport demand [1]. In addition to broadening the overall reach; security, reliability, and efficiency of such railways are significant topics. These are achieved by the signalisation of the railways. There are many global standards to regulate railways, such as the European Rail Traffic Management System (ERTMS). The ERTMS has created the European Train Control System (ETCS) levels and modes [2]. Levels are associated with the train-track communication, whereas modes are related to the operational status of the tracks/onboard equipment. ETCS has four numbered Levels 0-3 with varying standards.

- Level 0: Train is equipped with ETCS, but it is operating on a line without ETCS or national system or with the ETCS systems in commissioning,
- Level 1: Train is equipped with ETCS, it is operating on a line equipped with Eurobalises and optionally Euroloop.
- Level 2: Train is equipped with ETCS, it is operating on a line controlled by a Radio Block Centre (RBC) and equipped with Eurobalises and GSM-R.
- Level 3: In the interoperable part similar to level 2 but with train location and train integrity supervision based on information received from the train.

Levels 1, 2 and 3 are configured downwards compatible. This means that level 3 equipped trains can operate in level 1 and 2, and level 2 equipped trains can operate in level 1.

This project aims to align with the standards set by Level 3 of ETCS. ETCS Level 3 enhances train safety and efficiency by using advanced radio-based technology for train spacing, eliminating the need for fixed train detection devices. Trains autonomously determine their position by utilizing the RFID tags placed on tracks called "balises", and must also be capable of determining train integrity on board to the very highest degree of reliability. This system allows for real-time tracking of each train's location by sending positioning signals to a central control, enabling trains to move more closely and safely, following the principle of "moving block" operation. In ECTS Level 3 movement of trains is monitored and necessary orders are given by radio by a "dispatcher" [2]. A dispatcher is responsible for ensuring trains and crews move safely and efficiently across a railroad, they give warnings, alerts, and orders.

As of 2023, Turkey has 13.919 km of railways. 58% of them are signaled, 51% are electrical. Approximately 3.700 km of new routes are under construction. According to the *Ulaştırma ve Lojistik Master Planı,* by 2053, Turkey's railways will reach 28 thousand kilometers. [3] Ownership and maintenance of the Turkish railway infrastructure is managed by the State Railways of the Republic of Turkey (Türkiye Cumhuriyeti Devlet Demiryolları, TCDD). TCDD owns and maintains all public railways in Turkey, including the stations, ports, bridges and tunnels, and all facilities. To privatise the sector, TCDD Taşımacılık was formed to operate all railways in Turkey [4]. In Turkey, ETCS Level 2 is installed on the Ankara–Konya high-speed line designed for 250 km/h, reducing travel time from 10.5 hours to 75 minutes. The current railway network map in Turkey is given in Figure 1. Blue lines represent the high-speed train lines.

Figure 1: Railway Network Map of Turkey [5]

1.2 Utilisation of the Project by Savronik A.Ş.

Savronik Elektronik A.Ş. was established in 1986 and provides work in the following fields:

- Communication Systems
- Power and Control Systems
- Avionics Systems
- Intelligent Transportation Systems
- Digital Transformation Solutions
- Rail Transportation Systems
- Advanced Ammunition Technologies
- Simulation Solutions

In the field of Rail Transportation Systems, Savronik provides an Interlocking system, Central Traffic Control (CTC) Command Center, Track Intrusion Detection Systems, Switch Activation, Locking and Verifying Systems, and Automatic Train Protection and Control Systems (compatible with ETCS). Savronik has completed the signalization of the whole Konya-Karaman line of high-speed trains. They also possess monitoring rights to the line.

Many challenges arise in the signalization of railways. Widespread railway signalization systems are expensive and require too much infrastructure like power, communication, construction, integration, etc. Trains are not tracked based on identity, dispatchers tend to make human errors, and timetables change frequently. As mentioned, only 58% of all railways are signaled in Turkey as of today; this shows how serious the issue is on a national scale. There are some GPS-based train identification solutions; however, they are not accurate enough, especially in stations and crossings. GPS signals tend to be lost in tunnels as well. Different zones of signalisation have different systems, workers, and interfaces; there is no way to monitor the entire system centrally. Various governmental and private bodies are researching and designing products to be used to face these challenges. Savronik A.Ş. is trying to solve these issues by developing a train identification, tracking, localization, monitoring, and collision prevention platform that can be adapted to both the signaled and the non-signalled railways in Turkey.

For Savronik, this project can have several outcomes like improved safety in railway operation by reducing human error, greater efficiency of the system with fewer delays, and fewer accidents, meaning more cost savings. Savronik will be integrating this project into a project of their own that is currently under development. They will be increasing the number of RF readers and tags to broaden the scope of this project over the railways and with more trains. The existing components will be replaced with better, industry standard ones, such as a better RFID reader antenna that improves the reading distance and the maximum speed at which the train can move for accurate signalization. They will be integrating sub-systems like an IMU module for interpolating GPS data when satellites cannot be reached, like in tunnels. The completion of the project has the potential to address serious issues in railway signalization systems on multiple scales, from national safety and efficiency to global market opportunities and improved consumer experiences.

1.3 Target Users

The target end-user of this project is railway operators and infrastructure management entities, primarily TCDD Taşımacılık in Turkey, as well as any other organisation that may be affiliated with the maintenance, expansion, and administration of the railway. Engineers and technicians working in the rail transportation sector are the primary audience.

The anticipated financial capability is medium to large budgets, given the scale and critical nature of railway operations. This budget includes both the initial setup and the ongoing maintenance costs. The specific amount can vary based on factors like size of the railway network the project is being implemented on, the complexity of the system, the level of customization required, and the number of workers needed.

The target end-users are expected to have a technical background in engineering in railway operations and signaling systems. Users are likely to have knowledge of existing railway standards and systems, such as the European Train Control System (ETCS) and regional signaling protocols. End-users will be expected to have the needed background and expertise to utilize the Graphical User Interface (GUI) created in this project to monitor and manage the real-time track data provided by the system and make decisions based on it. Dispatchers that will be doing this work will be expected to undergo the necessary training.

1.4 Similar Products

Similar projects have been done with this motivation. One of these is the Eurobalise system. A Eurobalise is a rail-mounted device used in the European train control system (ETCS) [6]. These balises are pre-programmed and hold data that is read by train antennas. The system consists of two modules: on-track and on-board. The cost of the onboard equipment would be around €100.000 for new equipment and €200.000-€300.000 when existing equipment has to be adapted. The cost of implementing the on-track equipment depends on traffic density and cost allocation methods. To obtain precise estimates, a detailed analysis on a case-by-case basis of the rail network is essential. It is seen that recently the prices of installation for Eurobalise systems are falling. Eurobalises will allow the railway systems to make substantial savings once a sufficient number of trains are fitted out to enable the old systems, which are costly in terms of maintenance [7].

The Eurobalise system comes with advantages and disadvantages. On the plus side, they increase railway safety and enable cross-border train operations, potentially reducing infrastructure costs and allowing for system flexibility. However, there are high implementation costs, lengthy deployment times, integration challenges with existing systems, compatibility issues with older trains, and the need for reliable technology and cybersecurity measures [8]. And most importantly, despite automation, human errors can still occur due to the crucial roles of dispatchers and train operators.

1.5 Possibility of a Patent

This project introduces a novel implementation of a system similar to Eurobalises, which is a concept that has not been previously undertaken in Turkey. A patent research has been conducted to see how likely this project is to receive a patent. There are a number of patents [9,10,11] taken internationally to solve the signalization issues of railways with the utilization of RF. However, with research done within the Turkish Patent and Trademark Office on possible patents in Turkey, it was seen that no similar patented solutions existed. There were some patents and trademarks about railway control [12,13], but none of them relied upon RF technology.

Given that patents are typically jurisdiction-specific, applying only within the boundaries of the granted country, the absence of similar patented solutions in Turkey enhances the prospect of securing a patent for this project within the country.

2. REQUIREMENTS

Below is a list of the requirements for this project, categorized into functional and non-functional requirements. **SR-FUNC-140** has been added after CM3, no other modifications have been done.

2.1 Functional Requirements

The following section represents the functional requirements for the system design specifications of the wireless train signalization project.

SR-FUNC-010 There shall be one onboard device on each train that is capable of radio-frequency communication with the on-track RFID balises (also referred to as “checkpoints”, “tags”, and “balises” in this text), and a centralized data center. No trackside equipment shall communicate with the centralized data center.

Rationale: This requirement is derived from ETCS Level 3 standardization requirements for European railroad systems. Although not fully standardized, ETCS Level 3 oversees the involvement of no trackside equipment to communicate with a centralized data center. The onboard devices on the trains must fully carry out communication with the data center.

SR-FUNC-020 The onboard devices shall periodically communicate with the data center to report expedition information (Timestamp, Train ID, Expedition ID, Latitude, Longitude, Speed, Last Balise ID). The onboard devices shall also non periodically communicate with the balises upon encounter, to receive the identification of the balise.

Rationale: To track the current GPS location of the train, periodic information of its location is declared to the data center and subsequently updated in the GUI. The communication with the balises only occurs aperiodically, upon physical encounter.

SR-FUNC-030 Each balise shall transmit its identity and an error detection code to a passing train.

Rationale: To differentiate between balises and acquire the position of the train, a successful identification checkpoint ID and position is required.

SR-FUNC-040 Onboard transceivers shall be able to receive transmitted messages while in motion.

Rationale: To achieve successful data transmission between checkpoints and the train, onboard devices perform reliable transmission in motion.

SR-FUNC-050 Each onboard device shall have a unique ID apart from the assigned train ID.

Rationale: To have flexible usage of the onboard device independent of the train it is mounted on, unique identification for each device is required.

SR-FUNC-060 Train identity shall be assigned to onboard devices upon expedition initialization.

Rationale: To have flexible usage of the onboard device independent of the train it is mounted on, unique identification for each device is assigned to the train upon expedition initialization.

SR-FUNC-070 Onboard devices shall periodically broadcast their GPS coordinates, the latest checkpoint passed, and identity to a remote server.

Rationale: To achieve real-time tracking for monitoring and control, facilitate historical data analysis, and ensure accountability by distinguishing individual devices within the system, it is mandatory that onboard devices periodically transmit their GPS coordinates, checkpoint data, and identity to a remote server.

SR-FUNC-080 The GPS coordinates measured by the onboard device and the absolute GPS coordinates of the on-track transmitters (checkpoints) shall be compared on the application level of the user interface.

Rationale: To ensure reliable data integrity and regulation, prevention of system failures, and optimal operational efficiency, a comparison of GPS coordinates with user interface coordinate information is required.

SR-FUNC-090 Remote server shall store all messages received from onboard devices.

Rationale: To maintain data integrity, establish accountability through audit trails, and enhance system reliability, the requirement dictates that the remote server must store all messages received from onboard devices.

SR-FUNC-100 A collision detection software (server side) shall check if there are any trains on the same track that violate railway security regulations.

Rationale: To ensure safety, prevent accidents, and enhance operational efficiency, the requirement mandates the implementation of server-side collision prevention software that checks for trains moving toward each other on the same checkpoint line.

SR-FUNC-110 The signalization system shall accurately detect and alert the personnel (dispatcher) about potential collisions between trains, especially at intersections, switches, and crossings, ensuring the safety of passengers and railway staff.

Rationale: To ensure railway safety, it is essential to have accurate collision detection and timely alerts at critical locations to prevent accidents, protect lives and infrastructure, and uphold regulatory standards, legal compliance, and the reputation of railway organizations.

SR-FUNC-120 Stationary tags shall be placed in critical locations to ensure precise localization.

Rationale: To ensure safe and efficient railway operations, the requirement mandates the strategic placement of stationary transmitters on the track for precise train localization. This precise localization is vital for minimizing operational disruptions and safety concerns.

SR-FUNC-130 Onboard devices shall utilize a WiFi connection to send and receive messages to the remote database.

Rationale: To ensure reliable and adaptable communication, the requirement allows onboard devices to employ both GSM and WiFi for sending and receiving messages with the remote server. This flexibility enhances communication system resilience and maintains efficient data exchange across different network conditions.

SR-FUNC-140 The GPS coordinates measured by the onboard device and the absolute GPS coordinates shall have a maximum deviation of 4 meters..

Rationale: To ensure reliable and precise localization the error rate of the GPS Module should be kept at minimum. This is vital for minimizing operational disruptions and safety concerns.

2.2 Non-Functional Requirements/Constraints

2.2.1 Cost

SR-CST-150 The cost of a complete system with two onboard devices, 10 on-track transceivers, and a remote server shall not exceed 40,000 TL (as of 23.05.2024).

2.2.2 Train Speed

SR-SPD-160 Onboard device shall be able to read the data from the on-track transceivers while moving at 80 km/h.

2.2.3 Onboard Device Range

SR-RNG-170 The onboard transceiver shall be able to read the on-track transceiver ID data from a minimum horizontal distance of 1 to 3 m.

2.2.4 Size and Weight

SR-SW-180 The detached components of the onboard device shall have a maximum allowable size of 0.25 x 0.25 x 0.1 m and weight of 500 g, with its size and weight compliant indirectly to TS EN 50128 standard [14].

2.2.5 Power Consumption

SR-PW-190 The onboard device shall comply with the power requirements of the individual modules, ensuring that the system performs with a power consumption below 5 watts and a current draw under 500 mA.

SR-PW-200 The RFID reader and Wi-Fi module shall be powered by an external power source, adhering to their individual requirements.

2.2.6 Safety

The following section represents the safety requirements of the system.

2.2.6.1 System Reliance

SR-SAF-210 The system shall have manual override capabilities to address system malfunctions or unreliability promptly, standardized by TS EN 50126-1 [15] specifications for reliability, availability and safety.

Rationale: To promptly address system malfunctions or unreliability, this capability serves as a fail-safe mechanism to respond to unexpected issues swiftly, ensuring the system's continuous operation and minimizing the risk of disruptions, particularly in scenarios where system reliability is compromised.

2.2.6.2 Regulatory Compliance

SR-SAF-220 The system shall comply with the safety regulations and railway-specific standards set by the governing bodies (Turkish Standards Institute, Ministry of Transport and Infrastructure) such as but not limited to: TS EN 50126-1, TS EN 50128, TS EN 50155, TS EN 50159 [14,20,21]. The system shall comply with communication standards of ISO/IEC 18000-6:2013 [16] for RFID, TIA-232-F [17] for RS232, IEEE 802.11 [18] for WiFi and ISO 6709:2008 [19] for GPS.

Rationale: Regulatory compliance is crucial to prevent unsafe practices and maintain the integrity of railway operations. It ensures that the system meets the legal and safety requirements set forth by relevant authorities.

2.2.6.3 Data Security

SR-SAF-230 The signalization system shall guarantee the unassailable integrity and security of RFID data, compliant with TS EN 50159 [20]. It is imperative that authentication and access control measures are enforced to thwart data corruption, unauthorized access, or loss that could compromise railway safety.

Rationale: To ensure the absolute integrity and security of RFID data within the signalization system, robust authentication and access control measures are essential safeguards against data corruption, unauthorized access, or loss, all of which have the potential to jeopardize railway safety.

2.2.7 Environmental Issues

SR-ENV-240 The on-track transceivers shall be designed to exhibit resilience standardized by TS EN 50155 standard [21] for electronic equipment used on rolling stock, to the diverse challenges of the railway environment, including extreme weather conditions, vibrations, and physical hazards.

Rationale: Environmental resilience is crucial for ensuring the system can operate reliably under various environmental challenges. This requirement underscores the need to protect the system from potential environmental wear and tear that could compromise safety.

2.2.8 Health Issues

There is no constraint on the health issues of the proposed solution.

2.2.9 Global, Cultural, and Social Factors

There is no constraint on global, cultural, and social factors of the proposed solution.

3. BIG PICTURE

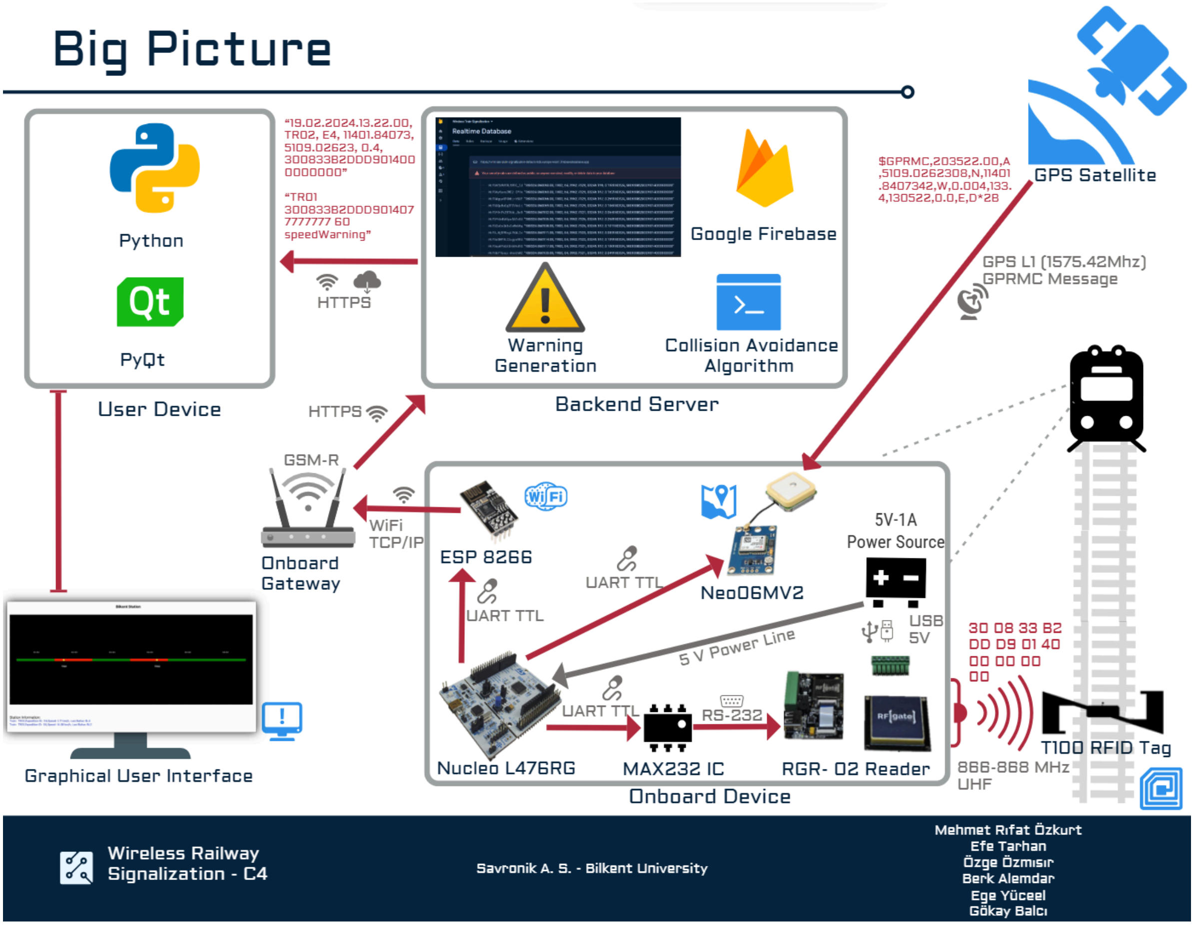

Figure 2: Big Picture

In the system's schematic overview, red lines and connections symbolize the communication methods, while boxes denote the devices or subsystems integral to the project. This system is composed of three main subsystems: the onboard device, the online database and broker system, and the graphical user interface (GUI).

The onboard device consists of two packages: the RFID package and the main package. Both are equipped with various peripheral modules including an RGR-02 RFID reader, a Microstrip 2-dBi ceramic RFID antenna, a GPS module, a MAX232 IC and an ESP8266 WiFi module. The RFID package is to be installed outside the trains (possibly below), hosting the RFID reader and the RFID antenna. This package is connected to the main package through a 5V power line and an RS-232 interface.

The main package hosts the communication peripherals: ESP8266 WiFi module, MAX232 IC and GPS module. These peripherals are interconnected with a Nucleo L476RG microcontroller on a development board. The ESP8266 module is mounted on the development board, whereas the other modules and the development board are fixed to the electronics enclosure. Within the main package, the modules communicate with UART signals to receive data from peripherals, generate a message package and upload it to a cloud database using available WiFi connections.

The online database and cloud functions operate on Google's Firebase service. The GUI, on the other hand, features a graphical service that not only displays track layouts of selected stations but also highlights events on the tracks. It marks occupied tracks in distinct colors and dynamically visualizes train movements using GPS data. Additionally, several algorithms are implemented to detect potential collisions and prevent accidents and report them to users.

The operational workflow of the system is as follows: The RFID reader, aided by the RFID antenna, scans RFID tags positioned at crucial points along the tracks, such as crossings, station entrances, and exits. Upon reading a tag, the RFID reader broadcasts the tag's ID, representing a specific track location. Along with the tag ID, the microcontroller compiles a data package encompassing a timestamp, GPS coordinates from the GPS module, and a pre-assigned train ID stored in its memory. This package is then transmitted to the online Firebase database via the ESP8266 WIFI module, ensuring the data is accessible to the GUI. The microcontroller is programmed to publish these data packets periodically, which include the ID of the last passed tag and the train's GPS location at that time. The GUI retrieves this data from Firebase using Python and displays it in real-time, while concurrently running various algorithms to ensure operational safety and efficiency.

4. METHODS AND IMPLEMENTATION DETAILS

4.1 Work Breakdown Structure and Project Plan

In this part, the workload of the project is divided into packages and tasks and explained in detail. The tasks are represented with a WBS (Work Breakdown Structure) diagram, which can be seen in Figure 3. The main tasks, which can be seen from the WBS chart required for completion of the project, and also the main milestones of the project will be mentioned briefly.

The aim of this project is to decrease the possibility of railroad accidents and undesired rule violations on train systems. To solve these problems, several components and subsystems are implemented. There are onboard devices on each train that are responsible for controlling the RFID reader, which receives the information of RFID tags placed on the track and also for transmitting information like GPS location and timestamps to a main database. To tackle this challenge, the project is divided into two subsystems: hardware and software.

Before starting with the technical structure of the project, it is proper to mention that all tasks proposed for this project have been completed before Committee Meeting 4.

The hardware subsystem contains the development boards, RFID components consisting of the reader, antenna and tags, GPS and WiFi modules, and their combination as an onboard device that are responsible for gathering the data from the train traveling on the railroad and transmitting this information to the main database.

The whole hardware set-up for two trains are completed and are working successfully. The RFID components are configured to the embedded device that will be located in a strategic location on the train, which will ease the RFID antenna to read the tags placed on train tracks. The RFID tags are coded, or their present identities are matched with location IDs, which are stored in a track that will provide information about the location of the junction that the train is passing or any location alongside the track where the RFID tag is placed. Finally, there is an RFID reader, which is controlled by the development board to do all necessary analog and digital conversions on the raw and continuous data captured by the antenna.

A GPS module is used to obtain the precise location data of the train traveling along the track. Since the RFID tags provide highly sparse data in time compared to a GPS module with a high sampling rate, the GPS will assist in correcting possible localization errors and also in critical points.

With the help of a WiFi module the obtained data is transferred to the web from each train using data transfer functions and protocols of Google Firebase. Each of these modules are configured to the embedded system by using C++ and available libraries. These tasks are collected under the name of the Peripheral Sensor and Communication Modules with task package number 2.2. The hardware subsystem of the project concludes with finalizing arrangements and modifications of the configuration of the hardware modules and devices.

The project also requires a second subsystem which consists of the software requirements of the project. These software tasks can be divided into 3 subtasks which are 3.1 the design of a database, 3.2 a graphical user interface and 3.3 signalization algorithms.

One of the most important task packages of the project is the design and implementation of TCP protocol on devices that require communication with the main server where the PCs with GUI and all development boards that will transmit data to the main database will require a wireless communication channel with the database. To accomplish this goal, client and server modules are implemented on one of the onboard devices and the main server.

This whole system mentioned is replicated. It is designed to be installed on two cars, with the ultimate goal of implementing it on trains traveling at approximately 100 km/h. A collision detection algorithm is designed utilizing the data stored in the database and the GUI. The algorithm is installed to the Firebase cloud functions so that it can operate independently as the cloud receives new data. This is task 3.2.2 in the WBS. These tasks have been completed between CM3 and CM4.

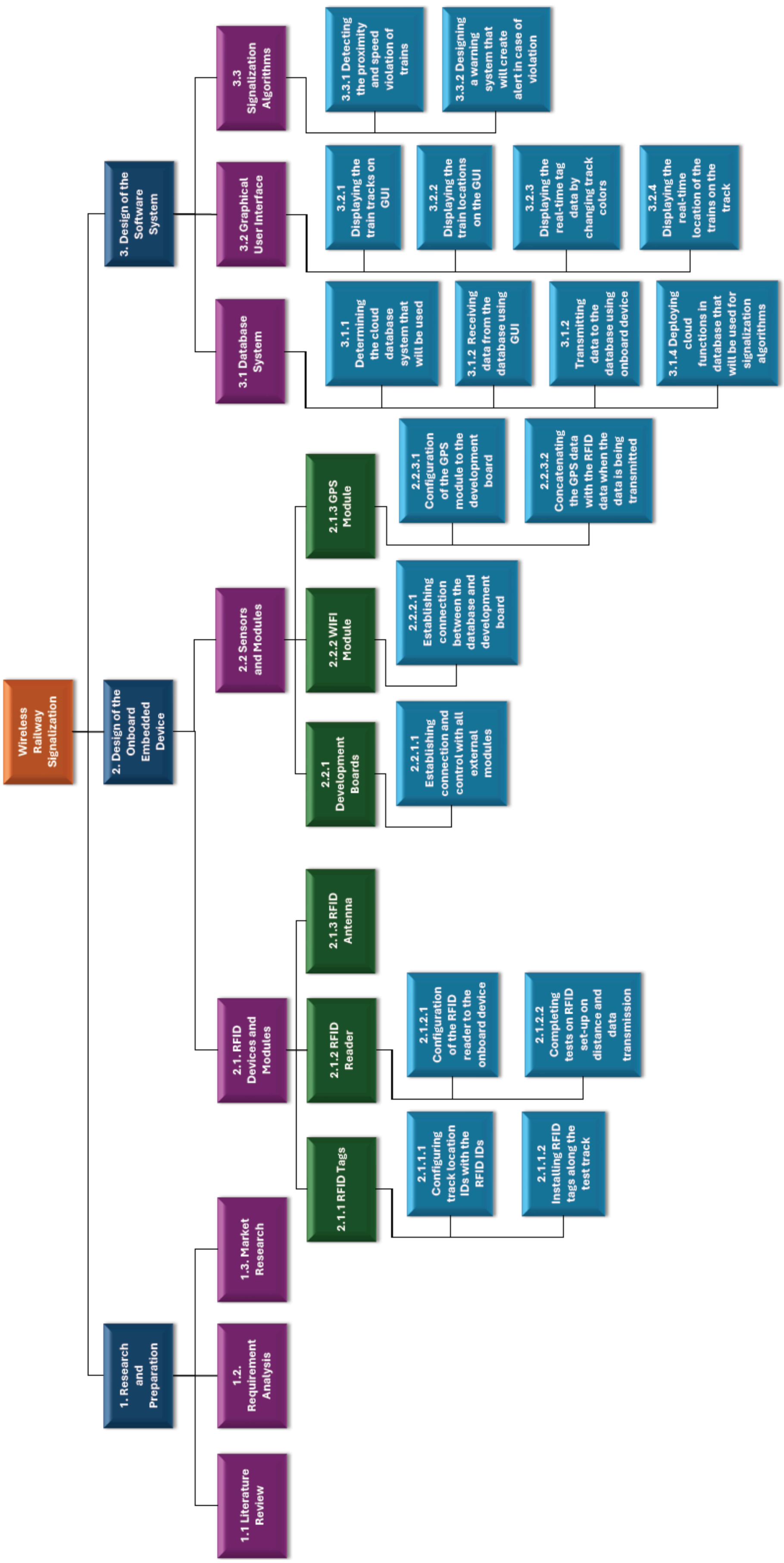

Figure 3: Project's Work Breakdown Structure

Like most industrial projects, the technical and sophisticated design of the product will need a facade for users. With this mission, task package 3.2 has become one of the essential aspects of the project, which is the design of a GUI (Graphical User Interface) for creating a channel for making the system controllable for people with no technical knowledge. The GUI includes the railroad plan as a visual 2D track with the indication of trains on the track blocks, occupied or available tracks, etc. It is designed using the PyQT5 library of Python, which simplifies the task. The GUI can currently access the Firebase Database and visualize the data coming from all trains on a railroad.

There are several milestones in the project which indicate the completion of significant tasks throughout the project process. The milestone track can be examined from Figure 4.

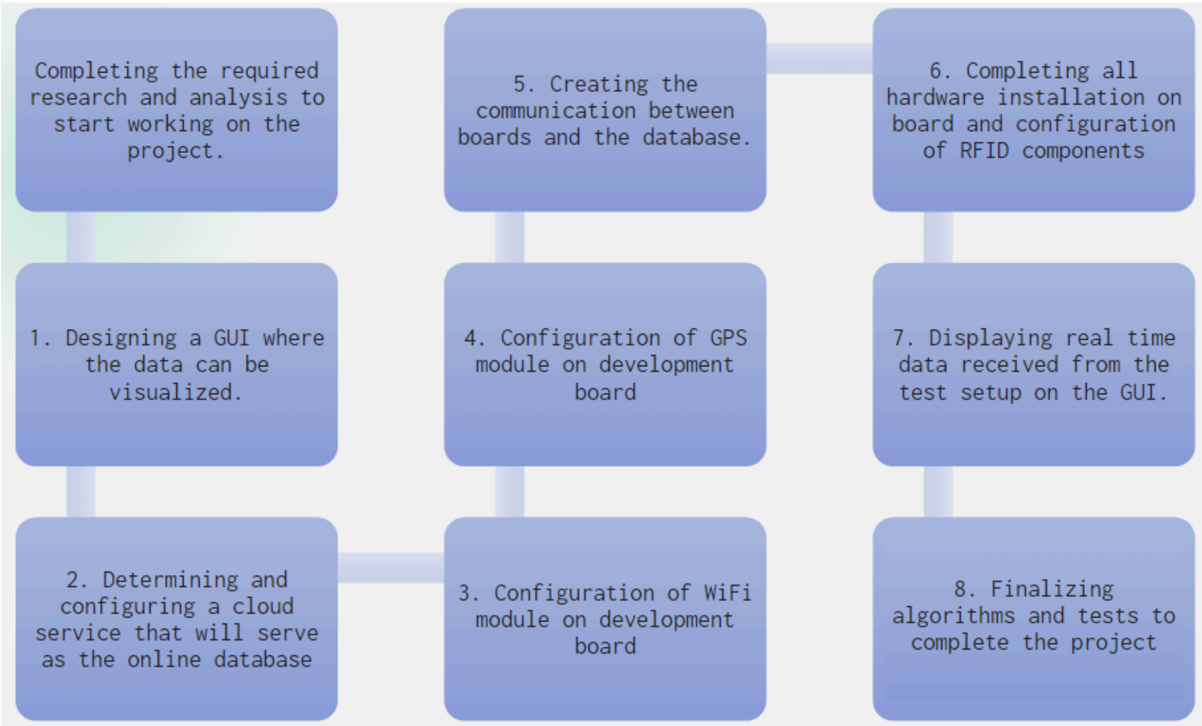

Figure 4: Project's Milestones

The first milestone of the project is the general research and analysis done for working on the project, including literature review, requirement analysis, and finally, market research. Until CM1, the counted tasks have been completed with the contribution of all team members since it is important for each individual member of the team to have adequate information to work on the project. This milestone included tasks 1.1-1.3 in the WBS seen in Figure 5.

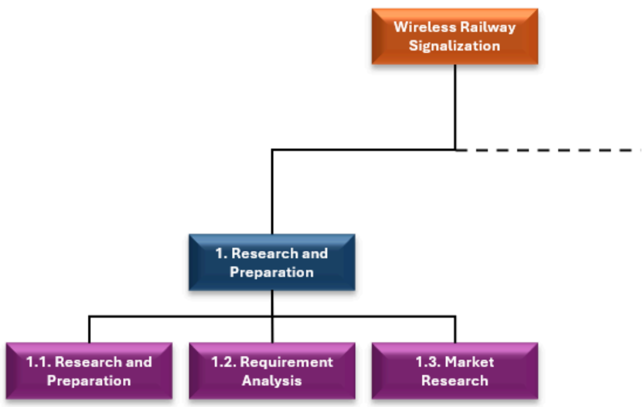

Figure 5: Research and Preparation WBS tasks

Since the hardware components of the project required a long process of finding requirements for the project, initially the first task packages to be completed are selected from the software system. Therefore, the first milestone of the system has been determined as the design of the database, which will also start the progress of the software system of the project. The process involves the design of a database protocol in which Google Firebase is utilized. Completing the main structure of the database is an important step for the project because the data that the company provided can be used and uploaded to the database for inspection. The success of this milestone can be measured by the ease of accessing the database and also how robust the database can be used for uploading new data and pulling previous train data. The tasks concerning the software system were underneath the title "3. Design of the Software System".

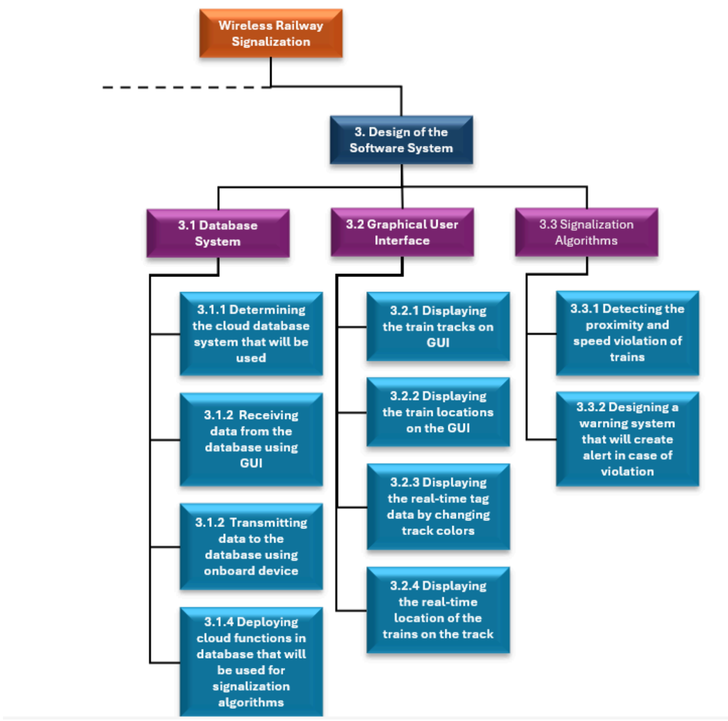

Figure 6: WBS Tasks for Software System

The second milestone of completing the GUI concludes most of the software workload of the project. This GUI has been designed using the sample datasets Savronik has provided that have the same structure as in this project. The GUI is considered to be successfully designed if all features of a signalization interface are available and operational on the screen. Since the GUI receives the data from the database, the connection between the database is also one of the success metrics of the project.

Following the communication, the next important milestone is the integration of the WiFi module to the board, and being able to access the database using it. During tests the Wi-Fi connectivity was established simply through a cellular hotspot, which assumes the continuous reception of a cellular signal. On a train, specialized systems such as GSM-R exist that may serve similar functions.

As a success metric, again, the strength of the connection between the development board and the server, being able to send small chunks of strings or numbers to the server and being able to connect the board to the database for data transmission with ease. Configuration of these hardware modules are all individually important milestones of the project since each of them must work well individually and also in cooperation, like a system with each other.

The fourth milestone of the project is attached to the first major achievement of the hardware part of the project, which is the integration of the GPS module into the board. The success metric for completing this milestone is ensuring the GPS coordinates measured by the onboard device and the absolute GPS coordinates have a maximum deviation of 4 meters for the project, which is acceptable for railroad or transportation systems, and also the speed of data acquisition.

The fifth milestone of the project is establishing the data pipeline and connection of development boards and the main server. This milestone also includes trials of sending timestamps and GPS locations of the boards to the main server, therefore starting to see the facade of the project. The success metric of this part is successful transmission information about GPS and time to the board's main server.

The next milestone is the configuration of the whole RFID system, which is completed successfully. How well the RFID antenna or the reader can receive the data from RFID tags on track and how robust the RFID reader can provide data for the system are some of the success metrics.

Tasks concerning the hardware system were under the title "2. Design of the Onboard Embedded Device" in the WBS.

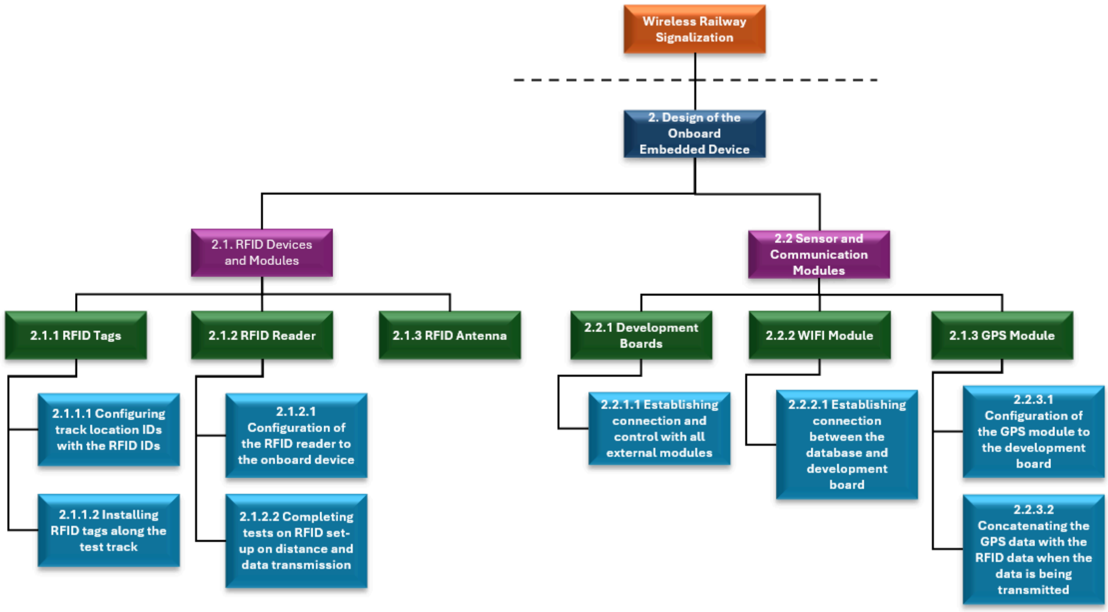

Figure 7: WBS Tasks for Hardware System

The 7th and 8th milestones consist of the final tasks and packages to complete the whole project, like displaying train tracks or trains on track by also indicating occupation and availability of tracks. Designing several signalization algorithms like collision detection systems is also one of the tasks. These tasks are completed successfully. The final hardware set-up for two trains are put together and the software system consists of the database and the GUI is completed. The success measure of this part is the accuracy of the designed algorithms and how accurate the user interface is to model the railroad environment using the data from the database.

All milestones, task packages, and people who are responsible for these tasks can be examined from the Gantt Chart in Figure 8.

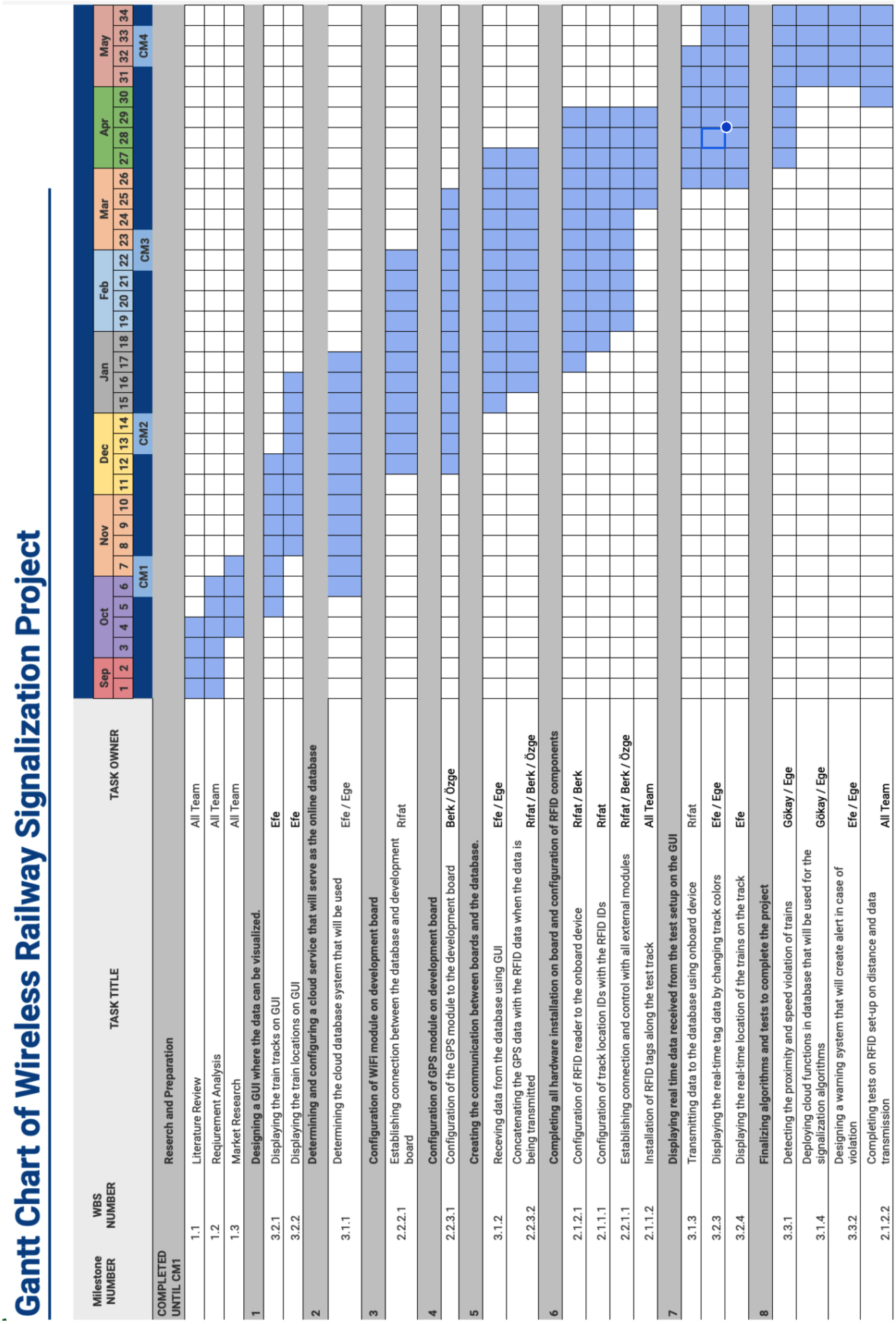

Figure 8: Project’s Gantt Chart

4.2 Methods and Progress

This section will address the major work packages and tasks of the project, providing a detailed explanation of the methodologies of each subsection.

Table 1: Table of Methods and Technical Approach

Task/Work Package	Approach/Technique	Methodology
System Design and Architecture	Employed a systematic analysis of requirements, considering both signaling and non-signalled railway environments.	• Utilized industry-standard architectural principles • Collaborated with company mentor and academic mentor • Gathered feedback and iteratively refined the design
RFID Tag Implementation	Conducted a thorough market analysis to identify RFID tags meeting project specifications.	• Tested identified RFID tags for durability and readability • Considered factors like signal strength and interference
RFID Reader Deployment	Conducted a market and literature analysis to identify RFID readers meeting the project specifications.	• Implemented RFID readers to evaluate performance • Evaluated coverage and data capture capabilities
Database and GUI Development	Utilized simulation tools to model system behavior and performance.	• Executed controlled tests in a simulated environment • Validated key components of the system
Communication Infrastructure	Designed a communication network to facilitate data transmission.	• Employed industry-standard communication protocols • Ensured compatibility and reliability
Iterative Refinement	Embraced an iterative development process to incorporate feedback from stakeholders and committee members.	• Adapted to evolving requirements • Held regular progress meetings to review feedback • Assessed results and made necessary adjustments to the project plan

4.2.1 Configuration of RFID Devices and Modules

The initial phase of implementing the RFID signalization starts with the configuration of the RGR02 RFID reader to the NUCLEO development board. Recognized for its robust interfacing capabilities, the NUCLEO board is integral for this purpose. Proper interfacing requires an accurate alignment of the reader's terminals with the corresponding pins on the NUCLEO board, ensuring efficient data exchange and signal integrity.

The antenna selection was also a challenging task, with a focus on achieving the desired gain and beam width. The gain reflects the antenna's capacity to intensify the RF signal in a particular direction, which directly impacts the reader's effective range. Concurrently, beam width quantifies the spread of the antenna's radiation pattern, influencing the spatial coverage, which determines the duration possible for a train to be able to read the antenna. The 3 dBi beamwidth of the antenna which is included in the package of RGR02 RFID is nearly 90 degrees which will be a strategic selection that guarantees optimized RFID signal propagation and reception. This antenna choice proved to be sufficient for the tests conducted.

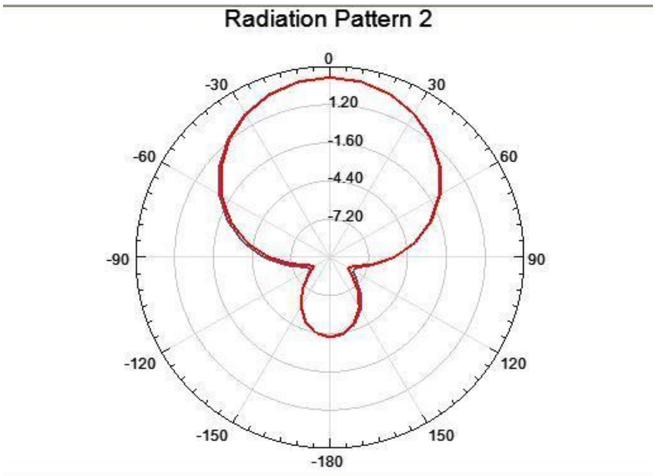

Figure 9: 3dB Beamwidth of the Default Antenna Inside RGR02 RFID-Reader Package [14]

Moving on with data management, constructing a location dictionary becomes important. This dictionary serves as a mapping system, linking RFID tag IDs to spatial attributes on the railway track. Such a framework ensures instantaneous and accurate identification, enhancing the operational efficiency of the RFID infrastructure. Upon successful interrogation of RFID tags by the RGR02 reader, the data must be transmitted to the Firebase database. Utilizing the WiFi module integrated within the NUCLEO board, the data can be sent to the database, ensuring that the location stack remains updated and synchronized.

In the deployment of RFID systems, several risks can emerge, central among them being data breaches or unauthorized data access, due to the wireless nature of RFID communications. Such breaches could potentially allow malicious entities to intercept, manipulate, or even replicate tag data. Additionally, there's the risk of signal interference from external sources, which could hinder optimal RFID functionality. To mitigate these concerns, it's essential to ensure periodic system audits combined with frequency-hopping techniques, which can reduce interference risks, ensuring consistent and secure RFID system operations.

In the implementation process of the RFID functionalities, several challenges were faced, both up to CM3 demonstration and after it. Before CM3 demonstration, the main objective was to establish a working communication interface between the RFID reader and the development board, which became a challenge as the onboard device was separated into two packages. Initially, the communication protocol between the development board and the RFID reader was planned to be UART and USB, where a UART-to-USB converter module was to be used between the modules. However, as the distance between the two packages increased, the protocol was switched to RS-232, since it accommodates higher voltage values that may perform better over a plain copper cable. Thankfully, the signal managed to travel uncorrupted for the distances required in the project demonstration.

In addition, the built-in functionality of the RFID reader became another issue, where the RFID reading window would be open for a short amount of time (~15 s) and require a restart every time it ended. It became crucial to correctly detect the end of the reading window and send the proper restart message to the module. However, in the case of a power-cycle in either of the packages, or a buildup of serial messages on the RFID module's buffers, the system would come to a halt and not restart reading. To tackle this, the communication interface was strengthened by adding checks and auto-restart commands that would try to restart RFID readings on its own.

After CM3 and up until CM4, the problems regarding communication with the module were fully solved. However, the resistance of the RFID module to environmental factors proved to be insufficient during the tests for CM4, where vibrations in the vehicle or other physical manipulations would easily break connections and render the system useless. Some damaged antenna cables resulted in inconsistent and erroneous readings. Even when fixed, the RFID readings may still become corrupted at random instances, and start working again. This is thought to be because of the delicate nature of the antenna and its potential to be affected by the slightest environmental factors, perhaps including static electricity and grounding issues.

4.2.2 Configuration of WiFi Module

The WiFi module that has been chosen for the project is one of the most widely used and practical components that is available online. There are several modules that cover the full usage of TCP methods in all major coding languages in the project. Even though it is one of the simplest WiFi modules available in the market, the ESP8266 module performed well beyond expectations, since the CM1. The WiFi module is used to access online databases that contain the data. Between CM1 and CM2, the communication with this module was a slight problem, where touching the module would corrupt communication signals. This was overcome in the early stages by soldering the module to a prototyping board and mounting it on the development board. A circuit design of the WiFi module can be seen in below Figure 10, where multiple switches have been installed alongside the module to ensure seamless resetting and reprogramming capabilities without hardware issues.

Before CM3, another functionality was assigned to this module, which was to correct incoming packets in case of bad characters. This was because the new database for the project was chosen to be hosted on Firebase, which faced issues with some of the characters sent by the STM32 board. Since the timings on the development board are crucial, the post-processing of the messages were left for the ESP module.

Between CM3 and CM4, there were no issues with the overall functionality of the WiFi module. However, the latency of the module in sending and retrieving data to/from the database required some improvements. The idea to install a buzzer to the ESP circuit and alert the train operators in case of warnings was brought up and tested. However, it was seen that while writing to the database introduced a 3-second latency, reading from it required 6 seconds, adding up to 9 seconds in total for each read-write sequence. Despite all efforts, the problem persisted and the idea was abandoned. However, the buzzer circuitry is still on the device and can be activated with uncommenting a few lines of code, for the case that the latency problem may be solved in the future. This element not working did not constitute a problem since in ECTS Level 3 all communication to trains is done by the dispatcher via radio.

There are possible risks involving WiFi communication in this project, such as the connection strength of the WiFi or the capability of the module to connect to an external database on the internet. These problems could be solved by using better WiFi sources, trying software solutions to increase performance, or changing WiFi modules in the worst case. A GSM-R connection is assumed on the train, which may be lost in certain parts of the tracks, which may be resolved by installing signal amplifiers in remote areas.

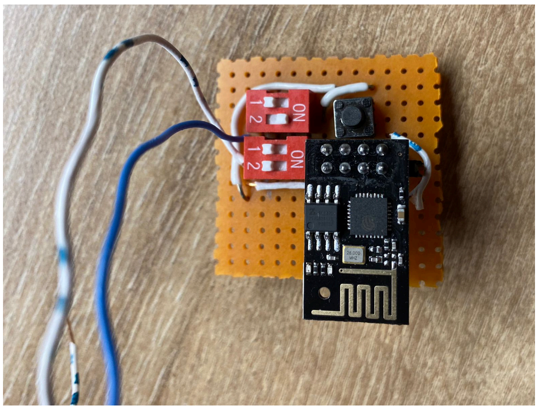

Figure 10: ESP8266 Module

4.2.3 Configuration of the GPS Module

The signalization of a railroad is mostly possible by achieving localization of trains on the track and observing the respective locations of the trains to detect any possibility of collisions or regulation violations. For this purpose, Savronik has developed a signalization technique based on using GPS to find the locations of the trains on the track, but GPS signals may not always be available on every part of the track and in the case of missing a signal the GPS system does not show the robustness to redetect the location easily and accurately. Therefore in this project, GPS is used as a support data supplier for the RFID tags like an interpolator that fills the gaps between each data point which is sent when the train passes on top of an RFID tag.

The GPS module requires no initialization and starts transmitting messages immediately. The configuration of the module and its communication interface was already completed up to CM3, where a working prototype was demonstrated. There are no significant improvements regarding this module between CM3 and CM4, as the module performs as expected.

Nonetheless, there are a number of issues regarding the GPS module. For instance, the module sometimes fails to lock onto a satellite, especially when indoors or near a large building. Usually, there were no problems with this while testing but for implementation on trains, there will probably be areas on the track where the GPS signal will be lost, depending on the current positions of the satellites. Similarly, sometimes the module outputs an incomplete timestamp, even if it is locked onto a satellite. The reason for this is still a mystery, but the software was later redesigned to accommodate this error.

Implementation of all hardware modules are given in Figure 11.

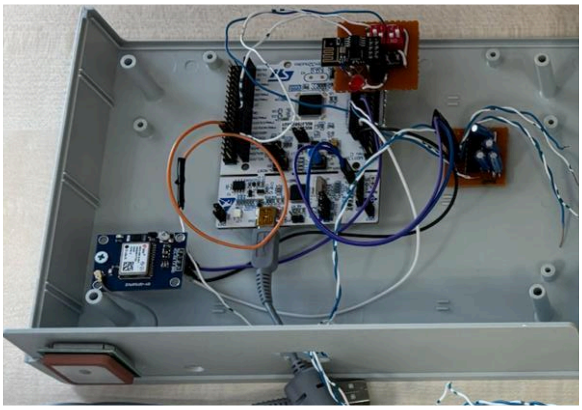

Figure 11: Implementation of all hardware modules

4.2.4 Establishing TCP Communication Channel

The data transmission between devices in the system is facilitated through a generic TCP Wifi channel by using the Firebase cloud services of Google. A WiFi module was configured on a development board within the train for this purpose. Additionally, the database computer and GUI computers are WiFi-enabled to ensure seamless communication with other system components. The establishment of the WiFi communication was carried out with programming the ESP board in C++ with the help of a Firebase library. Only programming the client was enough and there was no additional coding needed for Firebase server once the ESP board can log-in the server with a private link. This method was particularly more practical when compared with our previous solution which was establishing an MQTT server. This way, the communication channel is safer and more resilient, plus there is no need for selecting specific ports and adjusting waypoints as Google already handles them.

4.2.5 Creating the Database System

Designing a database using Google Firebase to gather data from onboard development boards is a key achievement in the project. This configuration collects data from the trains, categorizing it by timestamps or predefined tags set through a GUI interface. The final data package has the following format:

Devices: *GPS, MC, RFID*

Data*: Timestamp, Train ID, Expedition ID, Latitude, Longitude, Speed, Last Balise ID*

Ex*: "19.02.2024.13.22.00, TR02, E4, 11401.84073, 5109.02623, 0.4, 30 08 33 B2 DD D9 01 40 AA AA AA AA".*

To facilitate effective data acquisition from numerous devices on the trains, the design incorporates a Firebase Database. This method is crucial for sustaining system performance and ensuring data integrity. To counter data overflow and optimize management, automated backup and reset routines are included in the system.

Given the project's connection with the government's railway system, ensuring strong security measures in the Firebase Database is essential. This is especially important due to the sensitive nature of the data handled by the Firebase Database system. Security protocols for accessing the database are enforced in line with the project's scheduled timelines. Usually, third-party providers are discouraged for such projects, therefore a final product would require a separate, protected server to host the database.

A collision detection algorithm is installed to the Firebase cloud functions so that it can operate independently as the cloud receives new data. There are two warnings: proximity warning, and speed warning. Proximity warning is given if two trains are in adjacent blocks on the track. Speed warning is given if a train exceeds a threshold of speed, in this case it was 60km/h. Both warnings can be given at the same time as well. If there are no warnings at a time, the warning section of the database shows '0,0'. The warning messages are formatted as:

Proximity Warning*: Train ID1, Train ID2, Block Location of Train1, Block Location of Train2, Warning Type*

Ex: *"TR01 TR02 300833B2DDD9014077777777 300833B2DDD9014066666666 proximityWarning, 0"*

Speed Warning: *Train ID, Block Location of Train, Speed in km/h, Warning Type*

Ex: *"0, TR01 300833B2DDD9014077777777 60 speedWarning"*

If any safety concerns happen on the track the database turns on the warning flag, alerting the GUI and the dispatcher monitoring it. The dispatcher will be communicating with both trains involved via radio to alert them and take the necessary precautions. This procedure is in line with ECTS Level 3 standards mentioned before.

4.2.6 GUI Design

The user interface of the project is designed using the PyQt5 module of Python which enables the usage of practical and adaptable functions for user interface design. The GUI visualizes the data which is pulled from the database using libraries of Firebase. The data has the format mentioned in the previous section.

The interface starts with an authentication window where a username and password is required from the user to have access to the system. The usernames and passwords are stored in the local code where the users that can have access to the system can be easily registered. The "Login Window" of the GUI can be seen from Figure 12.

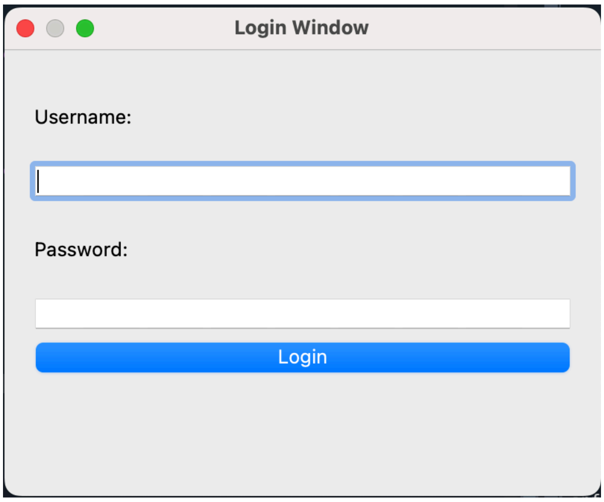

Figure 12: Login Window of the GUI

After the authentication is done and the user has access to the system, a desired station for surveillance can be selected from the given options. Creating a new station can be done by editing the csv file that contains information about a given station. This operation was not handled in an online database because the track information does not change regularly and therefore station registration can be done online. The "Station Selection Window" of the GUI can be seen from Figure 13.

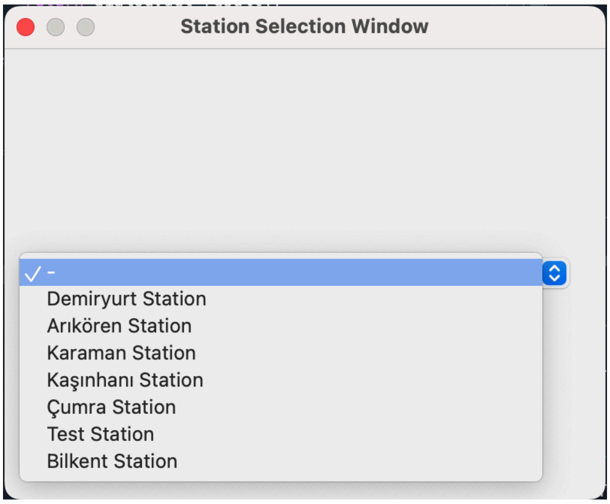

Figure 13: Station Selection Window of the GUI

After selecting the station that will be investigated, the main window of the GUI shows up. The window consists of a large graphical interface that contains the tracks colored in green and red, representing their occupancy and yellow dots with names of the trains below them. Under the interface the station information resides for any necessity for addressing quantitative information about the trains. In the case of an emergency situation, which are called as violations in our project, a red alert appears indicating the type of the warning and details of the warning as it is described above. The main GUI screen can be inspected from Figure 14.

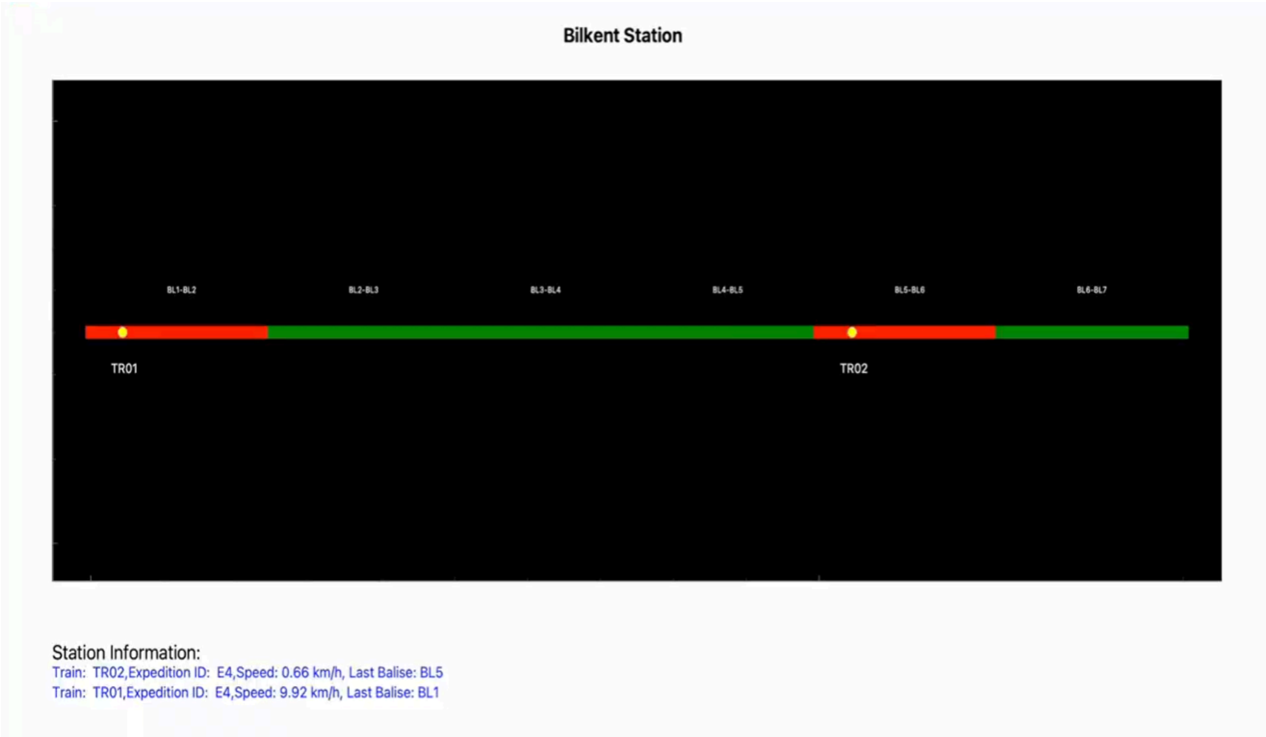

Figure 14: Final GUI Design

PyQt5 can be used for drawing graphics with the assistance of Python libraries like Matplotlib, turtle, etc. The tracks are drawn using analytical functions and parametric equations to minimize the real model with an acceptable ratio. The texts located on the various locations of the user interface, the color of the tracks, and train indicators dynamically change according to data in the database. The GUI accesses the database using specific libraries for communicating with Firebase.

Before CM3, the GUI was mostly completed. The only functionality added to the GUI was the display of current warnings, which was recently added to the project.

For the user interface, there are several possible risks throughout the software development procedure. A possible risk source is about achieving a certain level of robustness while communicating with the database. The TCP/IP implementation highly depends on the quality and properties of the wireless network used for data transactions with the database. The delay of printing the visualizations of the trains required a fast internet connection where it was impossible to install a portable wifi adapter inside the test cars therefore the tests were conducted using the wireless hotspot of the mobile phones.

4.2.7 Risks and Mitigation

Throughout the project, several risks were encountered. One significant risk was data transmission reliability within the onboard embedded device work package. There was a potential for data loss or corruption during transmission. Another risk was the accuracy of GPS data from the GPS module work package. Inaccurate GPS data could adversely affect train localization. We addressed this by conducting extensive testing and calibration of GPS modules and following a linear path during testing of the system. Lastly, system integration issues posed a risk within the software system work package, particularly the difficulty in integrating different system components (database, GUI, onboard devices). We mitigate this risk by following modular design principles and conducting integration tests at each development stage.

5. RESULTS, DISCUSSIONS, AND FUTURE DIRECTIONS

During the initial phases of the project, several functional and non-functional requirements were identified to measure the extent of the project's success. In this section, the alignment between the desired requirements and the project outcomes, as well as further discussions and future improvements, will be addressed.

5.1 RESULTS

Throughout the project, two onboard devices are capable of performing several tasks simultaneously. Specifically, both onboard devices can communicate with both passive and active components of the underlying system. The onboard devices successfully transmit critical information about the trains to the data center. As shown in Figure 16, this information includes the expedition ID, unique train ID, GPS coordinates, and the latest balise detected. This achievement satisfies the requirements SR-FUNC-10, SRC-FUNC-20 and SRC-FUNC-40.

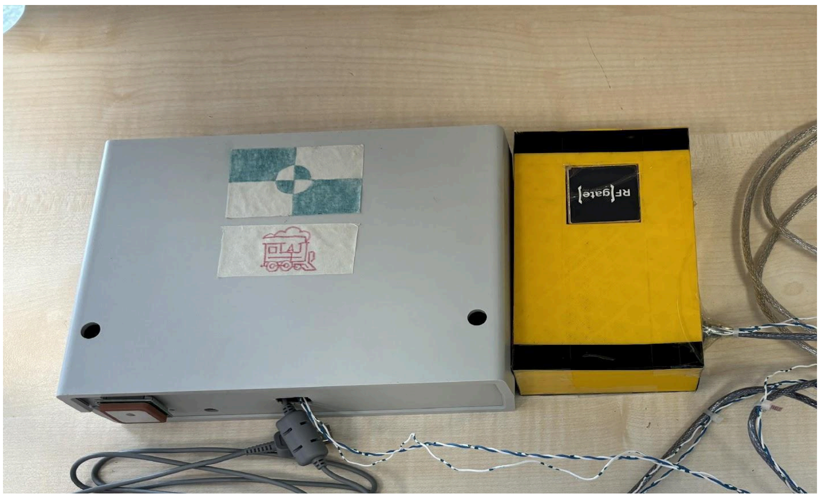

Figure 15: Complete Hardware Set-up

Hardware set-up consists of two closed boxes, one for the RFID package and one for the main box with the development board. The size of the RFID package is 100 x 160 x 45 mm and the size of the main box is 96 x 158 x 53 mm (indicated in Figure 15) which is designed to fit easily during any installment to the train, complying with requirement SR-SW-180.

The onboard device resided inside the trunk of the test vehicle, where the separate containment with the RFID reader and the antenna were installed to the car's trunk, facing downwards. The approximate height of the antenna was around 40 cm from the ground, though it was observed that anywhere higher than 25 cm and lower than 70 cm yields adequate reading performance. Furthermore, the group has conducted static tests for measuring the range of the RFID device and it is observed that the reader can detect balises up to 2.5m, which is aligned with the requirement SR-RNG-170. This variable is also limited by the logistics of the testing environment, where the test vehicle's trunk height and other suitable surfaces were the determinants. Still, this is a close imitation of a train's height, as disclosed by the company mentors.

The casing of the RFID reader and antenna is designed by our group and printed with a 3D printer using PLA material. The casing of the main onboard device is made of hard plastic obtained from outside due to its convenience in terms of size, roughness and availability of holes for power and communication connections.

The power consumption of the system has been carefully analyzed. The RFID module, which directly draws power in parallel with the processor, has a steady current consumption of 130 mA. The GPS module and ESP module, both drawing 45 mA and 50 mA respectively, receive their power via distribution through the processor. The processor itself typically consumes 100 mA, although these values can occasionally fluctuate. When all components operate simultaneously, the system's total current requirement is approximately 325 mA. Given that a 5V input is provided to the system, the total power consumption is calculated to be around 1.625 Watts. However, considering potential fluctuations in the processor's consumption, provisioning for up to 400 mA ensures reliable operation under varying conditions. Consequently, with a 5V input, the system's power consumption is thus designed to accommodate up to 2 Watts, ensuring sufficient power availability to run all modules efficiently and simultaneously. Given modest power requirements of 5V and 400mA (2 Watts), the system with all the underlying modules and sensors can easily operate with the train power outlet which complies with SR-PW-190 and SR-PW-200.

However, as many unexpected incidents may occur, the system has the possibility to shut down temporarily due to random incidents like weather, vibration signal loss and current fluctuations. In case of such scenarios, the hardware team has installed manual overriding capabilities to address these issues to keep the system operational and ready to perform effectively, satisfying the requirement SR-SAF-210.

The entire system costs around 18.000 TL. The most of the expenditure has been done for two RFID Readers + Antennas which took around 14.000 TL. The rest of the money was spent for the development board, GPS module, Wi-Fi module and the RFID tags with additional small spendings on cabling, casing, soldering, connectors, etc.. Although the total spending is much lower than the budget of 40.000 TL specified by SR-CST-150, this raised to question whether the system could be improved by purchasing a better antenna and reader to increase the RFID communication performance, but the system already works with the desired functionality and the group left this improvement to future works and saves 20.000 TL from the budget.

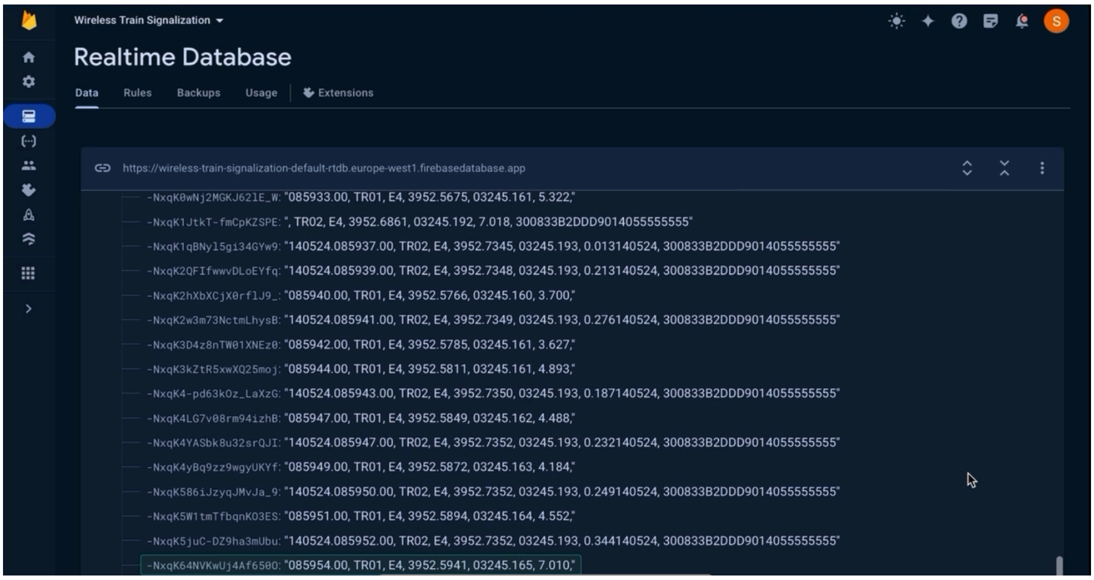

Figure 16: Database at Operation During Test

As indicated by Figure 16, the devices also successfully receive and propagate GPS information, which is critical for the signalization and warning stages. The critical information displayed in the database, as Figure 16, are not received spontaneously, but also stored in accordance with SR-FUNC-090. An offline program written by the team estimates the total deviation from the ground truth points to be less than 4 meters. This measure is verified using only the balise points since their absolute truth was known. However, due to the number of balises and the homogeneity of the test area, we have realistically interpolated the results to the general area. Though our results show a maximum deviation of 4 meters, this deviation may be heavily influenced by the latency between the RFID reader and the GPS module, as they must be synchronized to obtain a perfect measurement. These results indicate that we satisfy the requirement SR-FUNC-140.

Not only receiving and storing the data, but maintaining the security and integrity of the critical information is also an important topic. For this purpose, the database is safeguarded with a private key that requires the user to obtain for accessing the critical information. This service is supplied by Google itself and can be further improved by the company's additional methods. Yet, even this kind of precaution allowed the group to prevent any mischievous data corruption or unauthorized access which may compromise the project's success. This shows that the requirement SR-SAF-230 is satisfied.

The system is tested on the track beginning from the Odeon to almost guardhouse (university entrance), and 7 different balises are evenly placed along this track to capture the movement of the trains over a large area. As indicated in Figure 17, the placement of the tracks allowed for effective measurement of the system's performance as described in requirement SR-FUNC-120. Each balise is approximately 40 meters apart from the next. Given the GPS accuracy of 4 meters, this arrangement of balises helped in successfully evaluating the performance of the entire localization system, thus ensuring that requirement SR-FUNC-080 are satisfied. Additionally, the quiet and trafficless track next to the Odeon (Figure 17) allowed for the experiments to be conducted safely without the intervention of any external vehicles or individuals, satisfying safety requirements.

Figure 17: Test Track for CM4

Furthermore, the balises that are placed at the critical points are shown in the same figure. The design of the balises underwent several iterations, taking into account the possibility of a car smashing them. The group developed an interesting method of placing sponges underneath the wooden plates that hold the RFID tags to ensure they are not easily broken when a car passes over them. This method has proven effective, and the balises have become resistant to extreme pressures, ceasing to break, which further improved compliance with the safety regulations specified in the requirement SR-ENV-240.

The performance was influenced by a design modification to the test balises, implemented to address the low reading accuracy observed in pre-CM3 testing. To improve this, the heights of the balise tags were slightly raised to prevent contact with the ground, while positioning the reader antenna at the height equivalent to a car's trunk. This adjustment significantly enhanced reading accuracy, though it did not achieve perfection. Contributing factors to this issue include the alignment between the car and the balise, which varies with the driver's navigation—unlike trains, where track alignment ensures consistent tag and balise positioning.

Figure 18: A Balise with Sponge Installments for Safety

Each balise has its unique ID, ranging from 1 to 7. However, these ID numbers are encoded onto the RFID tags in a way that minimizes the probability of error from a wrong detection. This is achieved by encoding repetitions of the integer ID onto the balise so that, in the event of a misdetection, the balise can still read the data with high probability. Below is an example of the ID for balise number 1.

300833B2DDD901401111111l

The previous numbers are technical details of the configuration, and the last 8 figures represent the corresponding balise number, repeated eight times to minimize mis-detection, complying with requirement SR-FUNC-030. Additionally, each train also has a unique ID stored in its processor so that after initialization, both the database and the GUI automatically recognize the correct train, satisfying requirements SR-FUNC-050 and SR-FUNC-060.

After establishing all the functionalities required for the onboard devices, such as GPS localization, RFID & Wi-Fi communication, and programming functionalities, along with the coding of the database, GUI, and setting up the environment, rigorous tests were conducted to showcase the performance of the entire system.

Figure 19: Two Trains Displayed with the Critical Information at GUI

Figure 19 demonstrates an example test where two trains are tracked simultaneously. The yellow dots show the exact location of the trains at that current time using GPS, while the red regions indicate which tracks the trains currently occupy with the help of communication between the RFID reader and RFID tags. To present an accurate mapping of the trains, ensuring they do not leave the tracks due to GPS errors, the noisy measurements taken from the GPS are projected onto the space spanned by the tracks in a way that minimizes tracking error. From Figure 19, below the GUI, it can also be observed that critical information (e.g., Train ID, Expedition ID, Speed, and Balise ID) is provided to the user in real time. This shows that the data is accurately read by the onboard device, transmitted and stored in the database, then retrieved by the GUI from the database to be displayed to the end user. Accomplishing all these steps further demonstrates that the results satisfy requirements SR-FUNC-040 and SR-FUNC-070.

Furthermore, the system is expected to not only track the current state of the trains and record critical information but also create alarms in case of an emergency where trains may have an accident. There are two possible errors that our group has defined with the advice of the company. The first one is the proximity error, which alerts the end user when two trains are too close to each other, and the second one is the speed warning, which activates when a train exceeds a predefined speed limit.

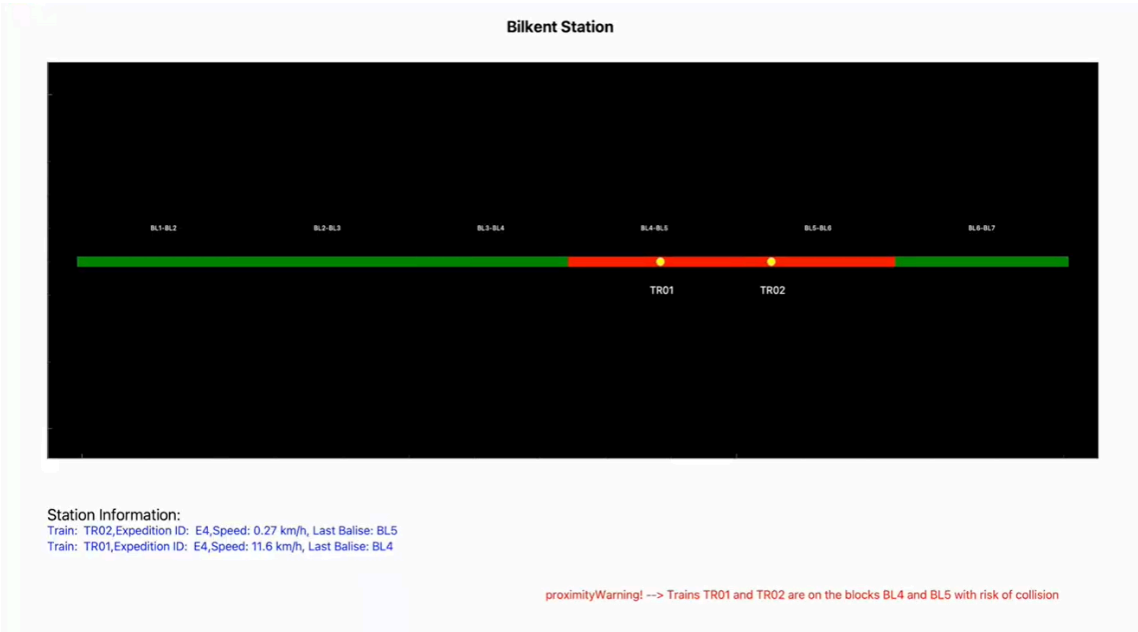

Figure 20: Proximity Warning on GUI

In the scenario shown in Figure 20, the second train starts the expedition earlier but eventually comes to a halt between balise 5 and balise 6 due to a fictional reason. Unaware, the first train starts the expedition from the same track, heading towards the stationary second train. Thanks to the alerting system, the end user receives a warning on the GUI when the trains are too close to each other, such that they occupy neighboring blocks. The proximity warning, indicated with red text, appears in real time and provides information about the names of the trains and the last balises passed.

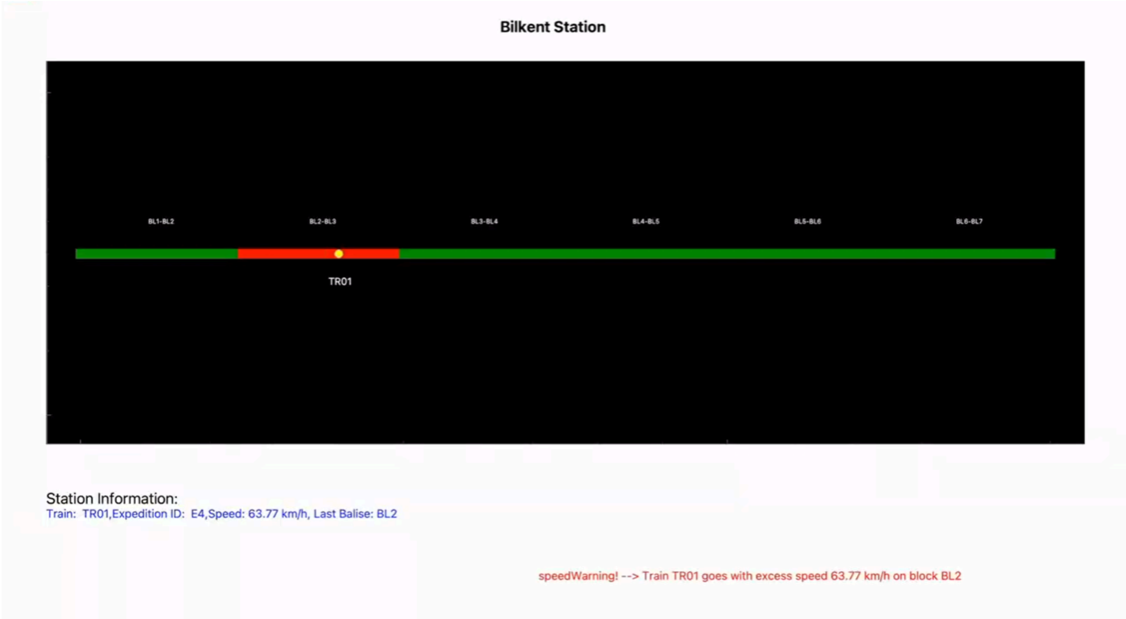

Figure 21: Speed Warning on GUI

The other warning type mentioned previously is the speed warning, which is intended to prevent a train from exceeding the speed limitations standard for safe travel. In Figure 21, the first train begins its journey from the starting point, but after passing the second balise, it starts to rapidly accelerate and reaches a speed of 63.77 km/h. When the speed exceeds the defined threshold (50 km/h for our small demo), the database recognizes the abnormality and raises a speed warning from the cloud. This warning is then read by the GUI and displayed to the end user to ensure safety. Accurately identifying and reporting these warnings to the end user demonstrates that the group has successfully fulfilled the requirements SR-FUNC-100 and SR-FUNC-110. The balise reading, retrieved while the speed warning was raised at 64 km/h, also demonstrates that the group satisfied the requirements SR-SPD-160, where the RFID reader is supposed to take measurements up to 50 km/h.

Figure 22: Warnings seen on Firebase Database

In the database, the aforementioned warnings are displayed as shown in Figure 22. When a speed warning is raised, the database displays the train that exceeds the limit, its current speed, and the last balise it passed. The system can simultaneously display all warnings, should such a situation arise. If there are no warnings at a time, the warning section of the database will show '0,0', indicating that there is no unusual activity.

The group followed the relevant guidelines of safety regulations and railway-specific standards set by the governing bodies (Turkish Standards Institute, Ministry of Transport and Infrastructure) as much as possible. Firstly, TS EN 50159-2/AC was adhered to, ensuring the integrity and security of safety-related communication within the transmission systems by including the private key authentication for database access and using 2.4Ghz encrypted WPA4 (Wi-Fi Protected Access) communication protocol. Secondly, TS EN 50128 guidelines were followed, specifying the procedures and technical requirements for the development of software for railway control and protection systems. [17] The group tried to adhere to TS EN 50128 by ensuring the functionality of each individual module through satisfying functional requirements SR-FUNC-XXX. Finally, TS EN 50129 was tried to be applied by focusing on the design, implementation, and maintenance of safety-related electronic systems for signaling by implementing the manual override capabilities and reducing localization error (through using GPS and RFID communication simultaneously). There are of course several other important guidelines that need to be followed for a complete industrial product such as TS EN 50155 that specifies the requirements for electronic equipment used on rolling stock, including environmental conditions like temperature, humidity, shock, and vibration. [17] However, for a small scaled project directed by undergraduate students, some of the guidelines set by Turkish Standards Institute are partially accomplished which aligns with requirement SR-SAF-220.

5.2 DISCUSSIONS AND LESSONS LEARNED

At the end of the project, the group successfully implemented a complete system with proper casing, packaging, integrity, and presentation. The process starts with local passive balises read by onboard devices responsible for processing various information sources, communicating with the satellite, and transmitting the finalized data package to a cloud system. In the cloud, the data is stored and processed for a safety-critical warning system, later retrieved by an informative GUI presenting all results to the end user. The project itself presents an MVP product that can be improved and scaled for real-life train signalization problems.

Despite our initial hesitations about using a cheaper alternative for the RFID reader and antenna due to budget limits, the RFID detection range was particularly impressive, reaching up to 3 meters. The entire communication pipeline also performed well, starting with accurately reading stationary balises, then combining GPS position data with other critical information, and transmitting it to the database and GUI. The GUI accurately displayed the entire track with real-time train positions and critical information, compatible across Windows, MacOS, and Linux. The GPS communication also succeeded, with a small deviation of 4 meters, sufficient for our operations.

On the other hand, there are aspects of the project that didn't go very well. First, the system is not fully waterproof due to affordable material selection. Additionally, the RFID reader's accuracy decreases at high speeds, forcing us to reduce the maximum operational speed requirement from 80 km/h to 50 km/h before Committee Meeting 4 for high accuracy. During experiments, the initial testing route was too large, leading to issues with patrolling and theft of balises, prompting us to choose a smaller area. We also hoped to implement the system on actual trains, but due to several constraints, we had to conduct our tests with cars. There was also some latency in the system due to the quality of the Wi-Fi module and the clock rate of the processor which are both critical in real-time systems. But this latency did not prevent the system from being operational and we still successfully completed the described functional requirements.

Some of these issues could be handled differently. For example, using a better material than PLA for the casing, with better insulating properties, could ensure a waterproof system. When the PLA print is observed closely, very small holes can be seen due to the quality of the 3D printer and materials. Additionally, a better RFID antenna could be purchased to allow the cars to travel at much higher speeds while maintaining accurate balise reading. However, we were unsure about the compatibility of some of the better RFID readers, so we didn't want to risk spending a large portion of our budget on a module that wasn't compatible with our system. Furthermore, choosing a better Wi-Fi module and processor can greatly improve the slight latency. Despite the 4-meter deviation, a better GPS module can also increase the precision of the localization, and upgrading these modules wouldn't require as much budget as upgrading the RFID package.

If another group were to start this project later, our recommendation would be to place more emphasis on carefully selecting sensors, even if it means avoiding the cheapest options. We realized that sometimes purchasing cheap components can be costly in the long run, as they can break easily or not perform as well as expected. For example, shortly before CM4, the coaxial cable of one of the RFID readers broke, jeopardizing the entire project since RFID reading was critical. We didn't have an extra coaxial cable at that time, so we had to go to Konya Sokak to purchase a new one, which was not easily found, and fix it. Choosing the right antenna is also critical, so we recommend that any future group properly research the beamwidth and radiation patterns of the antennas for the best selection. Overall, the main emphasis should be on selecting the right components because starting correctly ensures smoother progress with minimal problems.

Even if everything goes well and a group makes all the right decisions, some conditions can still be out of their control. For example, weather conditions can be a significant challenge. This project requires outdoor testing with multiple cars, and prior to CM3, the group had to conduct tests in snowy, harsh weather, which was beyond their control. Furthermore, testing required balises to be placed on roads, but traffic and people curious about the square objects on the road (balises) made it difficult for the group to conduct the tests. This led to a lot of intervention, causing some of the balises to be broken or stolen. Additionally, the broken RFID antenna cable was also beyond the group's control, as the incident occurred during testing, where vibrations caused by the movement of the cars contributed to the damage.

A major surprise that the group encountered during the project involved the balises. Initially, the wooden plates holding the RFID tags were placed directly on the ground, but for some reason, the RFID readers were failing to detect the balises. By chance, a group member slightly lifted the plate above the ground, which caused the readers to detect the balises with very high speed and range. The group realized that the wet ground underneath the plates was distorting the electromagnetic reflection from the balises, preventing detection. Consequently, the group decided to mount sponges underneath each balise to elevate them slightly. This addition proved to be an important improvement, as the cars passing over the balises were no longer breaking them due to the sponges' flexible structure, which absorbed the energy.

Moreover, initially, we anticipated the RFID reader and antenna to perform poorly due to their low cost, which was all our budget could afford at the time. However, the RFID module later proved to be effective, covering a long range with high-frequency readings. The only downside was its performance at high speeds, specifically when the car speed exceeded 70 km/h.

Most projects encounter problems with effectively and sturdily soldering and installing cabling. Otherwise, as the project becomes more complex, the chance of cables touching each other and causing short circuits increases. However, acknowledging this possibility, we properly isolated the cables from each other and soldered some parts of our system to circuit boards to prevent incidents where our components could burn. This preventive measure turned out to be effective, as expected. Additionally, we considered proper casing for the system necessary. Our 3D-designed casing successfully protected the RFID package installed behind the car, even at high speeds. Another important consideration was the adaptability of the GUI. One of our group members designed the GUI to allow easy changes to the tracks, use different setups, and authenticate with different users. This adaptability proved helpful for debugging and updating the GUI during pivotal points in the project.

For completing all the required tasks, we were not initially equipped with all the necessary skills. During the implementation of the safety-critical warning system in Google Firebase Cloud Functions, our group member responsible for this task had to learn JavaScript from scratch to be able to contribute effectively to the project. Additionally, none of the group members knew how to do 3D design for the casing of the RFID module and antenna. Therefore, one of the group members attempted to design the casing with very little prior knowledge.

The lack of knowledge needed for many tasks was not limited to these examples. Our hardware team had to learn various concepts about embedded programming, such as how buffers work in a processor, to efficiently process information coming from several peripherals simultaneously and minimize latency. Additionally, there were always programming challenges, bugs, and hardware-specific problems, requiring each group member to equip themselves with new skill sets. This was mainly accomplished by reading coding forums, watching YouTube videos, studying datasheets, seeking advice from mentors, and using generative AI for debugging and brainstorming solutions.

5.3 FUTURE DIRECTIONS

The potential future directions of this project involve substantial enhancements in both hardware and software components to elevate the reliability and effectiveness of train signalization systems. In terms of hardware, the adoption of superior materials that better withstand the vibrations and environmental conditions typical in rail transport is crucial. This includes upgrading the physical cover and power systems of the devices to ensure durability and consistent operation under varying conditions. Additionally, the selection of advanced hardware components such as RFID antennas, GPS modules and antennas, and WiFi modules will significantly improve the accuracy and persistence of signalization, which is essential for maintaining continuous communication with the train control systems.

On the software front, the integration of an Inertial Measurement Unit (IMU) could greatly enhance the system's capability by providing reliable data interpolation in areas where GPS signals are weak or erroneous. Moreover, the development of more sophisticated software algorithms for collision prevention could be generalized to cover a wider range of scenarios, enhancing safety across more complex railway networks. An important aspect of software improvement would also involve the creation of a user-friendly online interface, which requires secure authentication mechanisms. This interface would facilitate easy access and management of the signalization system, potentially broadening the scope for national implementation and international export. By focusing on these strategic enhancements, the project stands to not only improve national railway safety but also contribute positively to the economic reputation through potential exports, aligning with the broader goals of technological advancement and infrastructure resilience.

7. DETAILED EQUIPMENT LIST

Table 2: Detailed Equipment List

Requirement	Product Model	QTY	Unit Price (TRY)	Subtotal (TRY)	Way to Obtain
Development Board	Nucleo-L476RG	2	880.82	1,761.64	By purchase
GPRS Module	GY-NEO6MV2	2	140.00	280.00	By purchase
WiFi Module	ESP 8266	2	48.00	96.00	By purchase
RFID Tag	T100	10	67.59	675.90	By purchase
RFID Reader	RGR02	2	7,257.6	14,515.20	By purchase
Cloud Services	Google Firebase	-	-	-	By purchase
Total Cost				18,188.74	

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